**Electrohydrodynamic drying: Can we scale-up the technology to make dried fruits and vegetables more nutritious and appealing?**

**Daniel I. Onwude1,2, Kamran Iranshahi1,3, Alex Martynenko4, Thijs Defraeye1,4[[1]](#footnote-1)**

*1 Empa, Swiss Federal Laboratories for Materials Science and Technology, Laboratory for Biomimetic Membranes and Textiles, Lerchenfeldstrasse 5, CH-9014 St. Gallen, Switzerland*

*2Department of Agricultural and Food Engineering, Faculty of Engineering, University of Uyo, 52021, Uyo, Nigeria*

*3Department of Environmental Systems Science, Swiss Federal Institute of Technology, ETH-Zurich, Zurich 8092, Switzerland*

*4Department of Engineering, Dalhousie University, Faculty of Agriculture, Truro, Nova Scotia, Canada*

Electrohydrodynamic (EHD) drying is a promising technology to better preserve the nutritional content and sensory appeal of dried fruits and vegetables. To successfully scale up this technology, we need to rethink the current EHD dryer designs. There is also a significant potential to further enhance the nutritional content and sensory quality of the dried products by optimizing EHD process parameters. This study particularly highlights the current bottlenecks in scaling up the technology and in improving nutrient retention and sensory appeal of the dried products. We discuss plausible future pathways to further develop the technology to produce highly nutritious dried products. Concerning the nutritional content, we show that EHD drying preserves vitamins, carotenes, and antioxidants significantly better than hot-air convective drying. From the sensory perspective, we show that EHD drying enhances the color of dried products, as well as their general appearance. With respect to scalability, we show that placing the fruit on a grounded mesh electrode dries the fruit much faster and more uniformly than the grounded plate electrode. Future research should be directed towards simultaneous measurements of multiple food nutrients and sensory properties during EHD drying with a grounded mesh collector. Quantifying the impact of the food loading density on drying kinetics and energy consumption of the EHD drying process should also be a future research goal. This study gives promising insight towards developing a scalable non-thermal drying technology, tailored to the requirements of the current and future society.

# INTRODUCTION

Drying is one of the most common process technologies for preserving heat-sensitive plant-based foods such as fruits and vegetables. Drying ensures off-season availability and avoids the loss of fresh produce. Several dried fruits or vegetables contain substantial amounts of key minerals (iron, calcium), and are an important source of vitamins (A, E, C), phenolic antioxidants and dietary fibers [1]. These components are particularly essential for pregnant and breastfeeding women, elderly people and infants. Dried fruit can supplement an infant's diet already within the first year [2], [3] and can be locally sourced worldwide. For children, dried fruits are promoted as healthy snacks (e.g. """apple chips""" or """fruit sticks/bars""") or are used in cereals to increase their nutritional uptake [4], [5].

Standard convective drying methods (e.g., fan-driven, natural convective) are being used at an industrial scale to produce these dried fruits and vegetables. However, several of these drying methods lead to a significant loss of the aforementioned micronutrients and bioactive compounds due to elevated temperatures or a slow drying process [6], [7]. In addition to the loss of nutritional content, the sensory properties (softness, texture, color, flavor) of dried fruits and vegetables are often not that appealing to consumers, compared to other snacks. More advanced technologies, such as freeze-drying, retain better nutritional content and sensory quality. Such technologies, however, come at a much higher energy and environmental cost and also a higher product cost [8], [9]. This drives researchers and engineers towards developing innovative and sustainable drying processes. The particular focus is towards solutions that reduce the total energy consumption and carbon footprint of the drying process. At the same time, they aim to preserve the nutritional content of the fresh produce in the best way possible while ensuring optimal sensory appeal.

One such innovative drying technology is electrohydrodynamic (EHD) drying. EHD drying has recently gained significant interest as an alternative to standard convective drying. It is particularly suitable for drying of heat-sensitive foods, such as fruits and vegetables [10], [11]. This novel, non-thermal drying method is based on the direct use of electricity for the dewatering of wet biomaterials. A high voltage difference is invoked between emitter and collector electrodes, in the kilovolt range. This difference induces corona discharge resulting in local ionization of the air at the emitter electrode (Figure 1). This induces movement of the ions towards the collector electrode by the Coulomb force. Their resulting collisions of ions with air molecules lead to air movement, namely the so-called ionic wind. This technology has numerous advantages over convective air drying. These advantages can be categorized into those related to the drying process and those related to the resulting product quality. An advantage with respect to the drying process includes a shorter drying time. Drying is enhanced here by enhanced convective heat and mass transfer by the ionic wind and several other mass transfer mechanisms inside the product. An additional advantage is that the drying process has a lower energy consumption, so lower carbon emissions [12]–[14]. The reported advantages regarding product quality include better retention of nutritional content, flavor, and color, as well as lower shrinkage and higher rehydration capacity [11], [12], [15]–[17].

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***Figure 1. Schematic EHD drying mechanism showing corona discharge and interactions between electrons (not to scale).***

Most studies, however, only focused on improvements in one or a few nutritional or sensory quality attributes. These studies were also performed for specific fruit and vegetable, and a limited range of EHD process parameters. We currently lack a more holistic insight into the true impact of the EHD drying process on the complete set of key nutritional and sensory traits, compared to standard drying methods. In addition, the impact of the large set of EHD process parameters on these traits is still lacking. To find the optimal drying conditions, knowledge is required across a large range of voltages, electrode geometries, electrode distances, gaps between electrodes, spacings between each product, and product thicknesses. Given the large potential of EHD drying, it is also surprising that only a few working pilot-scaled EHD drying prototypes have been successfully designed in the last two decades [18]–[21]. Large EHD dryers have been locally developed for medicinal herbs drying [22]. However, to the best of our knowledge, there is still no known industrial EHD dryer for the production of dried fruits and vegetables. This raises the question of why this technology has not matured yet to industrial systems.

This paper aims to shed light on these open questions with respect to industrial upscaling of EHD drying technology and the enhancement of nutrient retention and sensory properties. First, we quantify the added value of EHD drying of fruits and vegetables in preserving the nutritional content and sensory properties compared to conventional air drying. We identify what it takes to bridge the large lacuna between current lab-scale research and future industrial scaled-up EHD drying devices. We show that future EHD dryers could be designed. We also highlight the perspectives of this for small-scale farmers and for the industry.

# EHD DRYING MECHANISM

EHD drying relies on airflow generation as a result of a high voltage difference between two electrodes (Figure 1). This generated airflow, also called ionic wind, can induce airspeeds of 0.1 - 10 m s-1 [11], [23], [24]. This """ionic wind""" coupled with other mass transfer mechanisms, driven by ion flow or an electrostatic field [25], [26], accelerates and alters the convective drying process. As a result, dehydrated products with different material properties and porous microstructures are created, compared to standard convective drying.

# PERFORMANCE INDICATORS FOR EHD DRYING

In order to evaluate the performance of an EHD drying process, and quantitatively compare it with other drying processes, the key performance indicators (KPI), as shown in Figure 2, are defined. Most of these performance indicators have been used in the past to evaluate the EHD drying of plant-based foods. They include drying rate, drying time, energy consumption, nutritional and sensory quality attributes, scalability, cost index, and greenhouse gas emissions [12], [14]–[16], [27]–[30]. These KPI's are defined below.

The drying rate (DR) is defined as the amount of moisture removed from a product per unit time [31]:

with (1)

where is the mass of water in the product (kg), is the mass of dry matter (kg), t is the time (h), and is the moisture content expressed in kg of water per kg of dry matter.

The drying time, quantified as the critical drying time (h) is defined as the time needed for a sample to reach the critical moisture content [32]. Critical moisture contentis defined as the averaged moisture content in the sample that corresponds to an equilibrium water activity, via the sorption isotherm, below which no spoilage occurs [33].

The energy consumption is quantified by means of specific energy consumption (SEC). The SEC is defined as the energy required to evaporate moisture from a product, per kilogram of water evaporated (kJ/kg)[34]:

(2)

where is the time during which the dryer is operated (h).

Metrics that quantify nutritional quality target the amount of available essential nutrients in dried food products. These nutrients are, for example, vitamins (mg/g of fresh weight), carotenes (µg/g dry weight), flavonoids (mg/100 g dry weight), polysaccharide (g/100g dry weight) and polyphenols (mg/100 g dry weight) [17], [35]–[37]. On the other hand, sensory quality implies the organoleptic properties of dried food. The sensory traits are detectable by human senses and determine the acceptability by consumers of the particular product. The sensory quality include color (lightness:0-100, redness or greenness: -60 to +60, and yellowness or blueness: -60 to +60), taste (%-score), hardness (N/m), appearance (%-score), and odor (%-score) [38]–[40].

The scalability is the ability to dry large amounts of foods with a similar efficiency as smaller amounts of products. Scalability of a dryer is quantified as the amount of dried product in the dryer divided by the total drying time of the products (Kg/h)[41]:

(3)

The cost index () is a metric indicative of cost-effectiveness. The CI is defined as the total cost incurred in producing a specific quantity of dried product, to the amount of dried product ($/kg of dried products) [42]:

(4)

where is the total cost of production ($)

Greenhouse gas emissions (GHGE) are used to determine the environmental impact of the production process. It is defined as the measured amount of equivalent CO2 emission per unit mass of the dried product (kg-CO2-equivalent/kg-dry product) [42]:

(5)

where is the mass of equivalent CO2 (kg)

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***Figure 2. Important performance indicators of the EHD drying process.***

# NUTRIENT RETENTION AND SENSORY QUALITY OF FRUITS AND VEGETABLES AS AFFECTED BY EHD DRYING

In the food industry, there has been an increasing demand for dried fruits and vegetables as healthy snacks because of their health benefits [43]–[45]. However, we are currently facing the problem of the availability of commercial dryers that can enhance the nutrients and sensory quality of dried fruits and vegetables.

## Why should we retain the nutritional and sensory quality of dried fruits and vegetables?

Fruits and vegetables are rich sources of vitamins (A, B, C, and E groups), minerals (especially electrolytes and trace elements), and phytochemicals, especially antioxidants [46]. These compounds provide an array of important functions in the body. For instance, vitamin A is important for growth and development, enhancing the body's immune system against diseases and maintaining good vision [47]. Electrolytes such as potassium help reduce high blood pressure, protect against stroke, and promote proper muscle functioning in humans. Selenium, a trace element, is essential for human reproduction, DNA synthesis, hormone metabolism, and protection against infections [48]. B-vitamins are important in converting food into energy [49]. Other micronutrients in fruits and vegetables, such as vitamins C and E, serve as powerful antioxidants that can protect cells from cancer-causing agents [50].

A lot of people in low- and middle-income countries have a deficiency in these essential compounds. For example, a report from the Chinese Academy of Agricultural Sciences indicated that in China, the average person obtains less than 0.06 mg of selenium (Se) per day [51]. About 72% of the studied persons were found to be selenium deficient. In India, children from low-income families consumed as little as 8.2 mg of vitamin C per day, which is only 20% of the recommended daily intake [52]. Other studies that were done in China and Gambia also found the daily intake of vitamin C in the diet of adolescents to be lower than the recommended [52]. These nutritional deficits could be alleviated by enhancing the nutritional composition of processed food that, at the same time, satisfy the subjective sensory perception of customers. Increasing the quality of the consumers, especially children's diet in this way, will help improve health and reduce their predisposition to infectious diseases. Dried fruits and vegetables could help serve this purpose. The main reason is that the raw material is produced all around the world, and the dried products can be preserved much longer, guaranteeing year-round access to nutrients. However, a lot of these heat-sensitive compounds are destroyed during drying. Since the nutritional content of these processed foods is often quite low, the potential of dried fruits to enrich the consumers' daily diet is still rather limited.

## How can we better preserve the quality of dried fruits and vegetables using EHD drying?

The impact of several standard drying methods on the nutritional composition and sensory properties of dried fruits and vegetables has been quantified extensively [53]. Hot-air, low-humidity air freezing, freeze-drying, microwave, and microwave–convective drying methods have all been used to preserve the vitamins, polyphenols, carotenoids, β-carotene, ascorbic acid, minerals, and color quality of various dried fruits and vegetables [54]–[57]. However, most of these drying methods still destroy a large part of the nutrients in dried fruits and vegetables due to elevated temperatures, and the slow drying process [51].

EHD drying provides a good alternative to the currently used conventional drying methods for fruits and vegetables (Table 1). This non-thermal drying technology has a unique drying mechanism (see section 2) that results in a low product temperature, coupled with high convective airflow, so a fast drying process. Due to these unique attributes of EHD drying, dried fruits and vegetables of higher nutritional density and enhanced sensory quality can be produced, compared to standard drying methods such as hot-air drying.

## How does EHD affect the quality of dried fruits and vegetables?

### 4.3.1 Nutritional composition

Table 1 provides a summary of selected EHD drying studies on the nutritional content and sensory quality of dried fruits and vegetables within the past decade. From Table 1, we analyzed how EHD process parameters impact the nutritional quality attributes of fruits and vegetables. Only two process parameters, namely voltage and gap between electrodes are correlated to a few nutritional quality attributes (carotene, vitamin C, flavonoid, and polysaccharides). Very few studies quantified the nutrient retention of EHD dried fruits and vegetables, and compared them to oven drying, ambient air drying, hot-air drying, and microwave drying. Studies in comparison with other high-end standard industrial drying methods, including freeze-drying, dehumidifier, and vacuum drying are not known. EHD drying was found to preserve carotene in dried carrots better (10% increment) than oven drying, but not so much for preserving the phenolic compounds in quinces. Polysaccharides in Chinese wolfberry was better retained by about 48% with EHD drying compared to oven drying. The retention of vitamin C (25%) and flavonoid (18%) in the Chinese wolfberry were also enhanced by EHD drying compared to ambient air drying. Figure 3 shows a typical framework of the impact of EHD drying on the nutritional composition and sensory quality of dried fruits and vegetables.

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***Figure 3. A typical representation of the impact of EHD drying process on the quality of fruits and vegetables***

The above analysis shows that the voltage and the gap between electrodes directly affect the ability of EHD dried fruits and vegetables to better retain nutrients (Table 1). Since only voltage and gaps between electrodes were considered (Table 1), it becomes very difficult to generalize the effects of EHD process parameters on the nutritional composition. Besides, very few nutritional quality attributes have been quantified in a limited number of studies. Therefore, we need more insight into what extent the multiple nutrients are preserved better (e.g., vitamins, minerals, phytochemicals). Moreso on how they are affected by multiple process parameters (e.g., voltage, the gap between electrodes) as compared with standard drying methods for adequate process optimization.

***Table 1. Selected literature on the impact of EHD drying of the quality of dried fruits and vegetables***

| **S/N** | **Products** | **Study** | **Processing conditions** | **Evaluation attributes** | **Main Findings** | **References** |
| --- | --- | --- | --- | --- | --- | --- |
| 1 | Apple slices | Experimental | Slice thickness = 8 ± 0.5 mm; Diameter = 42 ± 0.5 mm; Electrode distance = 2.5 cm; Voltage = 0, 5,10,15 kV; Air velocity = 0,1,3 & 5 m/s; Needle =1.5 cmL; Needle spacing =1 cm; Ambient temperature = 21 ± 1 ºC; MC1 = 11.12 - 7.12 g/g db | Color | Significant effect of EHD on color was observed and it increased with increased voltage at low velocity; High air velocity resulted in low color degradation. | [58] |
| 2 | Banana Slices | Experimental | 25 needle points (2.5 mm diameter); Slice thickness = 3 mm; Electric field = 6, 8, 10 kV/cm; Voltage = 12, 16 & 20 kV; Gaps between two electrode = 20 mm; Microwave power = 180 - 900 W; MC1 = 2.75 – 3g/g db; MC2 = 0.175g/g db | Rehydration; Shrinkage; Color | EHD gave a better performance for color, shrinkage and rehydration capacity compared to MWD; EHD drying led to 8% - 9% increase in the rehydration rate compared with MWD; About 25% - 31% reduction of shrinkage was also observed when drying using EHD as compared with MWD | [12] |
| 3 | Banana slices | Experimental | Electric field = 4.5, 6.5 & 8.5 kV/cm; 25 needles (2.5 mm diameter); Gap between electrodes = 34.6 mm; Electrode distance = 20 mm; Air velocity = 1m/s; OD = 50 - 70 ºC; HAD = 50 – 70 ºC; Slice thickness = 3 mm; Ambient temperature = 25 ºC; RH = 0.3 g/g; MC1 = 2.75 – 3 g/g; MC2 = 0.175 g/g | Rehydration capacity; Shrinkage; Color | EHD resulted in 19 - 24% reduction in shrinkage as compared with OD, and 31 - 32% reduction as compared with HAD; EHD also resulted in 23%-36%, and 9% - 33% reduction in the total color change of banana slices using OD and HAD, respectively | [59] |
| 4 | Carrot slices | Experimental  +  Empirical Modelling | Electrode distance = 100 mm; Needle diameter = 1 mm and 20 mm Long; slice thickness = 1 mm, 13 mmL, 8 mmW; Voltage = 0, 5, 10, 15, 20, 25 & 30 kV; Ambient temperature = 21 ± 2 ºC; RH = 30 ± 5%; MC = 90 ± 1%(wb) | Modelling using Lewis, Page, Henderson & Pabis, Logarithmic & Quadratic; Carotenes; Rehydration ratio | Page model was the best; Deff = 1.37x10-8 m2/s – 2.86 x 10-8 m2/s for 0 - 30kV; EHD enhanced carotene contents (10% increment) compared with OD; Rehydration ratio of EHD also increased by 10% compared with OD | [28] |
| 5 | Carrot slices | Experimental | Sample thickness: 2 mm; Sample diameter: 2 - 3 cm; 13 needles (2 mm diameter and 0.1 mm tip); Voltage = 10, 11.5 & 13 kV; de= 2, 2.5 & 3 cm; Electric field strength = 3.3 - 6.5 kV/cm; MC = 82% wb; RH = 24 ± 1-24.8%; HAD = 55 ºC (RH = 25 ± 1%) | Color and Shrinkage | EHD dried samples have better quality compared to OD & AAD; A reduction in the total color change of 89% - 95%, and 85% - 93% for EHD were obtained when compared with OD and AAD, respectively | [23] |
| 6 | Chinese Wolfberry | Experimental;  Empirical Modelling | AC voltage = 0, 20, 24, 28 & 32 kV; DC voltage = 28 kV; needle = 20 mmL, 1 mmD; Spacing between needles = 40 mm; Blanching = 10 min; MC1 = 69 ± 1%; MC2 = 17 ± 1/100g; Ambient Temperature = 25 ± 2 ºC; RH = 30 ± 5% | Shrinkage; rehydration ratio; Vitamin C;  **Modeling:**  Lewis, Henderson and Pabis, Logarithmic, Parabolic, Page, Dinani et al, Wang and Singh, Modified Page, Midilli, Weibull | High electrical field led to increased moisture removal, rehydration ratio, and vitamin C which also increased with increased voltage; Parabolic model was found to be the most suitable in the drying of Chinese wolfberry fruit | [14] |
| 7 | Chinese Wolfberry | Experimental | AC voltage = 0 - 48 kV; DC voltage = 18 - 54 kV; needle = 60 mmL, 1 mmD; Spacing between needles = 60 mm; electrode distance = 40 -120mm Oven drying = 55 oC; Ambient Temperature = 25 ± 2 ºC; RH = 30 ± 5% | Polysaccharides; Flavonoids | Voltage and electrode distance did not significantly affect the drying rate. Compared to oven drying, EHD drying increases polysaccharides retention by 32.55%, 29.55%, and 37.43% for AC, DC and 0kV electric field. EHD did not have a significant effect on the flavonoids content compared to oven drying | [60] |
| 8 | Chinese Wolfberry | Experimental | Needle = 20 mmL, 1 mmD; Sodium carbonate blanching = 10 minute; Voltage = 28 kV; Electrode distance = 100 mm; Needle spacing1 = 40 mm; Needle spacing2 = 2, 4, 6, 8, 10, and 12 cm; Drying temperature = 21 ± 2 °C; R.H = 30% ± 5%; MC1 = 76% ± 1%; Ambient wind speed (control) = 0 m/s | Shrinkage rate; Rehydration rate; Flavonoid Content; Polysaccharide Content; Structure (SEM) | The nonuniform electric field had a greater influence on the quality attributes under the drying process; The flavonoid content ranged from 0.13 ± 0.003 (2 cm spacing) - 0.08 ± 0.004 g/100g (6 cm spacing), control = 0.11 ± 0.006 g/100g; The Polysaccharides contents ranged from 16.0 ± 0.03 (4 cm spacing) - 12.3 ± 0.02 g/100g (10 cm spacing), control = 12.9 ± 0.03 g/100g; EHD enhanced the retention of flavonoid and polysaccharides; There was no significant difference in the shrinkage rates of Chinese wolfberry fruits with EHD treatment; Increase in the needle spacing decreased the rehydration rate; The nonuniform electric field and ionic wind using EHD drying technology greatly influenced the surface microstructure of the fruits compared to control | [17] |
| 9 | Mushroom slices | Experimental | Voltage = 0, 20, 25 & 30 kV; wire diameter = 0.15 mm; Velocity = 0.4 & 2.2 m/s; blanched slices = 2 min; slice thickness = 5 mm; electrode distance = 6 cm; Electric field strength = 0 - 5 kV/cm | Porosity; Shrinkage; Rehydration ratio; Color; Shear strength; Interior structure (SEM) | Increased voltage intensity resulted in increased moisture removal, shrinkage, porosity, shear strength, rehydration ratio, and color; Mushroom dried at 0 kV - 0.4 m/s had uniform hexagon polygon | [61] |
| 10 | Mushroom slices | Experimental | Voltage = 17, 19, & 21 kV; 6 wire (D = 0.3 mm, L= 6cm); Spacing between wire = 5cm; slice thickness = 3.1 mm; Slice diameter = 33.1 mm; Blanching = 2 min; electrode distance = 5,6 & 7 cm; Electric field strength = 2.43 - 4.2 kV/cm; Drying air temperature = 60 ºC; RH = 10% | Color and thermal properties | Color properties were significantly affected by combined EHD+HAD | [62] |
| 11 | Mushroom slices | Experimental | Voltage = 17, 19, & 21 kV; 6 wire (diameter = 0.3 mm, 6 cmL); Spacing between wire= 5 cm; Slice thickness = 3.1 mm; Slice diameter = 33.1 mm; blanching = 2 min; electrode distance = 5,6 & 7cm; Electric field strength = 2.43 - 4.20 kV/cm; Drying air temperature = 60 ºC; RH = 10% | Moisture content; Apparent density; Solid density; Porosity; Shear strength; Color; Water absorption capacity (WAC) | Increased voltage increased solid density and decreased apparent density; Decreasing electrode gap decreased apparent density and increased porosity; Increasing voltage and decreasing electrode gap, increased WAC and decreased shear strength; Compared to OD, EHD+HAD drying resulted in samples with more WAC and less shear strength; Increased voltage led to an increased change in color | [63] |
| 12 | Potato slices | Experimental | Needle length = 20 mm, diameter = 1 mm; Spacing between electrodes= 2, 4, 6, 8, and 10 cm; Electrode distance = 6 cm; Slice thickness = 4 mm (40 mmL, 40 mmW); Blanching = 5 min; Voltage = 18, 20, 22 kV; Ambient temperature = 25 ± 2 ºC; RH = 30 ± 5% | Moisture content; Appearance; Microstructure morphology; Rehydration ratio; Soluble reducing sugar; Material loss in rehydration process; | Samples dried using EHD gave better appearance; Voltage and spacing between electrodes also affected rehydration ratio; Starch was the most material loss during rehydration process; Drying at 20 kV and 4 cm electrode spacing was found to be the optimum condition considering drying rate, quality properties, and energy consumption | [64] |
| 13 | Quince slices | Experimental | Slice thickness = 2 mm; Voltage = 5, 7, 9 kV; 32 needles (D = 0.4 mm); Spacing between two electrode = 2 cm; HAD = 50 - 70 ºC; Air velocity = 1 m/s; Ambient temperature = 70 ºC; MC1 = 3.5-3.7 g/g | Total phenolic content; Antioxidant capacity | Increased voltage resulted in enhanced phenolic content (mg/g) (2 - 5%), and antioxidant activity (%) (21-26%); HAD had better quality compared to EHD | [16] |
| 14 | Quince slices | Experimental | Slice thickness = 2mm; Voltage = 5, 7, 9 kV; 32 needles (0.4 mm diameter); Spacing between two electrode = 2 cm; HAD = 50 - 70 ºC; Air velocity = 1 m/s; Ambient temperature = 25 ºC; RH = 10%; MC1 = 3.7 g/g | Shrinkage; Water absorption capacity; Shear strength; Color | Increased EHD voltage led to a significant reduction in MC, shear strength, and shrinkage; An increase in WAC and total color change was observed with increased voltage; There was no significant change in the color, shear strength, and WAC of the sample with increased voltage from 5 - 7 kV; Sample dried using HAD resulted in higher shrinkage and lower color compared with EHD; there was no significant difference between shear strength and WAC using both methods | [65] |
| 15 | Tomato slices | Experimental | Voltage: 6 – 10 kV;  4 needles (3 mm diameter each); Gap between electrode = 20 mm; de = 20 mm  MC1 = 94% wb  MC2 = 11% wb | Color and Shrinkage | EHD dried tomato slices had better appearance than sun and oven dried samples | [66] |

### 4.3.2. Sensory properties

From Table 1, the impact of three EHD process variables on the sensory properties was explored. These are voltage, the gap between electrodes, and electrode distance. The following sensory properties were measured in multiple studies, however not all together: color, appearance, rehydration ratio, shrinkage, water absorption capacity, and shear strength. It was found that EHD drying resulted in reduced color degradation (9 - 36% reduction) of apples, banana, carrot, and tomato slices as compared to standard convective drying methods. EHD also provides superior appearance, flavor, less hardness, less shrinkage (25% - 32% reduction), and better rehydration capacity (8% - 9% increase) of food compared to conventional drying methods. Researchers also explored the use of EHD drying in combination with convective air-drying (cross-flow) to enhance the color and textural quality attributes of dried fruits and vegetables (Table 1). However, its comparative advantage over EHD drying alone has not been properly elucidated. A few studies conducted blanching as a pretreatment prior to EHD drying to reduce the enzymatic reaction and improve the structural properties of dried fruits and vegetables [13], [63], [67]. However, the effect of blanching on different sensory properties of dried fruits and vegetables was not quantified.

From this analysis (Table 1), we see that voltage and electric field strength play a significant role in enhancing the color, rehydration capacity, shrinkage, density, porosity, and shear strength of dried fruits and vegetables. But not so much for the visual appearance. The electrode distance directly affects the improvement of color, apparent density, porosity, shear strength, and WAC of dried products. The gap between the electrodes is also significant in enhancing the color and rehydration capacity of dried fruits and vegetables. The analysis also showed that most studies focused on the effect of a few processing parameters on a few sensory properties of dried fruits and vegetables. As such, future studies should quantify the impact of multiple EHD drying variables on multiple sensory properties.

# EHD DRYING SCALABILITY

To examine the potential of scaling EHD to dry a large amount of food faster and more uniformly, a brief insight into several EHD dryer configurations is required. For this reason, we identified and analyzed the most relevant EHD design configurations for the drying of fruits and vegetables based on literature during the past decade.

## How can we scale-up EHD drying technology?

Table 2 highlights selected literature on EHD drying of fruits and vegetables using different electrode design configurations. In addition, several EHD design configurations are depicted in Figure 4. Some of these have been evaluated already in several studies and others have been proposed by the authors.

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***Figure 4. Schematics diagram of types of EHD design configuration for multiple fruits and vegetables: (1=drying chamber, 2 = needle electrode, 3= grounded plate collector, 4 = sample, 5=wire electrode, 6= grounded-mesh collector).***

***Table 2. Published data on EHD drying of fruits and vegetables using different design configurations***

| **S/N** | **Design Configuration** | **Study (product)** | **Operating Parameters** | **Impact** | **References** |
| --- | --- | --- | --- | --- | --- |
| 1 | Multiple needles–to-plate | Experimental (Tomato slices)  MC1 = 94% wb  MC2 =11% wb | Voltage: 4 -10 kV; 4 needles (3 mm diameter each); Gap between electrode = 20 mm; de = 20 mm | Drying rate enhanced by EHD; Shrinkage increased with increased voltage; EHD dried tomato slices had better appearance than sun and oven-dried samples. SEC value for EHD ranged from 4.4–16.5 kJ/g, over 200 times less than that of oven drying (3600 kJ/g) | [66] |
| 2 | Multiple needles–to-plate | Experimental (Carrot slices)  Sample thickness: 2 mm  MC = 82% wb | 13 needles (2 mm diameter and 0.1 mm tip); Voltage= 10, 11.5 & 13 kV; de = 2, 2.5 & 3 cm; Electric field strength = 3.3 - 6.5 kV/cm; R.H = 24 ± 1 - 24.8%; HAD = 55 ºC (RH = 25 ± 1%) | Increased electrode distance (de) increased the inception voltage; Energy consumption of EHD lower than HAD & AA; EHD dried carrot slices have better quality compared to others | [23] |
| 3 | Multiple needles-to-plate | Experimental (Kiwi fruit)  Sample thickness = 2 mm  MC = 84% wb | 1 - 17 needles (0.1 mm diameter); Voltage = 6, 10.5, & 15 kV; Field strength = 4.5 kV/cm; de = 0 - 8 cm; Ambient conditions = 24 ºC & RH = 20.8% | Voltage had a significant effect on the drying rate of kiwi fruit; Drying decreased with increased needle numbers | [27] |
| 4 | Multiple needles–to- plate | Empirical Modelling (using RSM) (Kiwi fruit)  Slice thickness = 2 mm; | 1 - 17 needles (0.1 mm diameter); Ambient condition = 24.0 ºC & 20.8 RH; Voltage = 6, 10.5 & 15 kV de = 0 – 8 cm; air velocity = 0.0 - 0.4 m/s; RSM = 4 factors & 3 coded levels (-1,0 & 1) BBD | **Kiwi Fruit**  MR Estimation:  For Energy Efficiency:  Energy Consumption (EC): | [12] |
| 5 | Multiple needles-to-plate | Experimental (Banana slices)  Slice thickness = 3 mm  MC1 = 2.75 – 3.00 g/g db; MC2 = 0.175 g/g db | 25 needle points (2.5 mm diameter); Electric field = 6, 8, 10 kV/cm; Voltage = 12, 16 & 20 kV; Gaps between two electrode = 20 mm; Microwave power = 180 – 900 W; | EHD gave a better performance for specific energy of consumption, color, shrinkage and rehydration capacity compared to MWD. The SEC value for EHD was 0.34 kJ/g while that of MWD 9.66 kJ/g. | [12] |
| 6 | Multiple needles-to-plate | Experimental (Banana slices)  Slice thickness = 3 mm  MC1 = 2.75 -3 g/g; MC2 = 0.175 g/g | Electric field = 4.5, 6.5 & 8.5 kV/cm; 25 needles (2.5mm diameter); Gap between electrodes = 34.6 mm; de = 20mm; Air velocity = 1 m/s; Oven= 50 - 70 ºC; HAD = 50 – 70 ºC; Ambient temperature = 25 ºC; RH = 0.3 g/g; | Drying time decreased with increased electric field intensity; EHD gave better performance on energy consumed, shrinkage and rehydration capacity compared to oven and HAD. The SEC value for EHD ranged from 2.55 - 2.99 kJ/g while those of oven and HAD are 20.9 – 33.9 kJ/g and 81.7 – 164.4 kJ/g, respectively. | [59] |
| 7 | Multiple needles-to-plate | Experimental + Empirical Modelling (Carrot slices)  Slice thickness = 1mm  MC = 90 ± 1% wb | Electrode distance = 100 mm; Needle diameter = 1 mm and 20 mm Long; Voltage = 0, 5, 10, 15, 20, 25 & 30 kV; Ambient temperature = 21 ± 2 ºC; RH = 30 ± 5% | Increased voltage resulted in increased drying rates; From 0.47 – 2.33 times at 5 – 30kV compared to control (3.3 – 26.7% decrease in drying time); Page model was the best; Deff = 1.37x10-8 m2/s – 2.86 x 10-8 m2/s for 0 – 30 kV; | [28] |
| 8 | Multiple needles-to-plate | Experimental (Chinese wolfberry) | Needle = 20 mmL, 1mmD; Sodium carbonate blanching = 10 minute; Voltage = 28 kV; de = 100 mm; Needle spacing1 = 40 mm; Needle spacing2 = 2, 4, 6, 8, 10, and 12 cm; Drying temperature = 21 ± 2 ◦C; RH = 30% ± 5%; Ambient wind speed = 0 m/s | EHD enhanced the retention of flavonoid and polysaccharides; Ionic wind had a greater influence on the drying characteristic parameters of Chinese wolfberry fruits, and the nonuniform electric field had a greater influence on the quality attributes under the drying process; Ionic wind speed decreased with the increase in needle spacing; With the increase of needle spacing, the drying rate of Chinese wolfberry decreased | [17] |
| 9 | Multiple needles–to-plate | Experimental + Empirical Modelling (Chinese wolfberry)  MC1 = 69 ± 1%  MC2 = 17 ± 1/100g | AC voltage = 0, 20, 24, 28 & 32 kV; DC voltage = 28 kV; needle = 20 mmL, 1mmD; Spacing between needles = 40 mm; Blanching = 10 min; Ambient Temperature = 25 ± 2 ºC; Rh = 30 ± 5% | High electric field led to high moisture removal, rehydration ratio, and vitamin C which also increased with increased voltage; Increased voltage led to increased SEC and energy efficiency (22.49%); EHD (3.92 kJ/g) saved about 17.12% of energy requirement compared to HAD (22.90 kJ/g); Parabolic model was found to be the most suitable in the drying of Chinese wolfberry fruit. | [14] |
| 10 | Multiple needles–to-plate | Experimental + Empirical Modelling (Banana slices)  Slice thickness = 3 mm  MC1 = 2.75 – 3 g/g db  MC2 = 0.175 g/g db | 25 needle points (2.5 diameter each); Distance between needle electrode = 34.6 mm; Electric field strength= 6, 8,10 kV/cm; Voltage=12,16, & 20 kV; de = 20 mm; Ambient Temperature = 25 ºC; RH = 0.3 g/g | Increased electric field strength resulted in increased drying rate and reduction in drying time of banana slices; The diffusion model was considered the most suitable; for 6-10kV/cm; for 6-10 kV/cm  Diffusion model constant equation: | [29] |
| 11 | Multiple needles–to-plate | Experimental (Apple slices)  Slice thickness = 8 ± 0.5 mm  MC1 = 11.12 - 7.12 g/g db | de = 2.5 cm; Voltage = 0,5,10,15 kV; Air velocity = 0,1,3 & 5 m/s; Needle = 1.5 cmL; Needle spacing = 1 cm; Ambient temperature = 21 ± 1 ºC | A negative effect of EHD on color was observed and it increased with an increased voltage at low velocity; High air velocity resulted in low color degradation rate; Energy consumption depends on AC/DC converter which is too low (1 - 2%) for the industry | [58] |
| 12 | Multiple needles–to-plate | Experimental (Quince slices)  Slice thickness = 2 mm  MC1= 3.5 - 3.7 g/g | Voltage = 5,7,9 kV; 32 needles (0.4 mm diameter); Spacing between two electrode = 2cm; HAD = 50 - 70 ºC; Air velocity = 1 m/s; Ambient temperature = 70 ºC; | Increased voltage resulted in reduced drying time, reduction in energy, enhanced phenolic content, and antioxidant activity (%) for quince slices; Less energy consumed compared to HAD; HAD = 48.66 times EHD; HAD dried faster than EHD; HAD had better quality compared to EHD | [16] |
| 13 | Multiple needles–to-plate | Experimental (Quince slices)  Slice thickness = 2mm  MC1 = 3.7g/g | Voltage = 5, 7, 9 kV; 32 needles (0.4 mm diameter); Spacing between two electrode = 2 cm; HAD = 50 - 70 ºC; Air velocity = 1 m/s; Ambient temperature = 25 ºC; RH = 10%; | Increased EHD voltage led to a significant reduction in MC, shear strength, and shrinkage of quince slices; An increase in WAC and total color change was observed with increased voltage; There was no significant change in the color and WAC of the sample with increased voltage from 5 – 7 kV; Sample dried using HAD resulted in higher shrinkage and color quality compared with EHD; | [65] |
| 14 | Multiple needles–to-plate | Experimental (Potato slices)  Slice thickness = 4 mm | Needle length = 20 mm, diameter = 1 mm; Spacing between electrodes= 2, 4, 6, 8, and 10 cm; de = 6 cm; Blanching = 5 min; Voltage =18, 20, 22 kV; Ambient temperature = 25 ± 2 ºC; RH = 30 ± 5% | EHD significantly affected the drying rate of potato slices; Increasing the voltage and reducing the spacing between the electrodes (10 cm – 6 cm) increased drying; Small spacing (2 cm) had a negative influence on the drying rate; Samples dried using EHD gave better appearance; The voltage and spacing between electrode also affected rehydration ratio; Starch was the most material loss during rehydration process; High voltage resulted in high energy consumed (Energy for 22 kV was 1.38 and 2.41 times higher than those of 20 kV and 18 kV, respectively) | [64] |
| 15 | Single wire-to-plate | Experimental (Mango slices)  Slice thickness = 5 mm  MC1 = 83 - 86% wb  MC2 = 50% wb | Blanched = 10 min; Air velocity = 0.3 m/s (EHD), 0.3 - 3.0 m/s (forced convection); 1 electrode; de = 4 cm and 7cm; Voltage = 10, 16, & 22 kV; | Drying rate was higher at high voltage and electrode distance with the lowest drying time compared to low voltage; The lowest exergy for EHD was 10kV and 4cm which is also applicable to exergy efficiency and exergy per unit area | [68] |
| 16 | Single wire-to-plate; Single wire-to-mesh; Single wire-to-wires; Single wire-to-parallel plates | Theoretical Modelling & Simulation (Apple slices)  Slice = 10 mm Length, 5 mm Height | Ambient Temperature = 20 ºC; Relative Humidity = 30%  de = 10 – 80 mm; Voltage = 12 – 40 kV; Wire radius= 0.05 - 0.50 mm; Air speed= 0.0906, 0.0950, 0.0853 | For apple slices, the bulk electric field strength is not a suitable parameter to evaluate and compare the effect of different geometrical configurations of electrodes; The space charge density at the emitter electrode, the approach flow airspeed and the convective transfer coefficient at the fruit surface have a nonlinear dependence on thevoltage at the emitter, the distance between emitter and collector, and the wire radius, respectively; The critical drying time increases linearly with increasing distance between electrodes or increasing wire radius; The critical drying time decreases in a very nonlinear way with increasing voltage between the electrodes; There was a clear difference between the drying kinetics of the 4 configurations investigated; The most suitable configuration, in terms of drying kinetics is the wire-to-mesh configuration | [69] |
| 17 | Single wire-to-plate (1.5L - 6L); Periodic wire-to-plate (4L - 30L; Periodic wire-to-mesh (4L - 30L) | Theoretical Modelling & Simulation (Apple slices)  Slice = 10 mm Length , 5 mm Height | Ambient Temp = 20 ºC; Relative Humidity = 30%  de = 20 mm; Voltage = 20 kV; Wire radius = 0.25 mm | For the first case: Differences in drying times of 24% (≈ 6 h) between the fastest and slowest drying apple slice were found (for wp = 1.5L), which will become even more pronounced if large amounts of products are dried; Drying occur progressively slower at high critical time and low CHTC; For the second case: The CHTC for each individual fruit and its critical drying time both significantly depend on the spacing between products; Increasing the spacing (wp) results in a steep increase in CHTC and decrease in drying time; For the third case: the CHTC and the drying rate of the product do not increase significantly with this increase in speed, and remain almost constant for all product spacing; the wire-to-mesh configuration minimizes interference of neighboring airflows and avoids recirculation of moist air in drying zone, hence provides more uniform drying. | [70] |
| 18 | Multiple wire-to-plate | Experimental (Mushroom slices)  Slice thickness = 3.1 mm | Voltage = 17, 19, & 21 kV; 6 wire (diameter = 0.3 mm, 6.0 cmL); Spacing between wires = 5cm; blanching = 2min; de = 5, 6 & 7cm; Electric field strength = 2.4 - 4.2 kV/cm; Ambient temperature = 60 ºC; RH = 10% | Increased voltage increased solid density and decreased apparent density for mushroom slices; Decreasing electrode gap decreased apparent density and increased porosity; Increasing voltage and decreasing electrode gap, increased WAC and decreased shear strength; Compared to Oven, EHD resulted in samples with more WAC and less shear strength; Increased voltage led to increased change in color value | [63] |
| 19 | Multiple wire-to-plate | Experimental + Empirical modeling (Mushroom slices)  Slice thickness = 5 mm | Blanching = 2 mm; 6-wires, (0.3 mm diameter, 26.0 cm length); Wire spacing = 5 cm; Voltage = 17,19, 21kV; de = 5, 6, & 7 cm; Electric field strength = 2.4 - 4.2 kV/cm; Ambient Temperature = 60 ºC; Rh = 10% | Core sample temperature increased with increased electric field intensity (increased voltage and reduced electrode distance); Increased drying rate was observed due to increased voltage and reduced electrode gap; Weakest models were Henderson and Pabis, and Newton models; Midilli and Kucuk model, and Tagnhian Dinani et al models gave the best result; Midilli and Kucuk:  Tagnhian Dinani et al: where G=gap; V=voltage | [67] |
| 20 | Single wire-to-plate  + HAD | Experimental (Mushroom slices)  Slice thickness = 5 mm | Voltage = 0, 20, 25 & 30 kV; Wire diameter = 0.15 mm; Velocity = 0.4 & 2.2 m/s; blanched slices = 2 min; de = 6 cm; Electric field strength = 0 - 5 kV/cm | Drying rate at low velocity (0.4 m/s) increases as voltage increase; At 0.4m/s cross flow, increased enhancement in water evaporation with increased voltage; High velocity (2.2 m/s) reduced enhancement due to reduced electric field effect; Increased voltage intensity resulted in increased moisture removal, shrinkage, porosity, shear strength, rehydration ratio, and color; Mushroom dried at 0 kV - 0.4m/s had uniform honeycomb network | [61] |
| 21 | Single wire-to-plate + HAD | Experimental (Mushroom slices)  Slice thickness = 5 mm | Voltage = 0, 20, 25 & 30 kV; Wire diameter = 0.15 mm; Velocity = 0.4 and 2.2 m/s; blanched slices = 2 min; de = 6 cm; Electric field strength = 0 - 5 kV/cm | At 0.4m/s crossflow, water evaporation increased with increased voltage (20 - 30 kV); At 2.2 m/s, the effect of voltage increase was negligible due to suppression of corona wind; The increased velocity and reduction in voltage resulted in decreased SEC; Low SEC and high drying rate was observed for 30 kV - 0.4 m/s. SEC for EHD (0.23 kJ/g – 0.91 kJ/g) lower than that of air tunnel drying (253.89 kJ/g -1046.92 kJ/g) | [71] |
| 22 | Multiple needles–to- plate + Solar power | Experimental (Kiwi fruit)  Slice thickness = 2 mm; | 1 - 17 needles (0.1 mm diameter); Ambient condition = 24.0 ºC and 20.8 RH; Voltage = 6, 10.5 & 15 kV; de = 0 - 8cm; air velocity = 0 - 0.4 m/s; RSM = 4 factors & 3 coded levels (-1,0 & 1) BBD | For EHD drying of kiwi fruit, high energy efficiency with increased voltage and number of discharge needles was observed. | [72] |
| 23 | Multiple wire-to-plate + HAD | Experimental (Mushroom slices)  Slice thickness = 2 mm | 6 wire electrodes; Wire spacing = 5 cm; Voltage = 17, 19 & 21 kV; de = 5, 6, & 7 cm; Constant Temperature = 60 ºC; R.H = 10% | For mushroom slices, a decrease in electrode gap and increased voltage resulted in decreased drying time; Increasing voltage increased Deff; Energy Consumption of EHD (0.118 - 0.492 kJ/g) was lower than HAD (238.63 - 286 kJ/g) alone. | [13] |
| 24 | Multiple wire–to- plate + HAD | Experimental (Mushroom slices)  Slice thickness = 3.1 mm | Voltage = 17, 19, & 21 kV; 6 wire (diameter = 0.3 mm, 6.0 cmL); Spacing between wires = 5 cm; blanching = 2 min; de = 5, 6 & 7cm; Electric field strength = 2.43 - 4.2 kV/cm; Ambient temperature = 60 ºC; RH = 10% | High voltage and small electrode distance resulted in increased drying rate and reduced drying time for mushroom slices; Color properties were significantly affected by combined EHD + HAD; There was no presence of freezable water in the sample dried using all combinations | [62] |

### 5.1.1 What are the commonly used EHD dryer design configurations?

From Table 2, the commonly used EHD dryer design configurations are the multiple needle-to-plate (Figure 4a), Single wire-to-plate (Figure 4b), and the multiple wire-to-plate (Figure 4c). These design configurations have been used to dry several fruits and vegetables such as tomato, carrot, kiwi fruit, banana, Chinese wolfberry, mushroom, apple, quince, mango, and potato using lab-scale setups (Table 2). Most EHD studies using these configurations were limited to a small number of fruits and vegetables, and not in commercial quantities. The process variables of voltage, electrode distance, the gap between electrode and airspeed were correlated to the drying rate, energy efficiency, and final product quality (Table 2). The impact of other parameters on the EHD drying process was not reported. These parameters include the shape and thickness of the food, and the size and geometry of the collector electrode. Others are the number of products that can be placed on the collector electrode (loading density), and spacing between products (for multiple products).

### 5.1.2 What are the hurdles in upscaling the commonly used EHD design configurations?

There is a growing interest in developing EHD drying technology for drying commercial quantities of fruits and vegetables. However, as is often the case with most novel food processing techniques, upscaling EHD drying to industrial systems has been difficult. One hurdle is that most laboratory-scale EHD dryers have used a plate collector electrode on which the fruits are placed [69]. It is difficult to achieve a uniform drying rate for multiple food products using these plate collector configurations [32]. When drying with a single wire, the EHD generated air-jets moves towards the plate and are then redirected to the sides over the products. When air passes over successive products, successive saturation of the air with vapor will occur. This will reduce the drying rate of products downstream. Similarly, drying using multiple wires, a rebound of multiple air jets from the product can occur. This causes a partial saturation of the recirculating air. This effect slows down the drying rate. In order to successfully upscale the EHD drying technology, there is a need to design a collector electrode that would result in a uniform and faster drying process. This will thereby reduce the energy consumption needed to operate the equipment.

### 5.1.3 Are there practical solutions towards the upscaling of EHD dryers?

We consider whether it is practical to develop EHD collector electrode designs that would result in a uniform and faster drying with minimal energy requirement, which could stimulate industrial implementation. To answer this question, we illustrated different EHD design configurations in Figure 4 that, in our opinion, can overcome the drawbacks of the existing configurations. These configurations include the multiple wire-to-mesh configuration (Figure 4d) or the multiple needle-to-mesh configuration (Figure 4e).

EHD dryers using these configurations will be more likely to increase the drying rate due to the uniform airflow around the products compared to the existing lab-scale design configurations (Figure 4d-e). Defraeye & Martynenko [69] have recently predicted the suitability of the wire-to-mesh configuration over existing design configurations in a simulation-based study. This configuration minimizes the interference of neighboring airflows together with lower blockage of the air thereby decreasing the recirculation of moist air in the drying environment. The unique aerodynamic impact of the grounded mesh collector on the drying rate of wet tissue was recently demonstrated by [25]. This configuration uniformly dries products on all surfaces with an increased drying rate. However, some hurdles are still present when upscaling this electrode configuration, as discussed below.

## 5.2 Upscaling the EHD dryer using the wire-to-mesh configuration

For effective upscaling of the EHD drying method, a configuration that is energy and cost-efficient, and will produce dried fruits and vegetables of optimum quality is needed [30]. From the analysis of the different EHD dryer configurations (Table 2), there is no known experimental study on EHD drying of fruits and vegetables using the wire-to-mesh configuration. This gap in information poses a barrier that must be overcome prior to the industrial implementation of the wire-to-mesh configuration.

To further develop the wire-to-mesh configuration for industrial upscaling, it is crucial to first demonstrate its scalability. This can be achieved by quantifying the impact of various processing variables on the drying kinetics, product quality, energy and cost-efficiency. These processing variables include the gaps between wire electrodes, geometry and size of electrode, product spacing, mesh size and spacing, sample thickness, and loading density. This information is important for process optimization and scaling of the EHD drying process. Particularly, the impact of the fruit loading density on the mesh is very important in optimizing the dryer. We cannot load the trays too densely probably as then airflow is restricted and the electrostatic field and ion flow can also be negatively affected. In addition, the mesh collector design (e.g., number of wires, the diameter of wires) plays a role in dryer optimization.

## 5.3 Energy consumption while upscaling

The EHD electrode configuration can affect the energy performance of the drying process. Since by changing the electrode configuration, the local electrostatic and ion flow conditions will change. Kudra & Martynenko [73] indicated the importance of energy consumption as a key criterion in upscaling the EHD drying process. The main question remains: will there be major changes in energy consumption during upscaling, if there is, to what extent? It has already been established that the energy consumption (in the form of specific energy consumption) during EHD drying of fruits and vegetables is lower than those of standard drying methods (Table 2). The specific energy consumption values for the EHD drying of fruits and vegetables with grounded plate electrodes are in the range of 0.12 kJ/g to 16.50 kJ/g (Table 2). These values are significantly lower than that of standard convective drying, which is in the range of 180 – 1800 kJ/g [74], [75]. The values for EHD were evaluated based on laboratory-scale EHD systems. However, these values may change depending on the total energy consumed by high-voltage AC/DC converters, and the capacity of the EHD dryer (loading density affects the drying time). It is foreseen that the energy efficiency of an industrial scale EHD dryer with the wire-to-mesh configuration will be higher as the production of the high voltage will be more efficient. This implies that the total energy consumption when drying a few fruit products is expected to be several times higher than that of a fully-loaded commercial EHD dryer. In any case, the energy consumption will depend on the interplay between different processing variables (Table 2) such as voltage, electrode distance, gap between electrodes, product spacing, amongst others.

# FUTURE TRENDS FOR EHD DRYING OF FRUITS AND VEGETABLES

## Perspective for nutritional content, sensory quality and upscaling

With a significant increase in the world population in the coming years [76], the demand for highly nutritious processed food will increase. This means that scientists and researchers will constantly be developing processes and technology to meet this demand. We anticipate that the novel EHD drying will become widespread in producing highly nutritious dried fruits and vegetables.

### 6.1.1 Open questions

Looking ahead, there are key questions that must be addressed before the enhancement of nutrients retention and sensory quality of EHD dried products can be achieved. In addition, these key questions must be answered for the successful upscaling of the EHD drying process for commercial purposes. These include:

* What is the impact of multiple EHD drying variables (e.g., voltage, electrode distance, product spacing) on the nutritional composition and sensory properties (e.g., vitamins, electrolytes, taste, flavor) of dried fruits and vegetables?
* What are the optimum processing variables to achieve the desired product quality and, at the same time, is energy efficient for EHD drying of multiple products using the wire-to-mesh configuration?

### 6.1.2 What are the opportunities for addressing these questions?

EHD drying experiments using the wire-to-mesh configuration should be conducted to simultaneously measure nutritional content (e.g., vitamin C, carotenoid) and sensory properties (e.g., color, hardness) of dried fruits and vegetables. Temperature, humidity, and weight loss data should also be measured during such drying experiments.

The development of a process from a laboratory scale to industrial scale is highly challenging. Several drying variables are dependent on the scale of the dryer; for example, the drying rate and critical drying time are strongly dependent on how much fruit is loaded in a dryer [77]. In this regard, computational modeling and optimization techniques are becoming useful tools in making decisions about industrial-scale dryers. To further develop and scale the EHD dryer with wire-to-mesh configuration into industrial systems, we need to access the effectiveness of loading the EHD dryer to full capacity over a wide range of operating conditions. This can be realized by modeling the EHD dryer with physics-based, finite element modeling methods. The scalability can then be quantified by showing the impact of fruit loading density on the performance (see section 3) of the EHD drying process.

## Perspective for small-scale farmers

Rural farmers are still highly dependent on traditional open sun drying. This drying method has inherent limitations, including a high reduction of nutrients because of prolonged drying time, and high product loss due to inadequate drying environment, insects, birds and rodent attacks, and variations in solar load [78]. Urban and semi-urban smallholders depend on solar dryers and convective fan-driven technology to dry food [79]–[81]. However, these drying methods are time-consuming and often result in dried products of low nutritional and sensory quality. As already shown in this paper, EHD drying can serve as a promising alternative to the currently used drying methods in rural and urban farms.

One of the expected hurdles towards the implementation of this technology for small-scale farmers is the issue of electric power supply for EHD drying. Most developing countries, especially in Sub-Sahara Africa, do not have a stable grid-connected electricity supply. Other commercial sources of energy are either unreliable or, for some farmers, too expensive. To overcome this setback, a solar-powered EHD dryer with a wire-to-mesh configuration can be employed. In other words, a standalone EHD dryer can be coupled to a solar photovoltaic (PV) system that can power the high voltage generator. This hybrid EHD drying system has a high potential for small-scale farmers because photovoltaic solar panels are easily and readily available, with government subsidies in most developing countries. Besides, a solar-powered EHD dryer with multiple needle-to-plate configurations has been shown to be highly energy efficient in the drying of kiwi fruit compared to a convective hot-air dryer [72].

With respect to cost, depending on the fruit loading density, the total cost for the EHD dryer is anticipated to be lower than that of a convective hot-air dryer. This is because the energy cost for the convective hot-air dryer is significantly higher (1730% increase in the energy used (kJ)) than that of EHD dryer [82]. However, the capital cost for EHD drying can be higher depending on the set-up components. This capital cost for EHD drying devices includes the cost of AC/DC high voltage converter, emitter electrodes, collector electrodes, and the drying chamber. The capital cost for a convective hot-air dryer includes the cost of the fan, heater, blower, and the drying chamber. A possible additional cost can come from the maintenance of the electrodes as they can attract dust.

Different solar dryers are used by urban farmers to dry fruits and vegetables. Depending on the fruit loading capacity of the dryer and the materials of construction, the total cost of producing these dryers are quite low. Typical examples are the indirect solar dryer (90kg-capacity) = $220.29US, mixed-mode solar dryer (90kg-capacity) = $151.79US, cabinet dryer (75kg-capacity) = $20US, and chamber dryer (200kg-capacity) = $64.10US [83], [84]. For a standalone solar PV dryer, the cost of a 200W rated dryer, including 5 PV modules, batteries, and controllers, is about $1,080US [85]. This is much higher than the cost of the aforementioned solar dryers. A solar-powered EHD dryer will have a higher capital cost due to the high voltage convertor and the electrodes. This added cost can be offset by the added product quality or the decrease in drying time, so increased throughput. The additional profit (e.g., the better nutritional quality of dried products) compared to hot-air and solar drying of fruits and vegetables, make that its potential should be further explored for small-scale farmers.

## Perspective for the industry

Upscaling of available laboratory-scale technology has posed a challenge when considering the introduction of new processes. The future state of developing EHD drying technology with the wire-to-mesh configuration or other configuration for the industry would demonstrate the scalability. Unfortunately, this has not been carried out.

A core requirement inherent to the production of highly nutritious dried products in commercial quantities is the effective monitoring of the drying process. Current technologies used in the food industry are generally autonomous and record key drying parameters such as temperature and relative humidity. For EHD drying, the electric current also needs to be monitored during the drying process.

Another problem for future implementation of the EHD drying technology in the industry is engineering ergonomics (industrial hygiene, safety and maintenance). Engineering ergonomics simply means man-machine interaction in an industry. Over time, the surface of the EHD dryer emitter and collector electrodes will be covered with dust or corroded. This can affect the performance of the EHD, so a periodic cleaning of electrodes is required. Drying is often a unit operation that leads to another unit operation in the food industry. In other words, dryers are installed in continuous lines with other processing equipment such as roaster, separator, destoner, grinder, etc. Due to the different operating requirements of these unit operations, implementing the EHD drying in this way may affect the drying rate of the products. Furthermore, the EHD dryer can cause a disturbance that affects electrostatic forces (electromagnetic interference) and audible noise. This can significantly affect the accuracy of sensor measurements. The installation of an EHD dryer in a typical food industry would involve grounding of the wire-to-mesh collector. This could also pose a problem if not adequately done. This is because grounded systems sometimes carry current flow, which can cause lightning strikes that can lead to severe accidents or injury. Therefore, the design of the EHD drying equipment area must be properly done from the beginning and must pass interference, emissions, and electrical safety tests.

# CONCLUSION

This study aims to help pave the way for the design of up-scaled EHD dryers that provide nutrient-dense and sensory appealing dried fruit and vegetables. We conclude the following:

* EHD drying improves the retention of vitamin C (~25%), carotene (~10%), polysaccharides (~24%), flavonoid (~18%), color, and enhanced the rehydration capacity and textural quality of dried fruits and vegetables.
* Nutritional and sensory quality of EHD dried fruits and vegetables are significantly affected by the applied voltage, electrode distance, and gaps between electrodes.
* Simultaneous measurements of different nutritional compositions and sensory properties of a certain fruit or vegetable are recommended for EHD drying. Here, the impact of EHD drying variables should be quantified, such as the applied voltage and the gaps between electrodes.
* The wire-to-mesh dryer configuration is the most suitable for upscaling the EHD drying process of fruits and vegetables and will likely also be more energy-efficient. The impact of the fruit loading density on the drying kinetics and energy consumption of this EHD wire-to-mesh dryer is still to be quantified.

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## AUTHOR'S CONTRIBUTING STATEMENT

**Daniel Onwude:** Conceptualization, Methodology, Project Administration, Investigation, Writing-Original draft, Review & Editing. **Kamran Iranshahi:** Review & Editing. **Alex Martynenko**: Review & Editing. **Thijs Defraeye:** Conceptualization, Methodology, Supervision, Project administration, Review & Editing.

## DECLARATION OF COMPETING INTEREST

The authors declare no conflict of interest.

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1. *Corresponding author:* [*thijs.defraeye@empa.ch*](mailto:thijs.defraeye@empa.ch) *(T.Defraeye) Empa, Swiss Federal Laboratories for Materials Science and Technology, Laboratory for Biomimetic Membranes and Textiles, Lerchenfeldstrasse 5, CH-9014 St. Gallen, Switzerland* [↑](#footnote-ref-1)