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# Encapsulation of food bioactive compounds using electrohydrodynamic techniques: from fundamentals to industrial applications

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The encapsulation of food bioactive compounds has gained significant attention as a strategy to improve their stability, bioavailability, and controlled release for functional food applications. Among emerging technologies, electrohydrodynamic (EHD) techniques—primarily electrospinning and electrospraying, offer unique advantages over conventional encapsulation approaches due to their ability to generate nanostructured carriers with high surface area, tunable porosity, and protective matrices under mild processing conditions. This manuscript provides a comprehensive overview of the fundamentals and industrial relevance of EHD-based encapsulation systems, highlighting the influence of processing parameters, solvent selection, and polymer–bioactive interactions on nanostructure morphology and performance. The review discusses the encapsulation of diverse bioactive compounds, including polyphenols, vitamins, peptides, probiotics, and essential oils, emphasizing improvements in stability against environmental stresses and enhanced gastrointestinal release behavior. Advances in multi-fluid electrospinning (coaxial and triaxial) and needleless electrospinning are examined for their scalability and potential in industrial adoption. Additionally, real-world case studies are presented to illustrate the integration of EHD nanostructures into functional foods, while challenges such as low throughput, solvent toxicity, and regulatory hurdles are critically assessed. Future perspectives stress the importance of food-grade polymer development, green solvent use, and process optimization for commercial feasibility. Overall, EHD-based encapsulation represents a transformative technology that bridges nanotechnology and food engineering, offering promising solutions for designing next-generation functional foods with improved health benefits, longer shelf-life, and enhanced consumer appeal.

KEYWORDS

**biosensor, electrohydrodynamic encapsulation, electrospinning, electrosprying, food bioactive compounds, food packaging, functional foods, nanostructured delivery systems**

## Highlights

- EHD techniques enhance stability and bioavailability of food bioactives.
- Electrospinning and electrospraying produce nanocarriers with tunable properties.
- Coaxial and needleless electrospinning enable industrial-scale applications.
- EHD systems protect sensitive compounds under mild processing conditions.

## 1 Introduction

The growing consumer demand for safe, high-quality, and health-promoting food products has led to an increasing focus on sustainable processing strategies and advanced encapsulation technologies (Dahiya et al., 2023; Selvakumar and Manjunath, 2025). Among the many bioactive compounds naturally present in plant and animal sources, such as polyphenols, carotenoids, flavonoids, terpenes, alkaloids, and peptides, many are highly sensitive to processing conditions, environmental stresses, and gastrointestinal degradation (Banwo et al., 2021; Mazumder, Chanda and Banerjee, 2025; Tripathy, Ranjan and Srivastav, 2025). Despite their proven health benefits, these compounds often suffer from low stability, poor solubility, and limited bioavailability, which restrict their effective utilization in functional foods and nutraceuticals (Tripathy et al., 2021a; b). To address these challenges, encapsulation has emerged as a transformative approach that protects bioactives, enhances their stability, improves targeted delivery, and ensures controlled release (Tripathy and Srivastav, 2023; 2025).

Conventional encapsulation methods, including spray drying, freeze drying, coacervation, and liposomal entrapment, have been extensively applied in food systems (Rakshit et al., 2023; Kumari et al., 2025; Nakra et al., 2025; Prabhakar et al., 2025; Rahim et al., 2025; Singh et al., 2025). However, these techniques are often limited by high processing temperatures, low encapsulation efficiency, large particle size, and restricted control over release kinetics. Electrohydrodynamic (EHD) techniques, primarily electrospinning and electrospraying, have gained growing attention as innovative encapsulation platforms due to their ability to generate nanoscale fibers and particles under mild processing conditions (Liu et al., 2025). By applying a high-voltage electric field to polymer solutions or melts, EHD processes can produce ultrafine structures with high surface area-to-volume ratios, tunable porosity, and tailored morphologies, making them highly suitable for encapsulating sensitive bioactive molecules (Shabani et al., 2025).

Electrospinning, which results in continuous nanofibers, and electrospraying, which produces nanocapsules or nanoparticles, offer remarkable advantages over conventional technologies. These include high encapsulation efficiency, improved solubility and dispersibility of hydrophobic compounds, protection against oxidation and thermal degradation, and controlled or stimuli-responsive release during digestion (Shabani et al., 2025). Importantly, these methods are versatile, allowing for the use of a wide variety of natural polymers, biopolymers, and food-grade carriers. Moreover, advances in coaxial, triaxial, and emulsion-based EHD systems have further enhanced the ability to encapsulate multiple bioactives simultaneously, protect them from harsh environmental conditions, and achieve targeted delivery to specific regions of the gastrointestinal tract (Drosou and Krokida, 2024a). Recent years have witnessed significant progress in scaling up EHD techniques, particularly through innovations in needleless electrospinning and multi-jet systems, which address the throughput limitations of traditional setups (Busolo et al., 2017). This progress has paved the way for potential industrial applications in food and nutraceutical sectors. Nevertheless, challenges remain regarding energy efficiency, reproducibility, regulatory acceptance of carrier polymers, and cost-effectiveness at commercial scales. Addressing these issues is essential to transform EHD encapsulation from a laboratory-based concept into a viable industrial technology capable of supporting the development of next-generation functional foods.

While previous reviews have contributed important overviews of electrospinning or electrospraying, most remain limited in three key respects: (i) they primarily emphasize materials fabrication or nanostructure characterization, with limited connection to food-specific functional performance, digestive stability, or matrix compatibility; (ii) they seldom address mechanistic relationships linking nanostructure, diffusion behavior, release models, and bioactive stability within real food environments; and (iii) they give minimal attention to scale-up bottlenecks, techno-economic feasibility, regulatory evaluation of nano-enabled food systems, and industrial adoption barriers. This review addresses these gaps explicitly by providing a mechanism-anchored, application-oriented, and industry-aware assessment of EHD encapsulation. It synthesizes recent advances from the last 5 years, highlights unresolved challenges such as throughput, reproducibility, solvent safety, consumer perception, and regulatory ambiguity, and proposes solution-focused research directions, including clean-label polymer engineering, green-solvent processing, hybrid scale-up architectures, and standardized safety assessment frameworks. It offers a strategic, forward-looking contribution that advances both scientific understanding and translational readiness of EHD technologies in functional food systems.

The primary objective of this review is to bridge the gap between laboratory-scale innovations and the industrial adoption of electrohydrodynamic (EHD) techniques, specifically electrospinning and electrospraying, as transformative tools for food bioactive encapsulation. By exploring the scientific principles governing these processes, the study examines how processing parameters, solvent selection, and polymer interactions can be strategically tuned to engineer nanostructured carriers, such as nanofibers and nanocapsules, with tailored morphologies and functional performance. Furthermore, the manuscript evaluated the efficacy of EHD systems in enhancing the stability, bioavailability, and targeted gastrointestinal delivery of diverse compounds, including polyphenols, vitamins, probiotics, and peptides. Finally, the article provides a critical assessment of recent engineering advancements in coaxial, triaxial, and needleless configurations to address current scalability hurdles, regulatory considerations, and the industrial feasibility of designing next-generation functional foods.

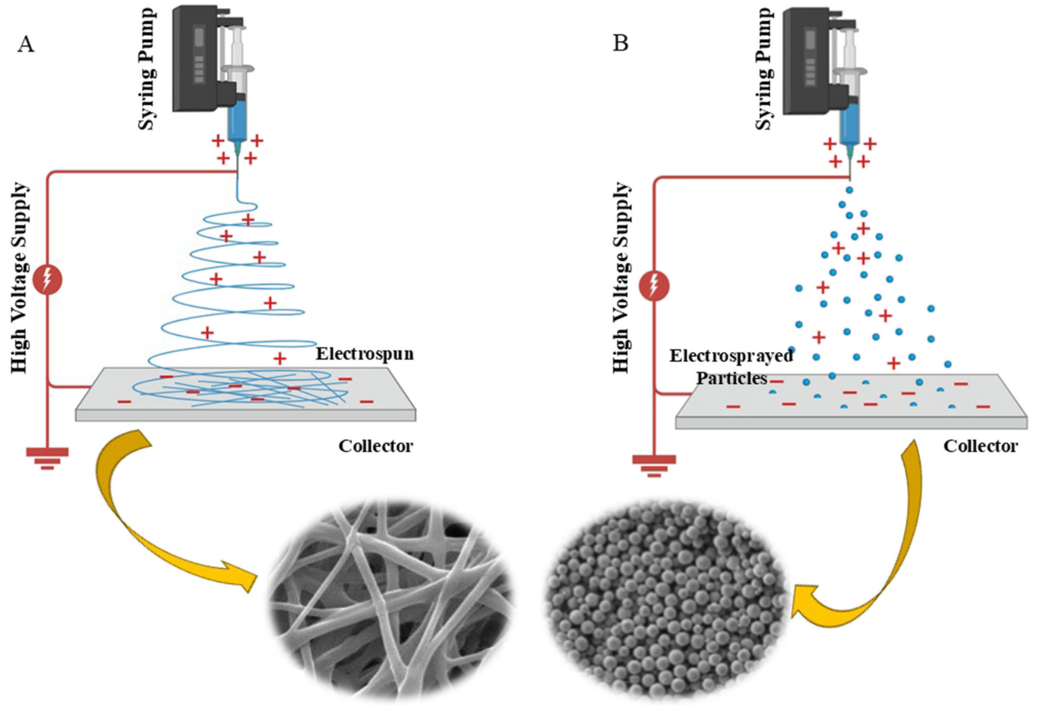

FIGURE 1
Electrohydrodynamic methods of encapsulation of bioactive compounds **(A)** Electrospinning; **(B)** Electrospraying (Bock et al., 2011; Munteanu and Vasile, 2021).

## 2 Fundamentals of electrospinning/spraying

Electrohydrodynamic (EHD) encapsulation is an advanced fabrication method that generates micro- or nanostructures by applying a high-voltage electrostatic field. This field charges the surface of biopolymer solution droplets, causing the ejection of a fine liquid jet from the spinneret (Silva et al., 2025). The two primary approaches under EHD processing are electrospinning and electrospraying (Figure 1). Electrospinning is a highly adaptable technique that produces nanofibers from polymer solutions or melts under a strong electric field. In this process, a high-voltage potential is applied between a conductive needle connected to a syringe containing the polymer solution and a grounded collector (Shabani et al., 2025). A syringe pump steadily feeds the polymer solution, while the electric field facilitates jet formation at the needle tip (Feng et al., 2023). As the electrostatic field intensifies, the droplet at the spinneret deforms into a conical shape known as a Taylor cone. When the electrostatic repulsion on the droplet surface exceeds the surface tension, the cone tip emits a fine, charged liquid jet (Essa and Mahmoud, 2024). During its trajectory toward the collector, solvent evaporation occurs, and the polymer chains elongate without breaking, resulting in continuous ultrathin fibers. The grounded or oppositely charged collector finally gathers these fibers, completing electrospinning (Vignesh et al., 2024).

Electrospraying, closely related to electrospinning, is an electrohydrodynamic method that produces nano- or microparticles instead of fibers, leveraging similar principles but with adjustments in solution properties to favor droplet formation (Monica et al., 2024). The setup mirrors that of electrospinning, involving a syringe pump to deliver a polymer solution at a constant flow rate through a needle, a high-voltage source to generate an electric field, and a collector that can be a solid plate, rotating drum, or even a liquid bath for wet electrospraying (Silva et al., 2025). Voltage application leads to charge accumulation on the solution droplet, forming a Taylor cone when electrostatic forces surpass surface tension, followed by the ejection of a charged jet. However, due to lower solution viscosity, higher surface tension, or other parameters, the jet breaks up into fine droplets *via* Coulombic fission and Rayleigh instability rather than elongating into fibers (Koekoekx, 2021). As these droplets travel toward the collector, solvent evaporation solidifies them into particles.

Beyond jet formation and process physics, the functional performance of EHD systems is critically determined by the relationship between the nanostructure and barrier property. Fiber diameter, porosity, and packing density collectively modulate the permeation of oxygen, moisture, and small solutes through the matrix. Nanofibers with smaller diameters (typically <300 nm) and high orientation generate tortuous diffusion pathways and tighter pore networks, thereby reducing oxygen transmission and delaying oxidative reactions, whereas highly porous or loosely packed mats exhibit faster permeation and moisture sorption due to shorter effective diffusion paths (Huang et al., 2021; Liu et al., 2025). Similarly, dense bead-free fibers improve barrier protection by limiting capillary water uptake, while bead-rich or ribbon-like fibers promote localized defect zones that accelerate gas and vapor transport. In electrosprayed particles, lower porosity and thicker shells enhance moisture resistance but

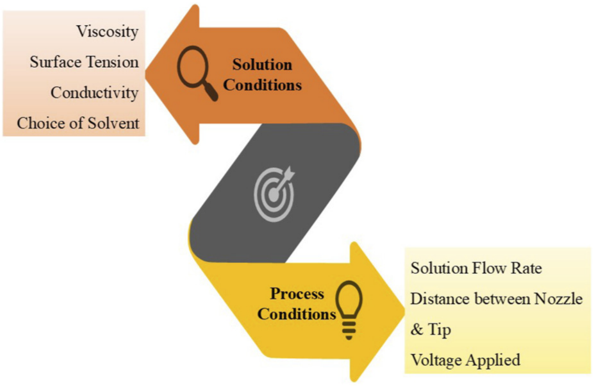

FIGURE 2
Different factors affecting electrohydrodynamic process of encapsulation of bioactive compounds.

may slow dissolution and delay release in gastrointestinal conditions (Dhiman et al., 2022). These structure–transport relationships explain why EHD systems can be tailored for either protective encapsulation (low-permeability matrices) or rapid functional release (porous or swellable networks), depending on the application needs in functional foods.

Equally important to performance are material–bioactive molecular interactions within the carrier matrix. Hydrogen bonding, hydrophobic interactions, ionic complexation, and cross-link density between polymers and bioactive compounds strongly influence the encapsulation efficiency, physical stability, and release kinetics. Hydrophilic polymers, such as pullulan, PVA, or gelatin, form extensive hydrogen-bond networks with polyphenols, vitamins, and peptides, thereby improving loading and suppressing crystallization or phase separation during jet solidification (Zhou et al., 2024a; Cabrera et al., 2024). Conversely, hydrophobic systems such as zein, PCL, or PLA promote hydrophobic association and π–π stacking with carotenoids and essential-oil constituents, leading to higher affinity binding and slower oxygen-induced degradation (Panagiotopoulou et al., 2022; Ramos-Souza et al., 2025) in polysaccharide–protein hybrids, ionic cross-linking and polyelectrolyte complexation (e.g., alginate–chitosan, fucoidan–protein) increase matrix cohesion and reduce molecular mobility, which lowers diffusion rates and shifts release toward sustained patterns (He et al., 2023; Ma et al., 2024). These interactions are not only chemical but also rheological: stronger intermolecular association increases chain entanglement during spinning, yielding smoother fibers with improved encapsulation stability and reduced burst loss during storage or digestion.

The release behavior of EHD-encapsulated bioactive compounds can be interpreted using classical transport and matrix degradation models, which clarify how material structure governs functional performance in food systems. In many hydrophilic nanofibers and thin electrosprayed shells, release is dominated by Fickian diffusion, where concentration gradients control the rate through the polymer network. Examples include vitamin- and polyphenol-loaded PVA or pullulan carriers that exhibit square-root-of-time release responses consistent with Higuchi-type diffusion kinetics (Quintero-Borregales et al., 2023; Carrillo-Cabrera et al., 2024). In matrices that undergo polymer relaxation, swelling, or plasticization in aqueous media, such as gelatin, starch, or pectin blends, the mechanism shifts toward anomalous or swelling-controlled release, where chain relaxation and water uptake jointly regulate mass transfer (Coelho et al., 2022; Yeganegi et al., 2025). Hydrophobic or semi-crystalline systems (e.g., zein, PCL, PLA) frequently exhibit erosion- or dissolution-controlled release, particularly under lipophilic or enzymatic environments, where matrix disintegration progressively exposes encapsulated compounds (Dias and Estevinho, 2025; İnan-Çınkır et al., 2024). Several recent EHD studies have further applied empirical models, such as Weibull or Korsmeyer–Peppas fits, to distinguish between burst-diffusion phases and long-term sustained release, highlighting how nanostructure morphology, polymer chemistry, and interfacial interactions collectively dictate the release mode and kinetics (Couto et al., 2023; Zhou et al., 2024b). Integrating these mechanistic insights strengthens the connection between EHD structure design and functional outcomes in stabilizing and delivering food bioactive compounds.

## 2.1 Factors affecting electrospinning/spraying process

### 2.1.1 Solution conditions

The characteristics of the polymer solution play a pivotal role in determining the diameter and morphology of electrospun fibers (Figure 2). The viscosity and surface tension of the polymer solution largely dictate fiber thickness and the occurrence of bead formation along the fibers (Kalluri, Satpathy and Duan, 2021). Additionally, the solvent used significantly influences fiber morphology, as both the physical and electrical behaviors of the solution are strongly dependent on solvent properties (Ahmadi Bonakdar and Rodrigue, 2024). Studies have demonstrated that binary or mixed solvent systems can generate finer fibers than single-solvent systems, balancing fiber quality and production efficiency (Valencia-Osorio, Aguiar and Álvarez-Láinez, 2025). Typically, the solubility of synthetic polymers rises as molecular weight decreases (Satchanska et al., 2024), whereas other properties such as viscosity, tensile strength, flexibility, and molecular chain entanglement increase with molecular weight (Campa-Siqueiros et al., 2024).

For optimal electrospinning, the polymer solution must have a sufficient polymer concentration to establish a network of molecular entanglements while maintaining a manageable viscosity to facilitate jet formation (Li et al., 2025). When the concentration is below the critical threshold, the applied voltage causes electrospraying and bead generation due to Rayleigh instability. Intermediate concentrations produce a combination of beads and fibers, while higher concentrations favor the formation of continuous fibers (Wang et al., 2022). However, overly concentrated solutions are problematic, as excessive viscosity impedes jet stability and can block the spinneret.

The overall behavior of the electrospinning process is governed by the interrelation of surface tension, viscosity, and electrical conductivity, all of which are influenced by the solvent type, polymer concentration, and molecular weight (Dobrynin et al., 2023). Viscosity, indicative of the degree of molecular entanglement, is crucial for maintaining the Taylor cone and ensuring stable jet flow. High viscosity supports consistent fiber formation, whereas low viscosity encourages droplet breakup and electrospraying (Wang et al., 2024). Polymer and solvent characteristics determine conductivity and affect charge transport and fiber uniformity. Excessive conductivity can lead to strong Coulombic repulsion, disrupting polymer chain entanglement and forming particles (Mousavi et al., 2024). Similarly, surface tension influences jet initiation. High surface tension resists fiber formation and often causes bead or droplet generation instead (Dai et al., 2023).

### 2.1.2 Process conditions

A key factor in the electrospinning process is the application of high voltage to the polymer solution (Figure 2). The magnitude of this voltage governs the electric field strength between the spinneret and the collector, directly influencing the drawing force exerted on the jet. When an electric charge is applied, the electrospinning process begins once the electrostatic force surpasses the surface tension of the polymer solution (Ahmadi Bonakdar and Rodrigue, 2024). The applied voltage and the distance separating the nozzle tip from the grounded collector are interdependent parameters since both determine the electrostatic field that drives the formation of micro- and nanostructures (Vignesh et al., 2024). Modifying the collector distance requires a corresponding adjustment in voltage to maintain stable jet formation, as improper spacing can result in incomplete solvent evaporation. Although higher voltages tend to produce finer fibers or particles, excessive voltages can destabilize the Taylor cone and cause morphological irregularities (Moreira et al., 2021). In electrohydrodynamic encapsulation of probiotics, elevated electric fields can compromise microbial viability, making it essential to use an optimal voltage that minimizes cell damage (Ma et al., 2023).

Another vital operational factor is the solution flow rate, which dictates the morphology and productivity of the process. Electrospraying generally yields uniform spherical particles at lower flow rates, whereas higher flow rates may cause bead formation or irregular morphologies such as microdroplets. The feed rate should match the spinneret output rate to sustain a steady jet (Barata, Paul and Belino, 2025). Increased flow rates often result in fibers with larger diameters, while slower flow rates favor the production of uniform nanofibers (Ghorani and Tucker, 2015). A large droplet at the needle tip, combined with a high feeding rate, reduces solvent evaporation time, forming beads or fused fiber junctions in the collected mat. In their investigation, Silva et al. (2022) reported that polymer concentration had the most pronounced impact on the aspect ratio of particles among the various process parameters. They observed that higher polymer concentrations increased the aspect ratio distribution, reducing morphological uniformity. Hence, maintaining a relatively low polymer concentration is preferable for uniform structure formation.

The elongation of the polymer jet occurs between the needle tip, where the Taylor cone develops, and the collector plate. The tip-to-collector distance (TCD) directly affects both the jet's flight time and the strength of the electric field (Monica et al., 2024). A shorter TCD generally favors smaller particle formation due to a stronger electric field, but too short a distance can cause particle aggregation owing to insufficient solvent evaporation. Conversely, excessively long distances reduce deposition efficiency and yield (Vignesh et al., 2024). At a constant voltage, increasing the TCD weakens the electric field, influencing jet splitting and attenuation. Consequently, as TCD increases from a minimal value, the average fiber diameter initially decreases, reaches an optimal minimum, and rises again with further increases in TCD (Shao et al., 2023).

## 3 Coating materials used in ESP

### 3.1 Polysaccharides

Electrohydrodynamic (EHD) processes have emerged as versatile platforms to encapsulate labile bioactives in micro/nanostructures with high surface area, and controllable release profiles. Within these systems, polysaccharides are especially attractive wall materials because they are renewable, food-grade or GRAS in many cases, and offer rich chemistries (hydroxyl, carboxyl, amine, sulfate) enabling hydrogen bonding, ionic crosslinking, and polyelectrolyte complexation with actives or co-polymers (Benalaya et al., 2024). Alginate remains a workhorse for EHD encapsulation owing to its anionic guluronic/mannuronic blocks that gel *via* $Ca^{2+}$ and its mild processing conditions. A key characteristic of alginate is its ability to interact with divalent cations, such as $Ca^{2+}$ and $Sr^{2+}$, resulting in the formation of a 3D network known as the "egg-box model" (Zhang et al., 2020). This structural capability makes alginate an ideal candidate for wet electrospraying (ES) techniques. Pectin (PEC) functions similarly as an anionic polysaccharide that gelates through cation cross-linking. However, PEC faces a specific limitation: its gels frequently swell when exposed to acidic conditions. This swelling can compromise the survival of bioacitves within the harsh environment of gastric juices (Ma et al., 2019; Jia et al., 2025). To address this, researchers often blend PEC with alginate to bolster the defensive properties of ES microcapsules. This synergy is illustrated in the work of Coghetto et al. (2016), where *Lactobacillus plantarum* was encapsulated using either sodium alginate (SA) or an SA/PEC mixture before being electrosprayed into a $CaCl_2$ hardening solution. Further, apple-pectin blended with poly (vinyl alcohol) (PVA) yields bead-free nanofibers with improved mechanical/thermal stability suitable for loading antioxidants and antimicrobials (Nawaz et al., 2023).

Chitosan (CS), a cationic polysaccharide, complements alginate through polyelectrolyte complexation, boosting encapsulation efficiency (EE) and modulating diffusion-controlled release (Feng et al., 2023). CS exhibits strong mucoadhesive capabilities due to the electrostatic attraction between its structure and the negative residues found in mucin glycoproteins (Alavi, Haeri and Dadashzadeh, 2017). The overall solubility of this biopolymer is governed by several critical factors, including its pH environment, molecular weight, the extent of deacetylation, and how acetyl groups are positioned along its chain (Ardila, Ajji, Heuzey and Ajji, 2018). To facilitate the electrospinning process, chitosan must be dissolved in acidic media. Common choices include trifluoroacetic, formic, or acetic acids, which can be utilized independently or in conjunction with organic co-solvents like dichloromethane and ethanol (Lin et al., 2019; Yilmaz et al., 2019). Research frequently focuses on altering the hydroxyl and amine functional groups to enhance the inherent characteristics of chitosan. N-substitution is the primary technique employed, where target molecules are first reacted with amino groups before addressing the hydroxyl sites (Ardila et al., 2018). Integrating chitosan with other substances, such as gelatin, polyethylene oxide (PEO), poly (ε-caprolactone) (PCL), or polyvinyl alcohol (PVA), creates robust molecular-level stability through hydrogen bonding (Ardekani-Zadeh and Hosseini, 2019; Lin et al., 2019; Munhuweyi et al., 2018; Vafania et al., 2019). These structural adjustments and polymer combinations serve to optimize the solution by reducing surface tension and increasing solubility. Furthermore, these changes make it possible to successfully integrate hydrophobic substances, such as essential oils, into the chitosan matrix.

Pullulan, a neutral, highly soluble polysaccharide with excellent film-forming ability, has been repeatedly electrospun into smooth fibers for oral films and rapid-dissolving formats. Blends with jelly-fig polysaccharide and xanthan gum have produced fast-dissolving nanofibrous films suitable for buccal/oral delivery of hydrophilic vitamins such as ascorbic acid, demonstrating improved dissolution kinetics and payload protection during processing (Poudel et al., 2020; Ponrasu et al., 2021; Cheng et al., 2024). While nanofibers derived solely from pullulan exhibit high water solubility and structural elasticity, their inherent abundance of hydroxyl groups prevents the integration of hydrophobic substances. To overcome these limitations, pullulan is often blended with secondary polymers. This hybridization enhances the thermal resistance of the resulting electrospun fibers compared to their pure counterparts. According to Xiao and Lim (2018), this improvement is largely driven by the formation of robust intermolecular hydrogen bonds, which stabilize the overall material architecture.

Natural starch is inherently hydrophilic, meaning it lacks a strong affinity for hydrophobic substances. This chemical mismatch typically restricts its effectiveness as a carrier for essential oils or hydrophobic compounds in nanoparticle form (Rostamabadi et al., 2019; Shishir et al., 2018). While various structural modifications such as chemical, physical, or enzymatic are often employed to improve starch's compatibility with lipids (Hoyos-Leyva et al., 2018), unmodified starch can still yield positive results under specific conditions. For instance, Fonseca et al. (2020) successfully integrated thyme essential oil into electrospun starch nanofibers using a formic acid solvent. Although the specific binding mechanism was not defined, FT-IR and TGA data confirmed high encapsulation efficiency (99.1%–99.8%) and robust protection of the oil's phenolic components.

## 3.2 Protein

Proteins are attractive wall materials for electrohydrodynamic encapsulation because their amphiphilicity, ability to self-assemble, and rich chemistry (ionic, hydrophobic, hydrogen-bonding, and covalent crosslinking) enable high loading, tunable release, and protection of sensitive bioactives (Moreira et al., 2021). Compared with many polysaccharides or synthetic polymers, food-grade proteins can form nano-/microstructures (fibers or particles) under relatively mild EHD conditions while offering enzymatically responsive matrices for gastrointestinal delivery (Vignesh et al., 2024). Whey readily electrosprays into submicron carriers and blends well with polysaccharides. WPI particles produced by electrospraying show sizes and morphologies that can be tuned *via* voltage and flow rate, supporting controlled release applications (Chatzitaki et al., 2024). WP demonstrates a greater protective ability as an encapsulation material than pullulan, and it effectively prolonged the survival of cells even at high RH (). Hybrid matrices such as dextran–WPI microcapsules fabricated by high-voltage electrospraying have been optimized for gastrointestinal stability and low cytotoxicity, while Maillard-type protein–polysaccharide conjugates further improve encapsulation efficiency and protection of bioactives (He et al., 2023; Zhou et al., 2024a).

As a hydrophobic, ethanol-soluble prolamin, zein is among the most EHD-friendly proteins, forming smooth electrosprayed nanoparticles and electrospun fibers with high encapsulation of hydrophobic compounds (carotenoids, polyphenols, essential oils). Electrospun zein fibers have been used to stabilize the light-sensitive bioactive antioxidant β-carotene (Fernandez et al., 2009). The β-carotene antioxidant was stable and widely dispersed inside the zein fibers, and its UV–vis light stability could be significantly increased compared to nonencapsulated control. Panagiotopoulou et al. (2022) demonstrate controllable particle size, high loading, and improved photothermal stability, while Tadele et al. (2025) analyses the practical pros/cons (e.g., need for aqueous ethanol; brittleness mitigated by plasticizers or blending). Further, electrospraying with soy protein isolates (often combined with emulsified oils) yields probiotic and bioactive microcapsules suitable for food fortification, while pea protein has shown strong encapsulation of water-soluble flavonoids and can be co-electrospun with zein to tailor hydrophilicity and thermal behavior (Kopjar et al., 2022; da Trindade et al., 2024). Unfortunately, electrospinning of pure soy protein is quite challenging and requires a carrier polymer to enhance molecular entanglement. Electrospun SPI/PEO fibers have been prepared and exhibit promising applications in the food industry (Wen et al., 2017). Although electron microscopy analysis indicated beaded nanofibers, the functionalized nanofibers obtained had good antimicrobial and antioxidant properties. It was noted that the incorporation of anthocyanin-rich red raspberry into denatured SPI solution exerted the higher anthocyanin retention and greater antimicrobial activity (Wang et al., 2013).

# 4 Encapsulation of bioactive compounds using ESP

## 4.1 Protective encapsulation for labile compounds (vitamins, polyphenols, carotenoids)

Electrospinning and electrospraying have emerged as powerful electrohydrodynamic (EHD) techniques for stabilizing labile vitamins, polyphenols, and carotenoids against degradation induced by light, heat, and oxidation. Their key advantage lies in combining mild processing conditions with tailorable polymer architectures, enabling precise control over protection and release behavior. A common issue across studies is the rapid oxidative and

**TABLE 1** Recent findings on the encapsulation of vitamins using electrospinning and electrospraying.

| Vitamins | Coating materials | Encapsulation method | Encapsulation conditions | Major findings | References |
|---|---|---|---|---|---|
| Vitamin C | K-carrageenan, polylactic acid | Electrospinning | Voltage: 15 kV<br>Flow rate: 0.3 mL/h<br>Needle inner dia: 0.4 mm<br>Tip to collector distance: 15 cm | Encapsulation prolonged the release time of vitamin C<br>Performed better antimicrobial and antioxidant properties *in vitro* and *in vivo* | Bai et al. (2025) |
| Vitamin D3 | Poly (ε-caprolactone) | Electrospinning | Voltage: 16 kV<br>Flow rate: 4.5 mL/min<br>Tip to collector distance: 6 cm | Encapsulated vitamin showed a more sustained release | Carrillo Cabrera et al. (2025) |
| Vitamin E | Zein | Electrospinning | Voltage: 20 kV<br>Flow rate: 2 mL/h<br>Tip to collector distance: 5 cm | Microfibers showed a sustained release of V-E at the higher concentration of zein | Dias and Estevinho (2025) |
| Vitamin E (α-tocopherol) | Zein | Electrospinning | Voltage: 25 kV<br>Flow rate: 2 mL/h<br>Tip to collector distance: 16 cm | The release percentage of α-tocopherol after 48 h varied between 11.95% and 53.9% | Hadian et al. (2025) |
| Vitamin B3 and K4 | Polyvinyl alcohol | Electrospinning | Voltage: 16 kV<br>Flow rate: 0.02 mL/h<br>Tip to collector distance: 8 cm | The PVA and vitamin B3 interaction had higher energy and was more exothermic and spontaneous than the PVA-vitamin K4 interaction | Cabrera et al. (2024) |
| Vitamin B12 | Pullulan | Electrospinning/ Electrospraying | Voltage: 10–20 kV<br>Flow rate: 0.25–0.6 mL/h<br>Tip to collector distance: 5 cm | Longest releases are associated with the structures loaded with VitB12 and highest pullulan concentration | Couto et al. (2024) |
| Vitamin C | Poly (ethylene oxide) | Electrospinning | Voltage: 14 kV<br>Needle inner dia: 0.4 mm<br>Tip to collector distance: 15 cm | Developed a color-detectable vitamin C controlled-release system | Shin (2024) |
| Vitamin B12 | Zein | Electrospinning/ Electrospraying | Voltage: 20 kV<br>Flow rate: 0.6–1.5 mL/h<br>Tip to collector distance: 5 cm | Encapsulated vitamin showed a more sustained release | Couto et al. (2023) |
| Vitamin B12 | Chitosan/polyvinyl alcohol | Electrospinning | Voltage: 13 kV<br>Flow rate: 1 mL/h | Nanofiber led to the lower, slower, and more continuous release of the vitamin with a slight decrease in biodegradability | Yekrang et al. (2023) |
| Vitamin B9 | Zein | Electrospinning | Voltage: 20 kV<br>Flow rate: 0.2–0.3 mL/h<br>Tip to collector distance: 7 cm | Encapsulation enhanced the vitamin B9 antioxidant activity in the food and nutraceutical fields | Coelho et al. (2022) |

thermal degradation of bioactive compounds, including vitamin C, vitamin B-complex, vitamin D/E, polyphenols, and carotenoids. The strategy consistently adopted involves careful material selection to create protective micro/nanostructures and process parameter tuning to modulate morphology, which directly governs mass transfer and exposure to external stressors. The food industry has been actively exploring novel encapsulation strategies to enhance the stability and bioavailability of essential vitamins (Table 1). To address the oxidative vulnerability of vitamin C, Bai et al. (2025) utilized electrospinning to create κ-carrageenan (KC)/polylactic acid (PLA) composite nanofiber membranes for the preservation of blueberries, encapsulating vitamin C (VC) within hydroxypropyl-β-cyclodextrin (HP-β-CD) inclusion complexes. The addition of these inclusion complexes increased the average fiber diameter and thermal stability while reducing crystallinity and hydrophobicity. Crucially, the encapsulation of VC in the HP-β-CD/KC/PLA matrix significantly prolonged its release time compared to non-encapsulated forms. These membranes demonstrated superior antioxidant and antimicrobial properties both *in vitro* and *in vivo*, effectively extending the shelf life of fresh produce.

Furthermore, for V B9 (folic acid), incorporating plasticizers into modified starch enabled the production of porous microstructures and thin films, while preventing the rapid recrystallization of the polymer (Coelho et al., 2022). High encapsulation efficiencies were achieved for various formulations, including 1% B9 in 12% modified starch and 5% B9 in 5%–10% zein films. Release studies in simulated gastric fluid and deionized water indicated that smaller, highly porous structures facilitated faster external diffusion, while compact films significantly prolonged the release time of the vitamin. For lipophilic vitamins, the

**TABLE 2** Recent findings on the encapsulation of polyphenols using electrospinning and electrospraying.

| Polyphenols | Coating materials | Encapsulation method | Encapsulation conditions | Major findings | References |
|---|---|---|---|---|---|
| Olive leaf polyphenols | Sweet almond gum, gelatin | Electrospinning | Voltage: 20–30 kV<br>Flow rate: 0.25–0.75 mL/h<br>Tip to collector distance: 10–20 cm | The release rate was high in the initial times and gradually decreased with the increase of the process time | Geravand et al. (2025) |
| Gallic acid, chlorogenic acid, dihydromyricetin, hesperidin | Polyvinyl alcohol, fucoidan | Electrospinning | Voltage: 12 kV<br>Flow rate: 0.6 mL/h<br>Tip to collector distance: 15 cm | The encapsulation of polyphenol within PVA/FUC electrospun nanofibers increased the enhanced antioxidant activity of nanofibers | Ma et al. (2024) |
| Tea polyphenol | Pullulan | Electrospinning | Voltage: 12 kV<br>Flow rate: 0.1–0.2 mL/h<br>Tip to collector distance: 10 cm | Nanofibers have higher antioxidant properties with the addition of tea polyphenols; antibacterial test showed that nanofibers had obvious inhibitory effect on the growth of *Staphylococcus aureus* and *Escherichia coli* | Zhou et al. (2024a) |
| *Prunus domestica* anthocyanins and epigallocatechin gallate | Kappa-carrageenan, poly (vinyl alcohol) | Electrospinning | Voltage: 30 kV<br>Flow rate: 0.7 mL/h<br>Tip to collector distance: 17 cm | The anthocyanin-rich electrospun fibers displayed color change when subjected to the different pH buffer | Goudarzi, Moshtaghi and Shahbazi (2023) |
| Black tea extracts | Polyvinyl alcohol | Electrospinning | Voltage: 28 kV<br>Flow rate: 2.5 mL/h<br>Needle inner dia: 0.8 mm | The mat obtained through the nanoparticles precipitated in BT aqueous extract PVA solution presented the highest total polyphenol content and antioxidant activity | Quintero-Borregales et al. (2023) |
| Catechin | Cyclodextrin inclusion complex and poly (vinyl alcohol) | Electrospinning | Voltage: 15 kV<br>Flow rate: 0.3 mL/h<br>Needle inner dia: 0.4 mm<br>Tip to collector distance: 15 cm | The successful incorporation of catechin into nanofibers was confirmed by fourier-transform infrared spectroscopy (FTIR) analysis of catechin C═C bond stretching | Yildiz et al. (2023a) |
| Jujube extract | Poly (vinyl alcohol) | Electrospinning | Voltage: 15 kV<br>Flow rate: 0.5 mL/h<br>Tip to collector distance: 15 cm | PVA nanofiber film encapsulated JE with an efficiency of about 83.54% and was released 42% of encapsulated JE into the atmosphere after 180 h | Ansarifar et al. (2022) |
| Eggplant (*Solanum melongena* L.) peel extract | Gelatin | Electrospinning | Voltage: 15 kV<br>Flow rate: 1 mL/h<br>Tip to collector distance: 10 cm | Electrospun gelatin nanofibers showed encapsulation efficiency greater than 90% of extract and a maximum release of 95% and 80% for the medium at pH 1.5 and 7.5, respectively | Estrella-Osuna et al. (2022) |
| Curcumin | Potato starch | Electrospraying and electrospinning | Voltage: 23 kV<br>Flow rate: 0.6 mL/h<br>Needle inner dia: 0.8 mm<br>Tip to collector distance: 15 cm | Curcumin encapsulated in starch capsules and fibers showed higher thermal stability at 180 °C for 2 h compared to unencapsulated curcumin | Pires et al. (2022) |

hydrophobicity of the polymer and solvent selection are crucial. In vitamin D3-loaded PCL fibers, solvent systems (DCM/DMF vs. TFE) were tuned to control fiber diameter and surface roughness, which directly influenced oxygen diffusion and release rate. Fibers produced with TFE were thinner and more linear, whereas the DCM/DMF system produced larger, rougher fibers with higher interconnectivity due to DCM's high volatility. While both systems achieved complete release, the DCM/DMF-derived fibers provided a more sustained release profile across different vitamin concentrations (Carrillo Cabrera et al., 2025). Apart from this, inclusion of vitamin E in zein (1%–30% w/v) resulted in thinner structures compared to those without the active compound. Release assays in ethanol showed that fiber-based structures provided a more sustained release profile than particles, which released the vitamin almost immediately (Dias and Estevinho, 2025). Carrillo Cabrera et al. (2024) fabricate polyvinyl alcohol (PVA) fibers containing a multivitamin complex through both simple and coaxial electrospinning. The core/shell structure, with the vitamin complex protected by a PVA shell, resulted in a significant 45% reduction in fiber diameter compared to pure PVA fibers. Release profiles revealed that the core/shell configuration provided a more controlled and gradual release compared to simple fibers, which exhibited a faster pattern resembling classical Fickian diffusion. Computational studies further supported these findings by analyzing the strong hydrogen bonding between PVA and specific vitamins, such as B3, which confirmed the stability and feasibility of the encapsulation process (Carrillo Cabrera et al., 2024).

Research into the encapsulation of polyphenols using electrohydrodynamic techniques has advanced significantly, with a focus on enhancing the stability and bioactivity of compounds such as catechins, tea polyphenols, and anthocyanins (Table 2). The utilization of polymer-free electrospinning was explored to encapsulate catechin using hydroxypropyl-β-cyclodextrin (HP-β-CD) as a solubilization enhancer, in comparison to traditional poly (vinyl alcohol) (PVA) blending. This approach successfully produced bead-free nanofibers without the use of organic solvents (Yildiz et al., 2023a). Findings revealed that catechin/HP β-CD inclusion complex (IC) nanofibers had a mean diameter of 720 nm, while catechin/PVA nanofibers were slightly larger at 760 nm. Proton NMR analysis confirmed high loading, with calculated molar ratios of 0.60:1.00 (catechin/HP-β-CD) for the fibers. Notably, the polymer-free CD-IC nanofibers exhibited significantly higher antioxidant activity compared to the PVA-based fibers, demonstrating the effectiveness of the inclusion complex in stabilizing the polyphenol (Yildiz et al., 2023b). In the coaxially electrospun gelatin/tea polyphenol@pullulan core–sheath nanofibers, material selection and process architecture were specifically utilized to achieve spatially organized encapsulation and sustained functional release. The study identified 15% (w/v) as the optimal TP loading concentration, which produced the smallest and most uniform fibers with a diameter of 153.524 nm. Transmission electron microscopy (TEM) confirmed a distinct core-shell structure with a core diameter of 100 nm and a shell thickness of 20 nm. These fibers exhibited rapid water solubility and enhanced antioxidant activity due to the addition of TP, demonstrating effectiveness in inhibiting the growth of *S. aureus* and *Escherichia coli* (Zhou et al., 2024b). Electrospun PVA nanofiber mats containing black tea (BT) polyphenols offer a complementary strategy, where the process design couples solvent-displacement nanoprecipitation with electrospinning to control polyphenol localization and release (Quintero-Borregales et al., 2023). By dripping ethanolic BT extract into different PVA solutions, it was found that using a BT aqueous extract as the solvent doubled the total extracted polyphenol content (TEPC) compared to using water as the solvent in PVA solutions. Further results showed that the mat produced from BT aqueous extract had approximately 24% higher antioxidant activity. Release studies in food simulants revealed that over 64% of polyphenols were released in hydrophilic environments and over 98% in lipophilic ones, with polymer chain relaxation being the dominant mechanism of release. The fabrication of sweet almond gum/gelatin electrospun nanofibers loaded with olive-leaf polyphenols (OLP) further underscores the role of biopolymer interactions and solution rheology in stabilizing phenolics during electrospinning. The inclusion of OLP influenced the physical properties of the spinning solution, increasing viscosity while decreasing electrical conductivity. Numerical findings indicated that the average fiber diameter increased significantly with polyphenol concentration, rising from 111 nm (polyphenol-free) to 410 nm for 20% OLP loading. Release profiles in simulated gastrointestinal fluids showed a high initial release rate that gradually slowed over time, demonstrating the potential for OLP to be used in therapeutic and food-related nano-delivery systems (Geravand et al., 2025).

Carotenoids are widely utilized in dietary supplements, cosmetics, and pharmaceuticals due to their health-promoting properties. However, their practical application is often limited by their inherent sensitivity to light, heat, and oxidation. To overcome these challenges, electrospinning and electrospraying have emerged as promising encapsulation strategies to enhance the stability, solubility, and bioactivity of carotenoids (Table 3). Carotenoid-rich watermelon extracts were incorporated into zein nanofibers using emulsion electrospinning. This technique utilized response surface methodology (RSM) to optimize process parameters, identifying 23 kV voltage, 1.7 mL/h flow rate, and a 12.75 cm tip-to-collector distance as ideal conditions (İnan-Çınkır et al., 2024). Under these conditions, the zein fibers entrapped 4.054 mg $kg^{-1}$ lycopene and 0.649 mg $kg^{-1}$ β-carotene, while achieving an encapsulation efficiency of 77.78% and encapsulation yield of 41.76%. The resulting nanofibers exhibited a mean diameter of 369 nm and a high negative zeta potential of −28.90 mV, indicating good particle stability. Furthermore, storage stability tests in model foods revealed that carotenoids remained significantly more stable within the nanofibers than in free oil, milk, or water. Further, polymer-free electrospinning was employed to encapsulate antioxidant β-carotene within cyclodextrin (CD) host matrices, specifically hydroxypropyl-β-cyclodextrin (HP-β-CD) and hydroxypropyl-γ-cyclodextrin (HP-γ-CD) (Yildiz et al., 2023b). This approach significantly improved the water solubility and photostability of the lipophilic β-carotene. Numerical results indicated that the stability constants (Ks) for β-carotene/HP-β-CD and β-carotene/HP-γ-CD inclusion complexes were 7 M-1 and 36 M-1, respectively, suggesting stronger complexation with HP-γ-CD. Scanning electron microscopy (SEM) confirmed bead-free fibers with mean diameters influenced by the solvent, such as aqueous systems, yielded thinner fibers (250 nm for HP-β-CD and 320 nm for HP-γ-CD). In comparison, organic DMF-based systems produced much thicker fibers, reaching a diameter of up to 1,130 nm for HP-γ-CD (Yildiz et al., 2023b). Another study focused on developing polymeric composites of zein and polyethylene oxide (PEO) to encapsulate pequi carotenoids. Two formulations were tested, including F1 (zein/PEO) and F2 (zein/PEO/pectin). Results showed that particle sizes for these tubular microfibers ranged from 2.00 to 5.02 μm. The inclusion of pectin in F2 significantly increased the fiber diameter compared to F1 ($p < 0.05$). Rheological analysis demonstrated that the addition of carotenoids increased the viscosity and structural integrity of the solutions, while maintaining thermal stability up to 250 °C. This encapsulation successfully protected the carotenoids from degradation, particularly in the F1 formulation (Ramos-Souza et al., 2025).

## 4.2 Encapsulation for enhanced solubility and bioavailability of hydrophobic compounds

The use of electrospinning and electrospraying techniques has gained increasing attention in recent years as effective strategies for

TABLE 3 Recent findings on the encapsulation of carotenoids using electrospinning and electrospraying.

| Carotenoids | Coating materials | Encapsulation method | Encapsulation conditions | Major findings | References |
|---|---|---|---|---|---|
| Pequi carotenoid | Zein and polyethylene oxide | Electrospinning | Voltage: 20 kV<br>Flow rate: 1800 μL/h<br>Needle inner dia: 0.6 mm<br>Tip to collector distance: 10 cm | Carotenoid degradation was not evident, indicating that the formulation may have offered a degree of protection and contributed to the effective encapsulation of carotenoids | Ramos-Souza et al. (2025) |
| *B. infantis* carotenoid | Polyvinyl alcohol | Electrospinning | Voltage: 16 kV<br>Flow rate: 0.8 mL/h<br>Tip to collector distance: 15 cm | The pigment-loaded PVA nanofibers exhibited antioxidant activity and antibacterial action against *S. aureus*, *B. megaterium*, and *S. marcescens* | Soni et al. (2025) |
| β-carotene | Whey protein isolate (WPI) and pullulan (PUL) | Electrospinning | Voltage: 19–23 kV<br>Flow rate: 0.1 and 0.2 mL/h | The findings suggest that WC-SP, with its superior β-carotene stability | Drosou and Krokida (2024a) |
| Carotenoids | Zein | Electrospinning | Voltage: 23 kV<br>Flow rate: 1.7 mL/h<br>Tip to collector distance: 12.75 cm | The electrospinning improved thermal stability of carotenoid microemulsion | İnan-Çınkır et al. (2024) |
| Carotenoid from watermelon | Zein or gelatin-pectin | Electrospinning | Voltage: 15 and 20 kV<br>Flow rate: 1 and 2 mL/h<br>Tip to collector distance: 10 cm | The highest encapsulation efficiency (% 79.74) was achieved with zein nanofibers including the mixture of acetic acid:ethanol: water (30:40:30) and 40% microemulsion | İnan-Çınkır et al. (2023) |
| β-carotene | Cyclodextrin complex | Electrospinning | Voltage: 15 kV<br>Flow rate: 0.5–1 mL/h<br>Tip to collector distance: 15–20 cm | β-carotene/CD inclusion complex nanofibers stabilize the encapsulated β-carotene against UV-mediated oxidation | Yildiz et al. (2023b) |
| β-carotene | Gum Arabic and whey protein isolate | Electrospinning | — | Encapsulation improved the stability of the carotenoids | Falsafi et al. (2022) |
| β-carotene | Poly (vinyl alcohol), alkali lignin | Electrospinning | Voltage: 15 kV<br>Flow rate: 0.3 mL/h<br>Needle inner dia: 0.4 mm<br>Tip to collector distance: 15 cm | PVA/AL/β-carotene nanofiber exhibited higher antioxidant activity than free β-carotene due to the protection of AL matrix and the special structure of nanofiber | Xiang et al. (2022) |

encapsulating essential oils, thereby improving their stability, bioavailability, and controlled release in food applications (Table 4). These techniques enable the fabrication of nanostructured fibers and coatings with tailored functional properties, making them highly suitable for active packaging and food preservation. The fabrication of long-lasting carriers for dill seed essential oil (DSEO) was achieved using a blend of cactus mucilage (CM) and poly (vinyl alcohol) (PVA) through emulsion electrospinning. The CM/PVA spinning emulsions produced uniform, tubular fibers with diameters ranging from 158 ± 18 to 230 ± 26 nm, indicating an appropriate rheological and electrohydrodynamic balance during jet formation (Mannai et al., 2023). The incorporation of DSEO did not disrupt fiber continuity, while thermogravimetric and FT-IR analyses confirmed strong polymer–oil interactions that supported structural stability and hindered premature volatilization. Notably, the system achieved a 100% encapsulation efficiency, indicating the complete retention of DSEO within the fiber matrix during spinning. The release profile revealed a sustained and prolonged liberation of the oil, contrasting with the rapid diffusion of free DSEO. Functionally, the loaded fibers displayed pronounced antimicrobial activity, with minimum inhibitory and bactericidal concentrations of 2.5 mg/mL and 5 mg/mL, respectively, against *Staphylococcus aureus* and *Pseudomonas aeruginosa*, highlighting their potential as active coatings in food and biomedical applications (Mannai et al., 2023). To extend the shelf life of highly perishable strawberries, thyme essential oil (TEO) was encapsulated in zein fiber films. The resulting fibers were bead-free and had a smooth surface. The addition of 4% (v/v) TEO increased the average fiber diameter from 195.0 to 402.3 nm, due to a reduction in solution conductivity. The zein/TEO fiber films were highly effective in active packaging, reducing weight loss by about 15% and maintaining 20% higher fruit firmness compared to controls after 15 days of cold storage. Additionally, the films showed significant antibacterial activity, with inhibition zones of 15.54 mm against *Bacillus cereus* and 8.12 mm against *E. coli* (Ansarifar and Moradinezhad, 2022). A novel bilayer film was developed by combining a sweet potato starch base with an overlapping layer of zein electrospun fibers encapsulating 60% (v/w) TEO. These films exhibited a well-integrated structure with a thickness of 0.194 mm and demonstrated superior functional properties, including thermal stability and an efficient water vapor barrier. The bilayer material displayed enhanced antioxidant activity and a controlled high release rate of TEO, highlighting its potential for sustainable active food packaging (Vitoria et al., 2025).

Addressing the lack of research on geranium essential oil (GEO) encapsulation, researchers utilized carioca bean starch as a natural and cost-effective polymer matrix for electrospinning. The produced

**TABLE 4** Recent findings on the encapsulation of essential oils using electrospinning and electrospraying.

| Essential oils | Coating materials | Encapsulation method | Encapsulation conditions | Major findings | References |
|---|---|---|---|---|---|
| Lemongrass EOs | *Ferula haussknechtii* gum/Polyethylene oxide | Electrospinning | Voltage: 20 kV<br>Flow rate: 0.3 mL/min<br>Tip to collector distance: 18 cm | These findings demonstrate that the inclusion of LGEO in bioactive edible coatings can significantly enhance antimicrobial protection | Jafari et al. (2025) |
| Clove Eos | Okra mucilage, pullulan | Electrospinning | Voltage: 15 kV<br>Flow rate: 0.4 mL/h<br>Tip to collector distance: 12.5 cm | Release studies in a fatty food simulant showed that nanofibers provided a sustained release over 24 h, compared to only 4 h for their counterparts loaded with free CEO. | Yeganegi et al. (2025) |
| Thyme Eos | Zein | Electrospinning | Voltage: 20 kV<br>Flow rate: 0.9 mL/h<br>Needle inner dia: 0.8 mm<br>Tip to collector distance: 20 cm | Zein/TEO electrospun fibers demonstrated antioxidant activity and a high release rate of TEO. | Vitoria et al. (2025) |
| Geranium EOs | Carioca bean starch | Electrospinning | Voltage: 13 kV<br>Flow rate: 1 mL/h<br>Needle inner dia: 0.8 mm<br>Tip to collector distance: 20 cm | Fibers containing 40% GEO showed a significant reduction in tested bacteria | Dos Santos et al. (2024) |
| Ginger EOs | Starch from avocado byproducts | Electrospinning | Voltage: 23 kV<br>Flow rate: 0.6 mL/h<br>Needle inner dia: 0.8 mm<br>Tip to collector distance: 20 cm | The fibers with 50% of ginger EO displayed antibacterial activity against *Escherichia coli*, proving the bioactivity of the starch-ginger EO fibers | Pires et al. (2024) |
| Dill seed Eos | Cactus Mucilage/Poly (vinyl alcohol) | Electrospinning | Voltage: 30 kV<br>Flow rate: 20 µL/min<br>Needle inner dia: 0.84 mm<br>Tip to collector distance: 15 cm | Electrospun nanofibers containing DSEO demonstrated bacteriostatic and bactericidal activities against foodborne pathogenic bacteria | Mannai et al. (2023) |
| Thyme Eos | Zein | Electrospinning | Voltage: 20 kV<br>Flow rate: 1 mL/h<br>Tip to collector distance: 15 cm | Thyme essential oil (TEO) encapsulated into zein electrospun fiber extended the shelf life of strawberry | Ansarifar and Moradinezhad (2022) |
| Cumin Eos | Zein | Electrospinning | Voltage: 20 kV<br>Flow rate: 8 mL/h<br>Tip to collector distance: 15 cm | Cumin essential oil loaded fiber mats inhibited the growth of *S. aureus* and *E. coli, B. cereus,* and *S. enterica* | Ghasemi et al. (2022) |
| Basil EOs | Soy lecithin | Electrospinning | Voltage: 20 kV<br>Flow rate: 0.3 mL/h<br>Tip to collector distance: 15 cm | The prepared nanofibrous mats could help maintain the quality of chilled pork during 4-day storage | Li C. et al. (2022) |

ultrafine starch fibers were uniform and continuous, with average diameters ranging from 249 to 373 nm. Confocal analysis revealed a uniform distribution of GEO, with loading capacities of 54.0%, 42.9%, and 36.5% for initial oil concentrations of 20%, 30%, and 40%, respectively. Notably, fibers with 40% GEO showed a significant reduction in pathogenic bacteria (*Listeria monocytogenes*, *S. aureus*, and *E. coli*), and the MIC of GEO for all tested pathogens was 2.95 mg/mL (dos Santos et al., 2024). Yeganegi et al. (2025) investigated a sustainable approach by encapsulating clove essential oil (CEO)-β-cyclodextrin (β-CD) inclusion complexes within a blend of okra mucilage (OM) and pullulan (PL) nanofibers. An optimal PL: OM ratio of 50:50 (v/v) was identified, producing bead-free nanofibers with a small average diameter of 247.73 nm. Compared to fibers loaded with free oil, which released the active compound in only 4 h, the inclusion complex-loaded nanofibers provided a sustained release over 24 h in fatty food simulants. These fibers also exhibited improved thermal stability and enhanced antibacterial and antioxidant properties (Yeganegi et al., 2025). Furthermore, a novel antimicrobial bioactive coating was developed using emulsion electrospinning of lemongrass essential oil (LGEO) combined with *Ferula haussknechtii* gum and polyethylene oxide (PEO) (Jafari, Sourki and Pashangeh, 2025). The resulting fibers, which had an average diameter of 0.56 µm, were uniform and bead-free across LGEO concentrations of 3%, 6%, and 9% (v/v). The coating with 9% LGEO exhibited the highest antimicrobial activity against both Gram-positive and Gram-negative bacteria, as well as *Aspergillus niger*. Furthermore, the electrospun fibers demonstrated significant antioxidant potential, with a radical scavenging activity of approximately 74.51%. Increasing LGEO concentration also affected the physical properties of the spinning emulsion, resulting in a decrease in viscosity and an increase in electrical conductivity (Jafari et al., 2025).

TABLE 5 Recent findings on the encapsulation of probiotics using electrospinning and electrospraying.

| Probiotics | Coating materials | Encapsulation method | Encapsulation conditions | Major findings | References |
|---|---|---|---|---|---|
| *Lactobacillus rhamnosus* GG (ATCC 53,103) | Poly (vinyl alcohol), alginate, cellulose | Electrospinning | Voltage: 80 kV<br>Tip to collector distance: 12 cm | The findings of *in vitro* GI analysis publicized the significantly improved survival of encapsulated probiotics from 11.01 to 5.32 and 13.84 to 8.69 (log CFU/mL) at pH 2 and 7, respectively | Nawaz et al. (2025) |
| *Lactiplantibacillus plantarum* 69–2 (LP69-2) | Poly (vinyl alcohol), fucoidan, ethyl cellulose | Electrospinning | Voltage: 17 kV<br>Flow rate: 0.6 mL/h<br>Needle inner dia: 0.5 mm<br>Tip to collector distance: 15 cm | The survival rate of LP69-2 embedded in PVOH-FUC@EC core-shell nanofibers was significantly elevated after simulated gastrointestinal digestion | Tan et al. (2025) |
| *Lactobacillus plantarum* | Gelatin, dextran | Electrospinning | Voltage: 16 kV<br>Flow rate: 1 mL/h<br>Needle inner dia: 0.3 mm<br>Tip to collector distance: 15 cm | Gelatin-rich shell phases provided stronger protection, likely due to gelation properties restricting bacterial mobility | Wu et al. (2025) |
| *Lactobacillus* spp | Poly (vinyl alcohol), hyaluronan | Electrospinning | Voltage: 25 kV<br>Flow rate: 1 mL/h<br>Tip to collector distance: 15 cm | The nanofibers had the bacterial cells successfully enclosed in them | Ilomuanya et al. (2024) |
| *Lactobacillus plantarum* | Dextran | Electrospinning | Voltage: 15 kV<br>Flow rate: 0.5 mL/h<br>Needle inner dia: 0.67 mm<br>Tip to collector distance: 15 cm | After 5 days of storage in room temperature and 4 °C, the loaded probiotic activity levels remained high | Wu X. et al. (2024) |
| *Lactiplantibacillus plantarum* 1–24-LJ and Pc | Poly (vinyl alcohol) | Electrospinning | Voltage: 15 kV<br>Flow rate: 0.3 mL/h<br>Needle inner dia: 0.46 mm<br>Tip to collector distance: 12 cm | After 28 days, the viability of the strain could still be above 6 log cfu/g | Zhang L. et al. (2023) |
| *Lactobacillus acidophilus* | Poly (vinyl alcohol), gum Arabic | Electrospinning | Voltage: 16.8 kV<br>Tip to collector distance: 15 cm | *In-vitro* assay indicated that probiotics with encapsulated showed significantly viability compared to free cells | Fareed et al. (2022) |

## 4.3 Viable encapsulation of live bioactive (probiotics)

The primary challenge in delivering probiotics is maintaining their viability during processing, storage, and passage through the gastrointestinal tract's harsh conditions. Traditional methods such as spray drying and freeze drying often compromise cell integrity due to high thermal stress or complex processing. Electrospinning has emerged as a superior alternative, utilizing high-voltage electric fields to produce submicron-to-nanoscale fibers at ambient temperatures, thereby providing a benign environment for sensitive bioactive substances. Recent studies have focused on optimizing polymer blends and advanced fiber architectures to maximize the viability of probiotics and their targeted delivery (Table 5). *Lactobacillus rhamnosus* GG was encapsulated within a composite matrix of polyvinyl alcohol (PVA), sodium alginate (SA), and carboxymethyl cellulose (CL). The optimized blend ratio of 50: 25:25 for PVA:SA: CL was found to provide the best spinnability for fabricating nanosheets (Nawaz et al., 2025). The resulting nanomaterial achieved an encapsulation efficiency (EE) of 82.06%, effectively shielding the bacterial cells. Most notably, the encapsulated probiotics demonstrated robust survival under simulated gastric conditions (pH 2), where free cells were eliminated; the encapsulated cells decreased from 11.01 ± 0.67 to 5.32 ± 0.94 Log CFU/mL after 60 min (Nawaz et al., 2025). Tan et al. (2025) utilized coaxial electrospinning to create core-shell nanofibers for the co-delivery of *Lactiplantibacillus plantarum* 69–2 and dihydromyricetin. The core solution consisted of PVA and fucoidan, while the shell was composed of ethyl cellulose (EC), a biopolymer resistant to gastrointestinal digestion. The study found that increasing the shell flow rate from 0.6 to 1.2 mL/h significantly increased the shell thickness from 64.94 ± 2.35 nm to 96.76 ± 3.62 nm, although it caused a decrease in overall fiber diameter from 205.21 nm to 129.46 nm. While the high voltage and acidic environment of the shell solvent caused an initial viability loss of 1.47–1.98 log CFU/g, the final survival rate after simulated digestion was significantly enhanced to approximately 88% when shell thickness was maximized. Targeting vaginal dysbiosis, this study integrated *Lactobacillus fermentum* into hyaluronic acid (HA)-PVA hybrid nanofibers. The biological evaluation indicated that while the viability of the bacteria decreased by approximately 3-log units during the process (from 8.17 to 5.18 Log CFU/mL), the resulting delivery system remained effective for localized therapeutic action (Ilomuanya et al., 2024).

Wu Y. et al. (2024) present a novel approach using oil-free W/W emulsion electrospinning to encapsulate *Lactobacillus plantarum* within core-shell nanofibers. The spinning solution was a blend of polyethylene oxide (PEO) and dextran (DEX). The loading efficiency achieved was 9.70 ± 0.40 log CFU/g, which is well above the required therapeutic threshold. The study highlighted significant stress resistance; while free cells were lost entirely after 60 min in simulated gastric fluid, the encapsulated probiotics only decreased by one order of magnitude after 120 min (from 8.79 ± 0.30 to 7.73 ± 0.22 log CFU/g). Furthermore, these fibers maintained high activity even after 5 days of storage at room temperature, with counts remaining >8 log CFU/g (Wu X. et al., 2024). Focusing on thermal stability, researchers explored the electrospinning of gelatin (GE) and dextran (DEX) W/W emulsions to protect *Lactobacillus plantarum* (Wu et al., 2025). The study demonstrated that phase inversion occurred at dextran concentrations above 9 wt%, significantly influencing fiber morphology and probiotic protection. Fibers with a gelatin-rich shell (7.5 wt% DEX) provided superior protection, retaining approximately 0.7 log more viable cells during gastric digestion than those with a dextran shell. Numerically, the encapsulated probiotics exhibited exceptional heat resistance: after exposure to 72 °C for 1 min, the loaded fibers maintained a high viability of 8.44 log CFU/g, whereas free cell counts plummeted to 3.90 log CFU/g (Wu et al., 2025).

## 4.4 Multifunctional and co-encapsulation strategies

Electrospinning and electrospraying have emerged as powerful electrohydrodynamic techniques for co-encapsulating multiple bioactive compounds within a single polymeric matrix, enabling simultaneous protection and controlled delivery of ingredients with complementary functions. The studies demonstrate how carefully tuned formulation variables and fiber architectures support synergistic stabilization, sustained release, and enhanced functional performance of co-loaded systems in food and packaging applications. Couto et al. (2023) explored the simultaneous encapsulation of epigallocatechin-3-gallate (EGCG) and vitamin B12 within a zein polymer matrix using electrospinning. Lower polymer concentrations (1%–5% w/v) favored the formation of micro/nanoparticles *via* electrospraying, while higher concentrations (30% w/v) resulted in continuous fibers through electrospinning. Encapsulation efficiencies varied markedly with formulation; however, most co-encapsulated samples exhibited EE values above 70%, and the highest efficiencies were obtained for formulations containing 30% zein and 1% total active compound, where both EGCG and vitamin B12 reached 100% EE. Release studies revealed the typical biphasic profile characterized by an initial burst followed by a stabilization phase, with fibers exhibiting significantly slower diffusion kinetics than microparticles. Mathematical modeling determined that the Weibull model provided the best fit for these release profiles (Couto et al., 2023). In the k-carrageenan/poly (vinyl alcohol) (KC–PVA) system, electrospinning was employed to co-encapsulate *Prunus domestica* anthocyanins (3%) together with EGCG at five or 10 μg $mL^{-1}$, creating hybrid fibers that combined pH-responsive sensing with antioxidant and antimicrobial capacity (Goudarzi, Moshtaghi and Shahbazi, 2023). The simultaneous incorporation of the two bioactives altered fiber structure and functionality, producing mats with increased thickness and elongation at break, alongside significant reductions in tensile strength, solubility, moisture content, and water-vapour permeability relative to the control film ($p < 0.05$). The anthocyanin component endowed the fibers with a clear pH-dependent chromatic transition, ranging from light pink at pH 1 to brown at pH 12, enabling visual spoilage monitoring through color change during storage. When applied to minced beef, co-encapsulated mats provided superior preservation performance after 15 days at refrigeration temperature, samples packed with the EGCG-anthocyanin fibers showed the lowest microbial growth and chemical spoilage indicators, while the treatment containing only PDE reached a total viable count of 7.21 log CFU $g^{-1}$, a pH of 6.63, and a TVB-N of 28.07 mg N 100 $g^{-1}$ (Goudarzi, Moshtaghi and Shahbazi, 2023). A different approach was taken to improve the stability and functionality of probiotics by co-encapsulating *Lactiplantibacillus plantarum* 69-2 (LP69-2) with various polyphenols, including gallic acid (GA), chlorogenic acid (CA), dihydromyricetin (DMY), and hesperidin (HES) (Ma et al., 2024). These were embedded within a novel polyvinyl alcohol/fucoidan (PVA/FUC) matrix using electrospinning at 12 kV and a flow rate of 0.6 mL/h. The strategy relied on the prebiotic and antioxidant synergy between the fucoidan and polyphenols to protect the probiotic cells. The addition of polyphenols significantly reduced the average diameter of the nanofibers compared to the PVA/FUC control. The survival rates of the encapsulated probiotics remained high, exceeding 85% immediately following the electrospinning process. The PVA/FUC/DMY formulation exhibited the highest antioxidant capacity, with a DPPH radical scavenging ability of 53.49%, and maintained the highest probiotic viability after 21 days of storage at 4 °C (Ma et al., 2024).

# 5 Applications of ESP encapsulate in food industry

## 5.1 Functional food development

In recent years, consumers have become more conscious of how their food choices impact health and are increasingly seeking products with enhanced nutritional quality and added bioactive benefits (Mena et al., 2024; Tripathy et al., 2022; 2023). Functional foods serve as an effective and accessible option compared to conventional supplements or herbal formulations, as they naturally integrate vital bioactive components into everyday diets, thereby attracting a broad spectrum of consumers (Süfer, 2025). Electrospinning have emerged as effective encapsulation techniques for incorporating bioactive compounds into food systems (Figure 3). Nanofibers produced by these methods provide high encapsulation efficiency, sustained release, and protection of sensitive compounds during food processing and gastrointestinal digestion, thereby broadening the possibilities of food fortification (Günal-Köroğlu et al., 2025). Thymol, a hydrophobic bioactive with strong functional properties, suffers from poor stability and solubility, which restricts its direct use in foods. To address this, Ali et al. (2025) encapsulated thymol into pullulan–whey protein isolate-based nanofibers (THY-PW-NF) and applied in bread fortification. The encapsulated thymol showed a recovery rate of 78.07% during bread preparation, superior to free thymol, while preserving bioactivity

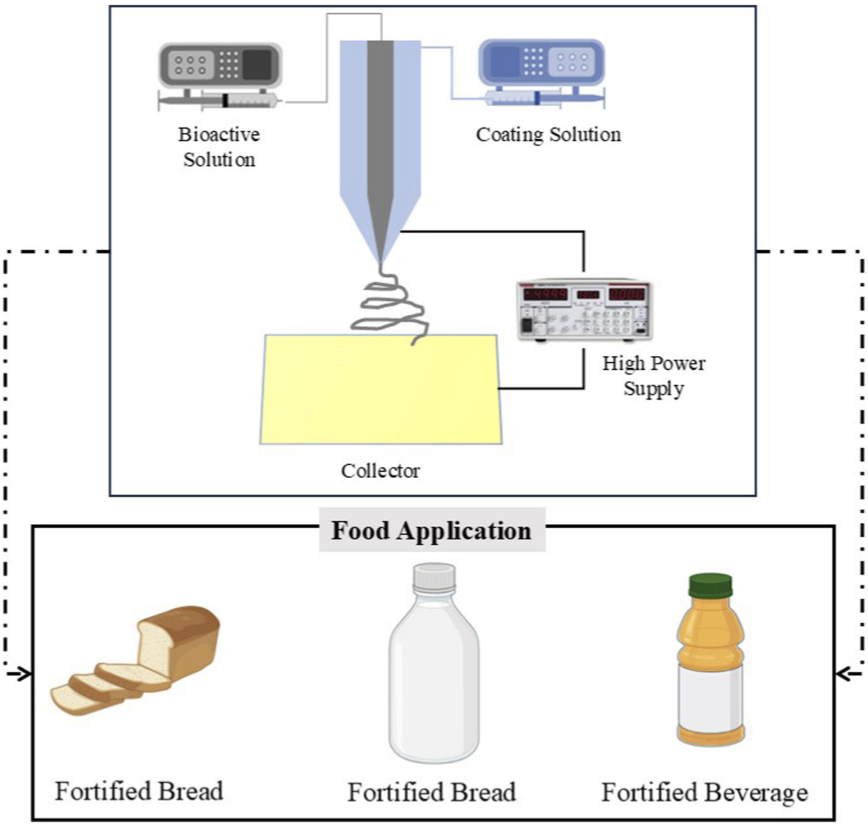

FIGURE 3
Application of electrospinning encapsulation technique for the development of functional food products.

after gastrointestinal digestion. The regulated release of thymol was attributed to its strong molecular interactions with the encapsulating wall matrix, which gradually disintegrated during simulated intestinal fluid digestion. Fortified bread displayed improved pasting and textural properties, and thymol released from nanofibers exhibited enhanced inhibitory effects on digestive enzymes (α-amylase, α-glucosidase, and pancreatic lipase). This slow dissolution enabled greater thymol retention within the bread, enhancing its inhibitory activity. Conversely, bread enriched with non-encapsulated thymol exhibited a markedly lower α-amylase inhibition of 10.25%, which was linked to thermal losses during baking and the consequent reduction in retained thymol (Ali et al., 2025). Cytotoxicity studies on Caco-2 cells confirmed the safety of nanofiber-based fortification within the tested concentration range, highlighting their potential in functional bakery products. Similarly, resveratrol, known for its poor bioavailability and chemical instability, was successfully encapsulated in whey protein isolate–pullulan nanofibers using optimized electrospinning conditions (18% TS, 18 kV, 0.6 mL/h) by Seethu et al. (2020). The resulting fibers had high encapsulation efficiency (up to 96.7%), nanoscale diameter (63–208 nm), and retained antioxidant activity. When applied in milk fortification, resveratrol-loaded nanofibers did not alter the physicochemical or sensory properties of the product, demonstrating their feasibility for dairy-based functional foods. In the case of resveratrol, the non-encapsulated form was released much more rapidly, reaching nearly complete release (98.5%) within 7 h. In contrast, only 73.72% was released from the nanofibre-encapsulated system over the same period. These findings confirm that incorporation into nanofibres enables a controlled and prolonged release profile, thereby supporting improved stability and potentially greater bioavailability of resveratrol within the gastrointestinal tract. Carotenoids such as lycopene and β-carotene are unstable and prone to degradation in foods. Zein fibers encapsulating watermelon carotenoid microemulsions were optimized at 23 kV, 1.7 mL/h, and 12.75 cm, yielding encapsulation efficiency of 77.78% and encapsulation yield of 41.76%, with lycopene and β-carotene contents of 4.054 mg/kg and 0.649 mg/kg, respectively. The electrospun matrix decreased diffusion coefficients and improved thermal stability of carotenoids, while fortification trials in model foods showed greater pigment stability in nanofiber-incorporated systems compared to milk, olive oil, and water. These results demonstrate the suitability of electrohydrodynamic encapsulation for stabilizing hydrophobic antioxidants during storage and functional food processing (İnan-Çınkır et al., 2024). Catechins, despite their strong antioxidant potential, have limitations due to bitterness, instability, and susceptibility to oxidation. A comparable approach was demonstrated for catechin fortification, where zein-based electrospun nanofibers achieved encapsulation efficiency of 92.8% and minimal fiber diameters of 95.2 nm at 18% polymer concentration, 20 kV, and 0.5 mL/h. The nanofibers exhibited hydrodynamic diameter of 172.3 nm, zeta potential of −26.3 mV,

TABLE 6 Applications of electrospinning in the food packaging and preservations.

| Bioactive compounds | Coating materials | Packaged products | Major findings | References |
|---|---|---|---|---|
| Lemon beebrush essential oil | Polycaprolactone | Meat | • Nanofibers preserved the chemical and microbial quality of meat<br>• Increase the storage time by 18 days | Bahramian et al. (2025) |
| Thyme essential oil and grape leaf extract | Zein | Iranian traditional butter | • Inhibit microbial growth<br>• Preserving physicochemical stability over a 30-day storage period | Karim et al. (2025) |
| Blueberry anthocyanin | Polylactic acid, quaternized chitosan | Blueberry | • Postharvest decay rate reduced from 70% to 23%<br>• Storage weight loss rate was reduced from 1.66% to 1.26%<br>• Film color changed from pinkish purple to light pink with increase of storage time | Xu et al. (2025) |
| Tannic acid | Polyvinyl alcohol, chitosan | Strawberry | • Extends shelf life by up to 6 days | He et al. (2024) |
| Cinnamon bark oil and clove bud oil | Cellulose acetate | Grapes and tomato | • Increase the storage time from 15 days to 30 days | Sethunga et al. (2024) |
| Anthocyanin and thymol | Gelatin, zein | Shrimp | • Shelf life of packaged shrimps was extended to 11 days at 4 °C | Wu Y. et al. (2024) |
| 1,8-Cineole | Polyvinyl alcohol, chitosan | Strawberry | • This film could extend the shelf life of strawberries to 6 days at 25 °C | Cheng et al. (2023) |
| Curcumin | Gelatin, chitosan | Protein rich food such as meat or seafoods | • The film presented high sensitivity of colorimetric behavior to ammonia (within 3 min) | Duan et al. (2023) |
| Oregano essential oil | Polylactic acid, polycaprolacton | Blackberry | • Nanofibrous material inhibited postharvest decay and deterioration of blackberry | Shi et al. (2023) |
| Proanthocyanidins | Zein, gelatin | Sweet cherries | • Respiration time was delayed by 5 days, and the peak of ethylene release was decreased by nearly half | Yuan et al. (2023) |
| Cinnamaldehyde, thymol | Zein, gelatin | Strawberry | • Packaged strawberries kept their freshness as long as 7 days at room temperature | Wu et al. (2023) |
| Oregano essential oil | Polylactic acid, polycaprolactone | Blackberry | • Nanofibers showed antibacterial and antifungal capacity<br>• Delayed postharvest decay, deterioration, and storage quality loss | Shi et al. (2022) |
| Eugenol | Gelatin | Beef | • Nanofibers maintained the textural properties and quality and freshness of the raw meat<br>• Increased the shelf life to 9 days | Yilmaz et al. (2022) |

and polydispersity index of 0.15, with sustained catechin release and preserved antioxidant activity. When incorporated into milk, the fortified product maintained physicochemical and sensory acceptability, confirming the suitability of electrohydrodynamic encapsulation for stabilizing polyphenols while mitigating bitterness and oxidation sensitivity in functional beverages (Rajunaik et al., 2024).

Milk-derived bioactive peptides possess health-promoting properties but are hindered by bitter taste, instability, and poor bioavailability. Pullulan-based nanofibers encapsulating casein-derived peptides were fabricated through electrospinning and applied for milk fortification (Rajanna et al., 2022). The encapsulated peptides demonstrated sustained release (75.3% after 8 h) under gastrointestinal conditions and retained antioxidant activity. Milk fortified with these peptide-loaded nanofibers did not show significant changes in physicochemical quality, confirming the suitability of nanofiber-based encapsulation for peptide delivery. Further, Zein electrosprayed capsules containing fish oil achieved high encapsulation efficiency of 83% ± 1% with mean capsule diameters of 2.4 ± 0.7 μm, remaining structurally intact in low-fat mayonnaise. After storage, mayonnaise fortified with capsules exhibited markedly lower hydroperoxide levels (2 meq/kg oil) compared to mayonnaise containing free fish oil (6 meq/kg oil), confirming oxidative protection and enhanced omega-3 stability within the food matrix. The system also increased viscosity and droplet size without adverse phase separation, demonstrating compatibility of electrosprayed structures in emulsified functional foods (Miguel et al., 2019). These findings underline the potential of electrosprayed zein capsules in enriching water-based food systems with omega-3 fatty acids. Electrospun nanofibers have been successfully applied for fortifying bakery, dairy, and emulsion-based food systems with a variety of bioactive compounds including polyphenols, carotenoids, peptides, and omega-3 fatty acids. These nanostructured delivery systems not only enhance bioavailability and stability of functional compounds but also maintain food quality and sensory attributes, making them highly relevant for the development of next-generation functional foods.

## 5.2 Food packaging applications

Currently, there is an increasing focus on active food packaging due to rising consumer awareness about food safety. These packaging systems often integrate bioactive agents with antimicrobial and antioxidant functions to extend the shelf life of food products. Nevertheless, the hydrophobicity and volatility of many such compounds restrict their efficiency in packaging applications. To overcome these limitations, electrohydrodynamic encapsulation has been identified as a promising technique to improve the stability and retention of active ingredients within packaging matrices (Table 6) (Vignesh et al., 2024). One notable application is the development of electrospun nanofibers incorporating lemon-beebrush essential oil–loaded metal–organic frameworks (MOFs) within a PCL matrix. The encapsulated system improved tensile strength from 62.3 to 68.2 MPa, while maintaining antioxidant and antibacterial activity with inhibition-zone diameters of 20.3 mm (*E. coli*) and 24.3 mm (*S. aureus*). When applied to red-meat storage at 4 °C, the films significantly preserved chemical quality indices and microbial stability, extending the shelf life by 18 days. This illustrates how electrohydrodynamic encapsulation, combined with porous carriers such as MOFs, can support long-term functional food protection and active preservation performance (Bahramian et al., 2025). Further advances were demonstrated through oregano-essential-oil β-cyclodextrin complexes embedded into PLA/PCL electrospun nanofibers for active packaging of blackberry fruit. During storage trials, the nanofiber mats successfully delayed postharvest decay and deterioration, confirming the role of electrohydrodynamic processing in retaining bioactivity and maintaining functional performance in biodegradable packaging for plant-based functional foods (Shi et al., 2022). Another approach involved cellulose acetate nanofibers (CANFs) loaded with cinnamon bark oil (CNO) and clove bud oil (CBO), which demonstrated uniform morphology, controlled release, and strong antimicrobial activity. When applied to grapes and tomatoes, this packaging successfully maintained microbiological safety for up to 40 days at 4 °C, compared to only 15 days in control samples (Sethunga et al., 2024).

Essential oils (EOs) are widely used in ENF-based packaging for their antimicrobial and antioxidant properties; however, their volatility and instability often limit effectiveness. To address this, dual encapsulation strategies have been explored. In functional packaging systems for fresh fruit, electrospun PVA/chitosan nanofibers incorporating 1,8-cineole–cyclodextrin inclusion complexes demonstrated that dual-encapsulation improves essential-oil stability and release performance. Films containing 40% (w/w) inclusion complexes exhibited enhanced mechanical and barrier properties, while the release of 1,8-cineole followed a sustained, non-Fickian diffusion behavior (Cheng et al., 2023). Application trials confirmed that the functional film extended strawberry shelf life to 6 days at 25 °C, compared with rapid deterioration in control samples, highlighting electrohydrodynamic encapsulation as a viable platform for the stabilization and gradual delivery of volatile antimicrobial bioactive compounds in minimally processed fruit products Electrohydrodynamic encapsulation has also been applied in dairy systems through the use of zein-based electrospun nanofibers enriched with thyme essential oil, grape leaf extract, and zinc oxide nanoparticles for the preservation of traditional Iranian butter. The optimized formulation produced uniform fibers with a mean diameter of 638 ± 164.69 nm, high hydrophobicity (137.5° contact angle), and antioxidant activity equivalent to 34% DPPH scavenging, while exhibiting inhibition-zone diameters of 11 mm (*S. aureus*) and 16 mm (*E. coli*). When applied to butter storage, the active nanofiber coating significantly reduced peroxide accumulation and microbial counts over 30 days, underscoring the value of electrospun encapsulated bioactives in enhancing oxidative and microbiological stability of high-fat functional foods (Karim et al., 2025). Beyond preservation, electrospun nanofibers are increasingly used in intelligent food packaging systems. A similar approach was employed in blueberry preservation using anthocyanin-loaded PLA/HACC electrospun nanofiber films, where encapsulation enhanced barrier, antioxidant, and antimicrobial performance while enabling freshness indication (Xu et al., 2025). The incorporation of 6% anthocyanin yielded films with improved thermal stability

**TABLE 7** Application of electrospinning on the development of biosensors.

| NanoFibers | Type of biosensors | Applications | Target compounds | Limit of detection | Sensitivity | Recovery rate | References |
|---|---|---|---|---|---|---|---|
| Carbon nanofiber/$Bi_2MoO_6$ | Electrochemical | Detect food adulteration such | Phenolic aldehyde vanillin | 0.0014–0.013 μM | 0.2401–1.7212 μA $\mu M^{-1}$ $cm^{-2}$ | 92.2%–103.3% | Malayalam Amarnath et al. (2025) |
| MXene-poly (propylene carbonate) | Electrochemical | Detection of synthetic cannabinoids | Cannabis | 0.66 ng/mL | — | — | Ghorbanizamani, Moulahoum and Timur (2025) |
| Nickel molybdate-carbon nanofiber | Electrochemical | Detection of rutin in grapes and apple | Rutin | 0.015 μM | 3.6 μA $\mu M^{-1}$ $cm^{-2}$ | Grape: 99.4%–101.9%<br>Apple: 99.6%–101.5% | Selvam et al. (2025) |
| Polypyrrole–Chitosan electrospun nanofiber | Enzymatic | Clinical applications | Acetylcholine | 5 μM | — | 93%–111.22% | Yildirim-Tirgil et al. (2025) |
| Nickel phosphide-adorned functionalized carbon nanofibers | Electrochemical | Detection in beverages | Tartrazine | 0.011 μM | 0.3606 μA $\mu M^{-1}$ $cm^{2}$ | 97.45%–99.37% | Gokulkumar et al. (2024) |
| $Bi_2S_3$-embedded carbon nanofibers | Electrochemical | Detection in food crops | Mycotoxin zearalenone | 0.61 μM | — | 98.9%–99.15% | Huang et al. (2024) |
| Cobalt nanoparticles embedded cellulosic nanofibers | - | Detection of meat quality | Clenbuterol | 1.14 nM | 4.7527 μA $\mu M^{-1}$ $cm^{-2}$ | 98.07% | Rehman et al. (2024) |
| Ag doped zinc ferrite embedded functionalized carbon nanofibers | Electrochemical | Chicken, shrimp, milk | Tetracycline | 1 nM | 21.77 $\mu A \mu M^{-1}$ $cm^{-2}$ | 96.2%–101.2% | Sebastian et al. (2024) |
| Dendrimer-modified montmorillonite (Mt)-decorated poly-Ɛ-caprolactone (PCL) and chitosan (CHIT)-based nanofibers | Enzymatic | Food and beverages | Monosodium glutamate | 7.019 μM | — | 103.125% | Atilgan et al. (2023) |
| Chitosan-carbon nanofiber | Electrochemical | Milk | Oxytocin | 24.98 ± 11.37 pg/mL | $2.77 \times 10^{-10}$ Ω/log ng $mL^{-1}/mm^2$ | 90.85%–113.34% | Mehrotra et al. (2023) |
| Carbon nanofibers doped with single-walled carbon nanoangle | Electrochemical | Dandelion tea and grape juice | Luteolin | 3.714 nM | 28.592 μA $\mu M^{-1}$ $cm^{-2}$ | 95.775%–103.830% | Zhang Z. et al. (2023) |
| Poly-l-lactic acid (PLLA)/anthocyanin nanofiber | Colorimetric | — | Bacterial concentration | 35.39 ppm | — | — | Li W. et al. (2022) |
| Polycaprolactone/chitosan nanofiber | Electrochemical | Tomato juice | Diazinon | 2.888 nM | — | 93.27%–108.30% | Topsoy et al. (2022) |

(melting enthalpy 44.41–45.02 J $g^{-1}$) and a smooth porous fiber structure with an average diameter of 307.43 nm. During storage, the films reduced the blueberry decay rate from 70% to 23% and lowered weight loss from 1.66% to 1.26%, demonstrating not only quality retention but also active functionality derived from electrospun nanostructures in fruit-based functional food systems. In shrimp preservation, electrospun nanofiber films co-loaded with anthocyanin and thymol were incorporated into a gelatin–zein matrix, demonstrating dual active and intelligent functionality. The resulting GZAT films exhibited enhanced mechanical strength. They reduced water vapor permeability compared with the control gelatin/zein film, while also providing vigorous antibacterial activity against *E. coli*, *L. monocytogenes*, and *S. aureus*. Functionally, the films extended the shelf life of shrimp to 11 days at 4 °C, while simultaneously serving as freshness indicators through pH-dependent color shifts, confirming the synergistic role of electrohydrodynamic encapsulation in both preservation and real-time quality monitoring in functional seafood applications (Wu Y. et al., 2024). These studies demonstrate that electrohydrodynamic encapsulation enhances the development of functional foods by improving the stability of bioactive compounds, enabling controlled release, extending shelf life, and integrating preservation with intelligent-sensing capabilities across diverse matrices, including seafood, fruits, dairy, and meat systems. The consistent improvements in antioxidant capacity, microbial inhibition, mechanical performance, and storage stability demonstrate that electrospinning and electrospraying are transformative technologies for packaging of food systems.

## 5.3 Biosensors

Electrochemical sensors based on nanomaterials have emerged as powerful tools for the rapid, sensitive, and cost-effective detection of bioactive compounds, contaminants, and illicit substances in food, environmental, and clinical samples. The integration of functional nanostructures, and electrospun polymeric nanofibers, has significantly enhanced sensor performance by increasing surface area, improving conductivity, and facilitating efficient analyte adsorption (Table 7). These advancements have expanded the applicability of electrochemical sensing platforms across diverse domains, from food quality control to clinical diagnostics and forensic investigations.

One such application involves the detection of vanillin, a widely used synthetic flavoring agent. To address the need for reliable and economical detection methods, a bismuth molybdate nanoplate–embedded carbon nanofiber-modified electrode (CNF/$Bi_2MoO_6$/GCE) was developed (Malayalam Amarnath et al., 2025). The nanocomposite, synthesized *via* ultrasonication and comprehensively characterized by XRD, FE-SEM, HR-TEM, Raman, and XPS, exhibited superior electrochemical performance with a wide linear detection range (0.01–367 μM) and an ultra-low detection limit (0.0014–0.013 μM). The sensor demonstrated high selectivity, stability, and reproducibility, achieving excellent recovery rates in food samples such as ice cream and chocolate. These findings highlight CNF/$Bi_2MoO_6$/GCE as a cost-effective platform for food quality monitoring (Malayalam Amarnath et al., 2025).

Similarly, the rise in cannabis legalization has underscored the urgent need for monitoring synthetic cannabinoids, which are structurally distinct but often more potent than natural cannabinoids like THC, and typically evade conventional drug tests. To address this, an electrochemical immunosensor integrating aminated MXene with poly (propylene carbonate) (PPC) nanofibers and monoclonal antibodies was developed by Ghorbanizamani, Moulahoum and Timur (2025). Electrospun onto screen-printed electrodes, the nanofibers provided enhanced surface area, sensitivity, and stability. The biosensor achieved a wide detection range (0.6–2,000 ng/mL in saliva), an LOD of 0.66 ng/mL, and excellent specificity and repeatability, establishing its potential for rapid and portable cannabinoid detection in forensic and clinical applications.

Another promising direction has been the detection of flavonoids, particularly rutin (RTN), due to their therapeutic benefits including antihypertensive, antioxidant, and anticancer properties. A nickel molybdate/carbon nanofiber (NMO@CNF) composite electrode was engineered, exploiting the synergistic effect of NMO's redox-active sites and CNF's high conductivity. This sensor achieved a wide linear range (0.3–510 μM), a low LOD (0.015 μM), and excellent reproducibility. Real-sample testing in grapes and apples yielded recovery rates above 99%, confirming its practical utility in food analysis. Similarly, a single-walled carbon nano-horn/carbon nanofiber (SWCNHs/CNFs) composite was fabricated for luteolin detection, achieving a detection limit as low as 3.7 nM with strong repeatability and reproducibility, further underscoring the capability of nanostructured carbon composites for flavonoid monitoring (Selvam et al., 2025).

Electrospun nanofiber-based platforms have also shown great potential in biomedical sensing. A highly sensitive acetylcholine (ACh) biosensor was constructed by Yildirim-Tirgil et al. (2025) using polypyrrole nanoparticles embedded in chitosan nanofibers, functionalized with acetylcholinesterase and choline oxidase (Figure 4). This design enabled efficient enzyme immobilization, improved conductivity, and enhanced analyte interaction. The biosensor displayed linear detection of ACh in the range of 10 μM–1 mM with a detection limit of 5 μM, alongside high stability over 30 days and reliable performance in serum samples, highlighting its promise for neurological diagnostics.

In the field of food safety, particular attention has been directed at monitoring banned growth promoters such as clenbuterol (CLN). To overcome limitations of existing sensing materials, a machine-learning-assisted electrochemical sensor was developed using a bimetallic zeolitic imidazolate framework (BM-ZIF)-derived N-doped porous carbon embedded with cobalt nanoparticles on cellulose acetate–polyaniline nanofibers. The smartly engineered nanofiber matrix facilitated rapid analyte diffusion and minimized ion transport issues, while machine learning algorithms optimized and validated electrochemical responses (Rehman et al., 2024). The sensor achieved remarkable sensitivity (LOD: 1.14 nM) and stability, retaining over 98% of current within 12 h, making it a pioneering approach for CLN detection in meat quality assessment.

The monitoring of antibiotic residues has also attracted significant research interest. A dual-functional sensor was designed for tetracycline, combining photocatalytic degradation with electrochemical detection using silver-doped zinc ferrite nanoparticles embedded in chitosan-functionalized carbon nanofibers (AgZFO/CHIT-CNF/SPCE). This electrode achieved a

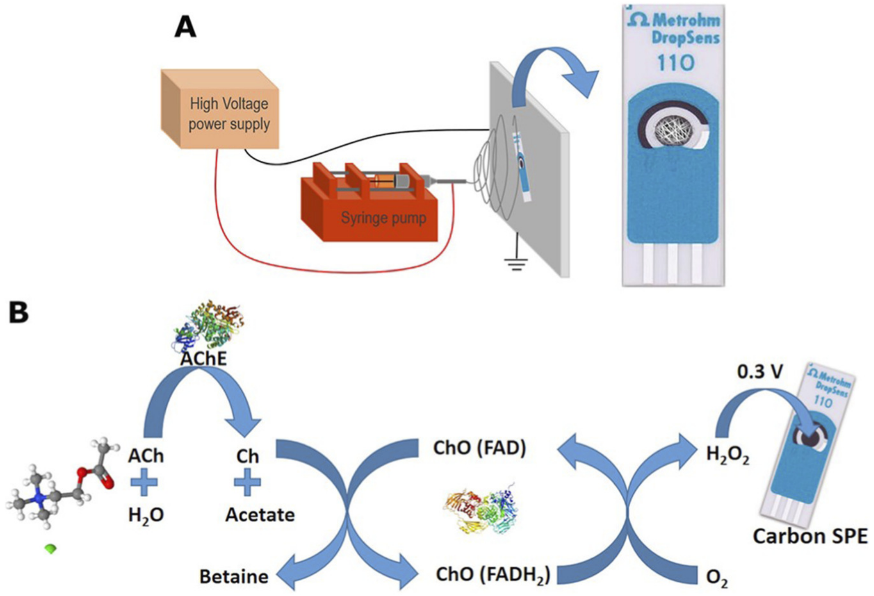

FIGURE 4
Schematic of **(A)** the electrospinning of PPy–CS nanofibers on the working electrode of an SPE and **(B)** the enzymatic acetylcholine detection mechanism (Adopted from Yildirim-Tirgil et al., 2025 with permission, License Number: 6110361282,450 dated 15 September 2025)

wide linear range (0.2–53.2 µM) with a detection limit of 1 nM and demonstrated strong stability, selectivity, and reusability. Validation with real-world samples such as milk, shrimp, soil, and wastewater confirmed its robust applicability for environmental and food safety monitoring (Sebastian et al., 2024). Nanofiber-based sensing has been applied for detecting pesticide residues such as diazinon (DZN). A nanofiber-modified screen-printed electrode, optimized at pH 5.25 with a scan rate of 50 mVs$^{-1}$, exhibited a low LOD of 2.888 nM and strong repeatability and storage stability. Successful detection in tomato juice samples with recovery values ranging from 93.27% to 108.30% demonstrated its effectiveness for practical pesticide residue monitoring (Topsoy et al., 2022).

The integration of advanced nanostructures, including carbon nanofibers, MXenes, metal oxides, MOF-derived carbons, and electrospun polymeric composites, has significantly advanced the sensitivity, selectivity, and stability of electrochemical sensors. These sensors have shown remarkable versatility across applications, from flavor authenticity verification (vanillin) and nutraceutical monitoring (rutin, luteolin) to clinical diagnostics (acetylcholine, synthetic cannabinoids), and food/environmental safety (clenbuterol, tetracycline, diazinon). Collectively, these studies underscore the potential of nanomaterial-enhanced electrochemical sensors as cost-effective, portable, and high-performance platforms for ensuring food quality, safeguarding public health, and advancing biomedical research.

## 6 Comparison between EHD and traditional encapsulation

Electrohydrodynamic (EHD) encapsulation differs fundamentally from traditional techniques such as spray drying, freeze-drying, extrusion, and coacervation in the way droplets or jets are formed and solidified. In EHD processes, a high electric field deforms a polymer/bioactive solution into a charged jet or fine droplets, which dry at (or near) room temperature to form nanofibers or sub-micron particles with very high surface-area-to-volume ratios. Recent reviews highlight that these mild thermal histories and finely tunable morphologies (fiber diameter, porosity, shell–core architecture) enhance the protection of labile compounds against oxygen, light, and heat, and can be engineered for diffusion-controlled or pH-triggered release (Coelho and Estevinho, 2023; Vignesh et al., 2024). By contrast, conventional spray drying typically operates at 120 °C – 200 °C and produces micro-scale particles; it is robust, continuous, and the dominant industrial choice for encapsulating flavors, essential oils, and vitamins, but the high temperature and longer residence times increase the risk of volatilization and oxidation (Jayaprakash et al., 2023; Fernandes et al., 2024). Freeze-drying offers excellent retention of volatile compounds and structural integrity; however, it is batch-wise, energy-intensive, and produces relatively large, porous particles with rapid release and poor flow properties (Drosou and Krokida, 2024b; Fernandes et al., 2024). Overall, traditional encapsulation excels in terms of scalability and cost, whereas EHD techniques offer superior structural control and gentler processing, albeit at the expense of lower throughput and increased process complexity (Coelho and Estevinho, 2023; Jayaprakash et al., 2023).

Head-to-head experimental comparisons illuminate these trade-offs. Laina et al. (2024) encapsulated a blend of oregano, rosemary, hypericum and chamomile essential oils in a whey-protein–pullulan matrix using electrospinning, spray drying and freeze-drying: spray drying achieved the highest encapsulation efficiency (EE: 89%–90%) and produced 5 µm microparticles, whereas electrospinning yielded uniform nanofibers (543 nm) with slightly lower EE but markedly slower, more Fickian release and better preservation of antioxidant activity during simulated gastrointestinal digestion; freeze-dried powders showed the highest yield but lower EE (~66%) and very rapid release due to their high porosity. For probiotics, Premjit and Mitra (2021) reported that electrospraying *Leuconostoc lactis* in a soy-protein/sunflower-oil matrix achieved 92.93% EE with viability loss <1 log CFU $g^{-1}$; notably, there was no significant difference compared with freeze-drying, indicating that an appropriately tuned EHD process can match traditional benchmarks while operating at lower temperatures. In the context of plant extracts, Solaberrieta et al. (2020) electrospun poly (ethylene oxide) fibers containing 5–20 wt% Aloe vera skin extract, producing smooth nanofibers with high encapsulation efficiency and sustained antioxidant activity, which suggests enhanced protection relative to non-encapsulated extract and conventional incorporation into films. Similar findings were observed for thyme essential oil encapsulated in zein–chitosan electrospun fibers, where sub-micron diameters and dense fiber networks enhanced antioxidant and antibacterial performance compared to unencapsulated oil and simple emulsions (Vafania, Fathi and Soleimanian-Zad, 2019). For lipophilic vitamins, Dias and Estevinho (2025) showed that EHD processing of zein solutions containing vitamin E can be tuned (1%–30% w/v zein) to switch from 0.4 to 0.9 μm particles to continuous fibers, enabling control over release kinetics and improving stability in cosmetic carriers, while conventional spray-drying of vitamins in zein remains scarce and typically yields larger, less uniform structures.

More recently, electrostatic spray drying (ESD) and related electric-field-assisted spray technologies have emerged as hybrid approaches that bridge EHD and traditional spray drying. Jayaprakash et al. (2023) compared electrospraying, nano-spray drying, and electrostatic spray drying, concluding that all three electric-assisted techniques operate at lower temperatures than classical spray drying and generally provide higher EE, narrower size distributions, and better stability for sensitive vitamins, phenolics, and probiotics, although industrial scale-up is still under development. From a broader perspective, Fernandes et al. (2024) and English et al. (2023) emphasize that spray drying and coacervation remain the most mature options for large-scale encapsulation of essential oils and flavors. However, they also note that nano- and EHD-based systems can significantly enhance bioavailability and targeted delivery when product value justifies higher processing complexity. Traditional encapsulation technologies are preferred when throughput, cost, and regulatory familiarity are the primary considerations, whereas electrohydrodynamic encapsulation is increasingly selected for high-value, heat-sensitive bioactives. This approach offers nanostructured carriers, fine control of barrier properties, and tailored release profiles, providing clear functional advantages that outweigh current limitations in scale and equipment cost.

## 7 Industrial relevance

The encapsulation of food bioactive compounds using electrohydrodynamic (EHD) techniques, such as electrospinning and electrospraying, holds significant industrial relevance as the global food sector increasingly shifts toward functional, fortified, and health-promoting products. Bioactive compounds including polyphenols, vitamins, carotenoids, flavonoids, and probiotics are often highly sensitive to environmental stressors such as light, oxygen, temperature, and pH, which can cause rapid degradation during processing, storage, and digestion. Conventional encapsulation methods like spray drying or coacervation have limitations in terms of encapsulation efficiency, particle size control, and scalability when dealing with such fragile compounds. EHD techniques, by contrast, offer precise control over particle and fiber morphology at the micro-to nanoscale, enabling the formation of encapsulation systems with superior barrier properties, controlled release behavior, and enhanced bioavailability. From an industrial standpoint, this capability directly supports the growing demand for value-added food products with extended shelf life, improved nutritional functionality, and targeted delivery within the gastrointestinal tract. Moreover, EHD encapsulation aligns with the industry's need for greener and more sustainable processing strategies, since these techniques typically operate at ambient temperature, consume less energy, and minimize the use of organic solvents, thereby preserving bioactivity and ensuring regulatory compliance with clean-label trends. Recent advances in scaling up EHD systems, such as the development of multi-needle, needleless, and centrifugal electrospinning/electrospraying units, are bridging the gap between laboratory innovation and industrial manufacturing, making it feasible to produce encapsulated bioactives on a commercial scale. This scalability enhances the potential for integrating EHD-based encapsulated bioactives into a wide range of food matrices, including beverages, dairy products, baked goods, snacks, nutraceutical supplements, and plant-based alternatives, thus opening diverse market opportunities. Additionally, the precise tailoring of encapsulation matrices using food-grade polymers, proteins, polysaccharides, or their blends allows industries to customize release kinetics, improve stability under processing conditions, and mask undesirable flavors or odors without compromising the sensory qualities of the final product. As consumer preferences continue to shift toward functional foods that deliver health benefits beyond basic nutrition, the industrial application of EHD encapsulation offers a competitive edge for food manufacturers seeking to differentiate their products and comply with regulatory requirements for efficacy and safety. In essence, the industrial relevance of EHD-based encapsulation lies not only in its technological superiority and sustainability but also in its capacity to translate fundamental scientific principles into scalable, commercially viable solutions that address modern challenges in food preservation, fortification, and functionalization.

## 8 Limitations and future perspective

The challenge of low throughput in electrohydrodynamic (EHD) encapsulation extends beyond simple productivity constraints and is closely tied to scale-up economics, energy demand, and process reproducibility (Figure 5). Conventional single-needle electrospinning typically operates at 0.1–1.0 $g/h^{-}$per needle, which is insufficient for industrial production volumes. Multi-needle arrays increase output, but they introduce issues such as jet interference, electric-field instability, and frequent clogging, particularly when working with viscous or particle-laden food-grade formulations. Needleless electrospinning

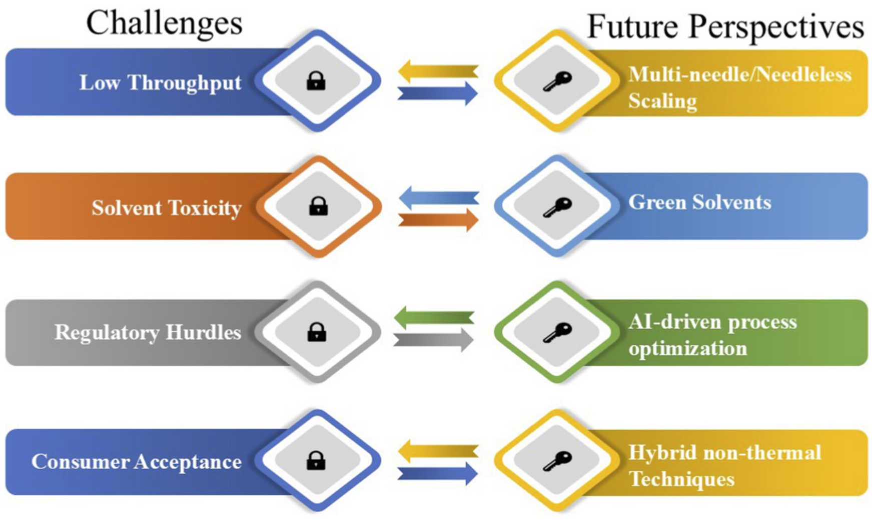

FIGURE 5
Schematic flow chart showing the challenges and future Perspectives of electrohydrodynamic encapsulation process.

systems, such as rotating-cylinder or wire-electrode units, can achieve 10–100 times higher throughput while improving energy efficiency and reducing maintenance requirements; however, they may compromise jet uniformity and increase fiber diameter variability, which affects encapsulation reproducibility and release consistency. Centrifugal electrospinning offers another promising route for large-scale fabrication, as the production rate scales with drum speed rather than electric-field intensity, thereby reducing power demand and enhancing safety in food-processing environments. Nevertheless, centrifugal systems may exhibit broader size distributions and are less suitable for complex multi-fluid or core–shell architectures. Thus, each scale-up strategy presents distinct advantages, trade-offs, and application niches: multi-needle systems are appropriate for high-precision functional ingredients, needleless systems are better suited for bulk packaging mats and coatings, whereas centrifugal systems are attractive for high-volume micro- and nanofiber production where morphology tolerance is acceptable.

From a technical-performance standpoint, additional challenges include variability in fiber morphology, energy efficiency, and environmental sensitivity of the process. Studies comparing lab- and pilot-scale operations report variations of up to 20%–35% in fiber diameter and encapsulation efficiency under fluctuating humidity and temperature conditions, highlighting the need for environmental control and predictive parameter modeling. High-voltage operation also contributes to elevated specific energy consumption relative to conventional encapsulation methods such as spray drying, particularly when prolonged spinning durations are required. Efforts to address these gaps include the integration of process-analytical technology (PAT), closed-loop humidity regulation, and data-driven optimization frameworks, which are beginning to reduce variability and improve techno-economic feasibility.

Material-related challenges are particularly pronounced for "clean-label" and minimally processed biopolymers, many of which exhibit poor chain entanglement, low molecular weight, or excessive hydrophilicity, leading to bead formation or jet breakup during EHD processing. Recent advances have focused on mild structural modification and bio-based blending strategies that retain label acceptability while enhancing spinnability. These include enzymatic crosslinking, physical pre-gelation, glycation (Maillard-type conjugation), and blending with pullulan, PEO, or plant proteins to enhance viscoelasticity and molecular entanglement density. Novel bio-derived polymers, such as pea-protein–polysaccharide conjugates, hemicellulose derivatives, and marine polysaccharide hybrids, have demonstrated improved electrospinnability and mechanical stability without the need for synthetic additives. These developments indicate a clear direction toward bio-based, food-grade carrier systems that balance spinnability with consumer-perception requirements.

Safety and regulatory considerations remain among the most significant barriers to commercial translation. Regulatory bodies such as the European Food Safety Authority (EFSA) and the U.S. Food and Drug Administration (FDA) do not regulate "electrospun materials" *per se*, but rather evaluate them under frameworks governing engineered nanomaterials, migration behavior, and ingestion safety. EFSA guidance emphasizes the need for case-specific assessment of particle size distribution, gastrointestinal fate, dissolution and degradation kinetics, surface chemistry, and bio-persistence, along with *in vitro* and *in vivo* toxicological testing to determine whether ingested structures behave as nanoparticles or conventional food matrices. Key contentious points include the extent of nanoparticle uptake across the intestinal epithelium, potential accumulation in secondary organs, and long-term effects of repeated dietary exposure. These issues are particularly relevant when carriers remain partially undigested or intentionally nano-structured. The EFSA Scientific Committee (2021) explicitly highlights parameters such as agglomeration state in digestive media, mucosal interaction, and particle translocation as critical determinants in the safety appraisal of nano-enabled food ingredients.

Market- and consumer-perception challenges also warrant structured consideration. Public attitudes toward nano-enabled food technologies remain cautious, with surveys across European and Asian markets reporting that 40%–60% of consumers express concern about the perceived health risks or "unnaturalness" of nanotechnology in foods. Acceptance improves significantly when applications are framed around clear consumer benefits, such as nutritional enhancement, freshness preservation, or reduction of synthetic additives, and when transparent communication and labeling strategies are implemented. Studies show that trust in regulatory oversight and scientific communication is a decisive factor influencing willingness to adopt nano-functional foods. Therefore, future commercialization pathways must integrate evidence-based risk communication, consumer education, and participatory engagement frameworks alongside technical validation.

## 9 Conclusion

Electrohydrodynamic (EHD) encapsulation, encompassing electrospinning and electrospraying, has evolved from a laboratory fabrication method into a transformative technological bridge between nanomaterials science and food engineering. Beyond acting merely as an encapsulation tool, EHD enables a top-down nano-architecting paradigm that delivers precise structural control, mild processing conditions, and versatile material compatibility. These core attributes directly overcome long-standing bottlenecks in bioactive delivery, including thermal and oxidative degradation, poor solubility, uncontrolled release, and limited bioavailability. Across vitamins, polyphenols, carotenoids, essential oils, peptides, and probiotics, the evidence presented in this review demonstrates that EHD-derived fibers and particles consistently provide protective stabilization, tunable matrix–bioactive interactions, and targeted gastrointestinal release, validating their role as an enabling platform for next-generation precision nutrition foods.

A unifying theme emerging from the literature is the Material–Process–Performance paradigm, wherein functional outcomes arise from the rational coupling of carrier chemistry with EHD processing pathways. For hydrophobic and poorly soluble compounds, alcohol-soluble proteins and emulsion electrospinning offer superior encapsulation, structural integrity, and sustained diffusion-controlled release. For pH-sensitive or site-specific delivery, multilayered polyelectrolyte shells and coaxial or triaxial architectures provide spatial compartmentalization and trigger-responsive protection. For probiotic viability, hybrid polysaccharide–protein matrices and low-temperature processing preserve cellular integrity while enabling mucoadhesive retention. These recurring patterns consolidate into generalizable design principles: (i) match bioactive polarity to carrier amphiphilicity; (ii) exploit core–shell geometries where selective protection or staged release is required; and (iii) tune fiber/particle morphology through solvent systems, viscoelasticity, and flow–field coupling to modulate mass-transfer kinetics and environmental stability. From an application-translation perspective, the review indicates a differentiated roadmap of technological readiness. Short-to medium-term deployment is most feasible in high-value, low-volume domains, such as active food-contact coatings, antimicrobial/antioxidant packaging films, nutraceutical powders, and functional ingredients, where precision release and premium functionality justify production costs. Conversely, bulk food fortification and large-throughput ingredient manufacturing remain longer-term targets, requiring advances in throughput, solvent sustainability, process reproducibility, and regulatory alignment. The convergence of EHD encapsulation with needleless and centrifugal scale-up platforms, green-solvent systems, food-grade polymer innovations, and process analytical monitoring is expected to narrow this translational gap progressively.

Looking ahead, the most promising trajectory lies in "smart" and adaptive encapsulation systems that integrate stimuli-responsive materials (pH, enzyme, temperature, redox, microbiome cues) with hierarchical EHD architectures to enable on-demand, site-specific, and multi-stage release. Next-generation opportunities include AI- and simulation-assisted formulation design, where machine learning and molecular modeling accelerate compatibility prediction and parameter optimization; and circular-bioeconomy frameworks that valorize food-processing by-products as sustainable carrier materials. Equally compelling is the convergence of EHD nanostructures with biosensing, active packaging intelligence, and personalized nutrition frameworks, where delivery carriers' function not only as protective matrices but as interactive platforms for health monitoring and functional feedback. Realizing this vision will require interdisciplinary progress in toxicological assessment, digestion-fate modeling, techno-economic optimization, and consumer-centric design. The EHD encapsulation has emerged as a pivotal bridge between nanotechnology and food engineering, offering a robust, structurally precise, and function-driven platform for engineering bioactive delivery systems with enhanced stability, tailored release kinetics, and elevated functional performance. As scientific, regulatory, and industrial ecosystems continue to mature around this technology, EHD-based encapsulation is poised to play a pivotal role in shaping the future of precision nutrition, sustainable food preservation, and next-generation functional food systems.

## Author contributions

ST: Conceptualization, Data curation, Formal Analysis, Methodology, Validation, Writing – original draft, Writing – review and editing. PS: Conceptualization, Supervision, Validation, Visualization, Writing – review and editing.

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## Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author ST declared that they were an editorial board member of Frontiers at the time of submission. This had no impact on the peer review process and the final decision.

## Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

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