Electrospinning and Its Application in Food Industry

Ganga A and Divyashree M

Department of Food Processing Technology, College of Food Processing Technology and Bio-Energy, Anand Agricultural University, Anand, Gujarat-388110

Corresponding Author: gangaachuthan99@gmail.com

Abstract

Electrospinning is a versatile nanotechnology technique used to produce ultrafine fibres from polymer solutions under an electric field. In the food industry, it enables the development of edible coatings, encapsulation of bioactive compounds, and controlled release systems for nutrients and flavors. Electro spun nano fibres improve food packaging by enhancing barrier properties and antimicrobial activity. This technology also aids in designing functional food ingredients with improved solubility and stability. Overall, electrospinning offers innovative solutions for food preservation, safety, and quality enhancement.

Introduction

A production process called electrospinning is used to create ultrafine fibres from a range of materials, including polymers, biopolymers, and ceramics. These fibres are typically between nanometres and micrometres in diameter. A tiny needle or tip is used to force a polymer solution or melt through, producing a charged jet that is subsequently pulled into a fibrous structure by an electric field. The resultant fibres are appropriate for use in tissue engineering, wound dressing, and medicines due to their special qualities, which include large surface area, porosity, and even biological compatibility (Wang et al., 2023). Sir William Gilber made the initial discovery of electrospinning in the latter part of the 15th century (Mirjalili & Zohoori, 2016).

Electrospinning mechanism

The process of electrospinning involves dissolving a polymer in a highly volatile solvent, which is then continuously pumped out of a syringe. Due to the electrostatic force applied, a separation of positive and negative charges occurs inside the liquid and charges of the same sign as the needle's polarity travel toward the surface, resulting in the production of a charged polymer droplet at the needle's tip (Xue et al., 2019). The droplet's surface charge density increases as the electrostatic field strength increases, which improves the mutual charge repulsion on the liquid's surface. Consequently, the droplet's surface area increases, reducing repulsion. Consequently, the drop shape changes to a "Taylor cone". Ultimately, the electrostatic repulsion overcomes surface tension, and a jet emerges, which is rapidly moving toward the collector. As the jet progresses towards the collector, the polymer solution elongates and undergoes a whipping phenomenon, while the solvent undergoes evaporation. These processes collectively result in the formation of very small fibres (Sun *et al.*, 2024).

1. Classification of electrospinning

Uniaxial electrospinning

Uniaxial electrospinning technology controls the spinning voltage using a high-voltage DC power supply, which in turn creates an electrostatic field of a certain strength between the needle and the receiving device. Driven by a constant-flow pump, the polymer fluid accumulated at the nozzle to form charged droplets (Lee *et al.*, 2023).

Coaxial electrospinning

Coaxial electrospinning, an innovative branch of traditional electrospinning technology, uses two plastic syringes to successfully construct coaxial nanofibres with core-shell structure (Wang *et al.*, 2020).

Emulsion electrospinning

Harsh conditions are not necessary for electroemulsion spinning (Inan-Cinkir et al., 2024). Emulsion electrospinning, as opposed to traditional electrospinning, may create core-shell fibres from a single nozzle. In electrospinning, water-in-oil (W/O) or oil-in-water (O/W) emulsions are added to polymers and processed through the use of electrospinning technology. As a result, less organic solvent is used and the spinning solution's stability is significantly increased (Falsafi et al., 2022).

Needle-free electrospinning

Needleless electrospinning is a process in which an electrostatic force is generated between the droplet and the collector when a voltage is applied without the use of a needle (Lee *et al.*, 2023).

Triaxial electrospinning

Triaxial electrospinning employs a more complex nozzle structure (Yu *et al.*, 2022). Spinneret consisted of three concentric nozzles for delivering the solution to the core, intermediate, and outer layers. Under the action of a high-voltage electric field, the nano fibers undergo stretching and refinement (Ghosal *et al*., 2021).

Applications in the food sector

Electrospinning technology has great potential for application in the food sector (Sun *et al*., 2024).

Application in food packaging

Food packaging is used to protect food from dust, physical damage, light, microorganisms, and humidity. Electrospinning is useful to produce different types of packages which include,

A. Antibacterial packaging
B. Antioxidant packaging
C. Intelligent packaging

Delivery systems for functional foods

Achieving the maximum bioavailability of active compounds using electrospinning considers the solubility, viscosity, and molecular weight of the polymer solution, as well as the conductivity and surface tension. The solubility and viscosity of a polymer solution are important factors in spinning. This depends mainly on the shape of the molecule, molecular weight, hydrophilicity, polymer-solvent interactions, and concentration of the dissolved polymer (Sun *et al*., 2024).

Encapsulation of bioactive compounds by electrospinning

Nanofibres prepared by electrospinning have the largest specific surface area and porosity. These properties significantly enhance the loading capacity of nanofibres for active compounds but also finely regulate their bioavailability and targeting efficiency. They are widely used to deliver various active compounds to their targets, providing strong support for more precise and efficient delivery (Liu *et al*., 2021).

Applications in the field of food analysis

Conventional testing equipment is expensive and the testing procedure is complex and time-consuming. Therefore, the rapid and accurate detection of harmful substances in food is essential to ensure food safety. Spun nanofibrous membranes with large surface area, high porosity, and surface functionalization are excellent conditions for developing a new sensor system for food and chemical analysis (Pan, 2024).

Analysis of antibiotics

Researchers have used electrospinning to combine polyacrylonitrile fibres and adenosine triphosphate-rare earth metal Tb^{3+} complexes. The unique fluorescent properties of the ternary system are attributed to adenosine triphosphate and Tb^{3+} coordination, which prevents the fluorescence burst that may result from water binding. Rapid on-site norfloxacin detection and analysis using a smartphone colour recognition app (Li *et al*., 2024).

Pesticide residue analysis

A new rapid test card for organophosphorus and carbamate pesticide residues was developed by combining polyvinyl alcohol (PVA) with acetylcholinesterase and indole acetate (IA) as raw materials. Pesticide residue test cards were prepared by electrostatic spinning (Pang *et al*., 2024).

Food composition analysis

The fusion of electrochemical and electrospinning techniques has successfully achieved the highly sensitive detection of synthetic pigments (Alizadeh *et al*., 2023).

2. Challenges

- Food safety standards demand non-toxic solvents and additives, which can limit material choices.
- Scaling it up for commercial food applications without compromising quality and reproducibility is challenging.
- High equipment costs and the need for specialized materials and conditions make the process expensive.
- Strict regulatory requirements for food-contact materials pose challenges for the use of electro spun fibres.
- Electro spun fibres made from natural polymers like proteins and polysaccharides can be highly sensitive to moisture, affecting their stability and functionality.
- Some electro spun food-grade materials have limited mechanical strength, which could hinder their use in packaging or structural applications.

3. Future Perspectives

- Electrospinning can be used to encapsulate bioactive compounds (e.g., vitamins, probiotics, antioxidants) for controlled release in food products.

- It offers potential for improving the stability and bioavailability of sensitive nutrients.
- Development of biodegradable and antimicrobial nanofiber-based packaging materials to extend food shelf life and reduce plastic use.
- Incorporation of smart sensing capabilities for detecting spoilage or contaminants.
- Electrospun fibres could be used to create novel textures in food products, mimicking natural fibres found in meat or plant-based alternatives.
- Potential to produce fibres that release flavors, nutrients, or functional ingredients in a controlled manner, improving the functionality of processed foods.
- Combining electrospinning with 3D printing and nanotechnology could lead to new applications in food engineering and design.

Conclusions

- Electrospinning is a cutting-edge technology with immense potential to transform the food sector.
- Ability to create nanofibres with high surface area, porosity, and controlled properties opens opportunities for innovative applications in food packaging, bioactive ingredient delivery, and food quality enhancement.
- With ongoing advancements in materials science and interdisciplinary research, electrospinning can pave the way for sustainable and value-added solutions in the food industry.
- Challenges such as scalability, cost-effectiveness, and regulatory compliance need to be overcome for its broader adoption.

References

Alizadeh, S., Pirsa, S., & Amiri, S. (2023). Development of a colorimetric sensor based on nanofiber cellulose film modified with ninhydrin to measure the formalin index of fruit juice. *International Journal of Biological Macromolecules*, 253, 127035.

da Cruz, E. P., Jansen, E. T., Fonseca, L. M., dos Santos Hackbart, H. C., Siebeneichler, T. J., Pires, J. B., ... & Dias, A. R. G. (2023). Red onion skin extract rich in flavonoids encapsulated in ultrafine fibres of sweet potato starch by electrospinning. *Food Chemistry*, 406, 134954.

Falsafi, S. R., Rostamabadi, H., Nishinari, K., Amani, R., & Jafari, S. M. (2022). The role of emulsification strategy on the electrospinning of β-carotene-loaded emulsions stabilized by gum Arabic and whey protein isolate. *Food Chemistry*, 374, 131826.

Gao, S., Li, X., Yang, G., Feng, W., Zong, L., Zhao, L., & Fu, Y. (2022). Antibacterial perillaldehyde/hydroxypropyl-γ-cyclodextrin inclusion complex electrospun polymer-free nanofiber: Improved water solubility, thermostability, and antioxidant activity. *Industrial Crops and Products*, 176, 114300.

Ghosal, K., Augustine, R., Zaszczynska, A., Barman, M., Jain, A., Hasan, A., & Thomas, S. (2021). Novel drug delivery systems based on triaxial electrospinning-based nanofibres. *Reactive and Functional Polymers*, 163, 104895.

Guan, Y., Li, F., Wang, Y., Guo, M., & Hou, J. (2024). "Reservoir-law" synergistic reinforcement of electro spun polylactic acid composites with cellulose nanocrystals and 2-hydroxypropyl-β-cyclodextrin for intelligent bioactive food packaging. *International Journal of Biological Macromolecules*, 274, 133405.

Huang, X., Teng, Z., Xie, F., Wang, G., Li, Y., Liu, X., & Li, S. (2024). Loading of cinnamon essential oil into electrospun octenylsuccinylated starch-pullulan nanofiber mats: Electrospinnability evaluation, structural characterization, and antibacterial potential. *Food Hydrocolloids*, 148, 109426.

İnan-Çınkır, N., Ağçam, E., Altay, F., & Akyıldız, A. (2024). Emulsion electrospinning of zein nanofibres with carotenoid microemulsion: Optimization, characterization and fortification. *Food Chemistry*, 430, 137005.

Lee, J., Moon, S., Lahann, J., & Lee, K. J. (2023). Recent progress in preparing nonwoven nanofibres via needleless electrospinning. *Macromolecular Materials and Engineering*, 308(9), 2300057.

Li, S. F., Hu, T. G., Jin, Y. B., & Wu, H. (2024). Fabrication and characterization of shellac nanofibres with colon-targeted delivery of quercetin and its anticancer activity. *International Journal of Biological Macromolecules*, 265, 130789.

Liu, L., Tao, L., Chen, J., Zhang, T., Xu, J., Ding, M., & Zhong, J. (2021). Fish oil-gelatin core-shell electrospun nanofibrous membranes as promising edible films for the encapsulation of hydrophobic and hydrophilic nutrients. *Food Science and Technology*, 146, 111500.

Mirjalili, M., & Zohoori, S. (2016). Review for application of electrospinning and electrospun nanofibres technology in textile industry. *Journal of Nanostructure in Chemistry*, 6, 207-213.

Pan, M. (2024). Nanomaterial-Based Optical Detection of Food Contaminants. *Foods*, 13(4), 557.

Pang, H., Xie, J., Meng, X., Sun, R., Chen, J., Guo, C., & Zhou, T. (2024). Portable organophosphorus pesticide detection device based on controllable microfluidic and luminol composite nanofibres. *Journal of Food Engineering*, 364, 111810.

Sun, F. L., Zhao, M. Y., Li, Y., Li, Z. Y., Li, X. J., Wang, N., & Tian, J. L. (2024). Research progress of electrospinning in food field: A review. *Food Hydrocolloids*, 110474.

Wang, M., Wang, K., Yang, Y., Liu, Y., & Yu, D. G. (2020). Electrospun environment remediation nanofibres using unspinnable liquids as the sheath fluids: A review. *Polymers*, 12(1), 103.

Wang, Y., Khan, M. A., Chen, K., Zhang, L., & Chen, X. (2023). Electrospinning of natural biopolymers for innovative food applications: A review. *Food and Bioprocess Technology*, 16(4), 704-725.

Xue, J., Wu, T., Dai, Y., & Xia, Y. (2019). Electrospinning and electrospun nanofibres: Methods, materials, and applications. *Chemical Reviews*, 119(8), 5298-5415.

Yu, D. G., Wang, M., & Ge, R. (2022). Strategies for sustained drug release from electrospun multi-layer nanostructures. *Wiley interdisciplinary Reviews: Nanomedicine and Nanobiotechnology*, 14(3), e1772.

* * * * * * * * *