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

Daniel I. Onwude^{1,2} | Kamran Iranshahi^{1,3} | Alex Martynenko⁴ |
Thijs Defraeye^{1,4}

¹ Empa, Swiss Federal Laboratories for Materials Science and Technology, Laboratory for Biomimetic Membranes and Textiles, St. Gallen, Switzerland

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

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

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

Correspondence

Thijs Defraeye, Empa, Swiss Federal Laboratories for Materials Science and Technology, Laboratory for Biomimetic Membranes and Textiles, Lerchenfeldstrasse 5, CH-9014 St. Gallen, Switzerland.
Email: thijs.defraeye@empa.ch

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Abstract

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 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. Particular emphasis has been given to quantifying the residual nutritional and sensory properties of EHD dried products, and possible EHD dryer configurations for farmers and the industry. Concerning the nutritional content, EHD drying preserves vitamins, carotenes, and antioxidants significantly better than convective air drying. From the sensory perspective, EHD drying enhances the color of dried products, as well as their general appearance. With respect to scalability, 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 toward 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. Research comparing EHD drying with commercially available drying methods such as freeze-drying, microwave-drying, and infrared drying should also be carried out. This study gives promising insight toward developing a scalable novel thermal drying technology tailored to the requirements of the current and future society.

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KEYWORDS

convective drying, EHD drying, food quality, novel thermal drying, plant-based foods, scalability

1 | 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 (Amoasah et al., 2019; Nkumah, 2016), and are an important source of vitamins (A, E, C) (García-Martínez et al., 2013; Sablani, 2006), phenolic antioxidants, and dietary fibers (Chang et al., 2016). 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 (Correia et al., 2017; Scaglioni et al., 2017) 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 (Johansson et al., 2010; Melanson, 2008).

Standard convective drying methods (e.g., fan-driven air drying, dehumidifier, solar drying) are being used at an industrial scale to produce these dried fruits and vegetables (Belessiotis & Delyannis, 2011; Mujumdar, 2000; Mujumdar, 2007; Pirasteh et al., 2014; Wang, 2013). However, several of these drying methods lead to a significant loss of the aforementioned micronutrients and bioactive compounds due to a slow drying process or at elevated temperature (Mbondo et al., 2018; Moses et al., 2014). 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. However, such technologies come at a much higher energy and environmental cost and a higher product cost (Galanakis et al., 2015; Onwude et al., 2017). This drives researchers and engineers toward developing innovative and sustainable drying processes. The particular focus is on 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 heat-sensitive foods, such as fruits and vegetables (Singh et al., 2012; Defraeye & Martynenko, 2018). This novel 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 electrical discharge resulting in local ionization of the air at the emitter electrode due to its large curvature (Figure 1). The ionized air is drifted toward the collector electrode by the Coulomb force. The resulting elastic and/or non-elastic collisions of the positively ionized air with neutral air particles during the air movement generate a secondary airflow, so-called ionic wind (Figure 1). Due to this ionic wind, moisture is removed convectively from a product to be dried. This technology has numerous advantages over standard 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 when compared to hot-air and solar dryers at low or ambient temperatures (Precoppe et al., 2015; Bechoff et al., 2010; Pirnazari et al., 2014). Compared to fan-driven airflow under the same environmental conditions, drying is enhanced by enhanced convective heat and mass transfer by the ionic wind. Besides, an additional heat supply can speed up the drying mass transfer process inside the product. A further advantage is that the drying process is reported to have a lower energy consumption, so lower carbon emissions (Eseghaghbeygi et al., 2014; Taghian Dinani et al., 2014a; Yang & Ding, 2016). Other reported advantages regarding product quality include better retention of nutritional content, flavor, and color, as well as lower shrinkage and higher rehydration capacity (Bajgai et al., 2006; Defraeye & Martynenko, 2018; Elmizadeh et al., 2017; Eseghaghbeygi et al., 2014; Ni et al., 2019; Pirnazari et al., 2014).

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,

FIGURE 1 Schematic EHD drying mechanism showing electrical discharge and interactions between positively ionized air and neutral air particles (not to scale). Note that different colored labels correspond to the different processes/phenomena/dryer components (e.g., green-colored ball shape = neutral air particles)

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 (Lai, 2010; Tuan et al., 2014; Liang, 2000; Liang, 2002; Takamatsu, 2012). Large EHD dryers have been locally developed for medicinal herbs drying (Martynenko & Kudra, 2019). However, to the best of our knowledge, there is still no known industrial EHD dryer to produce 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 the 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 convective 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.

2 | EHD DRYING MECHANISM

EHD drying relies on airflow generation as a result of a high voltage difference between two electrodes (emitter

and collector electrodes), typically in the range of 10 to 40 kV (Singh et al., 2012) (Figure 1). The emitter is typically a set of metal wires with a diameter of several hundred micrometers or a needle with a tip radius of several hundred micrometers. The collector is a plate or metallic mesh on which the drying material is placed (Figure 1). The emitter is often connected to a positive DC high voltage power supply, while the collector is usually grounded. Due to the large curvature of the emitter (i.e., sharp edges), which results in a high local electric field strength, the air around the emitter is locally ionized. This ionized air, driven primarily by the Coulomb force, moves to the grounded collector electrode of opposite polarity in order to induce airflow, so-called ionic wind (Tadeusz Kudra & Martynenko, 2019; Saneewong Na Ayuttaya et al., 2012). The minimum voltage required for initial corona discharge highly depends on the geometrical characteristics of the discharge and collector electrodes (curvature, emitter-collector gap, the spacing between the emitters) and the ambient conditions (humidity, temperature). Very high voltage leads to an increase in electric field strength, thereby expanding the ionization region until it reaches the grounded collector electrode. This results in spark-over or air breakdown phenomena (Martynenko & Kudra, 2019).

When fruits are placed on a grounded collector electrode (voltage = 0 kV) above an emitter electrode (voltage ≥ 10 kV) (Figure 1), air flow is created by ions generated in the corona discharge near the sharp electrode that drifts to the ground. As a result, the momentum of airflow is enhanced and cross flow or primary flow is generated. This generated airflow, also called ionic wind, can induce airspeeds of $0.1\text{--}10\text{ m s}^{-1}$ (Alemrajabi et al., 2012; Martynenko et al.,

2017; Defraeye & Martynenko, 2018). This “ionic wind” coupled with other mass transfer mechanisms, driven by ion flow or an electrostatic field (Martynenko et al., 2020), 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. A too high voltage should be avoided as this may result in noisy corona discharge or a complete breakdown of the air (Defraeye & Martynenko, 2018).

3 | 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 (Bajgai et al., 2006; Dalvand et al., 2013; Ding et al., 2015; Elmizadeh et al., 2017; Esehaghbeygi et al., 2014; Fylladitakis et al., 2014; Pirnazari et al., 2016; Yang & Ding, 2016). These KPI's are defined below.

The drying rate (DR) is defined as the amount of moisture removed from a product per unit time (Berk, 2018):

$$DR = -\frac{dM_w}{M_d dt} = -\frac{dX}{dt} \text{ with } X = \frac{M_w}{M_d} \quad (1)$$

where M_w is the mass of water in the product (kg), M_d is the mass of dry matter (kg), t is the time (h), and X 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 (Defraeye & Martynenko, 2019). Critical moisture content is 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 (Defraeye & Martynenko, 2019).

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) (Singh & Kumar, 2013):

$$SEC = \frac{\text{Input power} \times \Delta t}{M_w} \quad (2)$$

FIGURE 2 Important performance indicators of the EHD drying process

where Δt 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 (mg/g dry weight), flavonoids (mg/100 g dry weight), polysaccharide (g/100 g dry weight) and polyphenols (mg/100 g dry weight) (Bualuang et al., 2017; Ni et al., 2019; Sarker et al., 2020; Zhao et al., 2014). 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 qualities 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) (Antonio-Gutiérrez et al., 2019; Sharma & Prasad, 2001; Tan et al., 2009).

The scalability is the ability to dry large amounts of foods with 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) (Kasper et al., 2014):

$$\text{Scalability} = \frac{M_d}{\text{drying time}} \quad (3)$$

The cost index (CI) 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) (Tippayawong et al., 2008):

$$C_I = \frac{C}{M_d} \quad (4)$$

where C 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) (Tippayawong et al., 2008):

$$\text{GHGE} = \frac{M_{\text{CO}_2\text{-eq}}}{M_d} \quad (5)$$

where $M_{\text{CO}_2\text{-eq}}$ is the mass of equivalent CO₂ (kg)

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

There has been an increasing demand for dried fruits and vegetables as healthy snacks in the food industry because of their health benefits (Dominick et al., 2018; Rana & Paul, 2017; Vukasović, 2016). 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.

4.1 | 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 (Slavin & Lloyd Beate, 2012). 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 (Codex Alimentarius Commission, 2017). 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 (Filippini et al., 2017). B-vitamins are important in converting food into energy (Titcomb & Tanumihardjo, 2019). Other micronutrients in fruits and vegetables, such as vitamins C and E, serve as powerful antioxidants to protect cells from cancer-causing agents (Kong & Chandel, 2020).

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 (Huang & Zhang, 2012). 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 (FAO/WHO Expert Consultation, 2005). 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 (FAO/WHO Expert Consultation, 2005). These nutritional deficits could be alleviated by enhancing the nutritional composition of processed food that, at the same time, satisfies 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 worldwide, 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 either due to temperature effect or slow drying process. Often, the destruction of these compounds is much larger than the differences in the final quality of products dried using different drying methods or processing parameters. 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.

4.2 | 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 discussed extensively (Jayaraman & Das Gupta, 2014). Hot-air, low-humidity air freezing, infrared 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 (Madhava Naidu et al., 2016; Asami et al., 2003; İncedayi et al., 2016; Izli et al., 2014). However, most of these drying methods (e.g., hot-air) still destroy a large part of the nutrients in dried fruits and vegetables due to elevated temperatures or slow drying process (Huang & Zhang, 2012).

EHD drying provides a good alternative to the currently used conventional drying methods for fruits and vegetables (Table 1). This novel drying technology has a unique drying mechanism (see section 2) that results in a low product temperature, coupled with high convective airflow, so

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	<p>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 = $21 \pm 1^\circ\text{C}$; MCI = 11.12–7.12 g/g db</p>	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.	(Martynenko & Zheng, 2016)
2	Apricot	Experimental	<p>Sample size = $9 \text{ mm} \times 9 \text{ mm} \times 9 \text{ mm}$; Voltage = 10, 20 kV; Gap between two wires = 5 cm and needles = 40 mm; Electrode distance = 30 mm; Hot-air temperature = 40°C; air velocity = 1.5–2.5 m/s; Ambient temperature = $25 \pm 0.1^\circ\text{C}$; RH = 44%; MCI = 4.81 db; MC2 = 0.1 db</p>	Color; Rehydration; Microstructure	There was no significant difference between the color change of EHD dried products and those dried using hot-air at 50°C ; Hot-air drying at 40°C resulted in better overall color compared with EHD dried products; Rehydration ratio of hot-air dried samples are higher than those dried by EHD; The microstructure of samples dried using EHD were better preserved than those dried using hot-air	(Polat & Izli, 2020)
3	Banana Slices	Experimental	<p>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 to 900 W; MCI = 2.75 to 3 g/g db; MC2 = 0.175 g/g db</p>	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	(Esehaghbeygi et al., 2014)

(Continues)

TABLE 1 (Continued)

S/N	Products	Study	Processing conditions	Evaluation attributes	Main Findings	References
4	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 = 1 m/s; OD = 50–70°C; HAD = 50 to 70°C; Slice thickness = 3 mm; Ambient temperature = 25°C; RH = 0.3 g/g; MC1 = 2.75 to 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	(Pirnazari et al., 2014)
5	Carrot slices	Experimental+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°C; RH = 30 ± 5%; MC = 90 ± 1%(wb)	Modelling using Lewis, Page, Henderson & Pabis, Logarithmic & Quadratic; Carotenes; Rehydration ratio	Page model was the best; $D_{eff} = 1.37 \times 10^{-8} \text{ m}^2/\text{s} - 2.86 \times 10^{-8} \text{ m}^2/\text{s}$ for 0–30 kV; EHD enhanced carotene contents (10% increment) compared with OD; Rehydration ratio of EHD also increased by 10% compared with OD	(Ding et al., 2015)
6	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; $d_e = 2, 2.5 \text{ \& } 3 \text{ cm}$; Electric field strength = 3.3 to 6.5 kV/cm; MC = 82% wb; RH = 24 ± 1–24.8%; HAD = 55°C (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	(Alemrajabi et al., 2012)
7	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 ± 1/100 g; Ambient Temperature = 25 ± 2°C; 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	(Yang & Ding, 2016)

(Continues)

TABLE 1 (Continued)

S/N	Products	Study	Processing conditions	Evaluation attributes	Main Findings	References
8	Chinese Wolfberry	Experimental	AC voltage = 0 to 48 kV; DC voltage = 18 to 54 kV; needle = 60 mmL, 1 mmD; Spacing between needles = 60 mm; electrode distance = 40 to 120 mm Oven drying = 55°C; Ambient Temperature = 25 ± 2°C; 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 0 kV electric field. EHD did not have a significant effect on the flavonoids content compared to oven drying	(Yang et al., 2017)
9	Chinese Wolfberry	Experimental	Needle = 20 mmL, 1 mmD; Sodium carbonate blanching = 10 minute; Voltage = 28 kV; Electrode distance = 100 mm; Needle spacing ₁ = 40 mm; Needle spacing ₂ = 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/100 g (6 cm spacing), control = 0.11 ± 0.006 g/100 g; The Polysaccharides contents ranged from 16.0 ± 0.03 (4 cm spacing) - 12.3 ± 0.02 g/100 g (10 cm spacing), control = 12.9 ± 0.03 g/100 g; 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	(Ni et al., 2019)

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TABLE 1 (Continued)

S/N	Products	Study	Processing conditions	Evaluation attributes	Main Findings	References
10	Mint leaves	Experimental	Electrode distance = 30 to 50 mm; Voltage = 13 to 16 kV; Oven temperature = 40° C; Ambient temperature = 25 ± 1° C; RH = 25%; MCI = 0.75 g/g	Color	EHD dried samples had better color compared to oven and natural convection drying	(Esehaghbeygi & Karimi, 2020)
11	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 to 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	(Taghian Dinani & Havet, 2015a)
12	Mushroom slices	Experimental	Voltage = 17, 19, & 21 kV; 6 wire (D = 0.3 mm, L = 6 cm); Spacing between wire = 5 cm; slice thickness = 3.1 mm; Slice diameter = 33.1 mm; Blanching = 2 min; electrode distance = 5.6 & 7 cm; Electric field strength = 2.43 to 4.2 kV/cm; Drying air temperature = 60° C; RH = 10%	Color and thermal properties	Color properties were significantly affected by combined EHD+HAD	(Taghian Dinani, Hamdami, Shahedi, Havet, et al., 2015a)

(Continues)

TABLE 1 (Continued)

S/N	Products	Study	Processing conditions	Evaluation attributes	Main Findings	References
13	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 & 7 cm; Electric field strength = 2.43 to 4.20 kV/cm; Drying air temperature = 60°C; 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	(Taghian Dinani, Hamdami, Shahedi, & Havet, 2015)
14	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°C; 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	(Yu et al., 2018)
15	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 to 70°C; Air velocity = 1 m/s; Ambient temperature = 70°C; 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	(Elmizadeh et al., 2017)

(Continues)

TABLE 1 (Continued)

S/N	Products	Study	Processing conditions	Evaluation attributes	Main Findings	References
16	Quince slices	Experimental	Slice thickness = 2 mm; Voltage = 5, 7, 9 kV; 32 needles (0.4 mm diameter); Spacing between two electrode = 2 cm; HAD = 50 to 70°C; Air velocity = 1 m/s; Ambient temperature = 25°C; RH = 10%; MCI = 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 to 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	(Elmizadeh et al., 2018)
17	Tomato slices	Experimental	Voltage: 6 to 10 kV; 4 needles (3 mm diameter each); Gap between electrode = 20 mm; d_e = 20 mm MCI = 94% wb MC2 = 11% wb	Color and Shrinkage	EHD dried tomato slices had better appearance than sun and oven dried samples	(Eseghaghbeygi & Basiry, 2011)

d_e = Distance between emitter and collector; MCI = Initial moisture content; MC2 = Final moisture content; db = Dry basis; wb = Wet basis; L = Length; D = Diameter; W = Width; R.H = Relative humidity; AC = Alternating current; DC = Direct current; WAC = Water absorption capacity; OD = Oven drying; AAD = Ambient air drying; MWD = Microwave drying; HAD = Hot-air drying.

FIGURE 3 A typical representation of the impact of EHD drying process on the quality of fruits and vegetables

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 convective air drying.

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

4.3.1 | Nutritional composition

Table 1 summarizes 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) (Ding et al., 2015; Yang & Ding, 2016; Yang et al., 2017; Ni et al., 2019; Elmizadeh et al., 2017). 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 (Ding et al., 2015; Yang & Ding, 2016; Yang et al., 2017; Ni et al., 2019; Elmizadeh et al., 2017). Studies compared with other high-end standard industrial drying methods, including freeze-drying, dehumidifier, and vacuum drying, are unknown. 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 (Table 1). Polysaccharides in Chinese wolfberry were better retained by about 48% with EHD drying compared to

oven drying (Table 1). The retention of vitamin C (25%) and flavonoid (18%) in the Chinese wolfberry were also enhanced by EHD drying compared to ambient air drying (Table 1). Figure 3 shows a typical framework of the impact of EHD drying on the nutritional composition and sensory quality of dried 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 the extent to which 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. Also, more insight into the extent EHD drying and standard convective air drying reduces the residual nutrients of dried fruits and vegetables, compared to fresh produce is required. In any case, it is worthy to note that the changes in the nutritional content of dried products due to changes in process parameters or drying methods do not out-weight the loss in the nutrient as a result of the drying process.

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 (Martynenko & Zheng, 2016), banana (Esehaghbeygi et al., 2014; Pirnazari et al., 2014), carrot (Alemrajabi et al., 2012), and tomato slices (Esehaghbeygi & Basiry, 2011) 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 air-drying methods (Esehaghbeygi & Basiry, 2011; Elmizadeh et al., 2018; Yu et al., 2018; Taghian Dinani et al., 2015; Taghian Dinani & Havet, 2015a; Ni et al., 2019; Yang & Ding, 2016; Alemrajabi et al., 2012; Pirnazari et al., 2014; Esehaghbeygi et al., 2014). Researchers also explored the use of EHD drying combined 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 (Taghian Dinani, Hamdami, et al., 2014). 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.

5 | 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.

5.1 | 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.

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 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 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 (Defraeye & Martynenko, 2018). It is difficult to achieve a uniform drying rate for multiple food products using these plate collector configurations (Defraeye & Martynenko, 2019). When drying with a single wire, the EHD generated air-jets moves

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% wbMC2 = 11% wb	Voltage: 4 to 10 kV; 4 needles (3 mm diameter each); Gap between electrode = 20 mm; $d_e = 20$ 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)	(Eseghbeygi & Basiry, 2011)
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; $d_e = 2, 2.5$ & 3 cm; Electric field strength = 3.3 to 6.5 kV/cm; R.H = 24 $\pm$ 1 to 24.8%; HAD = 55°C (RH = 25 $\pm$ 1%)	Increased electrode distance (d_e) increased the inception voltage; Energy consumption of EHD lower than HAD & AA; EHD dried carrot slices have better quality compared to others	(Alemrajabi et al., 2012)
3	Multiple needles-to-plate	Experimental (Kiwi fruit) Sample thickness = 2 mmMC = 84% wb	1–17 needles (0.1 mm diameter); Voltage = 6, 10.5, & 15 kV; Field strength = 4.5 kV/cm; $d_e = 0$ –8 cm; Ambient conditions = 24°C & RH = 20.8%	Voltage had a significant effect on the drying rate of kiwi fruit; Drying decreased with increased needle numbers	(Dalvand et al., 2013)
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°C & 20.8 RH; Voltage = 6, 10.5 & 15 kV $d_e = 0$ to 8 cm; air velocity = 0.0 to 0.4 m/s; RSM = 4 factors & 3 coded levels (-1,0 & 1) BBD	Kiwi Fruit MR Estimation: $MR^{0.67} = 0.8823 + 0.0266V - 0.1377E + 0.0107U + 0.0041N - 0.0020V^2 + 0.0133E^2$ For Energy Efficiency: $\eta^{0.5} = 3.47 - 0.317V - 0.072E + 0.001N + 0.007V^2 + 0.028VE + 0.004VN + 0.025EN$ Energy Consumption (EC): $\log_{10}EC = 2.145 + 0.132V - 1.123E + 0.451U - 0.037N + 0.03V^2 + 0.116E^2 + 0.001N^2$	(Dalvand et al., 2014a)

(Continues)

TABLE 2 (Continued)

S/N	Design Configuration	Study (product)	Operating Parameters	Impact	References
5	Multiple needles-to-plate	Experimental (Banana slices) Slice thickness = 3 mm MC1 = 2.75 to 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 to 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.	(Esehaghbeygi et al., 2014)
6	Multiple needles-to-plate	Experimental (Banana slices) Slice thickness = 3 mm MC1 = 2.75 to 3 g/g; MC2 = 0.175 g/g	Electric field = 4.5, 6.5 & 8.5 kV/cm; 25 needles (2.5 mm diameter); Gap between electrodes = 34.6 mm; d_e = 20 mm; Air velocity = 1 m/s; Oven = 50 to 70°C; HAD = 50 to 70°C; Ambient temperature = 25°C; 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 to 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.	(Pirnazari et al., 2014)
7	Multiple needles-to-plate	Experimental + Empirical Modelling (Carrot slices) Slice thickness = 1 mm mmMC = 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°C; RH = 30 ± 5%	Increased voltage resulted in increased drying rates; From 0.47–2.33 times at 5–30 kV compared to control (3.3–26.7% decrease in drying time); Page model was the best; D_{eff} = 1.37×10^{-8} m ² /s – 2.86×10^{-8} m ² /s for 0–30 kV;	(Ding et al., 2015)
8	Multiple needles-to-plate	Experimental (Chinese wolfberry)	Needle = 20 mmL, 1 mmD; Sodium carbonate blanching = 10 minute; Voltage = 28 kV; d_e = 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	(Ni et al., 2019)

(Continues)

TABLE 2 (Continued)

S/N	Design Configuration	Study (product)	Operating Parameters	Impact	References
9	Multiple needles-to-plate	Experimental (Mushroom slices)	Drying air temperature = 20°C; 70% RH 1 m/s; Gap spacing: 3.0 to 3.5; Voltage DC = 12,14,15,16,18, 22; (stainless steel, 143 with 1 cm spacing and 42 with 2 cm spacing, r = 0.675 mm)	For mushroom slices, the drying rate decreased with the increase of needle density; EHD drying rate increased with an increase in electric field strength from 4 to 5.33 kV/cm at the same electrode gap; Effective moisture diffusivity increased with an increase in electric field strength at the same gap.	Martynenko et al. (2019a)
10	Multiple needles-to-plate	Experimental + Empirical Modelling (Chinese wolfberry) MC1 = 69 ± 1% MC2 = 17 ± 1/100 g	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; Ambient Temperature = 25 ± 2°C; 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.	(Yang & Ding, 2016)
11	Multiple needles-to-plate	Experimental + Empirical Modelling (Banana slices) Slice thickness = 3 mm MC1 = 2.75 to 3 g/g dbMC2 = 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; d _e = 20 mm; Ambient Temperature = 25°C; 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; $h_m = 3.08 \times 10^{-7} - 5.65 \times 10^{-7} m/s$ for 6–10 kV/cm; $D_{eff} = 3.12 \times 10^{-10} - 4.23 \times 10^{-10} m^2/s$ for 6–10 kV/cm Diffusion model constant equation: $a = -0.0005E^2 + 0.017E - 0.00477b = 0.0001E^2 - 0.0029E + 0.0807k = 0.0002E^2 - 0.0027E + 0.1101$	(Pirmazari et al., 2016)

(Continues)

TABLE 2 (Continued)

S/N	Design Configuration	Study (product)	Operating Parameters	Impact	References
12	Multiple needles-to-plate	Experimental (Apple slices) Slice thickness = 8 ± 0.5 mm MC1 = 11.12 to 7.12 g/g db	d_e = 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°C	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	(Martynenko & Zheng, 2016)
13	Multiple needles-to-plate	Experimental (Quince slices) Slice thickness = 2 mm MC1 = 3.5 to 3.7 g/g	Voltage = 5.7, 9 kV; 32 needles (0.4 mm diameter); Spacing between two electrode = 2 cm; HAD = 50 to 70°C; Air velocity = 1 m/s; Ambient temperature = 70°C;	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	(Elmizadeh et al., 2017)
14	Multiple needles-to-plate	Experimental (Quince slices) Slice thickness = 2 mm MC1 = 3.7 g/g	Voltage = 5, 7, 9 kV; 32 needles (0.4 mm diameter); Spacing between two electrode = 2 cm; HAD = 50 to 70°C; Air velocity = 1 m/s; Ambient temperature = 25°C; 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 to 7 kV; Sample dried using HAD resulted in higher shrinkage and color quality compared with EHD;	(Elmizadeh et al., 2018)

(Continues)

TABLE 2 (Continued)

S/N	Design Configuration	Study (product)	Operating Parameters	Impact	References
15	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; d_e = 6 cm; Blanching = 5 min; Voltage = 18, 20, 22 kV; Ambient temperature = $25 \pm 2^\circ\text{C}$; RH = $30 \pm 5\%$	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)	(Yu et al., 2018)
16	Multiple needles-to-plate	Experimental (Mint leaves)	Electrode distance = 30 to 50 mm; Voltage = 13 to 16 kV; Oven temperature = 40°C ; Ambient temperature = $25 \pm 1^\circ\text{C}$; RH = 25%; MC1 = 0.75 g/g	The optimum drying condition was 16 kV and 50 mm electrode distance; Compared to oven drying, the energy consumption during EHD drying was ~13 times lower	(Esehaghbeygi & Karimi, 2020)
17	Single wire-to-plate	Experimental (Mango slices) Slice thickness = 5 mm MC1 = 83 to 86% wb MC2 = 50% wb	Blanching = 10 min; Air velocity = 0.3 m/s (EHD), 0.3–3.0 m/s (forced convection); 1 electrode; d_e = 4 cm and 7 cm; 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 10 kV and 4 cm which is also applicable to exergy efficiency and exergy per unit area	(Bardy et al., 2016)

(Continues)

TABLE 2 (Continued)

S/N	Design Configuration	Study (product)	Operating Parameters	Impact	References
18	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°C; Relative Humidity = 30% d_e = 10 to 80 mm; Voltage = 12 to 40 kV; Wire radius = 0.05 to 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 the voltage 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	(Thijs Defraeye & Martynenko, 2018a)

(Continues)

TABLE 2 (Continued)

S/N	Design Configuration	Study (product)	Operating Parameters	Impact	References
19	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°C; Relative Humidity = 30% d_e = 20 mm; Voltage = 20 kV; Wire radius = 0.25 mm	For the first case: Differences in drying times of 24% ($\approx$ 6 h) between the fastest and slowest drying apple slice were found (for w_p = 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 (w_p) 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.	(Thijs Defraeye & Martynenko, 2019)
20	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 = 5 cm; blanching = 2 min; d_e = 5, 6 & 7 cm; Electric field strength = 2.4 to 4.2 kV/cm; Ambient temperature = 60°C; 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	(Taghian Dinani, Hamdami, Shahedi, & Havet, 2015)

(Continues)

TABLE 2 (Continued)

S/N	Design Configuration	Study (product)	Operating Parameters	Impact	References
21	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, 21 kV; d_e = 5, 6, & 7 cm; Electric field strength = 2.4 to 4.2 kV/cm; Ambient Temperature = 60°C; 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: $a = 0.932 - 0.023G + 0.013V - 0.0017G^2 - 0.0007V^2 + 0.0023GV$ Tagnhian Dinani et al: $MR = \exp\left(\frac{-(t-b)^2}{c}\right)$ where $G =$ gap; $V =$ voltage	(Taghian Dinani, Hamdami, et al., 2014)
22	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; d_e = 6 cm; Electric field strength = 0 to 5 kV/cm	Drying rate at low velocity (0.4 m/s) increases as voltage increase; At 0.4 m/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 - 0.4 m/s had uniform honeycomb network	(Taghian Dinani & Havet, 2015a)
23	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; d_e = 6 cm; Electric field strength = 0 to 5 kV/cm	At 0.4 m/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 ionic 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)	(Taghian Dinani & Havet, 2015b)

(Continues)

TABLE 2 (Continued)

S/N	Design Configuration	Study (product)	Operating Parameters	Impact	References
24	Multiple needles-to-plate + Solar power	Experimental (Kiwi fruit) Slice thickness = 2 mm;	1–17 needles (0.1 mm diameter); Ambient condition = 24.0°C and 20.8 RH; Voltage = 6, 10.5 & 15 kV; d_e = 0 to 8 cm; air velocity = 0 to 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.	(Dalvand et al., 2014b)
25	Multiple wire-to-plate + HAD	Experimental (Mushroom slices) Slice thickness = 2 mm	6 wire electrodes; Wire spacing = 5 cm; Voltage = 17, 19 & 21 kV; d_e = 5, 6, & 7 cm; Constant Temperature = 60°C; R.H = 10%	For mushroom slices, a decrease in electrode gap and increased voltage resulted in decreased drying time; Increasing voltage increased D_{eff} ; Energy Consumption of EHD (0.118–0.492 kJ/g) was lower than HAD (238.63–286 kJ/g) alone.	(Taghian Dinani, Havet, et al., 2014)
26	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; d_e = 5, 6 & 7 cm; Electric field strength = 2.43 to 4.2 kV/cm; Ambient temperature = 60°C; 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	(Taghian Dinani, Hamdami, Shahedi, Havet, et al., 2015a)
27	Multiple wire or needles -to- plate + HAD	Experimental (Apricot) Slice thickness = 9 mm	Voltage = 10, 20 kV; Gap between two wires = 5 cm and needles = 40 mm; Electrode distance = 30 mm; Hot-air temperature = 40°C, 50°C; air velocity = 1.5 to 2.5 m/s; Ambient temperature = 25 ± 0.1°C; RH = 44%; MC1 = 4.81 db; MC2 = 0.1 db	Shorter drying time was observed compared with drying using EHD or hot-air alone; Combined EHD and hot-air drying resulted in better color, and rehydration capacity	(Polat & Izli, 2020)

d_e = Distance between emitter and collector; MC1 = Initial moisture content; MC2 = Final moisture content; D_{eff} = Effective moisture diffusivity; db = Dry basis; wp = Wet basis; L = Length; D = Diameter; W = Width; r = Radius; wp = Product spacing; CHTC = Convective heat transfer coefficient; R.H = Relative humidity; AC = Alternating current; OD = Oven drying; AAD = Ambient air drying; MWD = Microwave drying; HAD = Hot-air drying.

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)

toward 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, which 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 for 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 air flow around the products compared to the existing lab-scale design configurations (Figure 4d–e). Defraeye & Martynenko (2018) have recently predicted the suitability of the wire-to-mesh configuration over existing design con-

figurations 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 Martynenko et al. (2020). Iranshahi et al. (2020) further designed a high-energy efficient grounded mesh collector in-silico. 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, an energy and cost-efficient configuration that will produce dried fruits and vegetables of optimum quality is needed (Fylladitakis et al., 2014). 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. The impact of the fruit loading density on the mesh is particularly 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 | What are the general design considerations for a scalable EHD dryer?

In designing a scalable EHD dryer for fruits and vegetables, the following vital requirements should be taken into consideration:

1. The product, electrode geometry and properties, as well as the ambient conditions, should be satisfactory for an efficient drying process.
2. The use of space and material should be economical.
3. The emitter electrodes should have sharp edges, so large curvature.
4. A wire mesh collector should be used for a uniform and fast drying process.
5. The collector electrode should be grounded or connected to a negative voltage.
6. Emitter should be connected to a positive DC supply as it is more energy and drying throughput efficient than negative DC.
7. The emitter electrodes should be placed directly above a grounded mesh collector.
8. The voltage at the emitter electrode should be high enough to cause a corona discharge but not so high that it could result in noisy corona discharge or a complete breakdown of the air.
9. The gap between the emitter electrode and the collector electrode should be sufficient not to cause spark-over.
10. The dryer loading capacity should be high to be energy and drying rate efficient.
11. The dryer should be of sufficient rigid construction to withstand any mechanical distortion.
12. The material of construction should be non-corrosive and nontoxic.
13. The dryer should be easily assembled and disassembled.

It is worth mentioning this list is not exhaustive as EHD drying technology is novel. The development of an EHD dryer may also depend on the design experience of a pilot EHD dryer.

5.4 | 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 (2015) 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 can be lower than those of standard drying methods, depending on the drying conditions (Table 2). The specific energy consumption values for the EHD drying of fruits and vegetables with grounded plate electrodes range from 0.12 kJ/g to 16.50 kJ/g (Table 2). These values are comparable with that of the convective belt dryer (3.8 kJ/g to 4 kJ/g (T Kudra & Martynenko, 2015)) but significantly lower than that of standard hot-air drying (even at very low temperature (Motevali et al., 2011)), which is in the range of 180–1800 kJ/g (Onwude et al., 2018; Onwude et al., 2016). The energy consumption for a convective drying process is mainly used to generate airflow (e.g., fan-driven) and heat the convective air. However, the SEC of a fan strongly depends on the fan type, the airspeed and the turbulence level it generates (Defraeye & Martynenko, 2018). 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, which could depend on the number of emitter electrodes, applied voltage, electrode distance, ion mobility in air, space charge density, electric field strength and the capacity of the EHD dryer (loading density affects the drying time). 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. It is foreseen that the energy efficiency of an industrial scale EHD dryer with the wire-to-mesh configuration will be higher, as the distribution of the electric field and the ionic flow will be more efficient. 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.

5.5 | How about hybrid EHD dryers?

EHD is often seen as a passive technology for enhancing heat/mass transfer by altering the boundary layer

flow in limited configurations. Compared to commercial hot-air, vacuum, freeze and microwave dryers, EHD may not necessarily result in a shorter drying time even though it is more energy-efficient. This raises the question of whether an upscaled EHD dryer can be used in a fast industrial food drying process. To answer this question, researchers have recently suggested the combination of EHD with other commercial dryers to reduce energy cost, reduce drying time and potentially improve product quality for the standard drying process. Taghian Dinani & Havet (2015b) studied the hybrid EHD + hot air drying (HAD) of mushrooms and showed that at 0.4 m/s crossflow, water evaporation increased. The effect of increased voltage was negligible due to the suppression of ionic wind by airflow from the fan. An increase in velocity and reduction in voltage resulted in decreased specific energy consumption (SEC). Taghian Dinani et al. (2014) had earlier stated that the energy consumption of EHD + HAD was lower than HAD for mushroom slices. Taghian Dinani et al. (2015) demonstrated that EHD + HAD significantly increased the total color change of dried mushroom slices compared to drying using HAD. The effect of a hybrid EHD dryer on the nutritional quality of dried products has not been accessed yet.

Generally, there are lots of open questions regarding the quality of dried products and energy consumption during hybrid EHD + HAD drying of fruits and vegetables. One of the possible ways to overcome this conundrum is to apply EHD + HAD intermittently. This will imply the generation of ionic wind for a certain time (HAD = off), and then the application of HAD (EHD = off), thereby reducing the total energy requirement for a continuous EHD + HAD drying process. In this way, more uniform temperature distribution and redistribution could be achieved. This could also lead to an improvement in the quality of dried products. Nonetheless, we still need to rethink if it makes sense to combine EHD dryer with a traditional drying method to further improve drying efficiency.

6 | FUTURE TRENDS FOR EHD DRYING OF FRUITS AND VEGETABLES

6.1 | Perspective for nutritional content, sensory quality, and upscaling

With a significant increase in the world population in the coming years (Cilluffo & Ruiz, 2019), 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 nutrient 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 an industrial scale is highly challenging. Several drying variables depend on the dryer scale; for example, the drying rate and critical drying time are strongly dependent on how much fruit is loaded in a dryer (Cárcel et al., 2011). 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 assess 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.

6.2 | 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 (Ekechukwu, 1999). Urban and semi-urban smallholders depend on solar dryers and convective fan-driven technology to dry food (Chen, 2019; Krause et al., 2019; Singh & Gaur, 2020). 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 be a promising alternative to the currently used drying methods in rural and urban farms.

Compared to solar dryers used by smallholder farmers, EHD drying can retain the total phenolic content of fruits by up to 95% (Elmizadeh et al., 2017) compared to 40%–80% retention for fruits dried using solar dryers (Lakshmi et al., 2018; Mongi, 2013). EHD also reduced total color degradation of fruits and vegetables by up to 16% compared to fruits dried using solar driers. This comparison is based on individual studies as no known studies compare the nutritional and sensory properties of EHD dried fruits and vegetables with those of solar-dried products under the same environmental conditions.

Notwithstanding, one of the expected hurdles toward implementing EHD drying 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 was found to be highly energy-efficient in the drying of kiwi fruit compared to a convective air dryer (Dalvand et al., 2014b). However, for a solar-powered EHD dryer to be sustainable, it should be made to be operational all year round in places with insufficient sunlight or during the winter/wet season. One way to achieve this is to incorporate thermal storage materials such as biomass. That means an intermittent drying mode where EHD is powered by the solar PV system after receiving little sun-

light, while the biomass works when there is no sunlight. Another approach is to integrate a solar battery to extend the use of the energy generated by the PV system. In any case, the potential of a solar-powered EHD dryer still needs to be explored.

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 the EHD dryer (Martynenko & Zheng, 2016). 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 air chamber. The capital cost for a convective hot-air dryer includes the cost of the fan, heater, blower, and drying air chamber. A possible additional cost can come from the maintenance of the electrodes as they can attract dust.

Urban and rural farmers use different solar dryers 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 is quite low. Typical examples are the indirect solar dryer (90 kg-capacity) = \$220.29 US, mixed-mode solar dryer (90 kg-capacity) = \$151.79 US, cabinet dryer (75 kg-capacity) = \$20 US, and chamber dryer (200 kg-capacity) = \$64.10 US (Prakash et al., 2017; Selvanayagi & Sampathkumar, 2017). For a standalone solar PV dryer, the cost of a 200 W rated dryer, including 5 PV modules, batteries, and controllers, is about \$1,080 US (Ahsan et al., 2016). 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 fan-driven air and solar drying of fruits and vegetables makes that its potential should be further explored for small-scale farmers. It is worthy to note that other commercial dryers such as infrared and microwave may outperform a solar-powered EHD dryer due to lower capital cost and not so high energy cost. In any case, a tradeoff between capital cost, energy demand, product throughput, quality of dried product, and environmental impact is required in selecting an appropriate dryer for small-scale farmers. A more detailed study comparing EHD drying with traditional dryers (e.g., solar dryers, hot-air dryers, vacuum dryers, etc.) used by small-scale farmers based on these various performance indicators is required.

6.3 | 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 scalability. Unfortunately, this has not been carried out.

Nevertheless, we compare the drying efficiency of an upscaled EHD dryer based on 25% loading capacity with traditional air dryers. Loading an EHD dryer up to 25% capacity (Defraeye & Martynenko, 2019) dried food up to ~2 times faster compared to drying potatoes at the same loading density in a traditional air dryer (at 30°C drying air temperature) (Bon et al., 1997). Similarly, at a loading capacity of 25%, drying of fruits using an EHD dryer can dry up to 40% faster compared to drying using a solar tunnel dryer at ambient air conditions (Bechoff et al., 2010). This means that it is faster to load an EHD dryer densely with food and dry than drying the same amount of food in an industrial traditional air dryer. However, it is challenging to compare standard forced convective drying airflow field with EHD driven airflow. The reason is that a proper comparison should imply that the airflow rates are about the same.

A core requirement inherent in producing 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 and power also need 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, and grinder. 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.

7 | CONCLUSION

A scalable EHD dryer should be able to provide dried products of high nutritional density, with a low amount of energy and production cost. It should also have less impact on the environment compared to the available standard drying methods. In this review, we have described some pathways which put this exciting goal within our reach. This paper presented an overview of the current state and future perspectives of EHD drying of fruits and vegetables concerning nutritional and sensory quality, as well as its scalability. We also highlighted the research directions that are essential for improving the quality of dried fruits and vegetables and upscaling the EHD drying process, but are still underdeveloped. To help pave the way for the design of up-scaled EHD dryers that provide nutrient-dense and sensory appealing dried fruit and vegetables, this study concludes with 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 compared to standard convective drying methods.
- 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.
- It is also interesting to note that hybrid EHD drying of fruits and vegetables has received limited attention. Future studies should explore the development of hybrid

EHD dryers for the industry as well as small-scale farmers.

- Adequate data comparing the upscalable EHD dryer in terms of cost, energy demand, and quality of dried products with commercially available dryers such as freeze dryer, microwave dryer, vacuum dryer, and infrared dryer are required.

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AUTHOR CONTRIBUTIONS

Daniel I. Onwude: conceptualization; data curation; formal analysis; investigation; methodology; project administration; resources; supervision; validation; writing-original draft; writing-review and editing. **Kamran Iranshahi**: investigation; writing-review and editing. **Alex Martynenko**: investigation; supervision; writing-review and editing. **Thijs Defraeye**: conceptualization; investigation; methodology; project administration; supervision; writing-review and editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ORCID

Daniel I. Onwude <https://orcid.org/0000-0002-2690-5823>

Kamran Iranshahi <https://orcid.org/0000-0001-5567-8263>

Thijs Defraeye <https://orcid.org/0000-0002-9835-5859>

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