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# Electrospinning and Its Applications in the Food Sector

**Ganga A [a++*], Divyashree M [a++] and Samit Dutta [a#]**

[a] *College of Food Processing Technology and Bio-Energy, Anand Agricultural University, Anand, Gujrat, 388110, India.*

***Authors' contributions***

*This work was carried out in collaboration among all authors. Author GA designed the study and wrote the first draft of the manuscript. Authors DM and SD edited the manuscript and collected data. All authors read and approved the final manuscript.*

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## ABSTRACT

Electrospinning is an advanced nanotechnology-based technique that enables the fabrication of ultrafine fibers with unique physicochemical properties. In the food sector, electrospinning has emerged as a promising tool for encapsulating bioactive compounds, improving the stability and controlled release of nutrients, analysis of different food components, pesticides, antibiotics, production of different food packaging systems includes antibacterial packaging, antioxidant packaging and intelligent packaging. This technology allows for the development of biodegradable, functionalized, and nanostructured materials that can enhance food quality, safety, and shelf life. Additionally, electrospun nanofibers can be used to incorporate antimicrobial agents, probiotics, and flavour compounds, offering novel applications in food preservation and fortification. However, challenges related to scalability, regulatory approval, and material selection remain critical barriers to large-scale industrial adoption. This review provides a comprehensive overview of electrospinning principles, techniques, Factors affecting the process, and applications, highlighting its future prospects and limitations.

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[++] *Research scholar;*
[#] *Professor;*
**Corresponding author: Email: gangaachuthan99@gmail.com;*

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*Keywords: Electrostatic spinning; food; packaging; encapsulation; nanofibers.*

## 1. INTRODUCTION

Sir William Gilbert made the initial discovery of electrostatic spinning in the late 15th century (Mirjalili & Zohoori, 2016). It is a process in which a polymer solution is involved, and the solution moves through the needle, because of the electrostatic force given by the voltage source, the solution overcome the surface tension eventually thin polymer fibres were formed. The fibres are further stretched to form nano or micro fibres and which will finally get collect on the collector (Mishra *et al*., 2018). Even though electrospinning has been known for centuries on recent years it is getting more importance in different sectors including food and pharmaceutical sector because of its versatility, simplicity, and affordability.

The technology of electrospinning is continuously being created with food applications. There are regulations and criteria for choosing and using raw materials for electrospinning (Ewaldz & Brettmann, 2019). Nanofibers made from natural and synthetic polymers, for instance, must exhibit exceptional spinnability, biodegradation, and biocompatibility qualities (Zhang, et al., 2023). Biocompatibility guarantees that the finished product is secure and innocuous for people (Zhou *et al*., 2023). Raw materials must have specific molecular weight and chain length to be electrospinnable. Functionality: To satisfy the needs of the application, raw materials should possess specific functions, such as UV protection, antioxidant properties, and antibacterial properties (Zhang & Yu, 2016). Auxiliary materials can be added to achieve these functional ingredients, but the quantity added must be kept within a specific range to guarantee the final product's steady performance. In general, loading techniques have improved as a result of advancements in electrostatic spinning technology. The ingredients for electrospinning should selected carefully, because they should not be toxic in nature, it should possess good spinnability and stability, other than that, material with some functionalities like antioxidant activity, antimicrobial activity are more preferable (Zhang & Yu, 2016).

This paper focuses on the primary workings and advancements of electrostatic spinning technology in food applications, including food packaging, the transmission of food bioactive components, and production of meat analogues and food component analysis (Davoodi, et al., 2021).

## 2. CLASSIFICATION OF ELECTROSPINNING TECHNOLOGY

Electrospinning is a versatile nanofiber fabrication technique that can be classified based on various criteria, including the setup design, processing method, and fiber formation mechanism. The two primary classifications are needle-based and needleless electrospinning, where the former uses a controlled nozzle for fiber production, while the latter enables large-scale fabrication using a free surface of the polymer solution. Another important distinction is between solution electrospinning and melt electrospinning, where solution-based methods involve polymer dissolution in a solvent, while melt electrospinning eliminates the need for solvents by using heat to liquefy the polymer. Additionally, electrospinning can be categorized as single-jet or multi-jet, depending on the number of jets used to enhance productivity. More advanced techniques, such as coaxial and triaxial electrospinning, allow for the production of complex nanofibers with core-shell or multilayered structures, enabling enhanced functionality for biomedical, filtration, and smart material applications. Understanding these classifications helps in selecting the appropriate technique for specific material properties and industrial applications.

### 2.1 Needled Electrospinning

Prior to electrospinning, the polymer is dissolved in a solvent. Once the polymer is fully dissolved, the syringe tube for electrospinning is filled with the polymer fluid. The hollow needle is linked to the DC power supply's positive terminal, while the metal collector is connected to the negative terminal as shown in Fig. 1. Needle electrospinning is a widely used technique for producing polymer nanofibers with controlled morphology and properties. It involves the application of a high-voltage electric field to a polymer solution or melt, which is ejected through a needle to form ultrafine fibers. This method allows for precise control over fiber diameter, alignment, and composition, making it suitable for various applications in biomedical engineering, filtration, sensors, and functional textiles (Jiang et al., 2024).

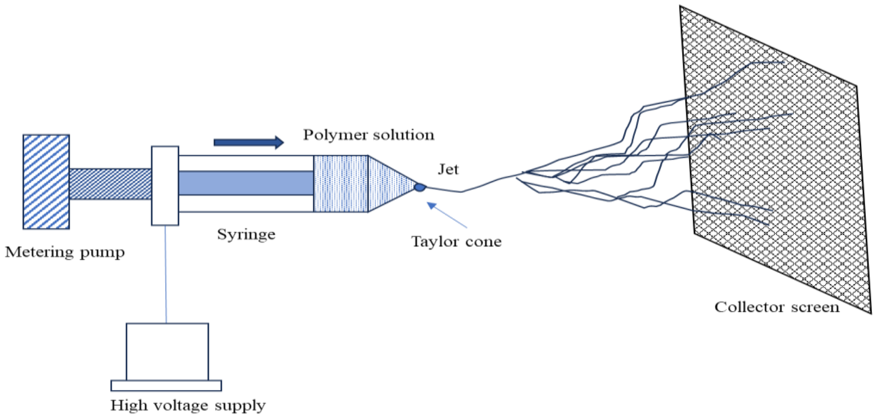


**Fig. 1. Needled electrospinning**

### 2.1.1 Coaxial electrospinning

Coaxial electrospinning is utilized to create core-sheath fibres. A coaxial spinneret made up of an outer and inner needle is frequently employed as shown in Fig 2a. Electrospinning in a coaxial manner can create fibres from core-sheath, hollow, different solution pairs, and functional fibres, that might contain particles. Coaxial electrospinning is commonly used to create hollow fibres, which usually have the real material as the shell and a temporary substance as the centre. Oil is frequently utilized as a temporary substance depending on the post-spinning procedure because it is comparatively easier to remove than other materials with a higher molecular weight (Begum & Khan, 2017).

### 2.1.2 Tri-axial electrospinning

In this case, three different solutions can be used to produce electrospun fibres. The spinneret has three concentric discs inside, which produces compound Taylor cone as shown in Fig 2b. It is possible to create triaxial fibres with different mechanical strengths and hydrophobicity.

### 2.1.3 Multi-needle electrospinning

Multi-needle electro-spinning involves increasing the number of needles, and it is the most straightforward method of boosting productivity. Needles that are attached to a high-voltage source and spinning solution is pumped to the spinneret assembly using a syringe pump. In the same dual spinneret configuration, two distinct sets of spinning solutions can be independently pumped as shown in Fig 2c. Continuous electrospinning requires a high voltage because of the vast bulk of spinning solution provided. Disadvantage of this method include, variable fiber size distribution, unstable electric field strength, clocking at the needle tips, and cleaning issues of many needles. The repulsion from neighbouring jets in multi-needle systems remains a problem even when a high flow rate of 1–18 mL/h is achieved (Khalf & Madihally, 2017).

### 2.1.4 Gas jet electrospinning

The process of gas jet electrospinning combines airflow around the spinneret with electrospinning. The airflow's tangential forces contribute to the development of the nanofiber and the construction of the Taylor cone on a drop of mixture as shown in Fig 2d. Small diameter fibers have been created using the extra stretching power that the gas jet offers. The electrospinning process is more efficient when the applied electric field forces and air flow are combined, and air flow speeds up the solvent's evaporation from the solution. Hyaluronic acid can only be spun in its natural state in this manner (Lin *et al*., 2009).

### 2.1.5 Conjugate electrospinning

In conjugate electrospinning the solution is separately delivered by syringes to two or three spinnerets. The receiver is a rotating drum controlled by a stepping motor as shown in Fig 2e. The fibres from the two or three oppositely charged electrospinning spinnerets were collected and stretched by the drum receiver with a constant speed. The nanofiber yarns, which can be produced by this, are dried under vacuum at room temperature (Kiyak *et al*., 2014).

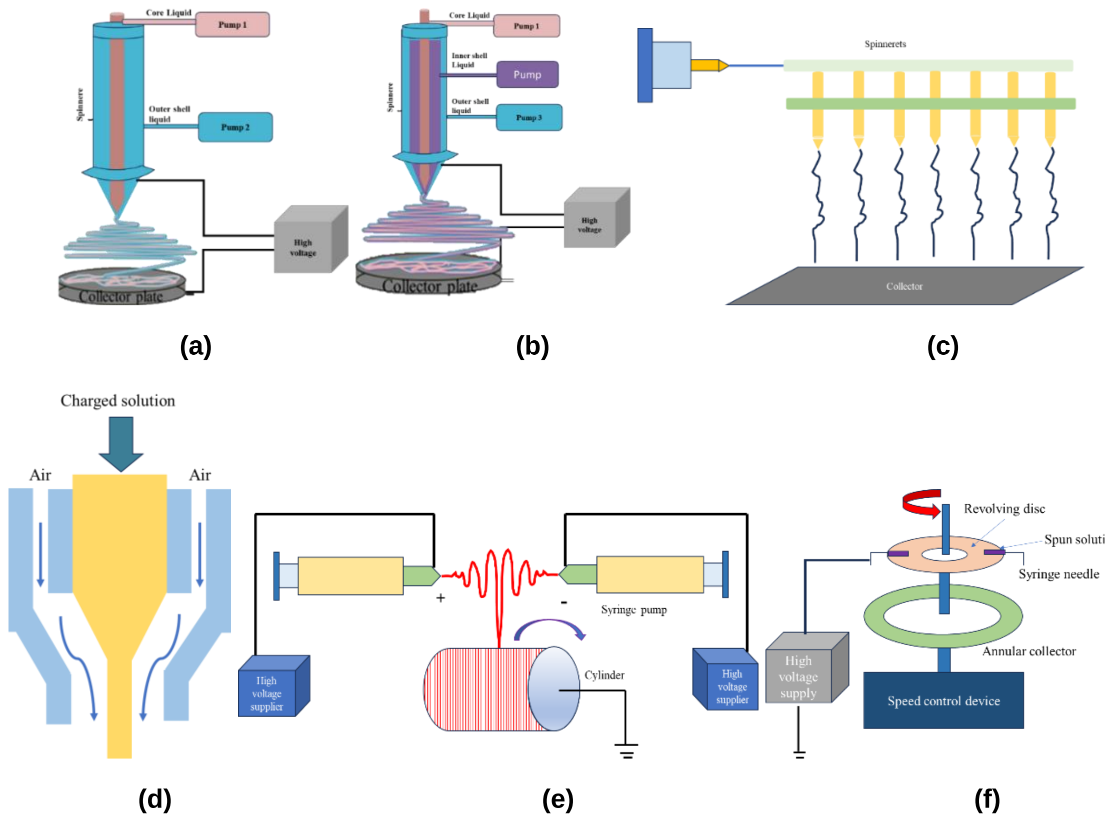


**Fig. 2. (a)Coaxial electrospinning, (b) triaxial electro spinning electrospinning, (c) Multi-needle Electrospinning, (d) Gas jet electrospinning, (e) Conjugate Electrospinning, (f) Centrifugal Electrospinning**

### 2.1.6 Centrifugal electrospinning

Centrifugal and electrostatic forces work together to stretch the fluid drop into fibers during centrifugal electrospinning. Pure centrifugal spinning of fibers requires the spinneret to operate at thousands rpm without the use of high voltage. On the other hand, centrifugal electrospinning allows for a 50% reduction in rotation speed. A dry nano-fibrous layer is left on the substrate as a result, the electric field helping to stretch the jets to extremely small dimensions while the solvent evaporates simultaneously. A lower voltage is needed to overcome the solution's surface tension and start electrospinning when centrifugal force is introduced. This technique is highly efficient for creating aligned nanofibers because it combines mechanical rotation with a lower voltage (Peng *et al*.,2017). Centrifugal electrospinning setup is demonstrated in Fig. 2f.

## 2.2 Needleless Electrospinning

An alternative electrospinning technique that produces nanofibers on a large scale is needleless electrospinning. Electrospinning nanofibers directly from an open fluid surface is referred to as needleless electrospinning. The needleless fibre generator (spinneret) shapes many planes simultaneously without the capillary effect, which is frequently associated with needle electrospinning. The spinning process is difficult to regulate in needleless electrospinning because the fly start is a self-composed process that occurs on a free fluid surface. Numerous spinneret forms with varying productivity levels have been developed for the needleless electrospinning method (Munir & Ali, 2020). There are different types of needles electrospinning methods includes bubble electrospinning, two layer fluid electrospinning, splashing electrospinning, melt differential electrospinning, gas assisted melt differential electrospinning, rotary cone electrospinning, rotating roller electrospinning, edge electrospinning and blown bubble electrospinning (Begum & Khan, 2017).

## 3. FACTORS AFFECTING ELECTROSPINNING

To achieve nanofibers with precise characteristics, it is essential to optimize various electrospinning parameters. These parameters can be categorized into three main groups: solution parameters, which include polymer concentration, viscosity, and conductivity; process parameters, such as applied voltage, flow rate, and needle-to-collector distance; and environmental conditions, including temperature, humidity, and air circulation. Proper optimization of these factors ensures the production of uniform, defect-free fibers tailored for specific applications (Ura & Stachewicz, 2024).

- **Solution parameters:** polymer concentration (C), polymer molecular weight (Mw), solution conductivity (k) and solution surface tension (γ)
- **Process parameters:** distance between the needle and collector (d), type of collector, applied voltage (V), and flow rate (Q)
- **Environmental factors:** air velocity, temperature, and relative humidity.

## 3.1 Solution Parameters

### 3.1.1 Concentration

Concentration of the solution controls the spinnability of polymer solutions. When the solution is overly diluted, it will cause production of individual drops rather than a continuous fiber. A mixture of beads and fibers with unstable nanofibers are produced at higher concentration. The production of bead-free nanofibers occurs at the optimum concentration (Deitzel *et al*., 2001). The impact of polycaprolactone (PCL) concentration in acetone was examined by Bosworth *et al*., who discovered that bead-free fibers with a broad range of sizes were produced at higher concentrations (10% w/v) (Bosworth *et al*., 2012). Similar results were reported by Gu and Ren for poly (D, L-lactide) (PDLA) in a solvent mixture of acetone and chloroform (2/1 v/v) (Gu & Ren, 2005). While continuous and homogeneous nanofibers were produced at higher concentrations (7 weight percent), bead-on-string structures were produced at lower concentrations (3 weight percent), and the average fiber diameter rose as the concentration of the polymer solution increased.

### 3.1.2 Molecular weight

A greater degree of surface wrinkling and a larger diameter with a better tensile strength and Young's modulus were the outcomes of increasing the molecular weight. As far as molecular weight effects go, beads were formed when the molecular weight is decreased while the concentration remains constant. Smooth fibers, on the other hand, are produced as the molecular weight increases (Eda & Shivkumar, 2007). The impact of molecular weight and concentration on (poly vinyl alcohol) (PVA) electrospinning was investigated by Mwiiri & Daniels (2020).

### 3.1.3 Conductivity of solution

Studies indicated that higher conductivity of solution leads to the production of thin uniform fibres (Zeng *et al*., 2003).

### 3.1.4 Surface tension

Surface tension play an important role in deciding morphology of electrospunfibers. For starting the production of fibers, the solution should overcome its surface tension and surface tension determines the upper and lower limits of the electrospinning window while all other factors are fixed (Haghi & Akbari, 2007). Study conducted by Deng *et al*, showed that morphology of gelatin nanofibers was affected by three different types of surfactants: cationic (cetyltrimethylammonium bromide, CTAB), anionic (sodium dodecyl sulphate, SDS), and non-ionic (Tween 80). They found that the surface tension abruptly decreased from 37.86 mN/m to 31.08 mN/m, 19.24 mN/m, and 19.76 mN/m, respectively, upon the addition of 1% SDS, CTAB, or Tween 80. Incorporation of surfactants in the polymer solution resulted fibres with smooth surfaces. However, use of SDS showed a significant increase in the fiber diameter (Deng *et al*., 2017).

## 3.2 Process Parameters

### 3.2.1 Distance between the needle and collector

The distance between the needle tip and the collector plays a crucial role in determining fiber diameter and shape by influencing jet stretching, travel time, and solvent evaporation. If the distance is too short, the jet has limited stretching, leading to the formation of larger, beaded fibers. Conversely, increasing the distance enhances stretching pressure, typically resulting in thinner fibers. Due to its significant impact on fiber morphology, adjusting this distance has become a key method for controlling nanofiber characteristics (Ahmadi & Rodrigue, 2024).

#### 3.2.2 Collector used

In terms of productivity, a conductive collector influences the reduction of the charge deposit on the fibers, thereby reducing the repulsive forces between the fibers, resulting in a higher number of fibers being collected. For a less conductive collector, the number of fibers deposited is reduced, and beaded fibers may form. When working with materials of low conductivity, it can be advantageous to decrease the charge density of the electrospinning jet by minimizing the accumulation of residual charges (Long *et al*., 2019).

#### 3.2.3 Applied voltage

Applied voltage plays a crucial role in shaping the initial droplet, forming what is known as the Taylor cone. When the supplied voltage exceeds a critical threshold, electrospinning begins. This causes the droplet's surface to accumulate enough charge to overcome the solution’s surface tension, leading to the ejection of an electrically charged jet (Ahmadi & Rodrigue, 2024). Numerous investigations have demonstrated that when the applied voltage increases, the electrical stress causes the fibers to continuously stretch, resulting in lower diameters (Ju *et al*., 2017). For instance, it was evident from Chowdhury and Stylios' morphological observations that, higher voltage caused formation of gather thinner Nylon 6 fibers (Chowdhury & Stylios, 2010).

#### 3.2.4 Flow rate

Flow rate is an important parameter for determining morphology and diameter of nanofibers. The flow rate has an impact on the Taylor cone's stability and jet velocity, therefore determining the ideal value is crucial. Because it provides enough time for solvent evaporation, decreasing the flow rate of the polymer solution typically leads to smaller nanofiber diameters and the formation of uniform fibers (Zargham *et al*.,2012). However, the solution at the needle tip is withdrawn more quickly than the flow rate produced by the electric forces when the flowrate drops below a particular threshold, creating an unstable jet that can result in beaded nanofibers or even needle blockage (Chowdhury & Stylios, 2012).

### 3.3 Ambient Conditions

The diameter and shape of electrospun nanofibers can be affected by environmental factors including temperature and humidity (Yang *et al*., 2017). Two opposing effects, an increase in the solvent evaporation rate and a decrease in the viscosity/surface tension of the polymer solution can be used to explain how temperature affects the average fiber diameter. Smaller PVP (polyvinylpyrrolidone) nanofibers were generated at both the lowest (283 K) and higher (303 K) temperatures, according to Vrieze *et al*. (De Vrieze *et al*., 2009).

Electrospinning at increased humidity led to the creation of large-diameter poly ethylen imine (PEI) fibers, as demonstrated by Icogluetal (İçoğlu & Oğulata,2013). This was described as, a decrease in jet elongation caused by the other quick precipitation of PEI in the polymer solution jet is due to water absorption. However, Pelipenko *et al*., found that as the humidity rose from 4% to 70%, the diameter of PVA nanofibers reduced (Pelipenko *et al*., 2013).

**Table 1. Electrospinning Parameters and Their Effects**

| Category | Parameter | Effect on Electrospinning | References |
|---|---|---|---|
| **Solution Parameters** | **Concentration** | - Low concentration: Produces droplets instead of fibers.- High concentration: Produces a mixture of beads and fibers.- Optimum concentration: Bead-free fibers form.- Example: PCL in acetone forms bead-free fibers at 10% w/v. | Deitzel *et al*. (2001), Bosworth *et al*. (2012), Gu & Ren (2005) |
| | **Molecular Weight** | - Low molecular weight: Bead formation.- High molecular weight: Smooth fibers with better tensile strength and Young's modulus. | Eda & Shivkumar (2007), Mwiiri & Daniels (2020) |
| | **Conductivity** | - Higher conductivity results in thinner, uniform fibers. | Zeng et al. (2003) |
| | **Surface Tension** | - Determines fiber morphology and electrospinning feasibility.- Lower surface tension (by surfactant addition) leads to smoother fibers but can increase | Haghi & Akbari (2007), Deng *et al*. (2017) |

| Category | Parameter | Effect on Electrospinning | References |
|---|---|---|---|
| | | fiber diameter.- Example: Addition of SDS, CTAB, or Tween 80 reduced surface tension significantly. | |
| **Process Parameters** | **Needle-to-Collector Distance** | - Short distance: Limited jet stretching, leading to beaded fibers.- Increased distance: Greater stretching, producing thinner fibers.- Controls fiber morphology. | Ahmadi & Rodrigue (2024) |
| | **Collector Type** | - Conductive collector: Enhances fiber deposition and reduces charge repulsion.- Less conductive collector: Leads to beaded fibers and lower fiber collection. | Long *et al*. (2019) |
| | **Applied Voltage** | - Forms the Taylor cone and initiates electrospinning.- Higher voltage enhances fiber stretching, reducing diameter.- Example: Increased voltage led to thinner Nylon 6 fibers. | Ahmadi & Rodrigue (2024), Ju *et al*. (2017), Chowdhury & Stylios (2010) |
| | **Flow Rate** | - Lower flow rate: Produces uniform, thinner fibers due to better solvent evaporation.- Excessively low flow rate: Causes jet instability and beading.- Excessively high flow rate: May lead to needle clogging. | Zargham *et al.* (2012), Chowdhury & Stylios (2012) |
| **Ambient Conditions** | **Temperature** | - Affects viscosity, surface tension, and solvent evaporation.- Higher and lower temperatures both influence fiber diameter.- Example: PVP nanofibers had varying diameters at different temperatures. | De Vrieze *et al.* (2009) |
| | **Humidity** | - High humidity can lead to larger fiber diameters.- Example: Increased humidity resulted in larger PEI fibers.- Exception: Higher humidity reduced PVA nanofiber diameter. | İçoğlu & Oğulata (2013), Pelipenko *et al*. (2013) |

## 4. APPLICATIONS OF ELECTRO SPINNING

Because of special qualities of electrospun fibers, the generated fibers have found usage in a variety of fields which includes, food and biomedical, environmental protection, sensors, and optical (Alborzi, et al., 2013). Electrospun fibers are particularly valued in the food and biomedical industries for their ability to immobilize enzymes and in active foods packaging. Tissue engineering, wound dressing, and medication delivery are areas were electrospun fibers are used. The uncountable application of electrospinning is due to its special characteristics which include diameters ranging from micro to nano meters, porousness nature, large aspect ratio and high surface-to-volume ratio, ability to produce fibers with an infinite number of chemical compositions, and the ability to produce different types of morphology by altering the spinneret.

### 4.1 Biomedical Applications

Biomedical applications include applications in drug delivery system, tissue engineering, and wound healing. Jalaja *et al*. created electrospun core-shell structured gelatin-chitosan nanofibers for biomedical applications, where the shell can mimic the extracellular matrix and the core can contain drugs and bioactive molecules (Jalaja *et al*., 2016). Movahedi *et al*. created core-shell nanofibers for use in biomedical applications using a novel coaxial air brushing technique. The core-shell nanofiber was created by using an air brush with a coaxial needle to flow two different polymeric solutions containing biomolecules polyethylene oxide (PEO)/poly-DL-lactide/PCL (polycaprolactone) in the core and PCL/PEO in the shell. The extensive potential of coaxial electrospinning in the biomedical field is demonstrated by the numerous reports and reviews that are available in the literature on the subject (Movahedi *et al*., 2020).

### 4.2 Application in Filtration Process

Numerous studies have examined the potential of electrospun fibers in the air filtration process. For air particle permeability and to prevent dangerous particulate matter like dust, pollen, and germs, the porosity of the nanofiber mesh must be controlled. A large number of airborne particles can interact with the electrospun fibers because of its layer-by-layer structure. Electrospun nanofibers have properties that make them suitable for air filtration (Xue *et al*., 2019). Electrospun ultrafine fibers were created by Zhang *et al*. for sophisticated face masks, that may physically stop viruses (Zhang *et al*., 2021).

## 4.3 Application in Sensor Development

Among all the uses of nanomaterials, sensors have long been a focus of research. To meet the requirements of the sensor response unit researchers have developed a variety of novel techniques for fabricating nanomaterials using conventional electrospinning. Many electrospun nanofiber-based nanomaterials are developed as gas sensors, chemical sensors, piezoelectric sensors, and biosensors (Ding *et al*., 2010). Gao *et al*, described a wearable stain sensor with the help of electrospun fiber to measure physiological activities of humans. Wearable strain sensors based on electrospun fibers offer significant potential for personalized healthcare due to their superior mechanical properties, breathability, and lightweight nature (Gao *et al.,* 2023). Photo-responsive electrospun polymer nanofibers represent a promising advancement in materials science, offering versatile applications across various fields. Their high surface area, porosity, and ability to integrate functional materials make them highly adaptable for sensory technologies, medical applications, environmental monitoring, and smart devices. The incorporation of light-responsive functionalities through chemical and physical modifications enables these nanofibers to exhibit unique behaviors such as photoisomerization, photochromism, and photocatalysis (Sharif *et al*.,2024).

## 4.4 Applications in Textile Industry

Because of better mechanical qualities as well as adjustable chemical and physical characteristics of electrospun nanofibers, they have emerged as a viable alternative reinforcing option for composites. Although electrospun nanofibers have some desirable properties for use as nano-fillers, not much research has been done on their potential use as reinforcements. They may be constructed using a particular kind of nano-fibrous architecture, which is most likely the cause of the restriction.

Nanoparticles have been added to composite nanofiber textiles using the electrospinning technique to give them new purposes. To give an engineered fabric technical features like electrical conductivity, strain resistance, and quality, additional components including metal nanoparticles, metal oxide nanoparticles, conductive polymers, and ionic liquids may be incorporated into these nano-fibrous structures (Akdere & Schneiders, 2021).

# 5. APPLICATIONS IN FOOD INDUSTRIES

There are numerous applications of electrospun fiber in food industry which includes antimicrobial packaging, antioxidant packaging, intelligent packaging, encapsulation of bioactive compounds, and for analysing different food components, antibiotics and pesticides.

## 5.1 Food Packaging System

Continuous polymer fibers with various morphologies and architectures can be produced via electrostatic spinning (Zhang *et al*., 2020). With this technology, we anticipate creating new food packaging materials that are biodegradable, biocompatible, and low toxicity. This satisfies the requirements of the contemporary food pack aging business with regard to efficiency, safety, and environmental protection (Zhang *et al*., 2018).

### 5.1.1 Antimicrobial packaging

According to research, fibers made using electrospinning technology that include antibacterial compounds have potent antibacterial properties and can successfully eradicate or stop the growth of bacteria on food surfaces. This opens up new avenues for the creation of safer and healthier food products (Alonso-Gonzalez *et al*., 2020). Researchers are paying more attention to antimicrobial enzymes as natural antimicrobial agents as food safety becomes more important. Antimicrobial enzymes are very effective biocatalysts because of their high specificity and thermodynamic efficiency. Researchers created fibrous membranes that were more successful at inhibiting *Escherichia coli* by loading glucose oxidase into polyvinyl alcohol (PVOH). The reaction of glucose produces hydrogen peroxide, which interacts with sulfhydryl groups and O double bonds in proteins and lipids to prevent the growth of bacteria. Gelatine, and chitosan were used as the foundation materials for spinning, and tannic acid and chitosan were used as the antimicrobial components to successfully create fiber membranes with antibacterial properties. When it comes to antibacterial activity, chitosan and tannins work in concert. Fruit may be preserved more effectively and sustainably with this fiber membrane, which has the potential to replace plastic films (Gulzar *et al*., 2022). In another study Gao *et al*, reported that the naturally occurring antimicrobial agent perillaldehyde can be efficiently used for production of antimicrobial packaging. Perillaldehyde showed an increased antimicrobial and antioxidant activity when combined with hydroxypropyl-γ-cyclodextrin in the form of inclusion complex nanofiber (Gao *et al*., 2022). A study conducted by Huang *et al*, reported that complex nanofiber produced by combining cinnamaldehyde essential oil (CEO) and pullulan (PLU) with electrospinning technique effectively increased antimicrobial property of pullulan against *Staphylococcus aureus, Escherichia coli,* and *Aspergillus flavus.* The reason behind increase of antimicrobial property was the stabilization of CEO by electrospinning (Huang *et al,* 2024).

#### 5.1.2 Antioxidant packaging

Zein, gelatine, proanthocyanidin, zinc oxide nanoparticles, and gallic acid were electrostatically spun to create a unique electrospun composite nanofibrous membrane. The produced composite nanofiber coating can lower cherry respiration to prevent fruit oxidation and infections since the proanthocyanidins and gallic acid added are naturally occurring antioxidants. Thus, according to Yuan *et al*. (2023), these two nanofiber films are suitable packing materials for efficiently halting oxidation and averting degradation (Yuan *et al*., 2023).

In a different work, alcohol-soluble maize proteins and gelatine were doped with four polyphenols (ferulic acid, quercetin, gallic acid, and proanthocyanidins), and electrostatic spinning was used to successfully create antioxidant fibrous membranes. According to the results notable freshness preservation effects were demonstrated by fiber membranes with 15% gallic acid and 10% proanthocyanidins. Proanthocyanidins, which may have uses as antioxidants, had a more noticeable impact on cherry preservation. These created low water loss, low hardness, weak respiratory strength, and slow decay in fruits (Zhao *et al*., 2023).

#### 5.1.3 Intelligent packaging

An inventive method of packaging is intelligent packaging technology. In addition to safeguarding food, it provides customers with real-time updates on alterations in freshness and quality throughout storage and transportation (Wen *et al*., 2021). High protein foods include fish, meat, and dairy products when it degrades, organic amines are released that react with dyes and discolour them (Liu *et al*., 2023). Electrostatic spinning of anthocyanins into chitosan and gum arabica was reported to produce fiber mats with thermal stability and water-blocking capabilities. When storing chicken fillets, fiber mats with high pH sensitivity under external settings exhibit a constant color shift, enabling customers to see the food's freshness while it is refrigerated (Shavisi & Shahbazi, 2022). In a related investigation, polylactic acid, butterfly pea flower extract, and cinnamon aldehyde were used to create hydrophobic nanofibrous membranes. Cinnamaldehyde's antibacterial properties were successfully enhanced by the addition of butterfly pea flower extract. The fibrous membrane's outstanding detection performance was demonstrated by the experimental results, which revealed that it rapidly changed color significantly when ammonia and hydrochloric acid gasses were present (Liu *et al*., 2023). In a study conducted by Guan *et al*., reported that polylactic acid composite with cellulose nano crystal and 2-hydroxypropyl-β-cyclodextrin can be effectively used for production of intelligent bioactive food packaging. There was an increase in mechanical strength of fiber when incorporated with tannic acid when compare with the polylactic acid fibers. Also, they reported that, the nanofibers have intelligent colour response towards various changes in the storage conditions and showed good antimicrobial property (Guan *et al*., 2024).

### 5.2 Encapsulation of Bioactive Compounds

Encapsulation is a desirable method for delivering unstable active substances (core material) to a specific location, protecting them, and promoting products by encasing them in various wall polymer matrices. Bioactive chemicals can be delivered with a finely regulated release to maximize their effectiveness and determine the ideal dosage (Ghorani & Tucker, 2015). Encapsulation of bioactive compounds are highly useful in nutraceutical industries. Highly unstable compounds like vitamins and other bioactive compounds can be successfully encapsulate using electrospinning techniques. There are numerous advantageous of encapsulation of bioactive compounds which includes protection from harsh environmental characteristics, controlled release of compound with masking undesirable flavors.

A study conducted by Basar *et al*, demonstrated that encapsulation of β-carotene with poly-ethylene oxide using electrospinning improved thermal stability and shelf-life. On storage of 96 h, there was 70% loss of bioactive compound without electrospinning and after electrospinning there was a huge decrease in bioactive compound loss (20%) (Basar *et al*., 2020).

Electrospun fibers containing folic acid or vitamin B9 have been created. In normal conditions folic acid deteriorates in the presence of light and acid (López-Córdoba, et al., 2016). Folic acid encapsulated in alginate-pectin-poly ethylene oxide (PEO), electrospun fibers shown good protection in acidic and light-induced environments (Alborzi *et al*.,2013). After 41 days of dark storage at pH 3, the fibers retain about 100% of their folic acid content. According to reports, these fibers show promise as transporters to add to food items like fruit juices and acidic drinks. Vitamin E is an essential vitamin that serves as a functional component. It can be included in food and drink items. Encapsulation preserves its bioactivity while overcoming its drawbacks related to low stability and bioavailability. According to Li *et al*, vitamin E exhibited good stability in a system based on soluble dietary fiber (SDF) (Li *et al*., 2016). Fathi *et al*, proposed dextran nano-fibers as a novel vitamin E encapsulation delivery mechanism. Approximately 98% of the vitamin E was contained within the nanofibers. About 6% of vitamin E may be released in gastric media, according to the release profile of the vitamin E in gastrointestinal media, while about 35% could be released in intestinal media (Fathi, et al., 2017).

## 5.3 Production of Meat Analogue

Increase in awareness about greenhouse gases and global warming, industries are searching for an alternative to reduce greenhouse gas emissions. When talking about greenhouse gases the main producers are cattle which are mainly used for meat purposes. To reduce greenhouse gas emissions the main alternative is introduction of meat analogues to market. But consumer preference towards such analogues is very less because of their undesirable structures. Development of techniques to produce a fibrous substance from plant proteins utilizing low-cost, less energy-intensive technologies can help overcome the obstacles to generating meat analogues. We can emphasize electrospinning as one of the various structuring methods for producing fibrous plant protein components that can be utilized to produce meat substitutes. Using a bottom-up approach, this method produces anisotropic structural components that are subsequently put together to create larger products (Forgie *et al*., 2023).

A study conducted by da Trindade *et al*, on electron spun fiber of zein and pea protein, demonstrated the significance of employing polyethylene oxide (PEO) and zein protein in the electrospinning process to create fibers for meat analogues. At 33% and 1% concentrations, respectively, the zein/PEO fibers showed a noticeably bigger fiber diameter, which might help create a fiber that resembles typical meat more. Additionally, this sample demonstrated exceptional hydrophilicity, which is necessary to ensure that vegetable protein-based products retain moisture and are juicy. It is also possible to emphasize this combination's strong thermal stability (da Trindade *et al*., 2024).

## 5.4 Food Analysis Applications

The testing process is intricate and time-consuming, and conventional testing equipment is costly. Thus, to guarantee food safety, prompt and precise identification of dangerous ingredients in food is crucial. Spun nanofibrous membranes with a high porosity, surface functionalization, and a wide surface area are feasible to create favourable circumstances for novel food and chemical analysis sensor systems (Huang *et al*., 2022).

### 5.4.1 Analysis of pesticide residue

Analysing pesticide residue in food is important to avoid rejection of agriculture products in export market as well as diseases due to long-term exposure of such pesticides. Traditional methods of pesticide analysis is time consuming as well as costly, to overcome this limitations researcher developed rapid detection kits and strips based tests for pesticide analysis. For the detection of carbamate and organophosphorus pesticide residues, a novel fast test card was created using indole acetate (IA) and acetylcholinesterase (AChE) as basic ingredients in combination with polyvinyl alcohol (PVA). Test cards for pesticide residue were created using electrostatic spinning. The foundation of this assay is the interaction between AChE and a particular pesticide, which, when present, inhibits enzyme activity and causes the color response to alter. Consequently, the developed test cards expand the range of electrostatic spinning applications (Zhai *et al*., 2020).

To find carbendazim (CBZ) residues in apple peels, a sensitive surface-enhanced Raman scattering (SERS) apta sensor was created. The sensor demonstrated strong SERS activity due to the interlaced fiber structure of the film and the bimetallic structure of AuNS-Ag. CBZ molecules, which were joined to AuNPs by nitrile-mediated Raman labelling to provide an optical anti-interference signal, were specifically caught by the aptamer during the detection procedure. Additionally, a non-invasive test using the "stick and peel" approach was conducted on apple peels at concentrations as low as 1.20 ng/cm $^{2}$ (Wei *et al*., 2024).

#### 5.4.2 Analysis of antibiotics

Analysis of antibiotics is very important because of the increases incidents of antibiotic resistance cases, due to uncontrolled use of antibiotics in agriculture and meat sectors. There are some emerging techniques for the rapid detection of antibiotics in the food items. One of the emerging technology is sensors made with electrospun fibers. Nanofibers that are overlapping and interwoven can create thin films with high surface areas and porosities by the relatively easy process of electrostatic spinning, which guarantees efficient interactions with target. Antibiotic detection employing covalent organic frameworks in conjunction with electrostatically spun fibers as substrates (Wang *et al*., 2020). In one study, researchers prepared a fluorescent sensor using in situ growth and hybrid spinning methods with polyacrylonitrile (PAN) and polymethylmethacrylate (PMM) as raw materials. This fluorescent sensor, which has a high sensitivity for antibiotic detection, provides a viable plan for future fluorescence-sensing studies (Li *et al*., 2024). Researchers also developed a fast, simple, sensitive, and cost-effective aptasensor based sensor with NH 2-MIL-101 (Fe) and carbonized PAN fibers using electrostatic spinning. Additionally, it was shown that the current response generated by the aptasensor could accurately quantify tetracycline concentration in water samples (Song *et al*., 2022).

#### 5.4.3 Analysis of food composition

Quick developments in nanotechnology have created new avenues for producing various food analysis tests. Researchers have discovered that food products can be analysed using enzyme-immobilized biosensors, which identify signals from biochemical reactions with the identified component. Using microfluidic chips, optical biosensors , which combines coaxial electrostatic spinning and glucose oxidase were created. The principle behind the technology is that the local amount of dissolved oxygen is decreased when glucose oxidase, oxidizes glucose. When it came to measuring glucose, this biosensor performed well (Ramon-Marquez *et al*., 2017).

## 6. INDUSTRIAL FEASIBILITY AND REGULATORY OF ELECTROSPUN NANOFIBERS

Electrospinning has gained significant attention for its ability to produce nanoscale fibers with high surface area and tunable properties. However, transitioning from laboratory-scale fabrication to large-scale industrial production requires addressing challenges related to scalability, industrial feasibility, regulatory compliance, and safety.

### 6.1 Scalability of Electrospinning and Industrial Feasibility

Scalability is one of the major challenges in electrospinning. Traditional needle-based electrospinning is limited in fiber production rate because it relies on single or multiple needles, leading to low throughput. To enhance scalability, several advanced techniques have been developed like needleless Electrospinning, and multi-Jet electrospinning. For large-scale production, companies are integrating robotic automation, inline fiber characterization, and solvent recovery systems to optimize efficiency and reduce waste (Sundarrajan et al., 2014).

### 6.2 Regulatory Aspects of Electrospun Nanofibers

For electrospun products to be used in biomedical, pharmaceutical, and food industries, they must comply with strict regulatory guidelines. For medical applications it should adhere to FDA (Food and Drug Administration), ISO 10993 (Biocompatibility), and Good Manufacturing Practices (GMP) regulations (Zhou et al., 2020). Nanofibers used in wound healing and drug delivery require sterility testing and cytotoxicity evaluations (Venugopal et al., 2008). Electrospun materials intended for food contact applications must comply with FDA 21

CFR Part 177 and European Food Safety Authority (EFSA) standards (Zander et al., 2016). Solvent-based electrospinning processes must follow Occupational Safety and Health Administration (OSHA) and Environmental Protection Agency (EPA) guidelines to minimize volatile organic compound (VOC) emissions (Bhardwaj & Kundu, 2010).

## 7. CONCLUSION

Electrospinning is an innovative and versatile technology that has gained significant attention in the food sector due to its ability to produce ultrafine fibers with tuneable properties. Bioactive chemicals have been successfully stabilized, released under regulated conditions, and encapsulated using this approach. Electrospun nanofibers have demonstrated promise in creating novel textural qualities, enhancing food safety, and creating biodegradable food packaging. Notwithstanding its encouraging uses, issues including cost-effectiveness, scalability, and regulatory problems must be resolved before it can be widely used in business. Future research should focus on optimizing processing parameters, researching novel biopolymer combinations, and assuring compliance with food safety laws. Electrospinning has the potential to completely transform the food industry with further developments, helping to create functional, sustainable, and health-promoting food products.

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Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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