

Review

Application of Electric Field Technologies in the Manufacture of Food Powders and the Retention of Bioactive Compounds

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Abstract: Electric fields have been used in the manufacturing of powders in a number of ways, including to enhance drying rates and retain heat-sensitive materials. Electrohydrodynamic drying and electrostatic spray drying use electric fields to accelerate the evaporation of liquid from a surface, resulting in faster drying times and improved product quality. These technologies are used in the food and pharmaceutical industries to manufacture powders from liquid feed materials. In addition to enhancing drying rates, the use of electric fields in powder manufacturing can also help to retain the bioactivity of compounds in the final product. Many bioactive compounds are sensitive to heat and can be degraded or destroyed during conventional drying processes. By using electric fields to dry powders, it is possible to reduce the amount of heat applied and therefore preserve the bioactive compounds in the final product. This article reviews the different mechanisms of various electric field assisted technologies, i.e., electrohydrodynamic atomization, electrohydrodynamic drying, pulsed electric fields and a new approach of electrostatic spray drying, along with their potential food industry applications.

Keywords: powder; electric field; electrohydrodynamic; atomization; drying; electrostatic spray drying; voltage



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1. Introduction

Dehydration is one of the most commonly applied food preservation processes, significantly extending the shelf life of foods through the removal of water to prevent microbial growth and enzymatic reactions. Drying is applied in all food industries, with spray drying, freeze drying and tray drying being typical examples. In addition to dehydration, comminution or size reduction may be required to form discrete powder particles, e.g., after freeze-drying. The final product should meet specific quality requirements for moisture content, morphology, particle size, particle size distribution, etc. In addition, powders may be classified as functional if intended to have a specific and advantageous physiological effect on health, performance, and/or well-being that goes beyond the provision of basic nutrients [1].

Spray drying is a well-established technology, not only in the food industry but also in the pharmaceutical, nutraceutical, chemical, and fertilizer industries, which transforms liquid feeds into stable powders. Spray drying has been extensively used to commercially prepare food powders such as tea, coffee, whey protein ingredients, milk powders, infant formula, etc. Apart from simply drying food materials, it is a versatile technique for specific objectives including microencapsulation, microbial inactivation, preservation, or improved product characteristics. Typically spray drying preserves the integrity of nutrients within food systems, but this can become a challenge when very heat-sensitive materials are present. Many authors have reported the thermal degradation of heat-sensitive food

materials because of the temperatures encountered during spray drying. For instance, whey proteins lost their native structure when milk protein concentrate was spray-dried at inlet air temperatures of 155 and 178 °C [2]. In addition, the Maillard reaction occurs during spray drying of skim milk, the extent of which has been shown to be proportional to the inlet temperature [3]. Some volatile or bioactive compounds are also adversely affected by the high temperatures which can be encountered during spray drying. Phycocyanin, a pigment protein complex, and lemongrass essential oil were reported to be reduced in heat-sensitive phenolic contents after spray drying [4,5]. Furthermore, a decrease in antioxidant activity was found in spray dried amla and honey powders when spray dried at high inlet temperatures [6,7]. Some powders may lose their stability after drying or after only a few weeks of storage. This effect can be attributed to the final moisture content of the powders [8,9]. If a powder has too much moisture, it can become unstable and prone to degradation or spoilage. On the other hand, if a powder is too dry it may become brittle or prone to breakage, which can also affect its stability [8]. The moisture content of the powders is highly influenced by the inlet–outlet temperatures during production as well as the humidity and temperature of the environment in which it is stored [9]. The sensory properties of spray-dried material can also deteriorate due to the heat degradation of colour, flavour, texture, and other sensory characteristics of the material, resulting in a lower-quality final product. For example, on transforming fruit juices into powder form, a loss of flavour compounds when exposed to high temperatures altered the sensory profile [10]. Hence, although spray drying at higher temperatures allows for efficient, high-capacity powder production, the potential for deteriorative changes in powders cannot be ignored, especially for high value products.

Freeze drying is an alternative, low temperature drying method which involves freezing the material to be dried before lowering the pressure to remove ice through sublimation. As a result, it can help maintain the integrity of highly heat sensitive components. In a study by Wilkowska et al. [11], where blueberry juice powders were produced by spray drying and freeze drying, freeze-dried powders showed better retention values of anthocyanins than their spray-dried counterparts (around 1.5-fold higher). On comparing the functional properties of freeze-dried and spray-dried egg white protein hydrolysates, freeze drying was shown to have positive effects on foaming and emulsifying properties [12]. However, the processing cost of freeze drying compared to spray drying is high and processing times are much longer [1]. Therefore, it appears that an approach is required that incorporates the benefits of spray drying while also overcoming the drawbacks, such as the usage of higher temperatures. Consequently, a number of studies have looked into optimising spray drying methods to reduce the damage to sensitive food, pharmaceutical, or biological products [13–15].

Electric field assisted drying technologies have emerged as promising methods to obtain a superior quality product with little or no harm to heat-labile components [16]. Many of these technologies have been explored in the food and bioprocessing industry in what is generally classified as electrohydrodynamics (EHD). EHD examines the motion of electrically charged fluids, which involves the study of the interaction of ionized particles and/or molecules with electric fields and the surrounding fluid. In this article, we review the EHD techniques which can be applied in the drying of foods to retain heat sensitive components of food materials which may otherwise be lost during drying. These have been identified as electrohydrodynamic atomization (EHDA), electrohydrodynamic drying (EHDD), pulsed electric field (PEF) and electrostatic spray drying (ESD). Among them, EHDA, which further divides into electrospraying and electrospinning, has been used in the production of various biopolymeric materials [16]. The history of EHDA can be traced back to the early 1990s for producing and processing micro-/nanoparticulate materials with a rich variety of food, nutraceutical and pharmaceutical applications [16]. ESD is a more recently developed technology, having commercial applications in the same domain with extra advantages such as continuous processing and better throughput [17]. EHDD involves the removal of moisture from solid and semi-solid food materials by means of

the production of electric wind [18]. PEF pre-treatment has been shown to be capable of enhancing drying rates when coupled with conventional drying [19]. Unlike EHDA and ESD, EHDD and PEF have mainly been explored at laboratory and pilot scales with limited commercial applications in the food industry to date [18,19]. In this review, the working principle of each technology will be presented, followed by reported applications on the preparation of food powders. Finally, the potential of each technology as a means of retaining heat-sensitive compounds during drying will be discussed.

2. Electrohydrodynamic Atomization

2.1. Principles of EHDA

EHDA is a liquid atomization process where an electric potential is applied to a capillary nozzle through which a solution is discharged at a controlled rate [20]. The solution emerges as a charged jet in the shape of a Taylor cone and extends in the direction of an electrode, which is typically a grounded stainless-steel collector, as shown in Figure 1. EHDA occurs in an open system and under the influence of electrical forces, the solvent present in the solution evaporates along its flight, ultimately depositing dry solid material on the collector. Typically, no external heating is required for drying the material by EHDA [21]. The competition between the electric stress and the surface tension stress at the liquid–air interface, as well as the kinetic energy of the liquid leaving the nozzle, dictate whether the jet fragments into elongated fibres or into tiny droplets [22]. The process where thin fibres are formed during EHDA is called electrospinning. On the other hand, when the jet breaks up into tiny droplets, forming particles in the micro/nano range, the process is called electrospraying. The only difference between electrospinning and electrospraying is, thus, in the morphology of the resulting structures, which in turn depends on the solution's properties, such as pH, conductivity, viscosity, and surface tension, as well as the instrument's settings, such as the magnitude of the applied electrical field, the flow rate of the solution, and the distance between the tip of the capillary and the collector [23,24]. Modifying the feed formulation and/or the processing conditions presents the possibility of controlling the morphology of the encapsulating structures, resulting in either fibres or particles [24]. Therefore, EHDA can be considered a liquid atomization technique using electric potential, producing either electrospun fibres or electrosprayed particles based on solution and instrument properties.

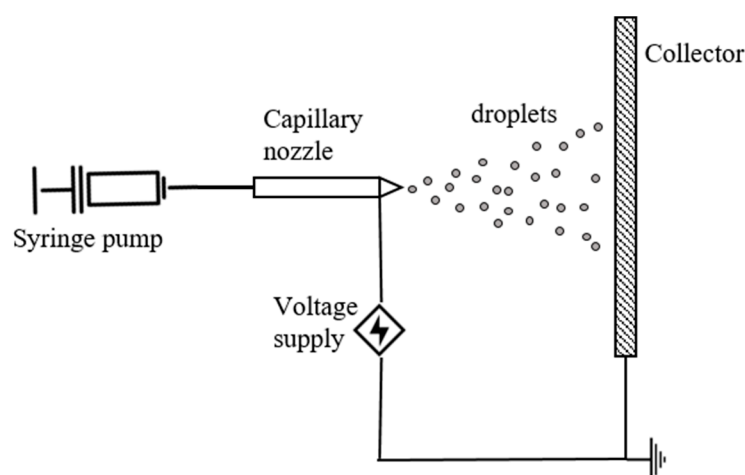


Figure 1. Schematic representation of an electrospraying process (adapted from Jaworek et al. [25]).

2.2. Application of EHDA in the Preparation of Food Powders

Most food applications favour particles over fibres, as powders are simpler to handle and disperse more easily within food matrices. The use of the electrospraying technique is very limited in foods because the solvent is typically water, which is not ideal for the electrospraying process. Due to its high boiling point, water vaporises significantly more

slowly than many organic solvents. Additionally, aqueous solutions have high surface tension values, which prevent steady jet formation during electrospraying [26]. This situation is sometimes improved by the addition of a surfactant that can lower the surface tension of the medium [27]. Moreover, the electrospraying of carbohydrates and proteins involves several technical challenges. Carbohydrates of low molecular weight do not generate sufficient viscosity in aqueous solutions, which can hinder the formation of stable jets [28]. The electrospraying of proteins can also be challenging for a number of reasons as proteins are sensitive to changes in temperature, pH, ionic strength and other factors, which can affect their structure and function [29]. As a result, electrospraying often requires careful control of these factors to ensure that the proteins retain their biological activity [29]. Another challenge is that proteins can aggregate during the electrospraying process, which can affect the final size and shape of the particles produced. To overcome this, additives such as surfactants or stabilizers to prevent protein aggregation can be used [30]. López-Rubio et al. [31] studied the suitability of protein (whey protein concentrate; WPC) and carbohydrate (pullulan) as encapsulating materials for *Bifidobacterium*, using phosphate-buffered saline (PBS) or skimmed milk as solvents. For various carbohydrate concentrations, pullulan dissolved in PBS was not conducive to electrospraying, with only a few drops recovered by the collector as a result of dripping. In contrast, a stable electrospray of WPC structures could be formed in PBS. In terms of protection ability, WPC-based sub-micro- and microcapsules proved a greater improvement in cell viability when compared to pullulan-based structures [31]. In another study by Khosroshahi et al. [32], probiotic cells' viability was evaluated in fermented wheat germ powders produced by electrospraying and freeze drying. Electrospraying resulted in a lower reduction of viable bacteria during drying compared to freeze drying, i.e., 0.55 log vs. 1.2 log cfu/g, respectively [32]. Cell viability was also more stable in electrosprayed powders; after 70 days, viable bacteria in the electrosprayed samples was 9.05 ± 0.45 log cfu/g compared to 7.86 ± 0.03 log cfu/g for freeze dried [32]. This study indicates that, compared to freeze drying, the electrospraying technique proved more effective at preserving the viability of the probiotic bacteria.

2.3. Potential of EHDA in Retaining Bioactive Compounds in the Preparation Food Powders

The most interesting application of electrospraying of foods is in the micro- and nanoencapsulation of bioactive food ingredients [19,33]. Electrospraying can make it possible to protect heat-sensitive compounds from adverse environmental conditions by encapsulating in a suitable carrier material with no thermal stress [34]. For instance, docosahexaenoic acid (DHA) encapsulated in ultrathin zein capsules fabricated by electrospraying showed excellent stability under a range of environmental conditions [35]. When different wall matrices were compared for the encapsulation of α -linolenic acid (ALA) using both spray drying and electrospraying techniques, electrospraying was superior in terms of microencapsulation efficiency and preservation of ALA [29]. Electrospraying can also be used to produce microcapsules of bioactive food ingredients [22]. Depending on the encapsulated items, these microcapsules use various release mechanisms to release their contents at the desired rate and timing [36]. As an example, anthocyanin-rich black carrot extract was encapsulated into electrosprayed chitosan structures and it was found that the extract was released well in the acetic acid medium because of the greater solubility of chitosan in acidic conditions [37]. Recent works on electrospraying include the encapsulation of essential oils in polymeric matrix systems yielding fibrous nano-films for antimicrobial packaging [38,39]. Hence, numerous studies have shown the high technological potential of electrospraying in food industry applications. However, commercial products are not available since the electrospraying of food powders has not yet become an established industrial scale process [24]. While there is great scope for innovation through the manipulation of formulations and processing variables, this interplay also makes process optimization complex and challenging. Moreover, the fundamental mechanism behind electrospraying, i.e., how the electrical forces drive the evaporation of solvent, is still not fully understood.

3. Electrohydrodynamic Drying

3.1. Principles of EHDD

EHDD is a non-thermal drying method where an electric field is applied to food materials to increase heat and mass transfer, primarily to accelerate the evaporation of a liquid from a surface [40]. This can be more efficient than other drying methods that rely on heat to evaporate the liquid, and it can also help to prevent overheating and damage to the material being dried. EHDD is often used in the food and pharmaceutical industries to dry products such as fruits, vegetables, and pills. EHDD involves the removal of water from solid or semi-solid products [18]. It is important to understand the mechanism of moisture removal, which can be used to obtain a better understanding of electric field effects. EHDD works through the application of a high voltage between a discharge electrode and grounded electrode to produce an electric wind that acts on a material surface to promote water evaporation (Figure 2). Under the influence of this electric wind, a secondary airflow is generated at the material–air interface, commonly known as corona wind or ionic wind. This secondary airflow disturbs the saturated boundary layer over the surface of the food material [41]. It increases the mass transfer rates of liquid and volatile components within the biological material to be dried [42]. Many authors have stated that this corona wind is the principal driving force behind the enhanced drying rates and reduced drying times [42–47]. Therefore, EHDD can be considered an innovative drying method that utilizes an electric field to evaporate water from food products, with benefits of increased efficiency and preservation of product quality.

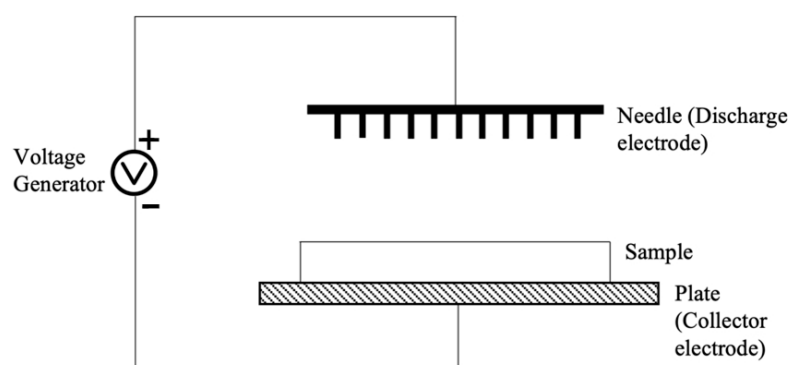


Figure 2. Schematic representation of an electrohydrodynamic drying process (needle-plate system), adapted from Nicholas and Abuzairi [48].

3.2. Application of EHDD in the Preparation of Food Powders

The very first application of EHDD in the field of food drying was in 1991, in which the drying characteristics of a potato slab that was subjected to electrical forces were studied [49]. It was reported that the drying rates of potato slabs were enhanced, with a corona wind of fairly low magnitude being the principal driving force. Subsequently, many studies were performed to maximize drying rates by arranging multiple point coronas over food materials [49–52]. Much research focused on demonstrating the potential of EHDD as a relatively energy-efficient and gentle technology compared to alternatives such as hot air drying and oven drying. Polat and Izli [53] dried apricot slices with EHDD, hot air drying, and a combination of EHDD and hot air drying. In terms of drying rates, the EHDD–hot air drying method was ~75% quicker than using hot air alone, which took 17 h of total drying time. Further, microstructural analysis of the EHDD dried samples showed that the native structure of the apricot slices was retained to a greater extent compared to after hot air drying [53]. Similarly, when EHDD of apple slices was compared with the hot air drying method, EHDD-dried apple slices exhibited more favourable properties, especially in relation to colour and shrinkage. The microstructural damage and degradation of phenolic compounds was also slightly lower with the EHDD method. The specific energy consumption in EHDD was 10–12 times lower than in hot air drying [54]. EHDD can also

be utilized in the preparation of fruit and vegetable powders. To illustrate this, Martynenko and Kudra [55] used EHDD technology to dry heat-sensitive grape pomace, which was further processed to produce grape seed oil and grape skin/seed powder of high nutritional and antioxidant value. Hence, the studies on EHDD in food powder preparation show that EHDD has the potential to enhance food drying rate and retain the native structure better than traditional methods such as hot air drying and oven drying, with a lower specific energy consumption and the ability to produce high-value food powders.

There is, however, a lack of knowledge relating to the influence of an electric field on water transport mechanisms in food materials during EHDD. Alongside convective moisture removal, other physical mechanisms can also contribute to moisture transport during the drying of foods. Thermodynamic considerations show that the internal energy of water molecules should increase when a field is applied, and this increase could be sufficient to overcome intermolecular hydrogen bonds resulting in vaporisation [56]. The thermodynamics also predict an exothermic process, i.e., ohmic heating, to occur within the food material when an electric current is passed through it [57]. Iranshahi et al. [58] characterized the dehydration mechanisms at play during the EHDD of plant-based materials. They identified mechanisms such as convection to the air, cell-membrane electroporation, electro-osmosis, surface evaporation and electrocapillary and thermocapillary flow; their relative contributions to the total mass flux are shown in Figure 3. Dehydration through convection contributes 93% of the mass flux, with a combination of the remaining mechanisms making up the balance (7%) [58]. However, these calculations are valid only during the constant drying rate period. In the subsequent decreasing rate period where the mass transfer is internally resisted, EHDD-driven mass transport mechanisms could be of higher importance as electric fields have a major impact on the internal resistances of the material, such as membrane permeability or capillary action [58].

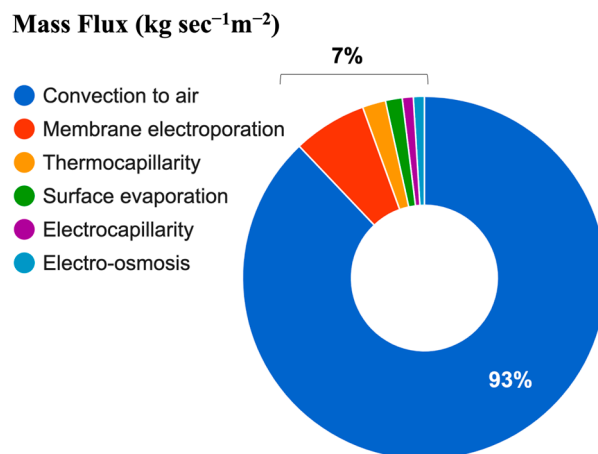


Figure 3. Contribution of different EHD-induced water transport mechanisms to the total mass transfer during the EHD drying process of plant-based materials (adapted from Iranshahi et al. [58]).

3.3. Potential of EHDD in Retaining Bioactive Compounds in the Preparation of Food Powders

It is clear that EHDD research has mostly focused on the drying of solid or semi-solid materials. Therefore, for the manufacture of powders, a comminution or grinding step would be required. In this sense, it is similar to freeze drying which is an established drying technique for the retention of heat sensitive materials. As much of the work presented here compares EHDD to hot air drying, showing the relative benefits of EHDD as a gentle drying operation, it is suggested that another valuable comparison would be to compare against freeze drying both in terms of bioactive retention and process cost/feasibility. In a recent study by Dima et al. [59], where probiotics were dried with EHDD and freeze drying, it was found that the viability and surface properties (zeta potential and hydrophobicity) of the EHDD dried probiotic cells were similar to the freeze-dried cells. This may indicate

that the EHDD process is able to preserve the structural and functional integrity of the cells to a similar extent to freeze drying. Another study compared the drying of mint leaves using a conventional oven (40 °C) and EHDD (25 °C) [60]. It was found that the oven dried mint leaves converted 17% more total chlorophyll into pheophytins compared to leaves manufactured by EHDD. Colour quality assessment also revealed better retention of the desired green colour when using EHDD [60]. Based on these findings, EHDD appears to be a promising alternative to traditional drying methods and has the potential to improve the quality and preservation of heat-sensitive materials.

4. Pulsed Electric Field Technology

4.1. Principles of PEF Technology

Another technique which employs an electric field in its operation is PEF technology. PEF involves the use of high voltage electrical pulses over a short period across a food product placed between two conducting electrodes. PEF is commonly used for the inactivation of microorganisms in foods and beverages. It is a non-thermal preservation technique that does not involve the use of temperature to kill microbial cells [19]. Microbial inactivation is achieved through the disruption of cell membranes under the influence of an electric field. The cell membrane normally acts as a semipermeable barrier and protects the microorganism from the surrounding environmental conditions. When high-voltage PEFs are applied the cell membrane is disrupted, resulting in the leakage of intracellular contents and the loss of cell metabolic activities [61]. The phenomenon of the disruption of cell membranes under the influence of an electric field is commonly called electroporation [62]. The components shown in Figure 4 typically make up a PEF unit in the food industry: a high-voltage pulse generator, a treatment chamber, a fluid-handling system and control and monitoring devices [63]. The PEF generator generates high-voltage pulses that are used to process the food material. The treatment chamber is the area where the food material is subjected to the pulsed electric field through electrodes which are typically positioned close together. This ensures that the electric field is concentrated enough to generate high voltage pulses [63].

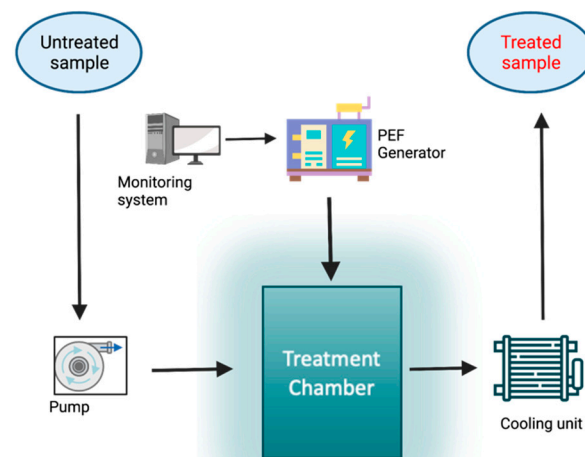


Figure 4. Schematic representation of a pulsed electric field unit (adapted from [63,64]; created with [BioRender.com](https://www.biorender.com), accessed on 2 January 2023).

4.2. Application of PEF in the Preparation of Food Powders

Other than microbial cell inactivation, PEF can also be used for enhancing drying rates. PEF-induced electroporation can ease the mass transfer and the diffusion of the inner components of a cell to the surface, which further enhances the drying operation [65]. The application of PEF as a pre-treatment for the drying of fruits and vegetables has attracted a lot of attention lately. Ostermeier et al. [66] investigated the applicability of

PEF pre-treatment for the industrial drying (oven drying) of onion. PEF treatment reduced drying time by 32% and increased the effective water diffusion coefficient by a factor of two [66]. Similarly, when okra was oven-dried by applying three different pre-treatment methods, i.e., blanching, microwave and PEF treatment, the samples pre-treated with PEF had the highest coefficient of diffusivity [67]. Additionally, during the hot air drying of red beetroots, PEF pre-treatment of the materials caused an increase in the moisture diffusivity. Drying time was also considerably reduced in the same experiment, as tissues were damaged under the influence of the electric field, facilitating moisture diffusion [68].

4.3. Potential of PEF Technology in Retaining Bioactive Compounds in the Preparation Food Powders

PEF pre-treatment can also help in retaining heat-labile and bioactive components during drying. In a study by Rybak et al. [69], where PEF was applied before the spray drying of red bell pepper juice, the quality of PEF-treated spray-dried powders showed a higher retention of heat-sensitive and bioactive compounds as compared to untreated juice powders. The vitamin C content of powders increased from 2.2 mg/100 g to 3.6 mg/100 g for samples pre-treated under an electric field strength of 1.07 kV/cm. It was suggested that PEF treatment facilitated the juice pressing and improved the extractability of Vitamin C by 18–25% as compared to juice prepared from untreated bell peppers [69]. A similar retention was observed for carotenoids; however, a higher PEF energy input had a negative influence on the retention of phenolic compounds [69]. Therefore, it is important to carefully control the energy input in PEF to ensure that the material being dried is not damaged or degraded. In general, higher energy inputs can lead to increased drying rates, but they can also cause the material to become overheated or damaged [70].

5. Electrostatic Spray Drying

5.1. Principles of ESD

ESD is a drying technique which applies an electrostatic charge to an atomised feed. The configuration of an ESD unit consists of four major components, as shown in Figure 5: a pumping system, an electrostatic two-fluid spray nozzle, a high voltage power supply, and inert drying gas, usually N₂ [17]. During electrostatic atomization, a pump (2) injects the conductive liquid feed (1) through an electrostatic nozzle (6), to which a high voltage generator (3) applies an electrostatic charge (usually 1–30 kV). As a result, the liquid that emerges from the nozzle as a conical jet experiences electrostatic (repulsive) interactions. After the liquid spray leaves the atomizing nozzle, it comes into contact with the drying gas (N₂) within a closed chamber with similar characteristics to those found in conventional spray dryers (7). During this, moisture from the droplet is transferred to the drying gas, which exits the chamber by means of a blower (10). Moisture transfer produces an electrically charged solid powder, which is collected in a suitable vessel (9) [71].

The feedstock is atomized by the heated, compressed nitrogen gas when it is pumped through the two-fluid nozzle, and an electrostatic charge is induced at the nozzle tip. This charge imparts an electrostatic effect on the atomized material, which may result in the stratification of components based on their polarity [71]. The charge on the atomized droplets drives the most polar part of the feed (typically water) to the shell, i.e., the outer surface of the droplet, with the least polar (fat, protein) tending to remain at the centre of the droplet, thus resulting in the presence of higher amounts of water at the surface during droplet formation [72]. Moisture transfers from the droplet to the gas phase during transit through the drying chamber. The transfer of moisture results in an electrically charged solid powder which is collected and neutralized in an electrically grounded collection system [17].

In both ESD and conventional spray drying (CSD), liquid droplets are atomized and sprayed into a stream of drying gas. The solvent is then driven to evaporate as a result of heat transfer from the drying gas to an atomised droplet (Figure 6). The finished product is a dry, powdered substance once the solvent has (almost) completely evaporated.

CSD has two distinct phases of drying: a constant-rate drying phase, and a falling-rate drying phase. Initially, the constant drying rate period appears when water is in excess and heat transferred from the air is used to provide the latent heat of evaporation [73]. This evaporation keeps the product temperature relatively cool, but as the drying cycle progresses many particles will form a shell on the surface of the drying particle, resulting in a lower evaporation rate. The constant drying period then transitions to a period of sensible heating, commonly known as the falling rate period, where the temperature of the particle raises to the point at which the solvent inside the shell is driven off [74]. ESD is purported to eliminate the falling-rate drying phase, as most of the water is present at the surface of the droplet due to the charge applied and the drying takes place in the constant-rate drying phase releasing the latent heat of vaporization. This helps in reducing the temperature experienced by the powder particle [75]. Hence, it is a low-temperature drying method where liquid feed can be dried into powder form at exhaust temperatures as low as 30 °C [71].

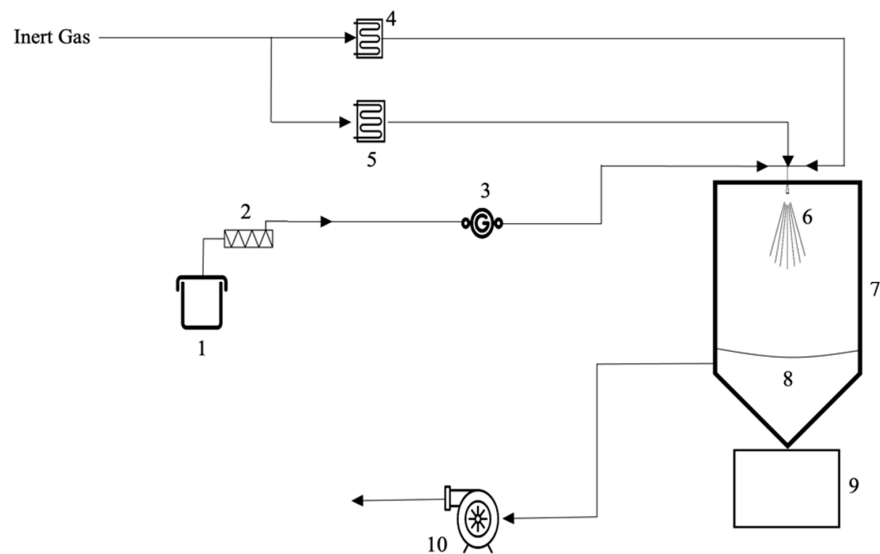


Figure 5. Schematic diagram of an electrostatic spray dryer: 1. Feed tank, 2. Pump, 3. Voltage generator, 4. Drying gas heater, 5. Atomizing gas heater, 6. Electrostatic nozzle, 7. Drying chamber, 8. Separation plenum, 9. Collection vessel, 10. Blower.

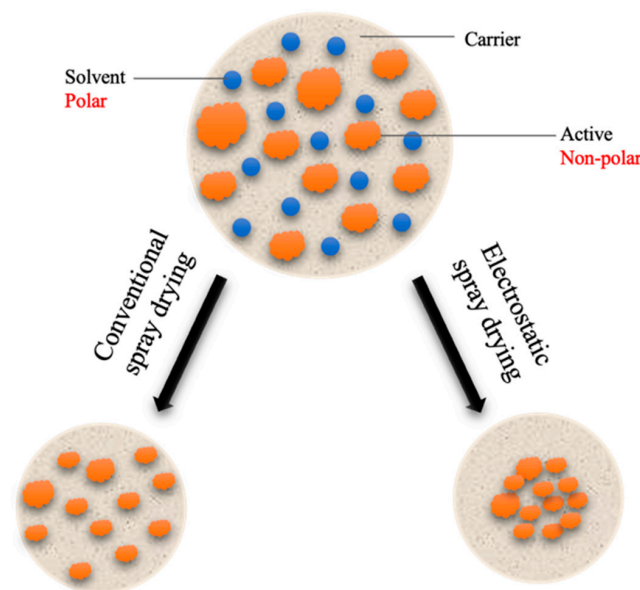


Figure 6. Differences in mechanism of conventional (left) and electrostatic (right) spray drying methods.

5.2. Application of ESD in the Preparation of Food Powders

ESD has applications in the food, nutraceutical and pharmaceutical sectors. In a study, drying of whole milk, skim milk and infant milk formula was carried out in a CSD and ESD dryer [71]. The drying conditions, i.e., inlet temperature and exhaust temperature for the CSD method, were 180 and 90 °C, respectively. The corresponding values for ESD were 90 and 35 °C. A voltage of 10 kV was applied to the feed in the ESD dryer. The observed values of moisture and water activity were similar and within acceptable limits for both ESD and CSD powders. Differences were observed in the surface composition of the powders [71]. The electrostatic effect lowered the surface fat of whole milk powder by 9%, and increased the protein and carbohydrate composition by 5% and 4%, respectively. This may be as a result of the different effects electrostatic charge has based on component polarity (as related above). The analysis of 5-hydroxymethyl furfural content as an indicator of Maillard Browning reported approximately 33% lower levels in whole milk powder, 57% lower in skim milk powder, and 11% lower in infant milk formula for ESD powders compared to CSD [71]. Another study carried out by Mutukuri et al. [72] explored the feasibility of ESD for producing a monoclonal antibody (mAb) powder formulation at lower drying temperatures than CSD. CSD of the mAb formulation at the inlet temperature of 70 °C failed to generate dry powders due to poor drying efficiency; ESD at the same temperature and 5 kV charge enabled the production of powder with satisfactory moisture contents [72]. On evaluating the protein stability of mAb powders, ESD at 70 °C showed better results compared to CSD at 130 °C analysed using solid-state Fourier transform infrared spectroscopy, differential scanning calorimetry, size exclusion chromatography, and solid-state hydrogen/deuterium exchange with mass spectrometry [72]. Hence, it can be said that the potential this technique holds in the manufacturing of thermally stable powders is promising. However, work completed to date is limited and should be expanded upon.

5.3. Potential of ESD in Retaining Bioactive Compounds in the Preparation of Food Powders

ESD is suitable for substances that are sensitive to heat and are susceptible to thermal degradation [72]. The use of low temperatures in its drying mechanism makes it an interesting technique for the dehydration of biological materials which contain heat sensitive materials and may become degraded in high heat methods [76]. For instance, the bioactive proteins present in bovine colostrum, such as lactoferrin, immunoglobulins and lactoperoxidase, lose their biological activity during heat processing. When colostrum was dried in an ESD dryer at a low inlet temperature of 90 °C with an electrostatic charge, immunomodulatory compounds were better retained (~16% higher bioactive yield retention) compared to powders produced by CSD [71]. Similarly, ESD resulted in lactoferrin powders which retained close to 100% of their starting biological activity [71]. Therefore, ESD may be a useful way to manufacture dairy powders with better retention of native structures for use in premium nutritional products, e.g., infant formula.

6. Factors Influencing Electric Field Technologies and Their Effects on the Retention of Bioactive Compounds

A common feature of EHD technologies is the use of an electric field to aid the removal of water. However, applications vary significantly not only as a function of the design of the system, but also as a function of the type of food material being processed, the strength of the electric field and its mode of application. The drying behaviour can be influenced by a number of factors, e.g., raw material properties such as moisture content, conductivity, diffusivity, and dielectric properties [77]. Electrical conductivity refers to the ability of a material to conduct an electric current, and is influenced by the presence of ions, moisture, and polar compounds such as proteins and carbohydrates in the food. In general, a sample with high electrical conductivity will have higher drying rates than a sample with low electrical conductivity, since it will heat up more rapidly [78]. The difference in the drying rates might also be associated with the dielectric properties of the sample.

The dielectric constant (permittivity) refers to the ability of a material to store electrical energy. During drying, the permittivity of the food can influence the rate at which moisture is removed, as the electric field can more easily penetrate through materials with higher permittivity [77,78]. However, after drying, these electrical properties will be different as the products' compositional and physical properties (structure, shape, size, moisture content) have changed [78]. Additionally, when powders are produced by processing under electric field, a surface layer of electrostatically charged particles may be formed during drying which can impact the flow and segregation of the powder [79]. However, this remains understudied in the literature and should be expanded upon.

Alongside the material properties, processing parameters such as voltage, electrical field strength, mode of voltage application, geometry of electrodes and the environmental conditions also play an important role in EHD processing [42]. During EHD processing, voltage is a crucial processing parameter. Optimizing the voltage is the first step in processing any product, as electrical gradient is the principal driving force. High voltages can induce structural changes in the components, whereas low voltages might not produce powders with satisfactory moisture content or water activity. Low voltages and high flow rates can result in the formation of an unstable jet. It is interesting to see at what voltages EHD techniques work, and how comparable they are to one another. Some of the recent studies conducted on different EHD techniques are listed in Table 1.

Table 1. Summary of some recent works on the electrohydrodynamic techniques with their working voltage, mode of voltage application and their main effects.

Operation	Working Voltage	Mode of Voltage Application	Main Effects	References
Electrohydrodynamic Atomization	5, 12.5 and 20 kV	Needle to Collector plate system	-An increase in applied voltage changed the morphology from spherical particles to elongated particles. -Higher retention of antimicrobial activity -Formation of small particle sized powders	[80]
	16 kV	Needle to Collector plate system	-More stable powders in retaining bioactivity compared to the powders undergone freezing and drying stresses.	[81]
Electrohydrodynamic Drying	0, 18, 22, 26, 30, 34 kV	Needle to plate electrode system	-Higher drying rates -With the increase in voltage, drying rate increases -Higher retention of nutrients than in control (0 kV)	[82]
	30, 40 and 50 kV	Needle-plate electrode system	-Drying rate, effective water diffusion coefficient, and rehydration ratio ↑ specific energy consumption of drying ↑ with increasing voltage.	[83]
Pulsed Electric Field coupled with convective drying	10 and 30 kV/cm, pulse duration of 6 μs	Parallel electrodes system	-Higher water absorption values indicating good stability during storage -Reduced viscosity of starch paste and reduced retrogradation rate	[84]
Pulsed Electric Field coupled with Ultrasound assisted drying	1.2 kV/cm, pulse duration of 200 and 600 μs	Parallel electrodes system	-Shortening of drying time -No damage to colour after drying -Retention of phenolic compounds	[85]

Table 1. Cont.

Operation	Working Voltage	Mode of Voltage Application	Main Effects	References
Electrostatic Spray Drying	1 and 8 kV	Electrostatic nozzle	-Sensory qualities were effectively preserved -Retention of most odour active compounds	[76]
	5 kV (For preliminary studies: 0, 5, 10, 15 and 20 kV)	Electrostatic nozzle	-Satisfactory moisture contents of powders at just 70 °C -Enhanced physical stability -Higher drying efficiencies	[72]

↑ indicates an increase.

It can be said that the effect of voltage on food properties can vary depending on the specific food and the type of processing it undergoes. In general, however, a high voltage can affect the physical and chemical properties of food in several ways. For example, high voltages can cause changes in the structure of proteins and other biomolecules, leading to changes in the texture and nutritional value of the food [86]. High voltages can cause the temperature of food to rise, which can cause changes in its flavour and texture [42]. It is important to carefully control the voltage during food processing to ensure that it does not negatively affect the quality of the final product. It is well-established that the voltage applied during EHDA, EHD drying and PEF has an impact on the properties of food. However, the effects of voltage on food properties during ESD are not well-known yet, as this technology is relatively new and requires further study.

7. Conclusions

A number of technologies which utilize electric fields to enhance drying rates and retain heat sensitive materials were presented. These technologies differ in how and where the electric field is applied. For example, PEF is suitable for use a pre-treatment prior to a separate drying step and EHDD applies electric current to solid/semi-solid state batch drying processes, whereas EHDA and ESD apply an electric charge to liquid feed materials in a continuous manner. However, in general, the use of an electric charge on food materials can result in increased drying rates, stability and functionality of the products. While these effects are promising, it remains to be seen how successfully this technology can be industrialised. For batch style applications, the benefits of EHDD compared to hot air drying are clear with respect to increasing drying rates. However, in terms of the retention of heat sensitive bioactives, more work should be carried out to compare with established gentle drying processes such as freeze drying. For continuous applications, it seems that the limitations of water as an ideal solvent, i.e., its high boiling point, restrict the application of EHDA in food applications. ESD has no such limitations as it combines the application of a charge to an atomised feed with conventional spray drying, albeit at lower temperatures. Therefore, it is an interesting technology with the potential to combine continuous processing (as is the case with CSD) with the retention of heat sensitive materials more akin to batch freeze drying. However, as for all the technologies presented here, this would need to be validated through further research to fully understand the mechanisms and benefits of this technology and to develop practical, industrial-scale processes.

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