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Electrohydrodynamic (EHD) drying: A sustainable non-thermal approach to enhancing the dehydration and quality of livestock-derived products

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Abstract

Electrohydrodynamic (EHD) drying has emerged as a trans-formative, non-thermal technology for food preservation, addressing the energy inefficiencies and quality degradation associated with conventional hot-air systems. Traditional methods account for approximately 15% of manufacturing expenses and contribute significantly to greenhouse gas emissions. In contrast, EHD leverages the phenomenon of ionic wind (corona wind) generated by a high-voltage electric field between emission and ground electrodes. This process converts electrical energy into mechanical energy, inducing moisture migration and evaporation at ambient temperatures without the need for intense heat. The effectiveness of EHD is governed by critical design parameters, including electrode geometry (point-to-plate configurations), discharge gaps, and material selection (e.g., tungsten or stainless steel). Research indicates that EHD can accelerate dehydration rates in meat products by nearly four fold while maintaining a superior porous micro-structure, enhancing rehydration ratios, and preserving nutritional integrity. In dairy and egg processing, EHD prevents protein denaturation and the Maillard reaction, resulting in powders with improved solubility, foaming, and gelling properties. Furthermore, it serves as a "gentle" method for maintaining pro-biotic viability, achieving significantly higher survival rates than thermal drying. Despite challenges regarding industrial scalability, initial capital investment, and by product management (ozone), EHD drying represents a sustainable "green" technology. It offers a 10 to 70-fold reduction in energy consumption compared to conventional methods. As consumer demand for high-value, nutritionally intact, and eco-friendly products grows, EHD is positioned to become a standard tool in the global food industry's sustainability toolkit.

Keywords: Electric field, electrohydrodynamic drying, ionic wind, non-thermal technology

1. Introduction

Drying is a critical unit-operation in animal products processing, serving as an essential preservation method. Drying occurs when the heat supplier vaporizes the solvent (liquid), the removal occurring from both the bound and unbound liquid phases, thereby reducing product volume and weight (Fathi *et al.*, 2022) ^[9]. This reduction facilitates easier packing, handling, and storage of food products (Bradford *et al.*, 2020) ^[3]. The conventional drying technologies presently used in the food industry are hot-air-based systems that are normally considered as energy-intensive processes with higher green house gas emissions accounting for approximately 15% of the overall manufacturing expenses (Menon *et al.*, 2020) ^[19]. This significant energy consumption, coupled with the potential for undesirable changes in food quality, has driven researchers to explore more efficient and effective drying technologies.

Electrohydrodynamic (EHD) drying is an emerging technology that leverages the phenomenon of ionic wind to directly extract liquid water from wet materials. It has been the best drying technology considering product quality, energy consumption, efficiency, and environmental protection from the emission of greenhouse gases. EHD drying has great potential to reduce food losses in production and distribution chains, as well as minimize waste from restaurants and households (Kudra and Martynenko, 2023) ^[11]. This emerging technology combines

energy efficiency with superior product quality, making it an attractive alternative to conventional drying methods. Electrohydrodynamic (EHD) drying is a non-thermal and energy-efficient technology, which appears to be a viable alternative to thermal drying (Martynenko and Kudra, 2016) ^[16]. The process involves the interaction of high-voltage electric field-generated corona wind with dielectric food materials. In Electrohydrodynamic (EHD) drying, an ion wind is generated between the emission electrode and the ground electrode. This ion wind interacts with the water molecules within the material. Water molecules migrate toward the region of higher electric field intensity under the influence of the electric field force. This directional movement of water molecules facilitates the removal of moisture from the material. Notably, EHD is a non-thermal process, making it both energy-efficient and eco-friendly. Moreover, it helps to retain the nutritional components of the material. Additionally, this technology can enhance the sensory quality of traditional products, thereby contributing to the improvement of the industry's economic efficiency (Lan *et al.*, 2025) ^[13]. The technology has gained recognition for its energy efficiency, environmentally friendly nature, and relatively low capital investment requirements. The technique is particularly suitable for sensitive materials that might be damaged by conventional high-temperature drying methods.

Corona Wind

EHD drying occurs in the presence of electric wind, also known as ionic or corona wind (Bashkir *et al.*, 2020) ^[2]. This phenomenon occurs through a fascinating series of events that convert electrical energy into mechanical energy. The process begins when electrons are emitted from an electrode known as the emitter electrode. These electrons are then accelerated by a high-voltage electric field (HVEF), leading to the ionization of gas molecules through what is called the Townsend effect. During this ionization, the electrons transfer kinetic energy to neutral gas molecules. The ionized particles then experience what is known as the ion drag phenomenon, which occurs due to friction resistance during collisions. Through momentum transfer with neutral gas molecules via these collisions, the electric wind or corona wind is generated. This corona wind plays a crucial role in the actual drying process (Ham *et al.*, 2024) ^[12].

Mechanism of Drying

The EHD drying mechanism involves several interconnected steps that work together to remove moisture from food materials: First, the electric wind impinges on the food material, creating turbulence in the water molecules present. This turbulence is greatest just below the emitter electrode (Defraeye and Martynenko, 2019) ^[7]. As a result of this impact and turbulence, water molecules acquire sufficient energy to undergo a phase change from liquid to vapor. The generation of electric concentration between concentric layers of the food material facilitates the diffusion of water from the inner layers to the outer layers (Ham *et al.*, 2024) ^[12]. This process continues until the entire food material is dried. The non-uniform electric field created between the two electrodes, the emitter electrode and the ground electrode, is responsible for the evaporation of water from the food. An important parameter in this process is the gap between electrodes, which generally varies from 1 to 10 centimeters. This gap is crucial for achieving the desired drying effects. The entire process occurs as a result of the conversion of electrical energy into mechanical energy, making it fundamentally different from

conventional thermal drying methods (Ciprian Foronda *et al.*, 2022) ^[4].

Secondary Effects and Benefits

One of the most interesting aspects of EHD drying is its secondary effect, which includes the lowering of the temperature of the food matrix. This phenomenon occurs for two primary reasons. First, there is rapid utilization of the heat of vaporization during the drying process. Second, the entropy of water molecules decreases due to their ordered orientation in the presence of the electric field (Misra *et al.*, 2018) ^[20]. This temperature-lowering effect offers significant benefits. Food characteristics are not negatively affected by thermal damage, which is a common problem in conventional high-temperature drying. This preservation of quality opens avenues for innovative applications, such as EHD-assisted freeze drying techniques, which could combine the benefits of both technologies.

Design of Equipment

The choice of electrode material significantly impacts performance. Research has shown that tungsten electrodes produce a relatively larger amount of current compared to stainless steel electrodes. However, copper and stainless steel remain the most commonly used electrode materials for EHD drying of foods due to their balance of performance, cost, and availability (Qu *et al.*, 2020) ^[23]. The geometry of the electrode plays a crucial role in determining evaporation rates. Point electrodes with conical ends offer higher evaporation rates compared to flat and hemispherical designs. Generally, larger curvatures of discharge electrodes result in higher water evaporation rates, making geometry optimization an important consideration in equipment design (Dalvi - Isfahan *et al.*, 2015) ^[5]. The most commonly used configuration in EHD drying systems is the point-to-plate electrode system. Different electrode types produce different jet patterns: a wire electrode can produce a slot-type jet, while a needle electrode produces a conical-type jet with a circular area. The choice of configuration depends on the specific application and the desired drying pattern (Defraeye and Martynenko, 2019) ^[7]. While increasing the number of electrodes can enhance drying performance, there is a point of diminishing returns. The rate of drying does not continue to increase after introducing a certain number of pointed electrodes for a fixed drying area. However, the use of multiple point-to-plate electrode systems does accelerate the drying process and provides more uniform drying of the targeted material (Martynenko and Defraeye, 2019) ^[15].

Optimal spacing between emitters is critical for efficient operation. If the emitting corona winds are placed too close together, significant energy losses occur due to interference. Conversely, if the gaps between needles or wires are too large, the effects of the corona wind may not adequately cover the entire food surface. Therefore, an optimal distance must be carefully maintained for each specific application (Dalvi - Isfahan *et al.*, 2015) ^[5].

The distance between the emitter electrode and the collecting electrode, known as the discharge gap, directly affects the electric field strength. As this distance increases, the electric field decreases, thereby lowering the drying rate. Research has shown that a spacing-to-gap ratio of 0.5 can result in efficient drying performance (Martynenko and Defraeye, 2019) ^[15].

Factor affecting EHD drying Process

Several process variables significantly influence the performance of EHD drying systems: (Martynenko and Kundra, 2020) ^[17].

Electric Field Intensity

The applied voltage directly affects the strength of the electric field. As voltage increases, the electric field strengthens until it reaches the collecting electrode. Higher voltages result in increased current flow, which enhances the ionic wind and thereby increases the drying rate. Notably, airflow increases quadratic with applied voltage, demonstrating the strong relationship between electrical input and drying performance (Xiao & Ding, 2022) ^[26].

Airflow and Ionic Flow

Electric fields without ionic wind have negligible effects on drying rate, highlighting the critical importance of the ionic wind component. The ionic wind combined with aerodynamic effects, has significant effects on moisture evaporation during EHD drying. The induced ion flow is influenced by the applied electric field, which in turn influences ion velocity, creating a cascade effect that drives the drying process (Paul & Martynenko, 2022) ^[21].

Air Temperature

Interestingly, EHD efficiency decreases as air temperature increases. This counter intuitive finding relates to how the electric field affects moisture from the core to the surface of the product (Han *et al.*, 2023). However, this characteristic also presents an opportunity: the EHD technique can be adopted for large-scale applications when provided with backup auxiliary heating, offering flexibility in process design (Paul & Martynenko, 2022) ^[21].

Humidity and Pressure

The relative humidity of the surrounding environment significantly impacts EHD performance. The effectiveness of EHD can be enhanced by decreasing the relative humidity during drying. High-humidity atmospheres lead to poor drying efficiency because evaporated water can condense on the electrode surface, affecting its emitting capacity and reducing overall system performance (Paul & Martynenko, 2022) ^[21].

Energy Efficiency

One of the most compelling advantages of EHD drying is its superior energy efficiency compared to conventional methods. The primary airflow velocity and corresponding energy consumption are significantly reduced while energy efficiency is increased during EHD operations (Han *et al.*, 2023).

Energy efficiency can be quantitatively assessed as the ratio of energy used for moisture evaporation to the total energy supplied. The specific energy consumption (SEC), which is the standard index for comparing the efficiency of different drying processes, is found to be much lower for EHD compared to conventional methods. This reduced energy consumption translates not only to cost savings but also to lower environmental impacts, making EHD drying an environmentally sound technology (Xiao & Ding, 2022) ^[26].

Application of EHD in Meat

For cooked beef, increasing the voltage has been shown to enhance the drying rate by 1.9 to 3.7 times compared to

untreated samples (Bai *et al.*, 2013) ^[1]. Meat dried via EHD exhibits significantly lesser shrinkage and a higher rehydration ratio. This means that when the meat is soaked in water for consumption, it returns to a texture much closer to its fresh state compared to oven-dried meat (Han *et al.*, 2023). Studies on sea cucumber and scallop muscle showed that EHD maintains the porous network of the muscle fibers, resulting in a more tender and appealing sensory profile. EHD-dried meat retains higher levels of soluble proteins and essential nutrients because it avoids the high-heat triggers that cause protein denaturation (Li *et al.*, 2006) ^[14].

Application of EHD in Dairy Products

Unlike thermal spray-drying, which exposes dairy ingredients to high temperatures EHD operates at ambient temperatures. In whey protein solutions, EHD treatment shows no significant change in the native structure of the proteins (Rizki *et al.*, 2024) ^[24] because EHD avoids high-heat triggers, it prevents protein denaturation and maintains higher levels of soluble protein. The process results in significantly lower Maillard reaction markers (like HMF) compared to conventional spray drying, preserving the nutritional quality of the milk matrix. Unlike thermal spray-drying, which can denature sensitive dairy proteins, EHD operates at ambient temperatures, preserving the molecular integrity of the food matrix.

EHD is considered a breakthrough for drying probiotic enriched dairy due to its "gentle" nature. Using a moving collector electrode, EHD can achieve a water evaporation rate of 76% while maintaining a 61% cell viability for *B. animalis*. This survival rate is significantly higher than that of hot-air drying, where the intense heat typically kills beneficial bacteria (Dima *et al.*, 2025) ^[8].

The physical interaction between the electric field (ionic wind) and the protein molecules enhances the resulting powder's utility. EHD-produced dairy powders (like egg white or whey) show improved functional properties, including superior foaming and gelling capabilities. Scanning Electron Microscopy (SEM) reveals that EHD maintains the porous network of fibers/particles rather than the dense, shrunken particles produced by hot-air drying. This porous structure allows the powder to return to a texture much closer to its fresh state when soaked in water (Zhang *et al.*, 2025) ^[27]. EHD in Egg Products (Pirnazari *et al.*, 2016) ^[22].

EHD-dried powder exhibits superior foaming capacity and stability because the "ionic wind" avoids the heat denaturation of globulin's required to trap air. The process yields gels with higher hardness and elasticity, making the powder an ideal binder for meat and confectionery products. EHD provide highly porous, flaky microstructure that allows for near-perfect solubility and faster rehydration compared to the dense particles of heat-dried powder. By operating at room temperature, EHD prevents the Maillard reaction (browning), maintaining a bright white appearance preferred by industrial buyers.

Advantages of EHD Drying

Unlike high-temperature drying methods that can degrade sensitive vitamins and bioactive compounds, EHD drying operates at lower temperatures, preserving the nutritional value of food products (Karim *et al.*, 2020) ^[10]. Foods dried using EHD technology maintain better color, texture, flavor, and overall sensory characteristics compared to conventionally dried products. The gentle nature of the process minimizes undesirable changes in food structure

(Vass *et al.*, 2019) ^[25]. EHD drying consumes significantly less energy than conventional drying methods, offering both economic and environmental benefits. For specialized applications like probiotic preservation, EHD drying has shown promising results in maintaining cell viability while achieving effective moisture removal.

Challenges

Despite its many advantages, EHD drying faces several challenges that must be addressed for widespread commercial adoption. The specialized equipment required for EHD drying represents a significant capital expenditure, which can be a barrier for smaller food processing operations (Martynenko & Kudra, 2022) ^[18]. Transitioning from pilot-scale to industrial-scale applications has proven difficult. The complexity of maintaining uniform electric fields over large areas and ensuring consistent product quality at scale remains a significant technical challenge (Paul & Martynenko, 2022) ^[21]. During the drying process, some product loss can occur, and there may be a reduction of certain nutrients despite the overall superior preservation compared to conventional methods (Dalvi-Isfahan *et al.*, 2023) ^[6]. The technology requires sophisticated control systems and careful optimization of multiple parameters, making it more complex to operate than conventional dryers (Vass *et al.*, 2019) ^[25]. Electrodes tend to attract dust particles, which can significantly affect EHD performance and require regular cleaning and maintenance. The high-voltage equipment can cause electromagnetic interference and generate audible noise, which may require additional shielding or isolation measures (Xiao & Ding, 2022) ^[26]. Working in a high-voltage environment necessitates stringent safety protocols, specialized training, and regular maintenance procedures to protect workers. Ozone and nitrous oxide are generated as byproducts of the EHD process. Exposure to these gases can adversely affect human lungs, requiring proper ventilation and air quality monitoring systems. Due to the challenges mentioned above, EHD drying has not yet achieved widespread commercial adoption in the food industry.

Future Prospects and Applications of EHD Drying

EHD drying is viewed as a primary successor to traditional drying methods that rely on extreme heat, which often result in "unacceptable quality degradation" because it is a non-thermal technology, it targets heat-sensitive food products that lose their biological utility when exposed to hot-air drying. It offers a sustainable solution that balances high-end product quality with a reduced environmental footprint compared to energy-intensive thermal systems. While the technology faces initial hurdles, its adoption is most likely to begin with premium sectors of the food industry. The technology is exceptionally well-suited for industrial drying of high-value products, where the superior final quality justifies the higher initial investment. As scaling challenges are overcome, the increased shelf life and retention of active ingredients (like probiotics or vitamins) provide a better return on investment than cheaper, quality-compromising methods. Modern consumers are increasingly health-conscious, moving away from ultra-processed foods toward those that look and feel natural. EHD produces items with high nutritional value while preserving the natural color and textural characteristics of the fresh product. Attributes such as bright colors (luminance) and original texture are increasingly valued by consumers, positioning EHD-dried products as premium offerings. As the food processing industry moves toward carbon neutrality,

EHD serves as a standard tool for energy reduction. By requiring 10 to 70 times less energy than conventional hot-air drying, EHD aligns with global environmental responsibility goals.

Conclusion

Electrohydrodynamic drying represents a significant advancement in food preservation technology. By using the power of electric fields and ionic wind, this innovative technique offers a compelling alternative to conventional drying methods. Its ability to produce superior quality food products while consuming less energy and causing minimal thermal damage positions it as a potentially transformative technology for the food industry.

While challenges related to scaling, initial investment, and safety protocols remain, ongoing research and development continue to address these limitations. As the technology evolves and becomes more accessible, EHD drying may well become an essential tool for producing high-quality, nutritious dried foods in an environmentally sustainable manner.

The journey from laboratory innovation to industrial application is rarely straightforward, but the fundamental advantages of EHD drying, which are energy efficiency, product quality preservation, and environmental sustainability which provide strong motivation for continued development and eventual widespread adoption in the food processing industry.

Conflict of Interest

Not available

Financial Support

Not available

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