ELECTROHYDRODYNAMIC DRYING OF FRUITS: EFFECT OF MATERIAL PROPERTIES AND ENVIRONMENTAL CONDITIONS

by

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ABSTRACT

Electrohydrodynamic drying is a novel nonthermal drying technique with simple equipment design, low operational costs, and relatively low energy consumption. It is an energy-efficient alternative to the conventional hot air-drying method. This study investigated the effect of material properties and environmental conditions on the EHD drying of fruits. Considering Atlantic Canada's production volume and market demand, an experimental study was carried out using apples and strawberries. The effect of slice thickness, load density, external airflow, and relative humidity was evaluated through multifactorial experiments. The drying efficiency and quality of EHD dried apples were compared to hot air-dried ones. The experiments showed that the drying flux and effective diffusivity were independent of the thickness and the drying flux was significantly reduced at higher humidity. Further, the effective diffusivity increased with an increase in external airflow. The specific energy consumption increased with reducing load density and was significantly smaller than hot air drying. In addition, the impact of EHD drying conditions on the quality of apple slices was insignificant in the range of experimental design, but significantly better than in hot air drying. It can be concluded that EHD is effective for drying thin fruit slices due to the low energy consumption and superior quality.

LIST OF ABBREVIATIONS

AC	Alternating Current
CCD	Charge-Coupled Device
CIE	International Commission on Illumination
DC	Direct Current
DI	Disintegration Index
EHD	Electrohydrodynamic
KOH	Potassium hydroxide
MC	Moisture Content
MR	Moisture Ratio
MW	Microwave
Na_2CO_3	Sodium carbonate
NaOH	Sodium hydroxide
RGB	Red Green Blue
RH	Relative Humidity
RR	Rehydration Ratio
SEC	Specific Energy Consumption
TEC	Total Energy Consumption
TPA	Textural Profile Analysis
TPC	Total Polyphenolic Content
GAE	Gallic Acid Equivalent
A	Area (m^2)
D_{eff}	Effective moisture diffusivity (m^2/s)
DR	Drying rate (g/h or g/s)
I	Current (A)

k	Drying rate constant (h^{-1})
L	Thickness (mm or m)
$\dot{m}$	Drying flux (g/m^2s)
N_{EHD}	EHD number (m^2/s)
P	Power (W)
t	Time (s)
u	Air velocity (m/s)
u_e	Ionic wind velocity (m/s)
V	Voltage (kV)
V_f	Final volume (m^3)
V_i	Initial volume (m^3)
W	Weight (g)
X	Moisture content (kg/kg)
Z_p	Electrical conductivity disintegration index
σ	Electrical conductivity (S/m)

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CHAPTER 1 INTRODUCTION

Food processing and preservation techniques are of high demand in recent years to meet the needs of the growing population. Consumers want convenience and variety in their food habits with equal importance to health and nutrition. Fruit production and processing are one of the most important sectors in Canada's agri-food industry. Despite the short growing season, Canada produces a wide variety of fruits. Apples are the major fruits produced in Canada in terms of production volume, followed by cranberries, blueberries, grapes, and strawberries (Horticulture, 2020). The high production volume and demand make it essential for farmers to produce value-added fruit products. In addition, fruits are highly susceptible to mechanical damage and microbial spoilage due to their high water activity. According to FAO, 45-55% of all fruits produced worldwide are wasted along the supply chain before consumption (Porat et al., 2018). Fruit losses and seasonal availability emphasize the need for fruit processing and preservation, primarily for juices, concentrates, and frozen or dried solids (Kowalska et al., 2018). Traditionally fresh fruits and vegetables were preserved by drying in open sunlight, then expanded to industrial solar and hot air dryers. Unfortunately, solar drying is unsuitable in Canada because of the short summer and few sunny days.

Drying is one of the oldest and most extensively used food preservation methods. In food and agriculture processing industries, drying is essential to extend shelf life, enhance quality, and convenient handling of products. Almost every food product undergoes dehydration in a certain stage of processing (Sokhansanj & Jayas, 2015). The drying process usually involves both heat and mass transfer. Heat transfer can be through conduction, convection, or radiation, while mass transfer consists of removing moisture from the surface by evaporation and internal migration of moisture to the surface. This internal migration necessitates one or more mechanisms such as diffusion, capillary flow, or internal pressure due to shrinkage (Mujumdar, 2015).

The majority (85%) of existing food dryers are convective types, using hot (70-90 ºC) air as the drying medium. The use of low temperatures is pertinent for the drying of thermally unstable foods and other heat-sensitive products compared to sludge or minerals. Despite the low energy efficiency (15-20%), hot air dryers are still widely used because of their simple operation. In the food manufacturing industries, drying accounts for 7-20% of overall energy expenditure (Kudra, 2004; Strumillo et al., 2015). Moreover, most of the energy requirements for hot air drying are met by the combustion of fossil fuels. Industrial heat generation techniques pose a serious threat to the environment contributing to greenhouse gas emissions and subsequent global warming (Schnitzer et al., 2007). Furthermore, high temperatures in hot air drying cause undesirable physical changes and nutrient losses in dry foods (Zhang et al., 2017). Hot air drying (50-90 °C) adversely affects fruit microstructure and color due to the degradation of pigments and browning reactions (Lewicki & Duszczyk, 1998). Chemical changes like deterioration of vitamin and bioactive components have also been reported during thermal drying (Maisnam et al., 2017).

Considering the growing issues of inefficient energy use, non-renewable energy sources, and carbon emissions along with product quality, immediate actions should be taken for the industrial adaptation of sustainable drying technologies. Numerous distinctive or hybrid non-thermal drying techniques could be used to alleviate the drawbacks of thermal drying. Unfortunately, the high capital and operational costs hinder their applications to everyday products. For instance, freeze-drying is a promising technique to preserve the nutritional quality and retain the visual appearance of dry products. Yet, its industrial uses are limited to pharmaceuticals and high-value products due to its high equipment costs, time-demanding, and labor-intensive nature (Ratti, 2001). Another prevalent technique used for moisture removal in commercially dried foods is osmotic dehydration. It has the benefit of retaining product quality and enhancing the storage life. However, it can be expensive and time-consuming as it must be combined with other techniques to reduce the moisture content to a storable level (Yadav & Singh, 2014). In the last few decades, researchers have also focused on hybrid drying techniques, combining hot air drying with ultrasound, microwave, or electric technologies, to preserve food quality and conserve energy (Zhang et al., 2017).

Electrohydrodynamic drying is a new and promising non-thermal drying technique for heat-sensitive foods. Several advantages of this innovative approach have been identified in lab-scale research, including a higher drying rate, energy efficiency, better dry product quality, and low capital and operational costs (Paul & Martynenko, 2021). An industrial-scale prototype of an EHD dryer was found effective in drying carrot, potato, cabbage, and green pepper with better product quality compared to conventional hot air drying (Liang & Ding, 2006). Still, several challenges are yet to be addressed in industrially upscaling the EHD dryer.

CONNECTING STATEMENT

Based on the introduction, EHD drying could be a good alternative to conventional hot air-drying techniques because of the energy efficiency and significantly low energy consumption. The nonthermal nature of EHD drying makes it highly suitable for drying heat-sensitive materials like fruits. However, several factors affecting the drying efficiency and product quality in EHD drying, are underexplored. Therefore, focused analysis and optimization of these factors are essential for commercializing EHD drying.

Chapter 2 provides a detailed literature review on the mechanism of EHD drying along with the factors affecting the EHD drying technique. In addition, the drying efficiency and quality changes during EHD drying are reviewed with a particular focus on fruits.

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CHAPTER 2 LITERATURE REVIEW

2.1 ELECTRODYNAMIC DRYING

2.1.1 Mechanism of Drying

EHD drying utilizes a high voltage corona discharge from two asymmetric electrodes of varying radii of curvature (point to plate) placed at a short gap, resulting in ionization of air and subsequent "ionic" wind (Singh et al., 2012). A schematic diagram of EHD flow is shown in Figure 2.1.

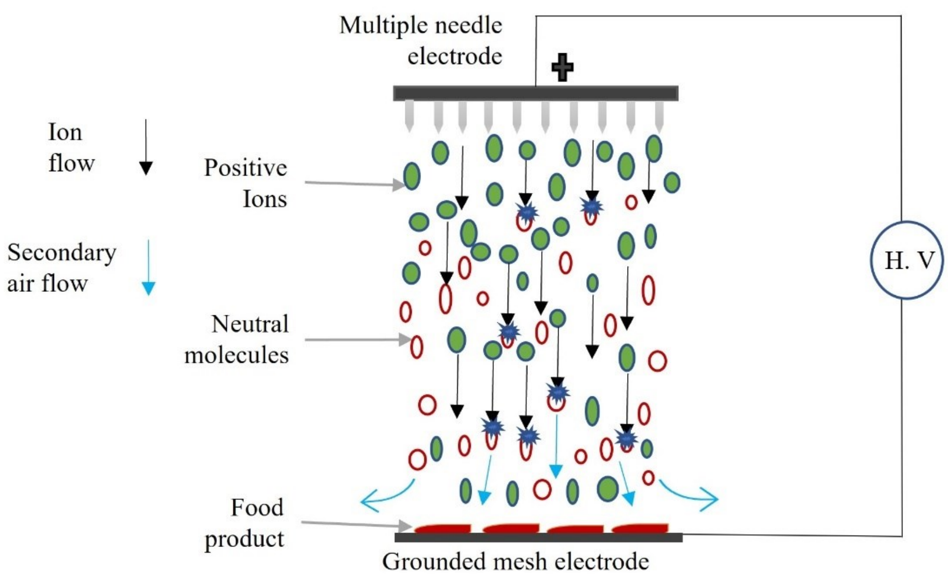


Figure 2.1: A schematic diagram of the EHD drying system

The strong non-uniform electric field drives the unipolar ions (negative/positive) from the discharge electrode to the collecting electrode resulting in primary ion flow. The secondary airflow is produced by the transfer of momentum from these high-velocity ions to the surrounding neutral air molecules by elastic and nonelastic collisions. The combined electric field-induced primary airflow and collision-induced secondary airflow are responsible for heat and mass transfer in EHD drying (Allen & Karayiannis, 1995; Bashkir et al., 2020).

According to Singh et al. (2012), the ionic wind continuously interrupts the saturated vapor boundary layer on the surface of food materials, accelerating water evaporation. The electric field and charge density contribute to the force required for moisture migration. The electric field could enhance moisture migration by the polarization of water molecules and changing the thermodynamic state of water at the surface of the material (Misra et al., 2018). The cell membrane acts as a dielectric material that maintains a potential difference. Under the influence of an external electric field, the charges accumulated on the inner and outer sides of the membrane create an internal electric field (Ni et al., 2020a). In a non-uniform electric field, water molecules are dragged from weaker to stronger fields (Liang & Ding, 2006). Furthermore, the orientation of water dipoles in the direction of the electric field lowers the entropy. These entropy changes and evaporative cooling are responsible for the low temperature of EHD dried materials (Hashinaga et al., 1999). A thorough analysis of the possible mechanisms of EHD drying by Iranshahi et al. (2021) confirmed that the convection of moisture due to the ionic wind is the most dominant mechanism (93% moisture removal) followed by membrane electroporation (6.73%).

The underlying mechanism and uniqueness of EHD drying lie in the simultaneous effect of the high electric field, cold plasma, and ionic wind on food materials to induce moisture removal (Liang & Ding, 2006; Misra et al., 2018). Cold or non-thermal plasma (CP) is an ionized gas composed of photons, ions, reactive species, and free electrons.

Intensive ionization of the air during EHD drying produces ions and reactive species creating a "low-density cold plasma" (Martynenko & Zheng, 2016). Interestingly, CP pre-treatments are reported to improve hot air drying kinetics in grapes (Ashtiani et al., 2020). It is important to note that a high electric field, being applied alone (without discharge), did not induce and even reduce moisture loss (Atungulu et al. 2005). Similarly, Misra et al. (2014) observed the suppressing effect of CP treatment on fruit respiration and moisture loss in cherry tomatoes. These results point to the significant impact of electric discharge and additional factors, such as the configuration of discharge electrodes, applied voltage, and drying conditions.

2.2 FACTORS AFFECTING EHD DRYING

2.2.1 Electrical parameters

EHD drying depends on various electrical parameters like the voltage, current, polarity, electric field strength, material, and geometrical properties of the electrode system (Kudra & Martynenko, 2019). The minimum voltage required for ionization is called the "inception voltage" (usually around 3 kV/cm), and the maximum voltage resulting in an arc discharge is known as the "breakdown voltage" (usually around 10 kV/cm) (Bashkir et al., 2020). The EHD drying occurs between these voltages, and the moisture evaporation rate increases linearly with the electric field strength. Yu et al. (2017) optimized 20 kV voltage and 4 cm electrode gap (electric field strength of 5 kV/cm) for EHD drying of potato slices based on drying rate, quality, and energy consumption.

Electric discharge can be induced by direct current (DC) or alternating current (AC) (Lai & Sharma, 2005). Even though a negative corona discharge (DC^-) was found to be more effective in moisture removal, AC power is preferable for industrial applications because of better energy efficiency (Bashkir et al., 2020; Martynenko & Kudra, 2021). Considering the geometry of the electrodes, multiple needles or wire electrodes, arranged with an optimum spacing between the emitter electrodes, are more suitable than single electrodes because of the coverage of a larger surface area (Bajgai & Hashinaga, 2001a; Martynenko & Kudra, 2020). Lai and Wong (2003) observed that a wire electrode is better than a needle electrode at voltages below 15 kV and the needle electrode has a slight advantage at higher voltages. Further, a mesh collecting electrode was more effective than plate collecting electrodes (Defraeye & Martynenko, 2019).

2.2.2 Material properties

There have been very few studies on the effect of material/sample properties on EHD drying. As with other drying techniques, the thickness of the product or the layer of particulate products is a significant factor in determining the drying rate. Ding et al. (2014) reported that geometrical characteristics such as thickness and cross-sectional area of beef slices significantly impact the drying rate during the first half-hour of the EHD treatment. It was also reported that the positive effect of EHD drying could be increased by reducing the sample thickness. Similarly, the EHD-induced drying rate decreased with the thickness of potato slabs (Chen et al., 1994). A detailed review of topical literature suggested that EHD drying is more effective for a thin layer of wet materials (Martynenko et al., 2021a). Material characteristics such as dielectric properties, texture and surface properties, diffusivity, microstructural porosity, and capillarity influence the efficiency of EHD drying (Anukiruthika et al., 2020).

The load/packing density of the material on the drying surface is another factor affecting the drying process. Onwude et al. (2021) studied the effect of fruit load density in the range of 3 to 70% on apple slices' drying time and specific energy consumption. The authors found that the drying time decreased with a high convective mass transfer coefficient at smaller load densities. However, the specific energy consumption (kJ/kg) was higher, exceeding the gain in drying time. Hence, it was suggested that drying a higher load of fruit slices in a single run is more efficient than drying the same amount of fruit in multiple runs.

2.2.3 Environmental conditions

Environmental conditions also significantly influence the drying process. The studies on the effect of conditions within the chamber and in the drying room on EHD-induced drying are scarce. The lowering of relative humidity (RH) from 70 to 30% enhanced the drying rate during EHD drying of white champignons (Martynenko et al., 2021a). Thus, the effect of EHD can be improved by decreasing air humidity. This effect could be attributed to the increased gradient of water partial pressure between material and air, which is the major driving force in drying. The moisture evaporation rate is mainly affected by the energy available at the material surface and the exchange of moisture to the atmosphere. Ambient air with a low vapor content/relative humidity could absorb more water from the material surface.

Additionally, the formation of ionic hydrates at higher RH decreases the mobility of charged particles in the air, reducing the drying efficiency. Another reason for poor drying efficiencies in the high humid atmosphere is the condensation of the evaporated water over the discharge electrode, affecting its emitting capacity (Anukiruthika et al., 2020). Rezaie et al. (2021) highlighted that the corona discharge is affected at high relative humidity. A more detailed investigation of the optimum humidity conditions is required for commercial applications of EHD drying.

Likewise, external airflow has a significant impact on EHD drying. A moderate external airflow enhanced the EHD-induced drying rate (Martynenko et al., 2021a). On the other hand, Zhong et al. (2019) observed that the external airflow above 0.2-0.3 m/s may decrease the drying flux in EHD drying. The possible reason explained was that the external airflow suppresses the positive effect of EHD-induced airflow by blowing ionic wind away from the material surface. Misra et al. (2018) stated that forced convection changes the mechanism of mass transfer in EHD drying. A suppression effect of airflow at higher velocities on the corona wind was also reported by Lai and Lai (2002) at an air velocity of 2.24 m/s. An external airflow at 1.0 m/s enhanced the EHD drying rate compared to airflow alone or a higher air velocity of 2.8 m/s (Lai & Sharma, 2005). A dimensionless EHD number (ratio of ionic wind velocity, u_e to air velocity, u, i.e., $N_{EHD} = u_e/u$) was introduced by Lai and Lai (2002) to quantify the interaction between external airflow and ionic wind velocity. The effect of EHD was significant only when this number was greater than 1. Considering the quality of the dried products, the convective airflow has been reported to mitigate the color degradation in EHD dried apple slices (Martynenko & Zheng, 2016).

2.2.4 Interaction between factors

The interaction between electrical parameters, material properties, and environmental conditions also affects the EHD drying rate. The effect of voltage, gap, electrode configuration, and air velocity on two different wet materials (tissue and sponge) was studied by Martynenko et al. (2017). The multifactorial experiment revealed voltage and airflow as the significant factors facilitating the mass transfer. A linear relationship between current and drying rate was also discovered in the range from 25 to 150 μA. Further investigations to explore the influence of non-controllable environmental factors like relative humidity and pressure, as well as material properties, are essential in the upscaling of the EHD drying technique.

2.3 EFFECT OF EHD ON FOOD DRYING

2.3.1 Drying kinetics

In a general drying curve, the point at which the drying kinetics change from constant to falling rate period is called the critical moisture content, and when the moisture content of the material reaches equilibrium with the surrounding air is called equilibrium moisture content (the end point of drying). The constant drying rate period corresponds to linear drying kinetics implying convection-limited drying and the falling drying rate period has exponential drying kinetics indicating diffusion-limited drying. The EHD drying has both constant and falling drying rate periods, or falling rate periods alone depending on the nature of the material to be dried (Martynenko & Kudra, 2016a). Liquids and gels mostly follow linear drying kinetics, whereas meat and seafood follow mostly exponential drying kinetics. Most fruits and vegetables have both constant and falling rate periods in EHD drying. This depends on the properties of drying air and the material being dried. Some major factors include air velocity, relative humidity, temperature, and the amount of free moisture available initially on the surface of the materials. It should be noted that the kinetics of EHD is similar to convective (hot-air) drying because of the presence of ionic wind (Kudra & Martynenko, 2015).

2.3.2 Effective diffusivity

Effective moisture diffusivity is a transport property, used in mechanistic models to describe the drying kinetics. It is a function of material moisture content and material structure. According to Fick's second law,

$$\frac{\partial X}{\partial t} = D_{eff}\nabla^2 X \text{.........................(2.1)}$$

D_{eff} (m^2/s) is the effective moisture diffusivity, X (kg/kg) is the moisture content on a dry basis, and t (s) is the time. This equation explains the moisture movement through a material during drying and the parameter effective moisture diffusivity accounts for all possible moisture diffusion mechanisms. When the thickness of the material is negligible compared to its length (infinite slab) and mass transfer occurs only from one side of the material, the D_{eff} value can be determined from the moisture ratio (MR) using the following equation:

$$MR = \frac{8}{\pi^2}\exp(\frac{-\pi^2 D_{eff} t}{4L^2}) \text{ ....(2.2)}$$

L (m) is the thickness of the material (Crank, 1979).

For food materials, the value of D_{eff} ranges mostly from 10^{-8} to 10^{-11} m^2/s (Marinos-Kouris & Maroulis, 2014). Various studies have investigated the influence of EHD drying on D_{eff} values. For instance, D_{eff} values increased with electric field strength for banana slices (Pirnazari et al., 2016) and applied voltage for mushroom slices (Dinani et al., 2014). The study by Dinani et al. (2014) revealed that the D_{eff} values in EHD-assisted hot air drying at 60 °C were 2.3 times higher than hot air drying alone. Ni et al. (2020a) reported that the chemical and ultrasound pre-treatments of goji berries before EHD drying significantly improved the D_{eff} values.

2.3.3 Specific energy consumption

EHD drying is known for its low energy consumption compared to other drying techniques. The ratio of energy used for moisture evaporation to the energy supplied to the dryer is defined as the efficiency of a dryer. However, it may vary depending on the total energy consumption, which includes the energy consumed by the power supply and auxiliary equipment. Hence, the specific energy consumption is a more accurate measure of the efficiency of the dryer (Kudra & Martynenko, 2015). It is the amount of energy required to evaporate a unit mass of water and is expressed in kJ/kg. An overview of energy consumption during EHD drying in comparison with other common drying techniques is given in Table 2.1. It can be observed that the energy consumption in EHD is very low compared to hot air drying because of the low electric power requirements.

Table 2.1: Comparison of energy consumption of EHD with other drying techniques

Product	**Equipment**	**Energy**	**References**
Spinach	Convective hot air and ambient air drying	EHD consumes less energy compared to other hot air-drying	(Bajgai et al., 2006)
Tomato slices	Oven drying and ambient air drying	Oven drying consumed energy about 200 times more than EHD.	(Esehaghbeygi & Basiry, 2011)
Carrot	Ambient air, EHD+, EHD-, and oven-drying	EHD+ (1300 kJ/kg) had smaller energy consumption followed by EHD- (2500 kJ/kg) which was very lesser than oven drying (17 MJ/kg)	(Alemrajabi et al., 2012)

Product	Equipment	Energy	References
Sea cucumber	Oven drying and ambient air drying	EHD consumed electric energy of 4386 kJ to remove 1 kg of water, whereas oven drying requires 20,582 kJ. 21.31% of the electrical energy required for oven drying.	(Bai et al., 2013)
Banana slices	Microwave (MW) drying	Mean values of energy consumption were 340 and 9660 kJ/kg for EHD and MW drying, i.e., MW drying required 28-fold higher energy	(Esehaghbeygi et al., 2014)
Kiwi slices	Oven drying and ambient air drying	Specific energy consumption was from 2450 to 2900 kJ/kg for electric field intensity of 3 to 5 kV/cm, whereas oven drying at 60 ℃ took 470000 kJ/kg.	(Rezaee et al., 2020)
White champignons	Forced air	Energy efficiency in EHD ranged from 3800 to 5400 kJ/kg while thermal drying required 266000 kJ/kg. Energy requirement increased with diffusive drying.	(Martynenko et al., 2021a)

2.4 Effect of EHD drying on food quality

2.4.1 Color

The color of food interacts with sensory properties, influencing consumers' perception of food quality (Francis, 1995). It is determined by pigments like flavonoids, carotenoids, and chlorophyll in plant-based food products (Shoji, 2007), and muscle pigments like myoglobin in meat and poultry products (Hari et al., 1994). Almost all conventional drying techniques affect the color due to the thermal degradation of these pigments. Non-enzymatic and enzymatic browning reactions are also responsible for the color changes (Lewicki & Duszczyk, 1998). The ions and free radicals are known to accelerate color degradation (Misra, 2016). The color of foods is usually estimated in CIELAB or RGB color space by using a basic colorimeter or computer vision system. The computer vision system is preferable due to its ability to measure color at random points or the distribution over the entire surface (Martynenko, 2017).

In EHD drying, the color of the food is the most investigated quality indicator. Researchers consistently report better retention of color in EHD drying compared to oven / hot air drying (Alemrajabi et al., 2012; Bai et al., 2013; Bajgai & Hashinaga, 2001a; Esehaghbeygi et al., 2014; Martynenko & Kudra, 2016b). In most cases, EHD drying had little effect on the color of dried foods; however, some researchers found an increase in color intensity. For instance, Bajgai and Hashinaga (2001a) found that EHD-dried spinach had a higher chlorophyll content. Similarly, Alemrajabi et al. (2012) observed that EHD-dried carrot slices had a vivid red color linked to the release of carotenoid pigments. Moreover, EHD-dried carrot slices had a higher "a" value than oven-dried samples and were similar to fresh samples. On the other hand, Dinani et al. (2015) reported that combined hot air-EHD drying at 60 °C resulted in the color loss of mushroom slices. However, it should be noted that when mushroom slices were dried in hot air at 50–70°C, a similar color degradation was observed (Kotwaliwale et al., 2007). It could be concluded that in combined hot air-EHD drying, the most important element impacting mushroom color is not EHD but rather a relatively high temperature, but this hypothesis requires further experimental verification.

On the other hand, highly reactive ions produced during EHD could have a direct impact on food color. For example, Li et al. (2006) observed a brown discoloration in okara cake just beneath the needle electrode, which they attributed to increased ionization. In another study, browning was observed in EHD-dried apple slices when exposed to a high electric field of 6 to 7.5 kV/cm and stagnant air conditions (Martynenko & Zheng, 2016). It can be concluded that airflow parameters such as ionization and convection can substantially impact food color during EHD drying.

2.4.2 Texture

The texture is another significant aspect of food quality. The food texture depends on its mechanical and microstructural qualities, as well as the drying technique (Martynenko & Janaszek, 2014). The heat/mass transfer and final quality of the dry product are determined by the initial texture (Chen & Opara, 2013). The texture of foods is typically assessed by sensory panels, or instrumental approaches (Bourne, 2002). Conventional hot air drying harms product texture because of non-uniform shrinkage, glass transition, and case hardening (Gulati & Datta, 2015).

EHD drying did not result in case hardening or crust formation due to more uniform volumetric shrinkage (Singh et al., 2012) and non-thermal nature. Only a few investigations on EHD drying have concentrated on the textural aspects of the dry product. Bai et al. (2013) found that EHD dried sea cucumber samples had reduced hardness and better chewiness upon rehydration compared to ambient and oven-dried samples. A study on the combined EHD-hot air drying (45°C) found that air velocity significantly impacted texture formation in mushroom slices (Dinani et al., 2015). In another study on combined EHD-hot air drying (70 °C) of quince slices, Elmizadeh et al. (2018) observed that increasing voltage from 5 to 7 kV slightly increased shear strength, which then reduced with a further rise from 7 to 9 kV. An increasing trend was observed in the hardness value of cooked rice in EHD dried rough rice/paddy, while the stickiness and adhesiveness were decreasing (Tirawanichakul et al., 2009). On the other hand, Thirumdas et al. (2016) reported a decrease in hardness and increase in adhesiveness for cooked rice samples upon plasma treatment. Unfortunately, these data could not be fairly interpreted without EHD drying experiments under ambient air conditions (free convection) as the control. Furthermore, the effect of EHD drying on textural qualities may differ from one product to another. Due to the scarcity of research in this field, it is critical to investigate the various effects of EHD drying on the textural characteristics of dried foods, which are linked to other quality aspects.

2.4.3 Shrinkage

When moisture is removed from high moisture foods, the cellular structure collapses, initiating shrinkage (Chen et al., 1994). At high temperatures, moisture migrates irregularly from the inside of the dried material to the outside environment. This results in microstructural stresses in the material and bending of the sides to the center. This stress is induced by temperature and moisture gradients. Porosity, microstructure, water absorption, texture, and organoleptic properties of food are all affected by shrinkage. Moreover, the rehydration ability is affected due to surface cracking at high shrinkage and crust formation (Mahiuddin et al., 2018). While some researchers reported that EHD drying does not affect food shrinkage (Ni et al., 2019; Yang & Ding, 2016), others report smaller shrinkage in EHD drying compared to oven-dried foods (Alemrajabi et al., 2012; Bai et al., 2013; Bai & Sun, 2011; Bajgai & Hashinaga, 2001b; Elmizadeh et al., 2018; Esehaghbeygi & Basiry, 2011). It should be noted that food materials exposed to EHD drying have a more uniform moisture distribution, resulting in smaller microstructural stresses and lesser shrinkage.

Alemrajabi et al. (2012) reported shrinkage of carrot slices as 63.16% for EHD^+, 65.04% for EHD^-, and 80.09% for oven-dried samples compared to 18.04% for ambient air drying. These results suggest that the shrinkage caused by EHD is considerably smaller than oven drying but higher than ambient air drying. Likewise, EHD drying of banana slices resulted in less shrinkage when compared to microwave drying (Esehaghbeygi et al., 2014). However, when compared to vacuum freeze-drying, EHD drying of sea cucumber resulted in stronger shrinkage (Bai et al., 2012b). The shrinkage of tomato slices dried by EHD increased in a small proportion to the increase in voltage and time (Esehaghbeygi & Basiry, 2011). It is in agreement with a study by Hashinaga et al. (1999), where the shrinkage of apple slices increased linearly with drying time. According to the authors, the increased intensity of EHD drying directly under the electrode induces more shrinkage, which deforms the surface and prevents moisture transfer. Higher drying rates, according to Tamarit-Pino et al. (2020), results in a more porous structure. Ni et al. (2020b) found that shrinkage changes as a function of food moisture ratio during EHD-hot air drying of Chinese wolfberry. When compared to oven-dried samples, Bai et al. (2012a) found that EHD drying resulted in a larger initial shrinkage rate but a reduced final shrinkage of scallops. This is due to rapid moisture removal during the initial stages of EHD drying when surface moisture is abundant. In EHD drying, the drying parameters can be optimized to reduce non-uniform shrinkage.

2.4.3 Rehydration properties

Rehydration is a complex process of reconstitution of dried foods with water or other liquids. It is considered a representative index of the damage caused by the drying (Lewicki & Duszczyk, 1998; Marabi & Saguy, 2004). Rehydration ratio is the ratio of water absorbed by the dried food to the dry sample weight. Rehydration rate refers to the kinetics of rehydration or the slope of a graph plotted with the rehydration ratio against rehydration time (Bajgai & Hashinaga, 2001b; Berk, 2009). The rehydration properties mostly depend on the microstructural characteristics of food, such as shrinkage, porosity, and structural dislocation. The temperature, pH, and composition of the soaking liquid also play an important role. Due to the non-reversible cellular breakage and dislocation during drying, the hydrophilic properties and water absorption capacity decrease, and the dry product often does not regain its original moisture content after rehydration (Ngamwonglumlert & Devahastin, 2017). The porosity of dried foods has a significant impact on their ability to rehydrate and absorb moisture (Saguy et al., 2005). The EHD-dried foods had better water absorption capacity than oven-dried samples because of higher porosity (Bai et al., 2013, 2008; Bajgai & Hashinaga, 2001b).

Several papers reported a positive effect of EHD drying on the rehydration ability of food products (Bai et al., 2013; Bajgai & Hashinaga, 2001b; Dinani, Hamdami, Shahedi, & Havet, 2015; Ni, Ding, Zhang, Song, Hu, et al., 2020; Yang & Ding, 2016). For example, Bai and Sun (2011) observed better rehydration in EHD dried shrimps than in oven-dried samples. Ni et al., (2019) found that increasing the spacing between needles in the discharge electrode resulted in a considerable decrease in the rehydration ratio, which they attributed to reduced exposure to the ionic wind during EHD drying. Furthermore, chemical or ultrasound pre-treatments before EHD drying enhanced the goji berry rehydration ratio (Ni et al., 2020a). Combining EHD with hot air drying could enhance the rehydration ratio even more (Polat & Izli, 2020). It is possible to conclude that EHD drying improves the rehydration ratio of food products, particularly when compared to thermal drying approaches. The high rehydration ratio indicates that EHD had little impact on the internal structure and quality of dried foods (Ni et al., 2019). The loss of solids during rehydration necessitates special attention. Soluble components from the dried foods may leach off into the rehydrating solution (Lewicki & Duszczyk, 1998). It is an indicator of the deterioration of dry products. Bajgai and Hashinaga (2001b) found that the solid loss was considerably smaller for EHD-dried radish slices compared to hot-air drying. The experiments on shrimps (Bai & Sun, 2011) and scallop muscles (Bai et al., 2012a) reported no solid loss compared with ambient dried samples.

2.4.4 Chemical and nutritional properties

The effect of EHD on the biochemical, nutritional, and functional properties of fruits is less explored. EHD drying has been reported to affect complex biomolecules like proteins (Dinani, Hamdami, Shahedi, Havet, et al., 2015; Singh et al., 2015), polysaccharides (Ni et al., 2019; Ni et al., 2020b), and vitamins (Bajgai & Hashinaga, 2001a; Yang & Ding, 2016). Dinani et al. (2015) put forward a hypothesis that the protein structure weakened in EHD drying due to the influence of positive and negative charges arising from the high-voltage electric field. However, EHD drying of Chinese wolfberry showed higher peak intensities on the infrared spectrum, indicating that bioactive components like polysaccharides, glycosides, amino acids, proteins, and sugar alcohols are preserved better than in ambient air-dried samples. The analysis of polysaccharide content showed higher values in the presence of ionic wind, which decreased with the increase of needle spacing, i.e., reduced exposure of the material to ionized air (Ni et al., 2019).

The phenolic content and antioxidant capacity of EHD-hot air-dried quince slices were reported to be lesser than hot air-dried ones. These results were attributed to the thermal degradation of the cell wall, oxidation reactions, and the products of the Maillard reaction, releasing more phenolic compounds and the subsequent increase in the antioxidant capacity (Elmizadeh et al., 2017). The flavonoid content of the EHD dried wolfberry at different needle spacing exhibited no significant difference between EHD and air-dried samples. However, the oven drying and combined EHD+hot air (60 °C) drying improved the flavonoid content, this can be due to the release of some flavonoids upon oxidation of phenolic compounds at high temperatures (Ni et al., 2020b). As this research area is underdeveloped, more studies should be performed to analyze the effect of EHD on polyphenolic content compared to thermal drying.

2.5 EHD DRYING OF FRUITS

Dried fruits are mostly consumed as nutritional snacks or combined with cereals, cookies, and dairy products, to improve their nutritional value. As mentioned before, conventional hot air-drying methods are more prevalent in food industries. This might lead to the loss of nutrients and affects the sensory appeal of the dried fruits. The studies on EHD drying on the fruit quality are summarized in Table 2.2.

Table 2.2: An overview of EHD drying of fruits (Modified from (Paul & Martynenko, 2021))

Fruit	EHD drying Conditions	Comparison methods	Effect on fruit quality	References
Ankara Pear 100 g of cuboids (11.6x11.68x3.9 3 mm)	Multiple wires to plate electrode (6 wires, 0.4 mm diameter) and multiple pin (72 needles, 30 mm length, 0.7 mm diameter); 15 to 30 kV; 5 cm electrode gap; 26 ºC; 28% RH	EHD+hot air combination (60 ºC; 17% RH; 1.5 and 2.5 m/s)	Better color retention Lightness was similar to fresh samples at 15 kV and 1.5 m/s. Higher rehydration ability at 25 and 30 kV Collapses in the microstructure	(Polat & Izli, 2021)
Apples McIntosh variety; 8±0.5 mm thickness and 42±0.5 mm diameter; initial MC 11.12 to 7.12 g/g.	Multiple pin electrode (90 needles, 1.5 cm long); DC+; 0, 5, 10, 15 kV; 2.5 cm electrode gap; 0, 1, 3, 5 m/s air velocity; 10 h with convection and 35 h without; 21±1 ºC	With and without forced convection	Enzymatic browning at high voltages (15 kV) and low air velocities (0-1 m/s) No curling or bending of apple slices was observed in the visual inspection	(Martynenko & Zheng, 2016)
Apples Slices of 2-3 mm thickness and 8.6 cm diameter	Multiple pin electrode (1-3 thick copper and thin sewing needles); AC; 3-16.5 kV; 1-3 cm electrode gap; 7 h; 18±1 ºC; 33-65 % RH	With oven drying at 55 ºC and ambient air drying	The Color was similar to pre-dried samples with higher lightness The shrinkage rate increased linearly with drying time and was twice that of oven-dried samples	(Hashinaga et al., 1999)
Apricot cubes About 270±10 (9 mm^3) apricot cubes in thin layers; initial MC 4.81 g/g.	Multiple wires to plate electrode (6 wires, 0.4 mm diameter) and multiple pin (72 needles, 30 mm length, 0.7 mm diameter); 10 and 20 kV; 30 mm electrode gap; 0 m/s; 1080-1560 min; 25±0.1 ºC; 44% RH	With hot air drying (40 and 50 ºC; 1.5 and 2.5 m/s) and EHD+hot air combination	Hot air drying (40 ºC) retained color better followed by EHD alone Microstructures were preserved in EHD and a cracked structure in the hot air Smaller rehydration ratio compared to hot air and EHD-hot air combination	(Polat & Izli, 2020)

Fruit	EHD drying Conditions	Comparison methods	Effect on fruit quality	References
Banana 20 g of 3 mm thick slices; initial MC 2.75-3 g/g	Multiple pin electrode (25 needles; 2.5 mm diameter); DC+; 12, 16, 20 kV; 20 mm electrode gap; 293-372 min; 25 ºC; 45±15% RH	Microwave drying (180 – 900 W)	Smaller shrinkage higher rehydration ability increased with voltage for EHD Better color retention, more degradation at higher voltages	(Esehaghbeygi et al., 2014)
Chinese wolfberry 50 g in 300 mL of 5% sodium carbonate for 10 min; initial MC 69±1%	Multiple pin electrode (20 mm long, 1 mm diameter); AC; 0,20,24,28,32 kV; 100 mm electrode gap; 22-49 h; 25±2 ºC; 30±5% RH	Between different EHD voltages	Rehydration ratio increased with voltage No effect on shrinkage Vitamin C content increased with voltage	(Yang & Ding, 2016)
Chinese wolfberry Immersed in a 5% sodium carbonate solution at 50 ºC for 10 min; initial MC 76±1%	Multiple pin electrode (20 mm long, 1 mm diameter); AC; 28 kV; 100 mm electrode gap; 40 h; 21±2 ºC; 30±5% RH	Ambient air drying, with and without ionic wind and different needle spaces (2-12 cm)	Better rehydration rate decreased with increasing needle space No effect on shrinkage Polysaccharides decreased with increasing needle space No effect on flavonoids No effect on the chemical composition Preserved nutrient content The appearance of crystal-like projections on the surface	(Ni et al., 2019)
Chinese wolfberry Immersed in a 5% sodium carbonate soln. at 50 °C for 10 min; initial MC 76±1%	Multiple pin electrode (20 mm length and 1 mm diameter); AC; 30 kV; 100 mm electrode gap; 3-18 h; 25 ± 2 °C; 30 ± 2 % RH	Ambient air drying; EHD; EHD (30 kV) + oven drying (60 °C, 40 h)	Better rehydration ability No change in shrinkage Higher polysaccharide content than ambient air More flavonoid content in EHD + oven. Components were affected. Holes appeared on the surface in SEM analysis	(Ni et al., 2020b)

Fruit	EHD drying Conditions	Comparison methods	Effect on fruit quality	References
Goji berry Pre-treatments: ultrasonic, sucrose ester, NaOH, Na_2CO_3, KOH; initial MC 78±1%	Multiple pin electrode; (60 mm length and 1 mm diameter); AC; 30 kV; 10 cm electrode gap; 25 ± 2 °C; 30 ± 2% RH	Between different pre-treatments	No change in shrinkage Better rehydration rate for pre-treated samples with the highest value for KOH Pre-treatments helped in nutritional preservation and structural integrity EHD without pre-treatments had a more regular structure	(Ni et al., 2020a)
Kiwi slices 45 g of 4 mm thick slices	Multiple pin electrode (13 needles, 2 mm diameter and 0.1 mm tip); DC; 15, 17.5, and 20 kV; 40-, 50-, and 60-mm electrode gap; 25 ± 1 °C; 25 ± 0.5% RH	Between different EHD intensities; oven (60 °C) and ambient (25 °C) air drying	Original color retained in EHD compared to oven drying Smaller shrinkage	(Rezaee et al., 2020)

2.5.1 Moisture sorption isotherms

Moisture content and its interaction with food components determine food's physical, chemical, and microbiological stability. Understanding the relationship between moisture content and water activity is essential for the drying and storage of foods. The moisture content of the product reaches equilibrium with the surrounding atmosphere at the end of the drying process. The moisture sorption isotherms reflect this thermodynamic equilibrium, and it is important for a better understanding of drying operations (Moraes et al., 2008). It has water activity or relative humidity plotted against the equilibrium moisture content. The moisture sorption isotherm of apples obtained by gravimetric and hygrometric methods is given in Figure 2.2.

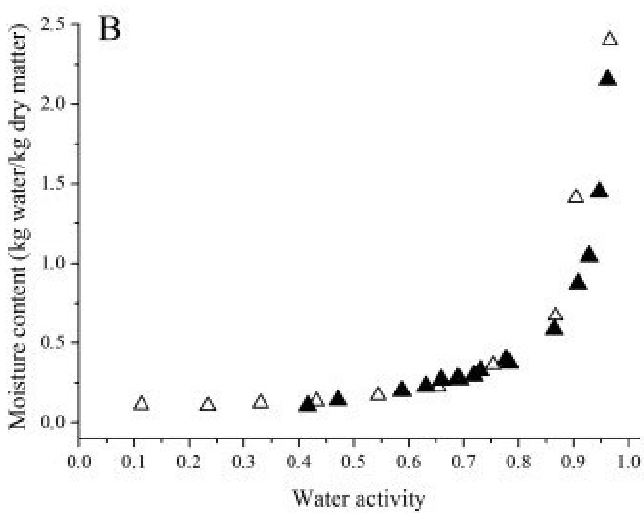


Figure 2.2: Moisture sorption isotherm for apples obtained by gravimetric (empty triangles) and hygrometric (solid triangles) methods at 20 °C

[retrieved from (Demarchi et al., 2013); Copyright permissions are given in Appendix B]

2.6 PROBLEM STATEMENT

Based on the literature review, the electrical parameters, material properties, and environmental conditions are the major factors affecting EHD drying. These EHD operating conditions influence the drying kinetics, effective diffusivity, energy consumption, and quality of dried products. In EHD drying of fruits, most studies focused on comparing EHD drying with ambient or oven drying. The effect of electric field intensities and electrode configuration has also been explored. However, the influence of material properties and environmental conditions is underexplored and must be investigated further. A focused study on the effect of sample thickness and load density on EHD drying efficiency is needed for upscaling to industrial dryers. Further, the quality changes under different drying conditions should be systematically analyzed. There are very few studies on the effect of EHD drying on fruit quality (Table 2.2). The impact of humidity and airflow on drying kinetics and product quality is also unclear. The interaction between these factors should also be investigated for the industrial scaling of the process.

2.7 RESEARCH OBJECTIVES

The main objectives of this work are:

1. To evaluate the effect of slice thickness on the drying kinetics, energy efficiency, and quality of EHD dried fruit slices.

2. To design and conduct a multifactorial experiment to investigate the individual effect and interaction between thickness, load density, external airflow, and relative humidity on EHD drying of fruit slices.

3. To compare EHD and hot air-drying techniques for fruit slices based on the drying kinetics, energy consumption, and quality attributes including color, shrinkage, texture, and microstructure as well as rehydration ratio, disintegration index, and total polyphenolic content.

CONNECTING STATEMENT

From chapter 2, electrical parameters, material properties, and environmental conditions are the major factors affecting EHD drying efficiency and the quality of dry products. There have been various studies on the EHD drying of fruits, mostly comparing different drying techniques. The literature review shows that the main and interaction effects of material properties and environmental conditions on EHD drying must be explored further.

Next, in chapter 3, a preliminary analysis of the material and environmental factors affecting EHD drying of fruits is presented with a particular focus on slice thickness. Apples and strawberries were the reference fruits chosen for the study, considering the production volume and the market demand in Atlantic Canada. The two fruits varied in texture, apples had a firm texture while strawberries are soft and mushy. The primary emphasis was to get familiar with the EHD drying technique and to modify the existing setup for image analysis of dry fruit slices. The hot air-drying conditions giving similar overall drying kinetics to EHD drying were used to compare drying characteristics and quality (Appendix A1). However, the drying rate constant and diffusivity varied with temperature and relative humidity in the hot air dryer (Table a). The results obtained from this study were further used to design a multifactorial experiment.

The results have been published as Paul, A., Astatkie, E., & Martynenko, A. Electrohydrodynamic drying of fruit slices: effect on drying kinetics, energy consumption, and product quality. *Journal of Food Processing and Preservation*, e16812. The copyright permissions are attached in Appendix B.

CHAPTER 3 ELECTROHYDRODYNAMIC DRYING OF FRUIT SLICES: DRYING KINETICS, ENERGY CONSUMPTION, AND QUALITY

3.1 INTRODUCTION

Drying is one of the most common methods of food preservation. When a hygroscopic material is dried, two mechanisms are involved: convective water evaporation from the surface and internal diffusion of moisture to the surface. Due to the moisture removal, the cellular structure will be collapsed, affecting the internal diffusion and resulting in material shrinkage (Mahiuddin et al., 2018). The thickness of the material significantly affects the drying rate and shrinkage (Mujumdar, 2015). Thermal (hot air) drying is the most commonly used drying technique in industries because of its simple operation. However, it is highly energy-intensive and adversely affects product quality (Kudra, 2004). The product quality could be significantly improved with nonthermal drying techniques.

Electrohydrodynamic (EHD) drying is a promising nonthermal technology with a simple equipment design, relatively small energy consumption, and low cost of operation. EHD operates at ambient temperature, producing low-density non-thermal plasma. Being accelerated in the electric field, non-thermal plasma creates the ionic wind, which disturbs the boundary layer and enhances the evaporation of water molecules from the surface of food material. Surface drying establishes a concentration gradient inside the food material, which is the driving force of water diffusion to the surface (Singh et al., 2012). The nonthermal nature of EHD drying makes it highly suitable for the drying of heat-sensitive materials.

A systematic review on the energy efficiency of EHD drying was given by Martynenko et al. (2021b). The specific energy consumption of conventional hot air drying is about 8000-80000 kJ/kg (Raghavan et al., 2005), while EHD drying requires only 14.7-2700 kJ/kg, depending on the drying mode (Lai & Lai, 2002). It should be noted that the energy efficiency of EHD drying depends mainly on the electrical parameters, material properties, and environmental conditions (Martynenko et al., 2021b). Hence, optimizing EHD drying conditions is critical for the commercialization of the technique.

Due to the convective mechanism of water evaporation, EHD is more effective for the thin-layer drying of plant-based foods (Bashkir et al., 2020). A detailed review of the changes in product quality upon EHD drying is provided in Paul and Martynenko (2021). Unfortunately, only a few studies reported the effect of material properties on the efficiency of EHD drying. For example, Chen et al. (1994) showed that the EHD-induced drying rate decreased with an increase in the thickness of potato slabs. Similarly, Ding et al. (2014) reported that the EHD drying rate increased with reducing the sample thickness. This study aims to evaluate the drying kinetics, effective diffusivity, and energy consumption of fruit slices, exposed to EHD drying. The study considers two different material textures: firm apple slices and soft strawberry slices of different thicknesses, to provide better insights into the effect of EHD drying. Visual quality attributes, such as color and shrinkage, were determined via computer vision and compared with conventional hot air drying.

3.2 MATERIALS AND METHODS

3.2.1 Samples

Fresh apples (var. McIntosh) and strawberries (var. Jewel) were procured from the local market and stored in a refrigerator at 4 ± 1 °C until use. Apples of visibly uniform size and ripeness were sliced to 1-, 2-, 3-, and 4-mm thickness with a professional food slicer (CFS – 155C, Cuisinart, Canada). Then they were cut into squares (2.54×2.54 cm) using an apple cutter to ensure consistency. Fifty-six (56) slices, arranged in 6×9 rows, were placed on the collecting mesh electrode. Thus, the initial surface area of apple slices was 0.0348 m^2 in each trial. Fully ripened strawberries with bright red color and almost uniform firmness were selected for the experiments. They were sliced into 3- and 4-mm slices using a sharp knife. The thickness of each slice was verified using a digital caliper (Mastercraft, Canada) with 0.1 mm tolerance.

3.2.2 Experimental setup

A schematic diagram of the experimental setup is shown in Figure 3.1. It consists of an AC power supply with power meter W, voltmeters V1 and V2 to measure voltage and current, a DC transformer, discharge and collecting electrodes, a digital scale, and a computerized system for continuous weight measurements (Figure 3.1).

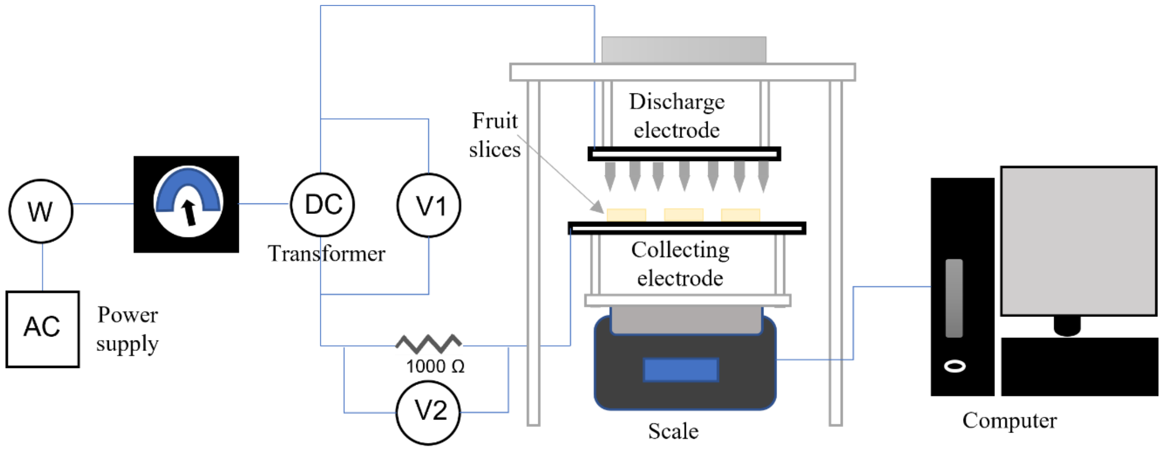


Figure 3.1. A schematic diagram of the EHD drying setup

The discharge electrode was connected to a positive pole of a high voltage DC transformer (Model 20B, Hipotronics, USA). The collecting electrode was connected to the ground through a precise 1 kΩ resistor for current measurements. The primary voltage, controlled by a variac, was measured by a multimeter (Fluke 110 True RMS, Fluke Corp., Everett, WA, USA), while voltage drop on the 1 kΩ resistor was measured by another multimeter (UA9233E, Uyigao Technology Co. Ltd., China). All experiments were performed at 22 kV and a 4.0 ± 0.1 cm gap was maintained between the discharge and collecting electrodes. A power meter (Intertek SK410 Energy Meter), connected to the AC power supply measured the total power consumption. Once the slices were placed on the mesh collecting electrode underneath the discharge electrode, the digital scale (HCB 1002, Adam Equipment, Oxford, CT, USA) was turned on for weight measurements every 10 seconds.

A picture of the EHD electrode system is shown in Figure 3.2.

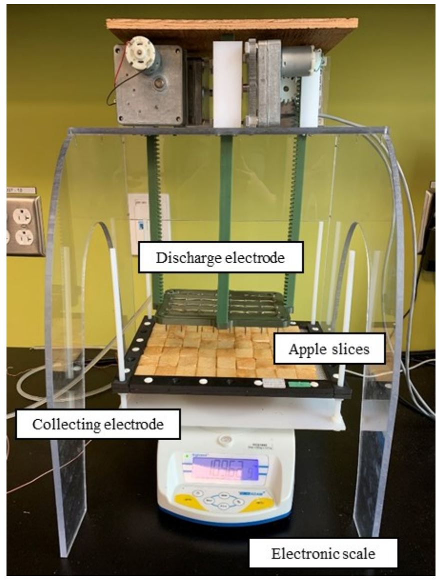


Figure 3.2. The EHD electrode system with apple slices

It consisted of a discharge electrode with 32 emitters, made of stainless-steel nails (2 cm long, 1.8 mm diameter, conical emitting tip with 0.25 mm radius at an angle of 41 ± 0.5°), fixed in a rectangular plastic holder 15.8×10.3 cm (Figure 3.2). The needles were arranged in 8x4 rows forming 2×2 cm square cells and were soldered together with a stainless-steel wire of 0.5 mm diameter. The collecting electrode with dimensions 23×16 cm was made of stainless-steel woven mesh with 0.406 mm thick 304-SS wire at an opening size of 0.864 mm (Bashkir, 2020). To avoid the sticking of fruits to the metal collecting electrode, a plastic removable mesh of 0.66 mm thickness and 0.4 mm opening size (Aboat, China) was used on top of the collecting electrode. The gap between the electrodes was finely adjusted to 4 cm with a motorized gear rack and pinion assembly connected to the discharge electrode with plastic rails. The mesh collecting electrode was fixed on the top of a 5 cm high plastic holder to create a safe distance between the digital scale and the electrode system. All trials were performed at ambient temperature (20 ± 2

°C) and 60% relative humidity. Humidity in the room was adjusted using a dehumidifier (Noma 50-pint, Energy Star, Canada).

An electrostatic attraction between electrodes influenced the weight of the fruit slices in the range of 0.6-1.0 g. Therefore, the recorded weight reflected two jumps at the beginning and end of the EHD drying due to the direct effect of the electric field. Another error was introduced due to the digital scale zero floating over significant drying time. Therefore, the true final weight of the dried fruit slices was measured after drying on the second calibrated scale. The errors introduced by the electrostatic attraction and the scale floating were subtracted during data processing. A graph for moisture content was plotted based on the real weight (g) over time (h). The effect of EHD drying on quality attributes (color and shrinkage) was compared with hot air drying at 40 °C and 0.15 m/s air velocity in a convective tray dryer (Model: UOP 8A, Armfield, England). These settings of hot air drying provided a drying regime, similar to EHD drying.

3.2.3 Moisture content and moisture ratio

The moisture content of the apple slices was calculated from the initial and dry weight of the apple slices. The initial moisture content (X_o) (g/g dry weight) of the apples used was determined after the completion of each trial as:

$$X_0 = \frac{W_{fresh} - W_{dry}}{W_{dry}} \quad \text{..........................(3.1)}$$

where W_{fresh} (g) refers to the initial weight of the apple slices, and W_{dry} (g) refers to the dry weight of the apples. The dry weight of fruit slices was determined after oven-drying in Fisher 255G oven, (Fisher Scientific, Nepean, ON, Canada) at 105 ºC for 24 h (apple slices) (AOAC, 2010) and strawberry slices at 70 ºC for 48 h (Bruijn & Bórquez, 2014).

The moisture ratio (MR) of fruit slices was calculated as follows:

$$MR = \frac{X_t - X_e}{X_0 - X_e} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.2)$$

where X_o (g H_2O/g dry mass) and X_t (g H_2O/g dry mass) are the initial and instantaneous moisture content at the time t, and X_e (g H_2O/g dry mass) is the equilibrium moisture content.

3.2.4 Drying rate and drying flux

The drying rate (DR) was calculated using the following equation for the overall period of drying:

$$DR = \frac{\mathrm{W_t} - \mathrm{W_{t+dt}}}{dt} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.3)$$

where W_t (g) is the weight of the sample at time t, dt (s) is the time increment. The difference in the weight measurements gives the amount of water evaporated over a specific interval of time.

The drying rate obtained for the first 30 min was used to calculate the drying flux ($\dot{m}$) or drying rate per unit area. The drying flux ($\dot{m}$) due to evaporation was equivalent to the mass reduction of the fruit slices per unit area per unit time:

$$\dot{\mathrm{m}} = \frac{1}{A} \times DR \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.4)$$

where $\dot{m}$ (g/m^{2}s) is the drying flux, A (m^2) is the area of evaporation, and DR (g/s) is the drying rate. The drying rate constant, k (h^{-1}) was determined in the falling rate period with the moisture ratio ($0.5 < MR < 0.2$) using Newton's exponential model for thin-layer drying:

$$MR = e^{-kt} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.5)$$

3.2.5 Effective moisture diffusivity

The effective moisture diffusivity (D_{eff}) was calculated from Fick's second law for a long drying period (MR < 0.1), and no internal heat transfer using the following equation (Crank, 1979):

$$MR = \frac{8}{\pi^2}\exp\left(\frac{-\pi^2 D_{eff} t}{4L^2}\right) \ldots\ldots\ldots\ldots(3.6)$$

$$D_{eff} = \frac{-4L^2}{\pi^2 t}\ln\left(\frac{\pi^2}{8}MR\right) \ldots\ldots\ldots\ldots(3.7)$$

where MR is the moisture ratio, k is the drying rate constant (s^{-1}), and t is the drying time (s). The fruit slice was considered as an infinite slab with the thickness L (m) because of negligible thickness compared to the length of the slices.

3.2.6 Energy consumption

The total energy consumption, TEC (kJ) was determined as the product of total power (including auxiliary equipment) and the drying time, for the overall drying period. The specific energy consumption (SEC) of EHD drying was defined as the amount of energy required to evaporate a unit mass of water in kJ/kg and calculated in terms of applied voltage, current and drying rate.

$$TEC = P \times t \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.8)$$

$$SEC = \frac{V \times I}{DR} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.9)$$

where the variables are the electric current I (mA), applied voltage V (kV), power P (W), and time t (s). Since the drying rate exponentially decreased with drying time, SEC was not constant, exponentially increasing towards the end of drying. The average *SEC* for the overall period of drying was determined by integrating the Equation (3.9) as shown below in Equation 3.10.

$$SEC_{avg} = \frac{1}{t_f - t_0} \int_{t_0}^{t_f} SEC(t)dt \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.10)$$

where t_0 is the initial time, and t_f is the final drying time. The TEC_{EHD} consumed for the moisture removal in EHD drying was calculated by multiplying the SEC_{avg} by the amount of water evaporated ($W_i - W_f$).

$$TEC_{EHD} = SEC_{avg} \times (W_i - W_f) \ldots\ldots\ldots\ldots\ldots\ldots (3.11)$$

3.2.7 Shrinkage

Radial and area shrinkage of fruit slices was determined by imaging. Initial and final images of the fruit slices were captured using two CCD cameras (Sony DFW-SX910, Tokyo, Japan), arranged orthogonal to each other for the top and side views. The region of interest (ROI) was illuminated with white light from a circular fluorescent lamp for apple slices at intensity of 225 lux and yellow light at 235 lux for strawberry slices. Images were calibrated and the area was determined from the initial and final images, using Vision Assistant 2018 (National Instruments, Austin, TX, USA) software (Chen & Martynenko, 2013). Since the vertically mounted camera didn't cover the whole region, shrinkage in the ROI was considered the representative indicator of the total area shrinkage. The thickness of the slices was determined using the Edge Detection Clamp subroutine. The volume of fruit slices was determined by the multiplication of the total area by their thickness. The volumetric shrinkage was determined using the following equation:

$$A_{shrinkage} = \left(1 - \frac{A_f}{A_i}\right) \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.12)$$

$$V_{shrinkage} = 1 - \frac{V_f}{V_i} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.13)$$

where A_i is the initial area, A_f is the final area, V_i is the initial volume, and V_f is the final volume of fruit slices.

3.2.8 Color

The color of the apple and strawberry was determined by computer vision. The color was measured from the images taken by the color CCD camera in reflected light. The region of interest was separated from the background through several filters in the IMAQ image processing software. The actual color values in the RGB color space were converted to CIELAB color space using the procedure given by Martynenko (2017). The color values in CIELAB coordinate system are expressed as L^*, ranging from 0 (darkness) to +100 (whiteness or brightness), a^* (redness to greenness), and b^* (yellowness to blueness). Color changes ΔE for each sample were then calculated, using the following equation:

$$\Delta E = \sqrt{(L^* - L_o^*)^2 + (a^* - a_o^*)^2 \; (b^* - b_o^*)^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.14)$$

where L_o*, a_o*, and b_o* are the initial color values of the fruit slices.

The browning index BI of apple and strawberry slices was determined from $L^*a^*b^*$ values using the following equations:

$$BI = \frac{100\,(x - 0.31)}{0.17}; \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.15)$$

$$x = \frac{a^* + 1.75\,L^*}{5.645\,L^* + a^* - 0.301 b^*} \ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.16)$$

3.3. RESULTS AND DISCUSSIONS

3.3.1 Drying of apple slices

The initial moisture content of the apple slices was in the range of 6.68 to 8.7 g/g, while the final (equilibrium) moisture content after EHD drying was 0.36-0.4 g/g. The equilibrium moisture content was determined from the constant weights at the end of drying and confirmed using the moisture sorption isotherm at 20 °C (Figure 2.2). The effect of EHD drying on the apple slice drying kinetics was presented with normalized moisture ratio curves (Figure 3.3), which allowed averaging of experiments with different initial moisture content.

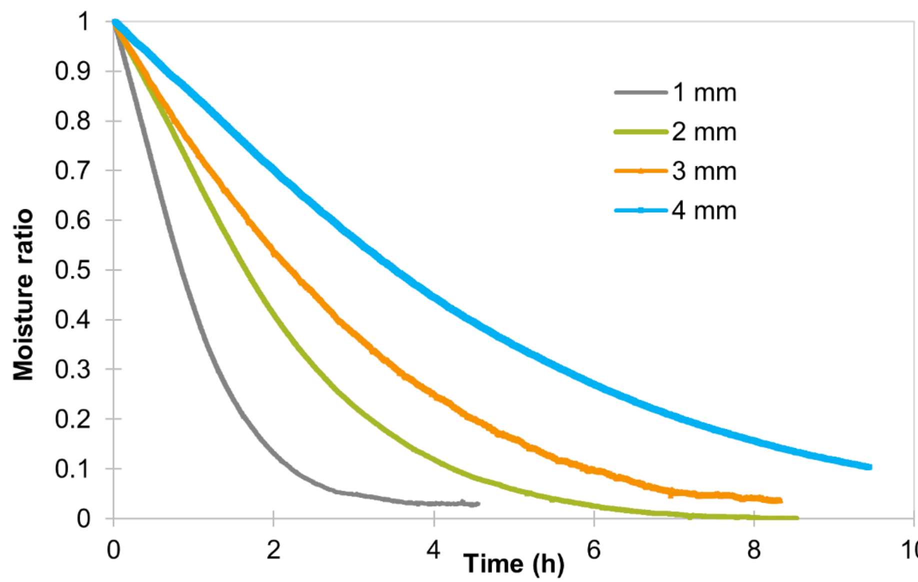


Figure 3.3. Drying kinetics of apple slices at room temperature and 60% relative humidity

From Figure 3.3, it follows that the drying rate significantly decreased with the thickness, i.e., it was maximal for 1-mm and minimal for 4-mm apple slices (Figure 3.3). The average drying flux, determined during the initial 30 min of drying, varied from 0.18

g/m^2s for 1 mm slices to 0.12 g/m^2s for 4 mm slices. Our results concur well with earlier studies on the effect of thickness in EHD drying (Chen et al., 1994; Martynenko et al., 2021a).

The first-order kinetics of moisture content without a constant rate period concurs with the results obtained by other researchers on the EHD drying of apples (Martynenko & Zheng, 2016), bananas (Pirnazari et al., 2016), and mushroom slices (Dinani et al., 2014). Results of apple slice drying at different thicknesses including drying time, drying rate constant, and EHD energy consumption are summarized in Table 3.1.

Table 3.1. The drying kinetics of apple slices (relative humidity 60%, voltage 22 kV).

Thickness (mm)	**Drying time (h)**	**Drying rate constant (h^{-1})**	**Effective diffusivity ($10^{-11} m^2/s$)**	**Current (µA)**	**Power (W)**	**SEC_{avg} (kJ/kg)**	**TEC_{EHD} (kJ)**	**TEC_{aux} (kJ)**
1	2.98	1.31	0.526	90.8	16.8	603	17	181
2	6.25	0.626	0.460	119.2	17.3	975	51	389
3	11.02	0.355	0.459	132.1	18.1	1271	99	718
4	15.71	0.249	0.540	139.9	18.6	1434	134	1052

**SEC_{avg}-Average Specific Energy Consumption, TEC_{EHD}-Total Energy Consumption by EHD dryer, TEC_{aux}-Total Energy Consumption by auxiliary equipment*

From Table 3.1, it follows that the thickness of apple slices had a significant impact on the drying time. Drying of 1-mm slices took only 3 hours while drying of 4-mm slices required about 16 hours. The drying rate constant (*k*) was determined from the plot of moisture ratio vs. time, using an exponential model (Equation 3.3). The *k* value was reduced almost by half for every additional 1 mm of thickness. The effective diffusivity (m^2/s) was calculated using Equation 3.5, from the drying rate constant *k* and slice thickness *L*, considering the shrinkage effect (Boutelba et al., 2018). The effective moisture diffusivity values were almost the same (0.5 ± 0.05) $\times 10^{-11}$ m^2/s for apple slices of all thicknesses. It confirms the initial hypothesis that the mass transfer in apple slices is diffusion-limited, governed by Fick's law and the diffusivity is independent of thickness.

The preliminary studies on EHD drying showed a significant impact of relative humidity at 20 ± 2 °C on the drying kinetics of apple slices (Figure 3.4).

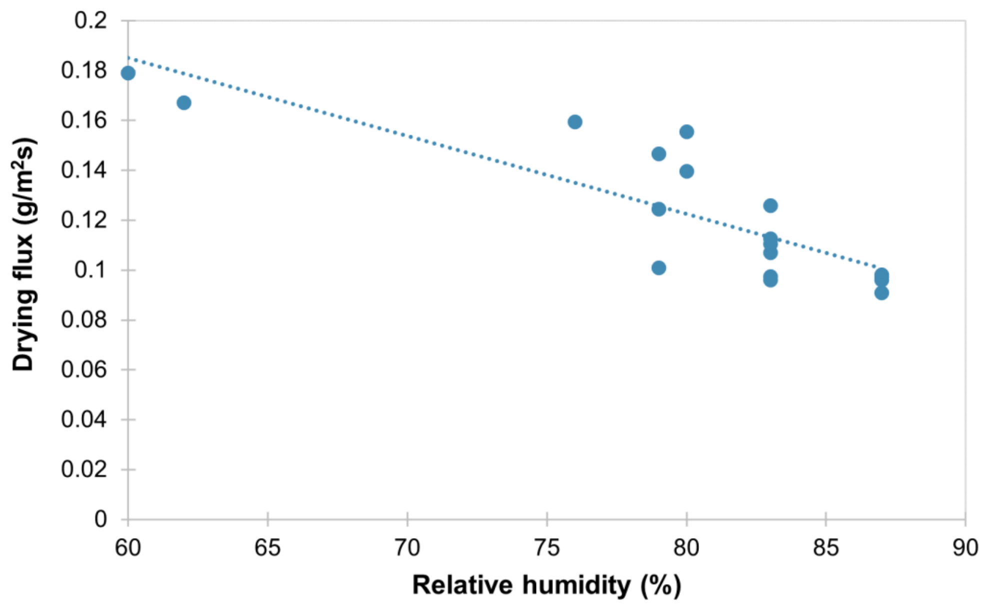


Figure 3.4: Relationship between drying flux and relative humidity for 2-mm apple slices

At conditions of low relative humidity, the drying flux was significantly higher, which concurs with the results of EHD drying of champignons (Martynenko et al., 2021a). These results show the need for controlled humidity in EHD drying to mitigate the negative effect of humidity on convective mass transfer.

Specific energy consumption (SEC) in EHD drying accounts for the actual discharge energy (exergy) used for the drying. It was not constant during drying, increasing with the decrease of the drying rate. The trend in the exponential increase of SEC towards the end of drying was similar for slices of different thicknesses (Figure 3.5).

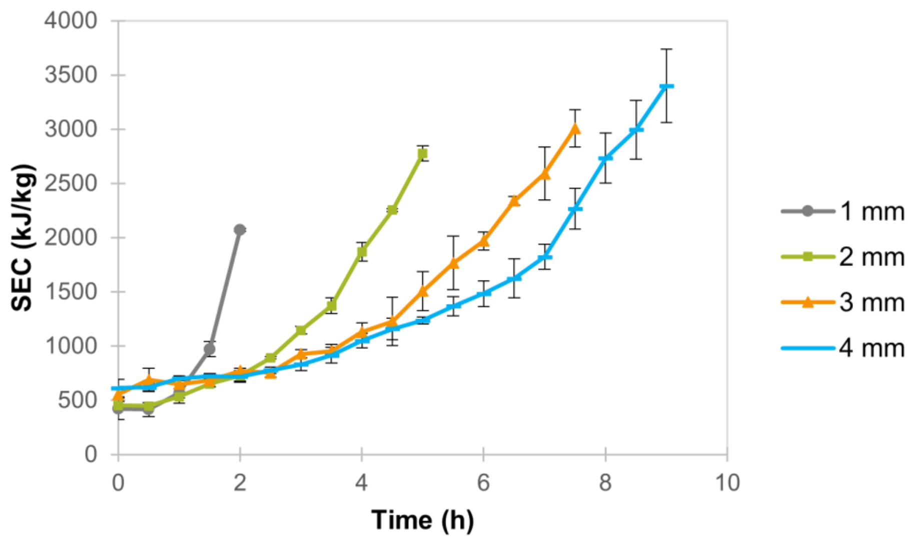


Figure 3.5: Specific Energy Consumption (SEC) of apple slices at different thicknesses

In the first hour of drying, *SEC* was almost independent of thickness, being in the range from 450 to 600 kJ/kg. The following increase of *SEC* depended on the slice thickness. The faster growth of *SEC* for 1 mm slices is related to the smaller water content and the more rapid decay of drying rate. In contrast, 4 mm slices, which required longer drying, demonstrated a prolonged increase in *SEC*. At the end of EHD drying, *SEC* increased to 2100-3400 kJ/kg. To compare energy consumed during EHD drying for different treatments, the average values for the entire drying period SEC_{avg} have been calculated using Equation 3.10 and presented in Table 3.1. The SEC_{avg} obtained in this study agreed with other works on EHD drying of fruit slices (120 – 2500 kJ/kg) (Martynenko et al., 2021b). Both SEC_{avg} and TEC increased with increase in thickness due to the considerable increase in drying time. The TEC_{EHD} was relatively small compared to the total energy consumed by the power supply and auxiliary equipment TEC_{aux}.

EHD drying of apple slices resulted in significant shrinkage. The results for the area and volumetric shrinkage of apple slices at different thicknesses for EHD and hot air drying obtained through computer vision are summarized in Table 3.2. In our experiments, 1 mm apple slices shrunk less than thicker pieces. It might be due to sticking 1-mm slices to the plastic mesh, which prevented further area shrinkage. For 2-4 mm apple slices, the differences in area and volumetric shrinkage were negligible: 35 ± 0.5% and 86 ± 1.0%, respectively. According to Madiouli et al. (2007), if the volume reduction of the solid matrix is directly proportional to the volume of evaporated water/mass loss, it is considered an ideal shrinkage. Considering that the dry matter for apples occupies about 13-14% of the overall volume, we conclude about almost ideal shrinkage of apple slices in EHD drying, which concurs with the report of Singh et al. (2013). The thickness shrinkage in EHD drying was significantly higher than in hot air-dried samples, indicating predominant water transport through the material surface.

Table 3.2: Shrinkage and color of apple slices

Initial Thickness (mm)	Final Thickness (mm)	Area Shrinkage (%)	Volumetric Shrinkage (%)	ΔE	Browning Index (initial)	Browning Index (final)	Browning Index change (%)
EHD drying							
1	0.31	28.52	75.69	3.22	12.59	12.91	2.46
2	0.46	35.53	85.17	4.65	12.70	13.05	2.71
3	0.61	35.04	86.79	3.75	12.75	13.11	2.81
4	0.8	35.25	87.05	2.83	12.69	12.91	1.72
Hot air drying							
3	1.2	51.49	78.52	5.12	12.80	13.77	7.59
4	1.4	56.24	82.34	5.77	12.54	13.51	7.74

Another important quality parameter in EHD drying is the color of the dry products. Analysis of Table 3.2 shows that the color change (*ΔE*) of apple slices with a thickness of 1-3 mm was almost similar, with the highest color change for 2 mm thick slices. In contrast, 4 mm apple slices appeared to keep their original color after EHD drying, with a significantly reduced browning index. The images of fresh and dried apple slices (1-4 mm) are provided in Appendix A2. The color changes and browning were more pronounced in hot air-dried samples, which concurs with the previous studies that demonstrated the effectiveness of EHD in controlling browning reactions and subsequent discoloration compared to ambient and thermal drying (Hashinaga et al., 1999). Browning of apple slices is associated with enzymatic or non-enzymatic oxidation of phenolic compounds. The enzymatic browning is caused by the action of polyphenol oxidase (Martinez & Whitaker, 1995). In contrast, non-enzymatic browning is caused by environmental factors, such as temperature, oxygen, pH, and consequent Maillard reactions (Manzocco et al., 2000). The negative impact increases with drying temperature, explaining the higher color change, and browning in hot air-dried slices.

3.3.2 Drying of strawberry slices

Similar experiments have been carried out using strawberry slices. The initial moisture content of strawberry slices was in the range of 9.7 to 11.8 g/g and an equilibrium moisture content of 0.2 to 0.29 g/g. EHD drying of strawberry slices also followed exponential drying kinetics. The summary of strawberry slices drying is provided in Table 3.3.

Table 3.3: Drying of strawberry slices (60% relative humidity, voltage 22 kV)

Thickness (mm)	Drying time (h)	Drying rate constant (h^{-1})	Effective diffusivity ($10^{-11} m^2/s$)	Current (μA)	Power (W)	SEC_{avg} (kJ/kg)	TEC_{EHD} (kJ)	TEC_{aux} (kJ)
3	13.72	0.285	0.247	145.4	18.1	1324	120	894
4	18.54	0.219	0.239	160.5	18.6	1756	185	1241

**SEC_{avg}-Average Specific Energy Consumption, TEC_{EHD}-Total Energy Consumption by EHD dryer, TEC_{aux}-Total Energy Consumption by auxiliary equipment*

Table 3.3 shows the same trend in decreasing the drying time with reducing the slice thickness. Similar to the case of apples, the effective diffusivity was independent of the thickness (0.24 ± 0.01) $\times 10^{-11}$ m^2/s. Comparing Tables 3.1 and 3.3, the drying rate constant *k* and effective diffusivity were higher for apples, which could be due to the capillary-porous structure of the apple matrix.

The change of SEC over drying time for 3-and 4-mm slices is shown in Figure 3.6.

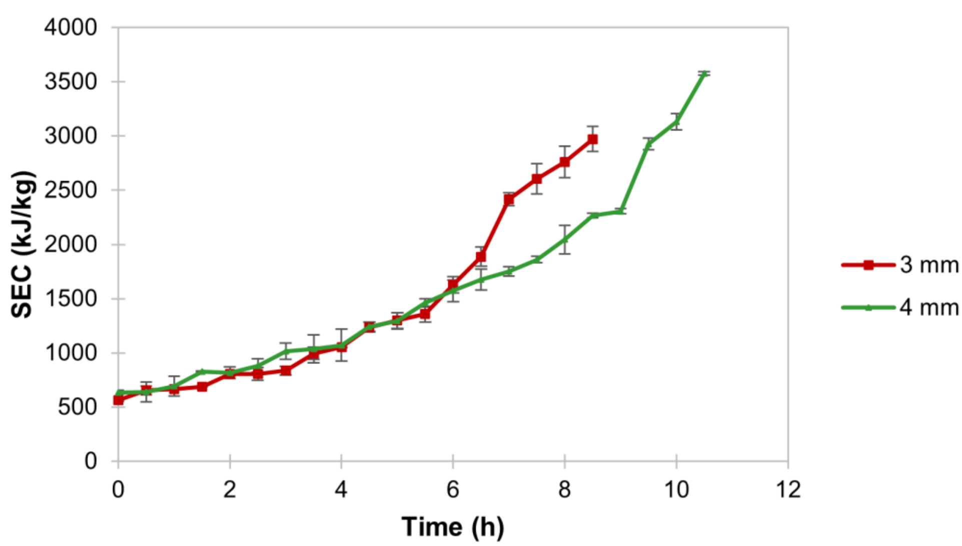


Figure 3.6: Specific energy consumption of strawberry slices at 3- and 4-mm thickness

Similar to apple drying, *SEC* was almost constant for the first hour, in the range of 550 kJ/kg, but increased towards the end of the drying to 3000-3500 kJ/kg. The average SEC_{avg} was 1324 kJ/kg for 3 mm slices and 1756 kJ/kg for 4 mm slices (Table 3.3). It is important to note that TEC_{EHD} was 6-7 times smaller than *TEC* of auxiliary equipment.

The shrinkage and color changes of strawberry slices after EHD and hot air drying are presented in Table 3.4. The area shrinkage of dried slices was about 36%, while the volumetric shrinkage was 91 ± 1%, irrespective of the thickness. Considering the dry matter of strawberry slices occupies about 7-9% of the overall volume, we can qualify the shrinkage of strawberry fruit as almost ideal. It should be noted that compared to usual thermal drying at 55-60 ℃, where temperature plays a significant role in shrinkage (Alemrajabi et al., 2012), a low-temperature EHD drying at 40 ℃ resulted in the same shrinkage for both EHD and thermally dried slices.

Table 3.4: Shrinkage and color of strawberry slices

Initial Thickness (mm)	**Final Thickness (mm)**	**Area Shrinkage (%)**	**Volumetric Shrinkage (%)**	**ΔE**	**Browning Index (initial)**	**Browning Index (final)**	**Browning Index change (%)**
EHD drying							
3	0.46	36.36	90.24	44.19	24.73	28.40	14.83
4	0.56	36.06	91.05	45.02	23.61	29.02	22.94
Thermal drying							
3	0.61	39.38	87.67	34.92	24.28	30.44	25.37
4	0.85	41.56	88.46	35.23	24.89	29.14	17.05

The color change and browning index of strawberry slices showed no significant effect on thickness (Appendix A3). EHD drying caused a higher color change than hot air drying, concurring with the conclusions of Polat and Izli (2020). It could be explained by the negligible effect of low-temperature drying on the thermal degradation of anthocyanins, responsible for the red color in strawberries (Oancea, 2021). In the present study, both EHD and hot air-dried strawberry slices were darkened mostly along the edges, close to the outer skin. Due to non-uniform color distribution, the browning index was not conclusive. Further studies are necessary to understand better the effect of an electric field on the degradation of anthocyanins.

3.4 CONCLUSION

It can be concluded that fruit thickness significantly affects EHD drying kinetics and energy consumption. The drying rate decreased with the fruit thickness. Consequently, the time required for EHD drying to the equilibrium moisture content increased with fruit thickness from 3 h (1 mm) to 16 h (4 mm) for apple slices, and from 14 h (3 mm) to 19 h (4 mm) for strawberry slices. The effective diffusivity was independent of thickness, higher in apple slices than in strawberries. The average specific energy consumption increased with thickness because of the increase in drying time and it was higher for strawberry slices.

The shrinkage of apple slices was about 85%, while strawberry slices shrank to 90%, which could be qualified as an ideal shrinkage with negligible porosity. The color of apple slices significantly changed with thickness, with the least color change and browning for the thick slices (4 mm).

High relative humidity negatively impacts the EHD drying. With the humidity increase, drying flux of 2-mm apple slices decreased from 0.18 g/m^2s (60% RH) to 0.10 g/m^2s (85% RH), while for 3-mm strawberry slices it dropped from 0.15 g/m^2s (60% RH) to 0.11 g/m^2s (85%) RH.

CONNECTING STATEMENT

From the preliminary analysis, it was evident that the material properties and environmental conditions considerably affect the EHD drying of fruit slices. Hence, a multifactorial experiment was designed to evaluate the effect of slice thickness, load density, external airflow, and relative humidity on the EHD drying of apple slices. Strawberries were not used for further drying experiments. Likewise, the 4 mm thick apple slices were omitted due to longer drying times. A new EHD drying apparatus with more needles and larger coverage area was designed.

The results presented in chapter 4 have been submitted for publication in the journal "Foods".

CHAPTER 4 THE EFFECT OF SLICE THICKNESS, LOAD DENSITY, EXTERNAL AIRFLOW, AND RELATIVE HUMIDITY ON THE DRYING EFFICIENCY AND QUALITY OF EHD DRIED APPLE SLICES

4.1 INTRODUCTION

Most studies on EHD drying of foods are focused on the effects of electrical parameters and electrode configuration on the drying efficiency and energy consumption. Less attention was paid to the effects of material properties and environmental conditions, such as air temperature, velocity, and relative humidity. The effect of material thickness on EHD drying was evaluated for potato slabs (Chen et al., 1994), fish (Bai et al., 2011), and beef jerky slices (Ding et al., 2014). It was found that the drying rate decreased with an increase in thickness in all cases. The effect of fruit load density on the drying kinetics and specific energy consumption was explored by Onwude et al. (2021). They reported that the decrease in load density from 70% to 3% reduced drying time but increased specific energy consumption. The effect of external airflow on EHD drying was more complex. The drying rate increased with air velocity to some critical values and then decreased. The critical air velocity depended on the electric field intensity (Lai & Lai, 2002; Zhong et al., 2019). The relative humidity (RH) is another crucial factor affecting EHD drying kinetics, but its effect is underexplored. Bai et al. (2011) and Martynenko et al. (2021a) reported that low RH is beneficial for EHD drying. Zhang et al. (2021) reported that high RH could facilitate heat transfer and increase the drying rate in the constant rate period of drying, whereas low RH enhances moisture diffusion in the falling rate period. However, these conclusions, relevant to hot air drying, have never been tested for EHD drying.

The product quality is crucial for the industrial adaptation of the EHD drying technique. The quality of EHD-dried products was mostly compared with natural or hot air drying (Paul & Martynenko, 2021). It was widely reported that EHD dried products retained the natural quality better than hot-air dried. EHD drying preserved pigments like chlorophyll (Bajgai & Hashinaga, 2001a) and carotenoids (Ding et al., 2015) with final color almost similar to the fresh samples (Alemrajabi et al., 2012; Bai & Sun, 2011; Hashinaga et al., 1999; Rezaee et al., 2020; Yang et al., 2017). The rehydration ratio was higher in EHD dried products (Bai & Sun, 2011; Bajgai & Hashinaga, 2001b; Ni et al., 2019; Yu et al., 2017) with a superior texture (Bai et al., 2013). Furthermore, EHD drying resulted in lower shrinkage (Alemrajabi et al., 2012; Bajgai & Hashinaga, 2001b; Dinani & Havet, 2015; Elmizadeh et al., 2018) with fewer microstructural changes (Ni et al., 2020a; Polat & Izli, 2021). The bioactive and nutritional components like vitamins (Bajgai & Hashinaga, 2001a; Liang & Ding, 2006), flavonoids (Yang et al., 2017), and polysaccharides (Ni et al., 2019) were also better preserved in EHD drying. In most cases, the quality changes were correlated with EHD operating conditions like voltage (Singh et al., 2015; Xiao & Ding, 2022; Yang & Ding, 2016), external airflow (Dinani & Havet, 2015; Martynenko & Zheng, 2016; Singh et al., 2015), or the effect of pre-treatments (Ni et al., 2020a; Ni et al., 2020b). Ni et al. (2019) found that the cellular disintegration of Chinese wolfberry was proportional to the applied voltage and ionic wind intensity. Unfortunately, research on the effects of material properties and environmental factors on product quality is very scarce. A recent study reported a considerable effect of thickness on shrinkage, color, and browning of EHD-dried apple slices (Paul et al., 2022). Martynenko et al. (2016) reported that external airflow below

1.0 m/s reduced the enzymatic browning in EHD drying of apple slices. However, external airflow above 1.0 m/s provoked significant visible browning (Martynenko et al., 2021a).

The literature review shows that material properties and environmental conditions are among the factors affecting EHD drying kinetics. However, the influence of these factors on the quality attributes, such as shrinkage, color, rehydration ratio, disintegration index, and total polyphenolic content, is not yet investigated. A focused study on the combined effects of material thickness, load density, airflow, and humidity on the efficiency and quality of EHD drying is required for upscaling this technology to industrial application. This challenge was addressed by a multifactorial experimental design, followed by statistical analysis.

4.2 MATERIALS AND METHODS

4.2.1 Experimental apparatus

The lab-scale EHD dryer described in section 3.2.2 was modified for the study. The EHD system was equipped with multiple pins to mesh electrode system, as shown in Figure 4.1. The pins were attached to a fiberglass breadboard (Vector Electronics Inc., Canada) of dimensions 240×170×2 mm. The fiberglass consisting of 72 nails was arranged in 12 rows in the nodes of the rectangular grid with a 2 cm gap and was affixed to a plastic holder of 23x16 cm. The discharge electrode was fixed on a plexiglass frame and hung from the top using plastic rails. It was connected to the positive pole of a high voltage power supply (Universal Voltronics, USA), providing direct current (DC). The experiments with EHD drying were performed at 20 kV voltage and a 4 cm electrode gap, providing electric field strength of 5 kV/cm.

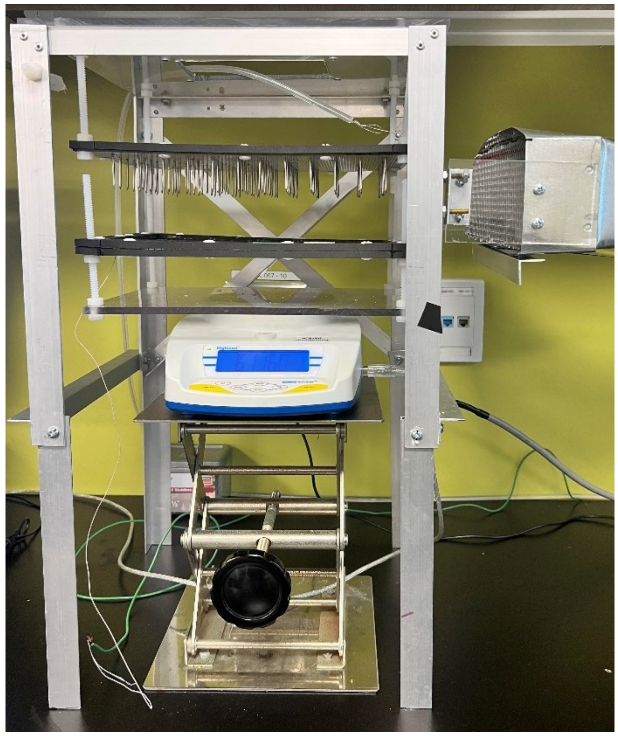


Figure 4.1: EHD dryer

An air blower was added to the experimental setup for EHD drying. The external airflow in the drying chamber was controlled using a 1.5 kW blower (model 3HMJ5, Dayton Electric Co., IL, USA) attached to a flexible aluminum pipe. The rectangular (26 x 10 cm) opening of the pipe was fixed 9 cm away from the electrodes. An airflow straightener prevented turbulence and uneven airflow distribution above the surface of dried material. The relative humidity (RH) in the drying room was measured using a wet and dry bulb hygrometer (model B6030, Baker Instruments, Canada).

4.2.2 Drying experiment

The apples were sliced into pieces of 1-, 2-, and 3-mm thickness as described in section 3.2.1. The slices were spread uniformly at 50% and 100% load densities on the mesh. Slice load density (packing density) in our experiments is the ratio of area covered by slices on the collecting mesh electrode to the total area of the mesh. At 100% load density, 56 apple slices were arranged in 6×9 rows without any gap between the slices, and for 50% load density, 27 slices were arranged in a chess pattern with a 1-slice (2.54 cm) gap, 4 and 5 slices in every alternate row. The experiments were conducted without external airflow and at controlled air velocities of 0.5 and 1 m/s. The range of the variables used for the multifactorial experiment is shown in Table 4.1.

Table 4.1: Experimental design with three independent factors

No.	**Sample Code**	**Thickness (mm)**	**Load density (%)**	**Airflow (m/s)**
1	1-50-0	1	50	0
2	1-50-0.5	1	50	0.5
3	1-50-1	1	50	1
4	1-100-0	1	100	0
5	1-100-0.5	1	100	0.5
6	1-100-1	1	100	1
7	2-50-0	2	50	0
8	2-50-0.5	2	50	0.5
9	2-50-1	2	50	1
10	2-100-0	2	100	0
11	2-100-0.5	2	100	0.5
12	2-100-1	2	100	1
13	3-50-0	3	50	0
14	3-50-0.5	3	50	0.5
15	3-50-1	3	50	1
16	3-100-0	3	100	0
17	3-100-0.5	3	100	0.5
18	3-100-1	3	100	1

The air velocity was measured with a hot wire anemometer (model 405i, Testo instruments, Canada). The apple slices were dried to the equilibrium moisture content. To evaluate the effectiveness of EHD drying, the drying quality of EHD dried apple slices were compared with apple slices (2 mm) dried in a convective tray dryer at 40 ℃ and 0.15 m/s. It was not possible to control relative humidity (RH) to specific values in this experimental setup. A general factorial design with three factors (3x3x2) was created in Minitab 19, and the experiments were performed in triplicates.

Each set of experiments was carried out in random order and the results were statistically analyzed. The experiments with outlier data were rejected and repeated.

4.2.3 Drying characteristics

The drying characteristics and specific energy consumption was determined using the procedure given in section 3.2.

4.2.4 Quality attributes

4.2.4.1 Shrinkage

Area and volumetric shrinkage of apple slices were determined using the procedure given in section 3.2.7.

4.2.4.2 Color

The color changes (ΔE) of apple slices upon EHD and hot air drying was determined using the procedure described in section 3.2.8.

4.2.4.3 Rehydration ratio

To assess the rehydration capacity of the EHD and hot air-dried apple slices, 2 g of the dried slices were immersed in 30 mL ultrafiltered water at 25 °C for 1 h. The water was drained, and the excess water was removed by lightly pressing the slices with an absorbent paper. The rehydrated slices were weighed, and the rehydration capacity was determined using the given equation:

$$RR = \frac{Wt - Wd}{Wd} \times 100 \text{ ....(4.1)}$$

where *RR (%)* is rehydration ability, W_t is the weight of rehydrated slices, g; and W_d is the weight of the dried slice, g.

4.2.4.4 Disintegration index

The electrical conductivity disintegration index, Z_p, was used for the estimation and comparison of damage on apple slices after EHD or hot air drying. The initial electrical conductivity, σ_i (S/m) of fresh intact apple slices, was measured using a benchtop conductivity meter (Model 860031, SPER scientific). The slices were added to 30 mL distilled water and mechanically shaken in a rotary shaker for 30 min. Similarly, the electrical conductivity σ was measured after drying. Then, the conductivity σ_d was determined after drying of slices in a hot air oven at 105 °C for 24 h (dry matter), and the disintegration index can be calculated using the equation:

$$Z_\mathrm{p} = \frac{\sigma - \sigma_i}{\sigma_d - \sigma_i} \text{......................................(4.2)}$$

where Z_p is '0' for intact apple slices and '1' for completely damaged slices.

4.2.4.5 Total Phenolic Content (TPC)

The Folin–Ciocalteu method was used to evaluate the TPC of EHD dried apple slices. The dried apple slices were ground to powder, and 0.5 ± 0.01 g of powder was weighed and mixed in 10 mL ultrafiltered water. The polyphenols were extracted in a water bath at 100 °C for 30 min. The mixture was cooled to room temperature and centrifuged at 4500 rpm for 15 min. The supernatant (200 μL) was carefully pipetted to 1 mL of 1:10 diluted Folin's reagent. After about 4 min, 800 μL of 7% sodium carbonate solution (Na_2CO_3, 75 g/L) was added to the solution and incubated in the dark at room temperature for 2 h. Gallic acid at concentrations of 0-500 mg/L was used to plot the standard calibration curve. The absorbance against the blank was determined at 765 nm using a UV visible spectrophotometer (model Genesys 150, Thermo Scientific). The TPC of the dried slices was expressed in mg of gallic acid equivalents (GAE) per gram of dry weight (Zhao et al., 2019).

4.2.5 Statistical analysis

The multifactorial experiment was designed with four factors using a general full factorial design in Minitab 19 statistical software. The analysis of variance (ANOVA) using a general linear model was performed to study the effect of thickness, load density, external airflow, and RH on the drying characteristics and quality. The assumptions of normality and constant variance were verified for each response variable by examining residuals. Tukey's post hoc test was used for the multiple mean comparisons at a 0.05 significance level. Relative humidity could not be controlled during the experiment. Therefore, RH was used as a covariate in the statistical multifactor analysis.

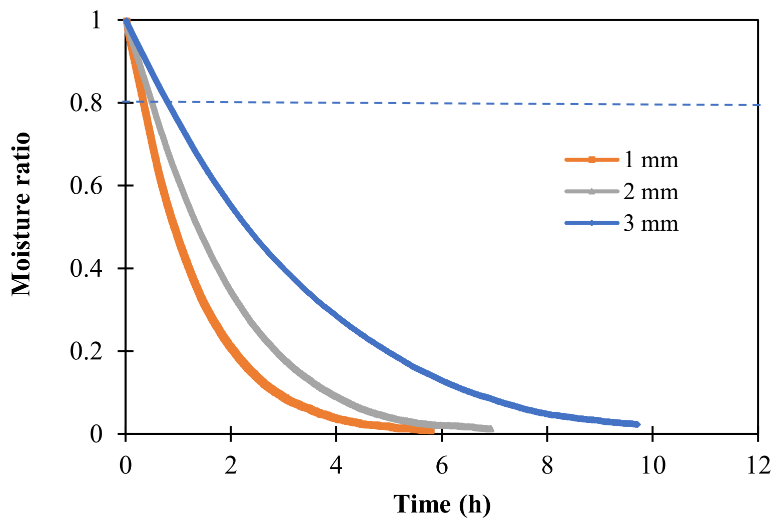
4.3 Results and Discussion

4.3.1 Drying characteristics

A multifactorial experiment was conducted to evaluate the effect of slice thickness, slice load density, external airflow/forced convection, and relative humidity (RH) on the EHD drying kinetics of apple slices. The experiments were performed in random order with 3 replicates over 5 months (November 2021-March 2022). The initial moisture content of apple slices was 8.7 ± 0.2 g/g and it was dried to the equilibrium moisture content of 0.38 ± 0.02 g/g.

4.3.1.1 Drying flux

The example of drying kinetics of apple slices for different thicknesses is shown in Figure 4.2.



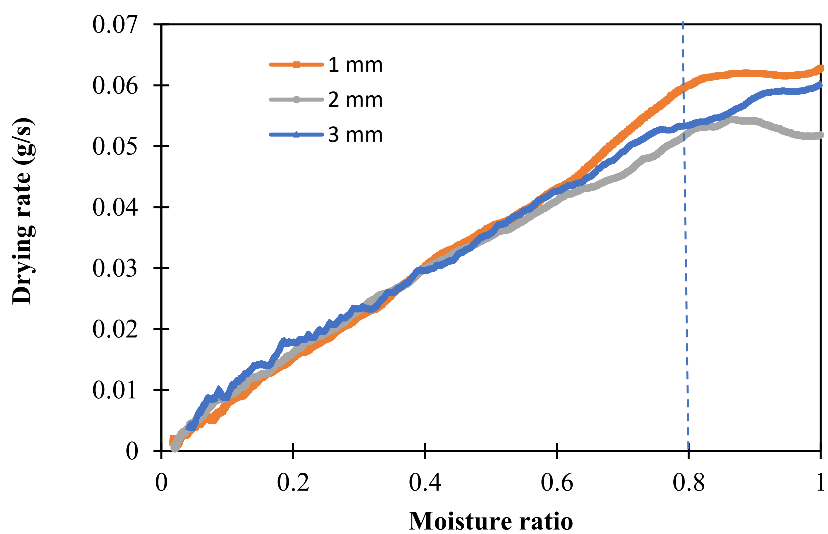


Figure 4.2: The drying kinetics of apple slices (100% load-0.5 m/s-52% RH)

It follows that within the first 30 min of drying (1<MR<0.8), there was linear drying kinetics, which indicated a constant drying rate period. This behavior was observed in both EHD and hot air drying. Hence, the drying rate was determined as the slope of weight changes (g) versus time (s). To exclude the effect of load density (evaporation area), the drying rate (g/s) was divided by the total area (m^2) to obtain drying flux. The changes in drying flux of apple slices from the multifactor experiment is shown in Figure 4.3. The data are presented as combined effects of three factors, namely thickness, load density, and airflow velocity with the corresponding coding (Table 4.1).

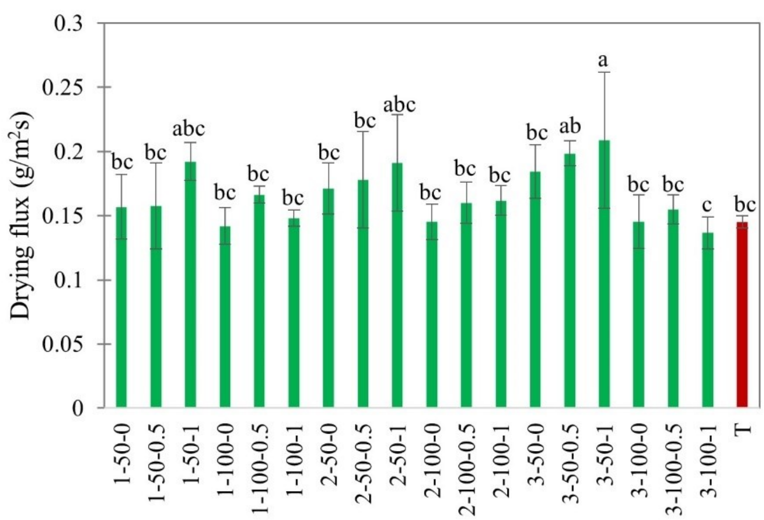


Figure 4.3: Drying flux of EHD (marked in green and labeled as thickness-slice load density-airflow) and hot air-dried (marked in red as T) apple slices.

In food drying, material thickness is a critical geometrical characteristic, determining the mode of mass transfer. It was found that EHD is more effective for thin-layer drying due to the convective mechanism of mass transfer (Bashkir et al., 2020). Previous studies reported that the EHD drying rate was significantly reduced with increased thickness of potato slabs (Chen et al., 1994) or beef jerky slices (Ding et al., 2014). Our experiments (Figure 4.3) showed that drying flux is independent of thickness. It could be explained by the convective action of EHD, which affects only surface water, depending on the surface area, but not thickness. On the other hand, the effect of the slice load was significant. Drying flux was considerably higher at 50% load density, implying higher moisture transfer rates (Figure 4.3). This could be attributed to the better convection regime, where moisture escapes through the gaps between slices. This assumption is supported by the additional positive effect of forced airflow at 50% load, but almost negligible at 100% load.

The general effect of airflow on drying flux was more complex, depending on load density. This complexity is related to the possible interaction between external airflow and EHD flow (Zhong et al., 2019). In our experiments, the most consistent positive effect of external airflow was observed at a low air velocity of 0.5 m/s (Figure 4.3), which agrees with earlier observations (Lai & Lai, 2002). A suppression effect of airflow at high velocities on the ionic wind was reported elsewhere. The possible explanation was that the external airflow suppresses the positive effect of EHD-induced airflow by blowing ionic wind away from the material surface. At low electric field strength, the ionic wind becomes weak, and even small external airflow could interrupt the ionic wind. The drying flux of hot air dried apple slices was similar to EHD drying.

Relative humidity (RH) in the multifactorial experiments was variable in the range of 50-65% and therefore considered an uncontrollable factor. The single effect of RH on drying flux was evaluated in a separate set of experiments (2 mm-100% load-0 m/s). The air temperature in the relative humidity trials was about 22 ± 4 ^{o}C.

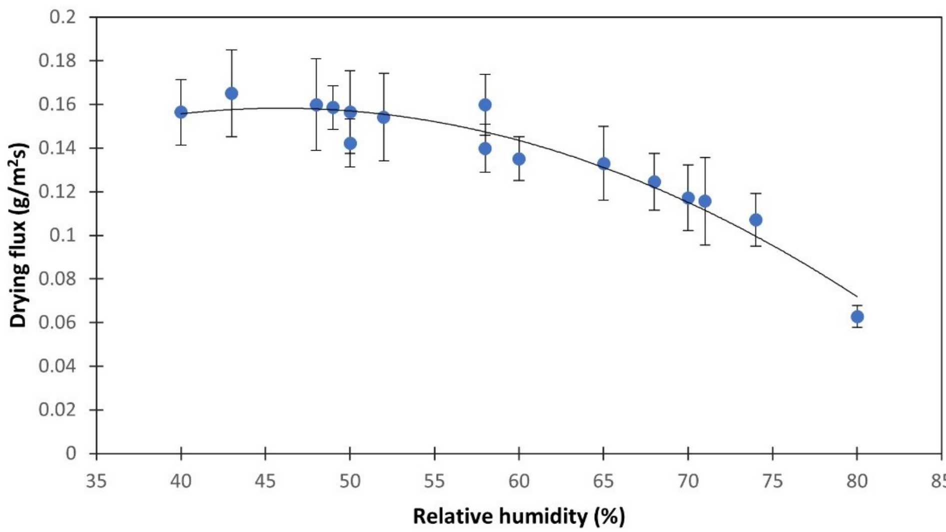


Figure 4.4: Changes in drying flux with relative humidity

Figure 4.4 shows the effect of RH on the intensity of EHD drying. In the range from 40 to 50% RH, the drying flux was constant, so this range does not affect the electro-convective mass transfer. As the RH increases, the average drying flux of apple slices decreases. It could be explained by the decrease of water pressure gradient at higher RH, which is the major driving force of mass transfer (Iranshahi et al., 2021). Ambient air with a high vapor content/relative humidity loses the ability to absorb more water. Also, the formation of ionic hydrates at higher RH could be an additional factor, decreasing the mobility of charged particles, which in turn reduces the drying efficiency (Martynenko et al., 2021a; Sakata & Okada, 1994; Zhang et al., 2017). It could be observed that relative humidity above 65% is considerably limiting EHD drying.

4.3.1.2 Drying rate constant

The drying rate constant, *k* was determined as the slope of moisture ratio vs the time graph using Newton's exponential model ($R^2 > 0.99$) in the falling drying rate period (0.5

< MR < 0.1). Higher *k* values indicate a faster drying process. A considerable difference was observed in the drying rate constant of EHD dried apple slices at different thicknesses and air velocities (Figure 4.5).

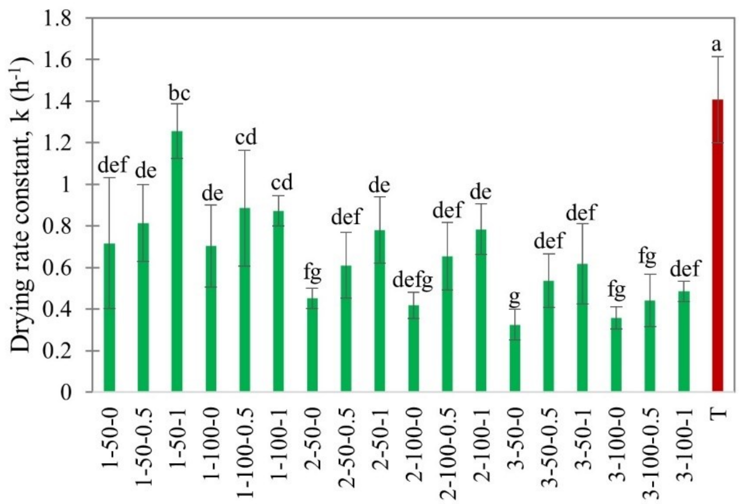


Figure 4.5: Drying rate constant of EHD (marked in green and labeled as thickness-slice load density-airflow) and hot air-dried (marked in red as T) apple slices.

The *k* value decreased significantly with increasing thickness, which could be explained by the drying theory (Mujumdar, 1997). Increasing air velocities also resulted in a higher drying rate constant (Figure 4.5). However, the slice load density did not affect the drying rate constant. The possible explanation is that at MR<0.5 the shrinkage of slices created a gap between them for the moisture to escape. The highest drying rate constant in EHD drying was for 1 mm slices at 50% load density, and 1 m/s airflow. The drying rate constant for hot air drying was notably higher indicating the influence of temperature on diffusive moisture transfer during the falling drying rate period (Figure 4.5).

4.3.1.3 Effective diffusivity

The effective diffusivity (D_{eff}) was calculated from the drying rate constant and final slice thickness, considering the shrinkage effect. Figure 4.6 portrays the effective diffusivity of EHD and hot air-dried apple slices.

Figure 4.6: Effective diffusivity of EHD (marked in green and labeled as thickness-slice load density-airflow) and hot air-dried (marked in red as T) apple slices.

The effective moisture diffusivity increased considerably with an increase in air velocity (Figure 4.6). This concurs with the observations on the EHD drying of white champignons with forced air convection (Martynenko et al., 2021a). The effective diffusivity in EHD drying at 20 ºC was (0.517 ± 0.11) $\times 10^{-11}$ m^2/s, which was significantly smaller than in hot air drying at 40 ºC (1.216 ± 0.14) $\times 10^{-11}$ m^2/s. This difference indicates the major effect of temperature on moisture diffusion (Figure 4.6).

4.3.2 Specific energy consumption

EHD drying is highly acclaimed for its low energy consumption (Martynenko et al., 2021b). In this study, the specific energy consumption (SEC) of EHD drying was about 390.85 kJ/kg to 673.68 kJ/kg, whereas for hot air drying, it was about 8000 kJ/kg (Figure 4.7).

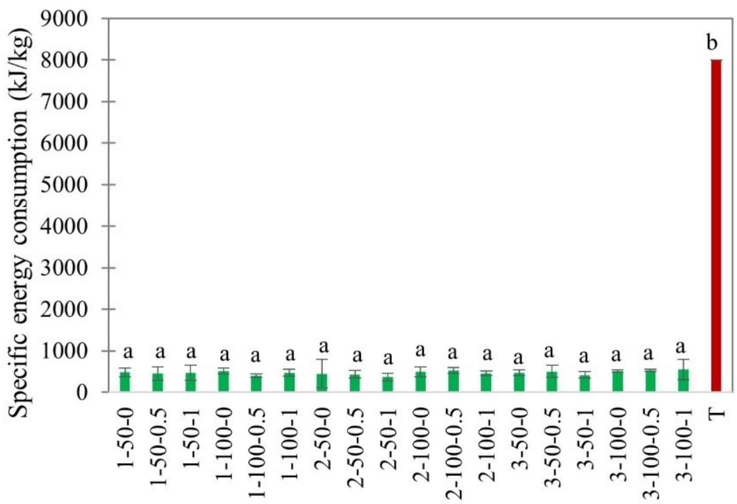


Figure 4.7: Specific Energy Consumption of EHD (marked in green and labeled as thickness-slice load density-airflow) and hot air-dried (marked in red as T) apple slices.

The SEC did not significantly change with the combination of factors studied. The SEC in EHD drying was 12-20 times smaller compared to hot air drying (Figure 4.7). It was no difference, however, among EHD treatments. This again confirms the potential of EHD drying as a sustainable alternative to conventional hot air-drying techniques.

Table 4.2 summarizes the statistical ANOVA p-values from the multifactorial experiment showing the significance ($p < 0.05$) of the main and interaction effects of factors (external airflow, slice thickness, and slice load density) on the drying characteristics of apple slices from the multifactorial experiment.

Table 4.2: The p-values obtained from the multifactorial ANOVA for drying characteristics at a 0.05 significance level

Factors	**Drying flux (g/m^2s)**	***k* (h^{-1})**	**D_{eff} (10^{-11} m^2/s)**	**SEC (kJ/kg)**
thickness	0.206	**0.000**	0.218	0.212
load	0.000	0.123	0.123	**0.031**
airflow	0.041	**0.000**	**0.000**	0.445
thickness*load	**0.018**	0.433	0.494	0.154
thickness*airflow	0.896	0.549	0.710	0.290
load*airflow	**0.041**	0.084	0.132	0.614
thickness*load*airflow	0.614	0.181	0.336	0.738
Lack-of-Fit	0.311	0.504	0.844	0.132

Note: Significant effects that require comparison of multiple means are marked in bold

The ANOVA results from Table 4.2 reveal significant main and interaction effects of the considered factors on the drying characteristics. The factorial plots for significant main and interaction effects are shown in Appendix A4. There were significant interaction effects of thickness-load and load-airflow on the drying flux, with slice load density having a highly significant effect alone. It could be explained by the positive effect of load distribution on the lateral diffusion, as well as convection mass transfer. The reason for the significant interaction effect (thickness*load) on the drying flux is not completely clear. This interaction is possibly related to the positive effect of spacing between slices on the convective mass transfer. The drying rate constant *k* was substantially affected by both thickness and airflow. The main effects of thickness and airflow reflect improved diffusive and convective mass transfer in the falling rate period of drying. Likewise, a considerable effect of external airflow on effective diffusivity was observed.

The significant effect of load density on SEC could be explained by the fact that drying at 100% or 50% load density requires the same amount of input energy in kJ, but the amount of evaporated water (kg) is two times smaller. So, the efficiency of EHD drying with 50% load density is reduced by half than at 100% load density. This was similar to the results obtained by Onwude et al. (2021), where an increase in slice loading density decreased the specific energy consumption in EHD drying of apple slices. Hence, optimization of material load density is important for the commercialization of EHD drying because, even though low load densities provide faster drying, it might not be economical.

4.3.3 Quality

4.3.3.1 Shrinkage

Shrinkage occurs due to the microstructural stress and collapse of cellular structure during drying (Mahiuddin et al., 2018). Moisture removal results in the loss of turgor pressure and subsequent shrinkage (Bajgai et al., 2007). In this study, the shrinkage was evaluated through sample imaging using a computer vision setup (Martynenko, 2017). The area and volumetric shrinkage of EHD and hot air dried apple slices are shown in Figure 4.8.

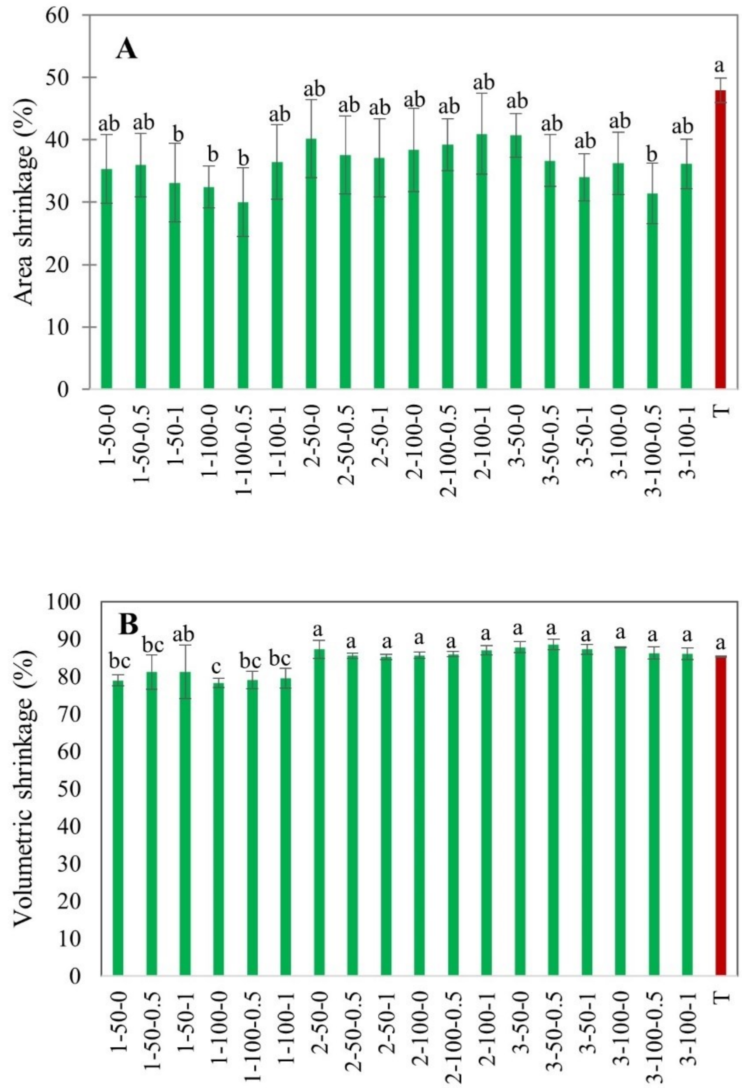


Figure 4.8: Area (A) and Volumetric (B) shrinkage of EHD (marked in green and labeled as thickness-slice load density-airflow) and hot air-dried (marked in red as T) apple slices.

The area and volumetric shrinkage depended on the thickness of apple slices. From Figure 4.8A, it follows that 1 mm slices experienced slightly smaller shrinkage than 2 and 3 mm. This could be due to the shorter drying time (approximately 4 h), considering that shrinkage increases with drying time (Esehaghbeygi & Basiry, 2011). There was no significant effect of external air velocity and load density on the shrinkage of EHD-dried apple slices. The volumetric shrinkage of 82-92%, obtained in the study, were similar to the shrinkage values reported for EHD-dried mushrooms (Dinani & Havet, 2015). In their study, volumetric shrinkage increased with an increase in air velocity from 0.4 to 2.2 m/s. In contrast, in our study, the effect of airflow was not observed. It could be explained by smaller air velocity, which did not exceed 1.0 m/s. The area shrinkage of apple slices was 36.21 ± 6.29% in EHD, smaller than in hot air drying (46.78 ± 3.53%), indicating smaller microstructural stresses in EHD. This agrees with the results obtained in previous studies (Alemrajabi et al., 2012; Elmizadeh et al., 2018). Surprisingly, the volumetric shrinkage did not show any significant difference between EHD and hot air-dried apple slices (Figure 4.8B).

4.3.3.2 Color

The color of the foods affects the consumer's perception of quality. Color is often adversely affected due to pigment degradation, browning, or oxidative reactions during high-temperature drying (Lewicki & Duszczyk, 1998). The enzymatic browning due to the polyphenol oxidase enzymes is mainly responsible for the browning in apple slices in the presence of oxygen, while non-enzymatic browning occurs due to Maillard reactions at high temperatures (Martinez & Whitaker, 1995;Singh et al., 2015). Most non-thermal drying techniques focus on preserving the color and appearance of dried products. The color changes in the multifactorial EHD drying experiment were compared with hot air drying in Figure 4.9.

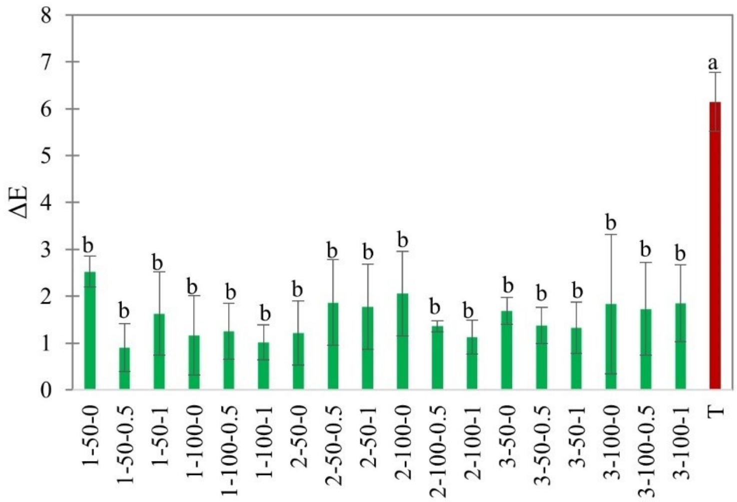


Figure 4.9: Color change, ΔE of EHD (marked in green and labeled as thickness-slice load density-airflow) and hot air-dried (marked in red as T) apple slices.

In EHD drying, the ions and charged species of low-density plasma produced by discharge electrodes could inhibit enzymes and halt the browning reactions (Misra et al., 2016). This might be responsible for the lesser color changes in EHD-dried slices compared to hot air-dried (Figure 4.9). In our experiments, it was no significant difference in color among EHD treatments. The average color change (ΔE) was 1.53 ± 0.4 for EHD versus 6.78 ± 1.05 for hot air-dried slices. Smaller color changes in EHD-dried slices compared to hot air-dried could be attributed to enzyme inactivation, as well as lower temperature of drying. Similar results were obtained in EHD drying of carrot slices (Alemrajabi et al., 2012), kiwi slices (Rezaee et al., 2020), and tomato slices (Esehaghbeygi & Basiry, 2011) in comparison with hot air drying. Based on the results of our study, we can conclude that EHD is effective in reducing the browning reactions and maintaining the physical appearance of dried apple slices.

4.3.3.4 Rehydration ratio

The rehydration ratio is a crucial parameter used to determine the dry product quality. A higher rehydration ratio indicates lesser damage to the cellular structure and water-holding components like protein and starch molecules (Marabi & Saguy, 2004; Paul & Martynenko, 2021). The changes in the rehydration ratio of EHD dried apple slices under various drying conditions are given in Figure 4.10.

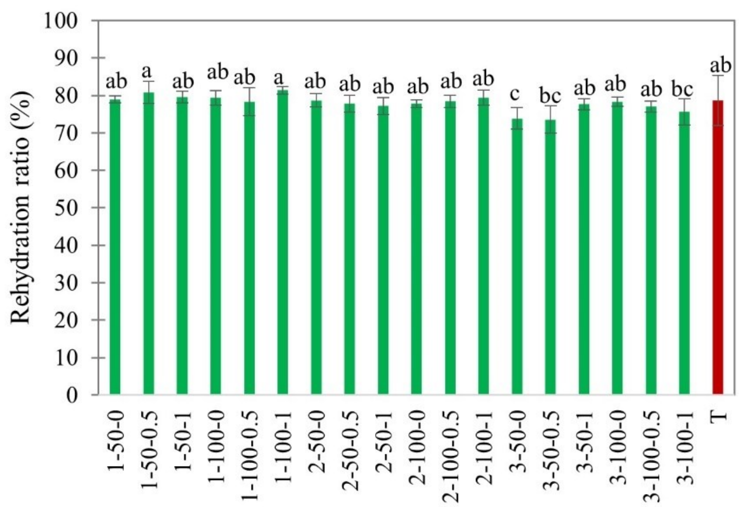


Figure 4.10: Rehydration ratio of EHD (marked in green and labeled as thickness-slice load density-airflow) and hot air-dried (marked in red as T) apple slices.

From Figure 4.10, EHD dried apple slices of 3 mm thickness had slightly smaller rehydration capacity. This might be because the standard weight of the dried apple sample 2.0 g was taken as a fixed parameter in the rehydration experiments, resulting in a smaller number of slices at higher thicknesses and thereby reduced area for water absorption. Another reason for the higher rehydration ratio in thinner slices could be the difference in porosity. Dinani et al. (2015) reported that shorter drying results in a more porous structure and thus higher water absorption rates. There was no significant difference in the rehydration ratio of EHD and hot air-dried apple slices for 2 mm slices (Figure 4.10).

4.3.3.5 Disintegration index

The disintegration index (DI) is another important quality parameter determining the damage to the internal microstructure of the dry products. The electrical conductivity method was used to determine the degree of cell disintegration. Usually, it is used to measure the severity of the treatments, for example, electroporation in pulsed electric field processing (Rahaman et al., 2019). The leaching out of cellular components because of cell disintegration results in higher electrical conductivity (Ni et al., 2019). The DI values from our experiment are provided in Figure 4.11.

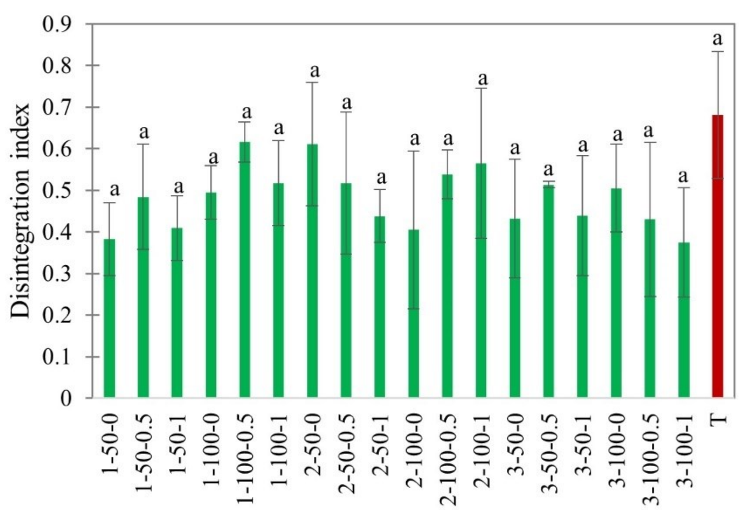


Figure 4.11: Disintegration Index of EHD (marked in green and labeled as thickness-slice load density-airflow) and hot air-dried (marked in red as T) apple slices.

In our experiments, the disintegration index of EHD-dried apple slices didn’t change for the range of studied factors (Figure 4.11). A slightly higher disintegration was observed after hot air drying, indicating more damage to the cellular structure. The average DI in EHD-dried apple slices was 0.48 ± 0.02 compared to 0.69 ± 0.12 for hot air-dried slices.

4.3.3.6 Total polyphenol content

Fruits are rich in polyphenols, which are known for their antioxidant activity and health-promoting properties (Shoji, 2007). The total polyphenol content (TPC) in apples was determined as milligram gallic acid equivalent per gram of dry weight using the Folin-Ciocalteau method (Singleton et al., 1999; Zhao et al., 2019) and shown in Figure 4.12. The TPC of fresh apples were 2.8 mg GAE/g dry weight.

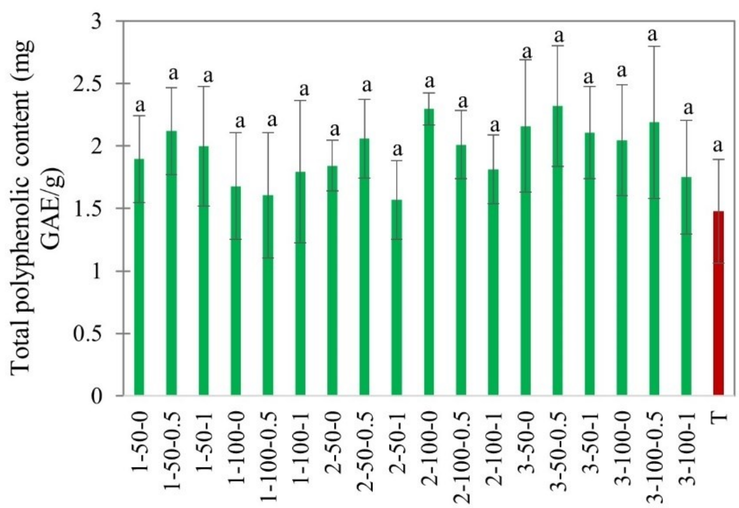


Figure 4.12: Total polyphenolic content of EHD (marked in green and labeled as thickness-slice load density-airflow) and hot air-dried (marked in red as T) apple slices.

Figure 4.12 shows that there was no significant difference in the TPC among EHD treatments in the range of studied factors. The TPC content was mostly retained in EHD drying but was lesser in hot air-dried slices. The average TPC in EHD dried slices were 1.95 ± 0.19 and 1.4 ± 0.05 mg GAE/g dry weight for hot air dried apple slices. Some studies report an increase in phenolic compounds after thermal drying (Elmizadeh et al., 2017). A couple of possible reasons for this phenomenon have been mentioned: (1) the release of phenolics due to cellular rupture or (2) producing phenolics as secondary oxidation products. However, the temperature in our study did not exceed 40 °C, which is below the threshold for thermal degradation reactions and the formation of subsequent products.

In summary, our experiments did not show the significant effect of environmental factors on product quality in the range of experimental design. Table 4.3 summarizes the statistical ANOVA p-values showing the significance ($p < 0.05$) of the main and interaction effects of factors (relative humidity, external airflow, slice thickness, and slice load density) on the quality of EHD dried apple slices.

Table 4.3: The p-values obtained from the multifactorial ANOVA for quality attributes at a 0.05 significance level.

Factors	**Area shrinkage**	**Volume shrinkage**	**ΔE**	**Rehydration Ratio**	**Disintegration Index**	**Total polyphenolic content**
thickness	**0.031**	**0.000**	0.547	0.000	0.256	0.108
load	0.493	0.055	0.540	0.088	0.436	0.304
airflow	0.544	0.967	0.216	0.388	0.267	0.171
thickness*load	0.561	0.235	0.105	0.202	0.116	0.061
thickness*airflow	0.879	0.197	0.654	0.806	0.751	0.451
load*airflow	0.161	0.644	0.736	0.740	0.709	0.513
thickness*load*airflow	0.934	0.325	0.042	**0.003**	0.140	0.831
Lack-of-Fit	0.897	0.729	0.359	0.497	0.679	0.124

Note: Significant effects that require comparison of multiple means are marked in bold

The ANOVA table (Table 3) shows significant effect of thickness on both area and volumetric shrinkage. This could be due to the faster drying of thinner slices, as discussed above. A significant interaction effect of thickness, load density, and airflow on the rehydration ratio could be explained by the major effect of thickness, which was mostly observable in the 3 mm apple slices. It is also important to mention that the increase in relative humidity prolonged drying time, and in this way indirectly affected volume shrinkage, disintegration index, rehydration ratio, and phenolic content ($p<0.05$). However, multiple means comparison tests could not be performed on the given relative humidity conditions.

4.4 CONCLUSION

The effect of material properties, such as slice thickness and load density, and environmental conditions, such as relative humidity and external airflow, on the drying kinetics, specific energy consumption, and quality of EHD dried apple slices were studied. The drying characteristics and quality attributes were compared with hot air drying at 40 °C and 0.15 m/s as the control. The drying flux in the constant drying rate period mostly depended on load density and relative humidity. The drying flux substantially increased with a decrease in relative humidity to the range of 40-50%. The drying rate constant in the falling drying rate period depended on the slice thickness. Effective diffusivity, as well as the drying rate constant, both increased with air velocity. The smallest specific energy consumption was at 100 % load density.

The effect of electrohydrodynamic drying on product quality was not significant. No significant difference in color, disintegration index, and total polyphenolic content among EHD treatments was observed in the range of factors studied. However, the shrinkage and rehydration ratio changed significantly with the thickness of the apple slices. In general, EHD-dried apples retained better quality compared to hot air drying, especially in color and shrinkage. The microstructural damage and degradation of phenolic compounds were also slightly smaller in EHD drying. Hence, EHD drying proved to be effective for thin fruit slices with better drying kinetics, low energy consumption, and superior quality. The impact of EHD drying on product texture and sensory properties should be further investigated.

CONNECTING STATEMENT

The preceding chapter presented the effect of material properties and environmental conditions on the drying kinetics, specific energy consumption, and quality of EHD dried apple slices. It was found that the slice thickness, load density, external airflow, and relative humidity significantly impacted the drying characteristics, but the influence on product quality in the range of experimental design was minimal. EHD drying better preserved the color and polyphenolic content with smaller area shrinkage and cellular disintegration compared to hot air-dried apple slices. The next chapter compares the textural properties of EHD and hot air-dried apple slices at different thicknesses. The microstructural changes in apple slices are also evaluated through microscopic images.

CHAPTER 5 TEXTURAL AND MICROSTRUCTURAL CHANGES IN ELECTROHYDRODYNAMIC DRIED APPLE SLICES

5.1 INTRODUCTION

Texture is an important physical property determining the quality and consumers perception of dried foods. Textural properties are affected by the microstructure, mechanical properties, initial texture of raw material, and the drying conditions (Chen & Opara, 2013; Martynenko & Janaszek, 2014). Textural Profile Analysis (TPA) is one of the most common instrumental methods for analysing textural properties of heterogeneous food materials. TPA works by applying prefixed mechanical load to the food material in different compression cycles utilizing appropriate probes. The force – time plot obtained from TPA is used to calculate the textural properties.

In TPA, hardness is the peak force that occur during the first compression. It determines the freshness of the food. Cohesiveness is the ability of the food material to withstand a second deformation and maintain textural integrity. Springiness is the ability to spring back to the original shape after the load is removed, while resilience is the ability to regain the original height. Adhesiveness is the work required to overcome the attraction between the food surface and surface of other materials (probe) which come in contact with the material. Gumminess and chewiness are secondary textural properties calculated from the primary textural properties (Stable microsystems).

Conventional hot air drying harms product texture because of non-uniform shrinkage, glass transition, and case hardening (Gulati & Datta, 2015). EHD drying did not result in case hardening or crust formation due to more uniform volumetric shrinkage (Singh et al., 2012). Only a few investigations on EHD drying have concentrated on the textural aspects of the dry product. Even then, the studies were concentrated on the textural properties of cooked (Tirawanichakul et al., 2009) or rehydrated (Bai et al., 2013) samples after EHD exposure. Textural changes were reported by increasing voltage (Elmizadeh et al., 2018) and air velocity (Dinani & Havet, 2015) in combined EHD-hot air drying. In addition, several studies on convective drying have reported the dependence of food texture on the final moisture content. A dramatic increase in the hardness of convective dried apple slices was observed below some critical level of moisture content (Bourne, 1986; Martynenko & Janaszek, 2014).

In this chapter we analyze the textural properties of EHD and hot air-dried apple slices at different thicknesses with respect to the final moisture content. The microstructural changes in the apple slices before and after EHD and hot air drying was also evaluated through microscopic images.

5.2 MATERIALS AND METHODS

5.2.1 Drying experiment

The drying experiment was performed in the EHD, and hot air dryer described in section 4.2.1. Apple slices of 2, 3, and 4 mm were used for the textural analysis. Apple slices were dried in an EHD dryer at 20 kV to an equilibrium moisture content of 0.38 ± 0.02 g/g (approximately 0.4 g/g) at 60-65% RH. The equilibrium moisture content was determined from the constant weights at the end point of the drying and confirmed using Figure 2.2. The apple slices were arranged in a 100% load density without external airflow. At the same time, apple slices were dried in a thermal dryer at 40 °C and 0.15 m/s airflow to the equilibrium moisture content of 0.25 ± 0.01 g/g at 16% humidity. To compare the effect of moisture content on the texture of dried apple slices, another set was dried in the thermal dryer up to a moisture content of 0.4 g/g. The moisture content was determined using equation 3.1 from section 3.2.3.

5.2.2 Texture analysis

Textural properties of EHD and hot air-dried apple slices were determined in a TA-XT texture analyzer (Stable Microsystems Ltd., Surrey, UK) using a cylindrical probe (1-inch diameter) and in the Exponent v6 software. For soft apple tissues with minimal thickness, the system was calibrated with a 30 kg load cell prior to the analysis, and a moderate 20% compression strain was used (Martynenko & Janaszek, 2014). The analysis was carried out in two cycles with a constant compression rate of 2 mm/s and a 5 s delay between the cycles. The cylindrical probe exerted uniform pressure on the whole apple slice, and the minimal thickness created an overload for the above settings. Therefore, two apple slices were stacked, one on top of another, to avoid the probe from touching the test table. Texture properties were calculated from the force-time plot in the Exponent software.

5.2.3 Microscopic examination

The cross sections of fresh, EHD and hot air-dried apple slices were taken using surgical blades. The cross sections were placed on a glass slide and stained with Loeffler's methylene blue for microscopical staining (Mayor et al., 2005). After 15 s, the slides were washed with distilled water to remove the excess stain, and the coverslips were affixed on top of the cross sections. The cross sections of apple slices were viewed under an optical microscope at 100x magnification. The images were captured using a digital camera (Leica DM500, Leica microsystems Inc., Canada) and imaging software (Leica LAS EZ).

5.2.4 Statistical analysis

The effect of thickness and moisture content on the textural properties were statistically analyzed in Minitab 19 software. The ANOVA was fit to a general linear model, and the assumptions of normality and constant variance of residuals were confirmed. The multiple means comparison for statistically significant main and interaction effects was performed using Fishers LSD at a 0.05 significance level.

5.3 RESULTS AND DISCUSSIONS

5.3.1 Texture analysis

The EHD drying experiments were conducted at 60-65% RH, at an equilibrium moisture content of 0.38 ± 0.02 g/g (approximately 0.4 g/g) for apple slices, below which the moisture content cannot be further reduced. However, the low humidity (16%) in the thermal dryer reduces the equilibrium moisture content to 0.25 ± 0.01 g/g. Therefore, the effect of final moisture content on texture was also evaluated along with thickness and drying technique. The preliminary results from texture analysis are given in Table b (Appendix A5). The hardness of EHD and hot air-dried (0.25 g/g and 0.4 g/g final moisture content) apple slices are shown in Figure 5.1.

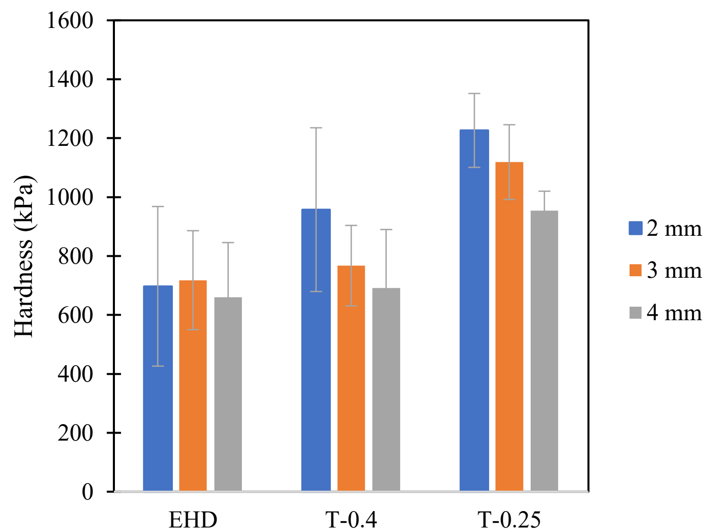


Figure 5.1: Hardness of EHD (0.4 g/g final moisture content) and hot air-dried (0.4 g/g and 0.25 g/g final moisture content) apple slices

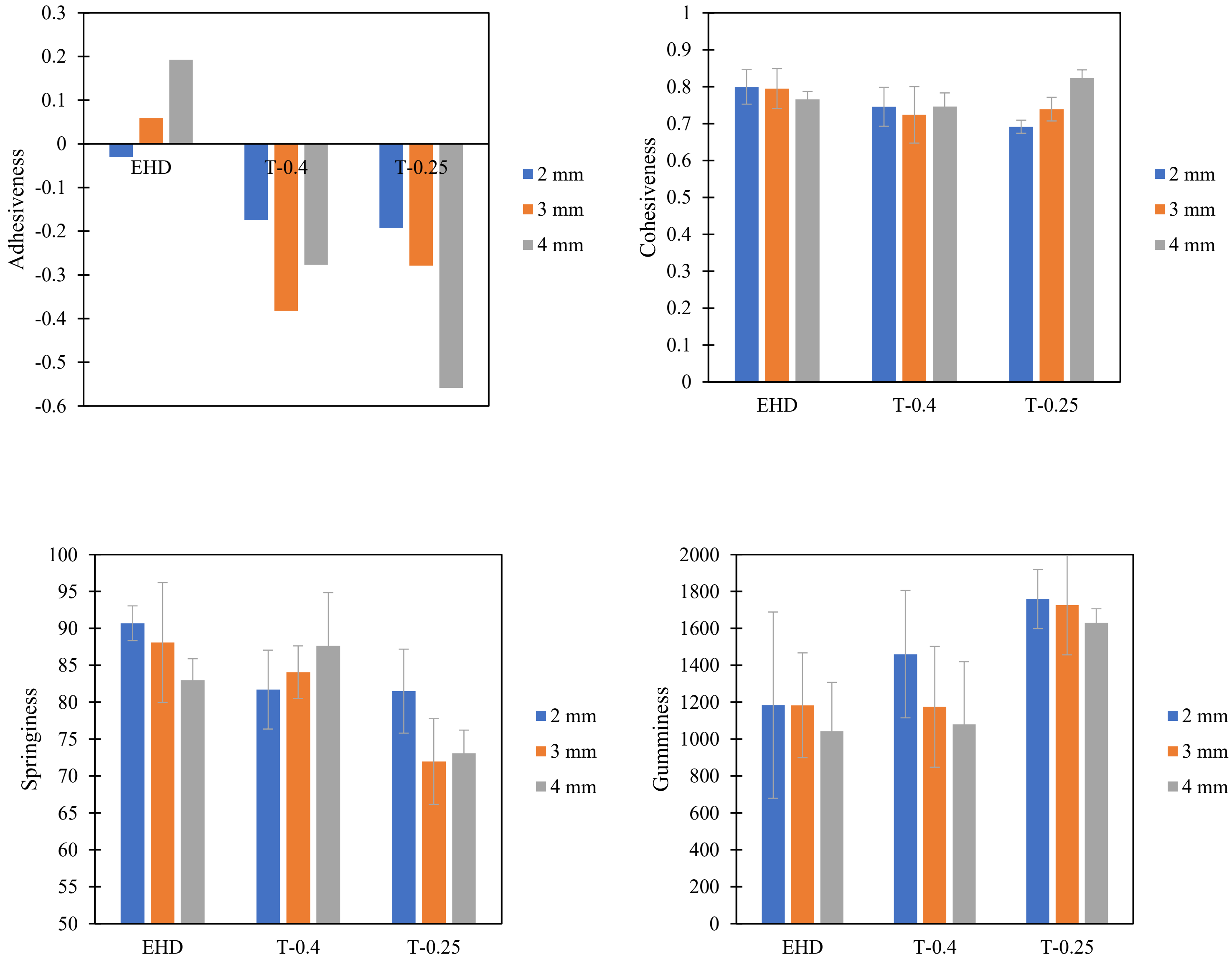
It was observed that hardness significantly changed with the final moisture content, but it was almost the same for EHD and hot air-dried apple slices at the same final moisture content of 0.4 g H2O/g dry weight. This was in accordance with the results obtained in previous studies on the textural analysis of apple slices (Bourne, 1986; Martynenko & Janaszek, 2014). The authors reported that the glass transition occurs after a critical moisture content level, dramatically increasing the hardness values.

Most of the studies analyzing textural properties of dried fruit slices focused on the hardness and crispiness. Since the apple dried in EHD was not crispy/brittle and was soft to touch, the properties like adhesiveness, cohesiveness, springiness, gumminess, and chewiness were studied. The statistical analysis shows that the textural properties including hardness, springiness, and gumminess changed with final moisture content and not with the thickness (Table 5.1). The effect of final moisture content on adhesiveness was marginally significant at a 0.05 significance level.

Table 5.1: The ANOVA p-values of textural properties at a 0.05 significance level

Factors	**Hardness**	**Adhesiveness**	**Resilience**	**Cohesiveness**	**Springiness**	**Gumminess**	**Chewiness**
EHD/T-Moisture Content	**0.006**	0.051	0.579	0.189	**0.009**	**0.017**	0.147
Thickness	0.248	0.302	0.308	0.425	0.532	0.505	0.3
Interaction	0.889	0.151	0.054	0.142	0.328	0.958	0.989

The textural properties of EHD and hot air-dried apple slices are shown in Figure 5.2.



Adhesiveness
EHD
T-0.4
T-0.25
Cohesiveness
Springiness
Gumminess
2 mm
3 mm
4 mm

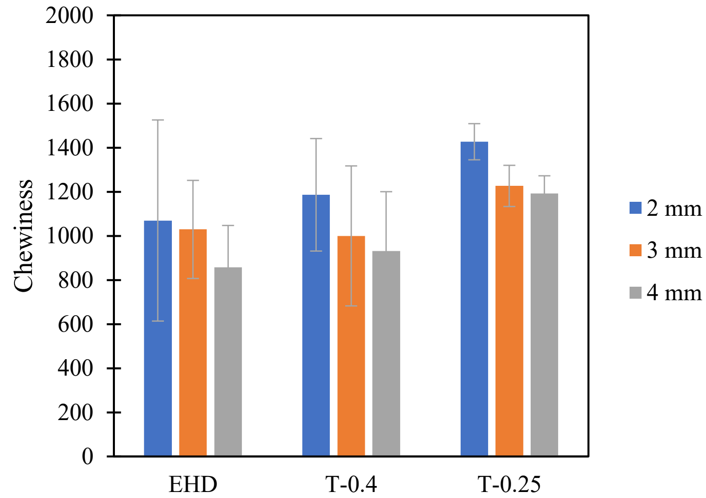


Figure 5.2: Textural properties of EHD (0.4 g/g final moisture content) and hot air-dried (0.4 g/g and 0.25 g/g final moisture content) apple slices

In Figure 5.2, adhesiveness values were positive for EHD dried apple slices at 3- and 4-mm thickness, indicating a softer texture. It was in the negative range for all other drying conditions explored, irrespective of thickness and final moisture content. Springiness, the ability to spring back when a force is released, was lowest for hot air dried at 0.25 moisture content, whereas the gumminess, a product of hardness and cohesiveness, was the highest. The cohesiveness and chewiness didn't exhibit significant variations between the drying type, thickness, and final moisture content.

5.3.2 Microscopic analysis

EHD drying is primarily a surface phenomenon, imparting surface microstructural changes. The charged particles interact with the outer layer, causing perforations and enhancing moisture diffusivity (Ni et al., 2019; Yu et al., 2017). Therefore, apple slice cross sections were viewed under a microscope to observe these morphological changes. The microscopic images of fresh, EHD and hot air-dried apple slices are shown in Figure

5.3. The slides were viewed in an optical microscope at 100x magnification. Methylene blue was used for staining, but the images are shown in black and white for more clarity.

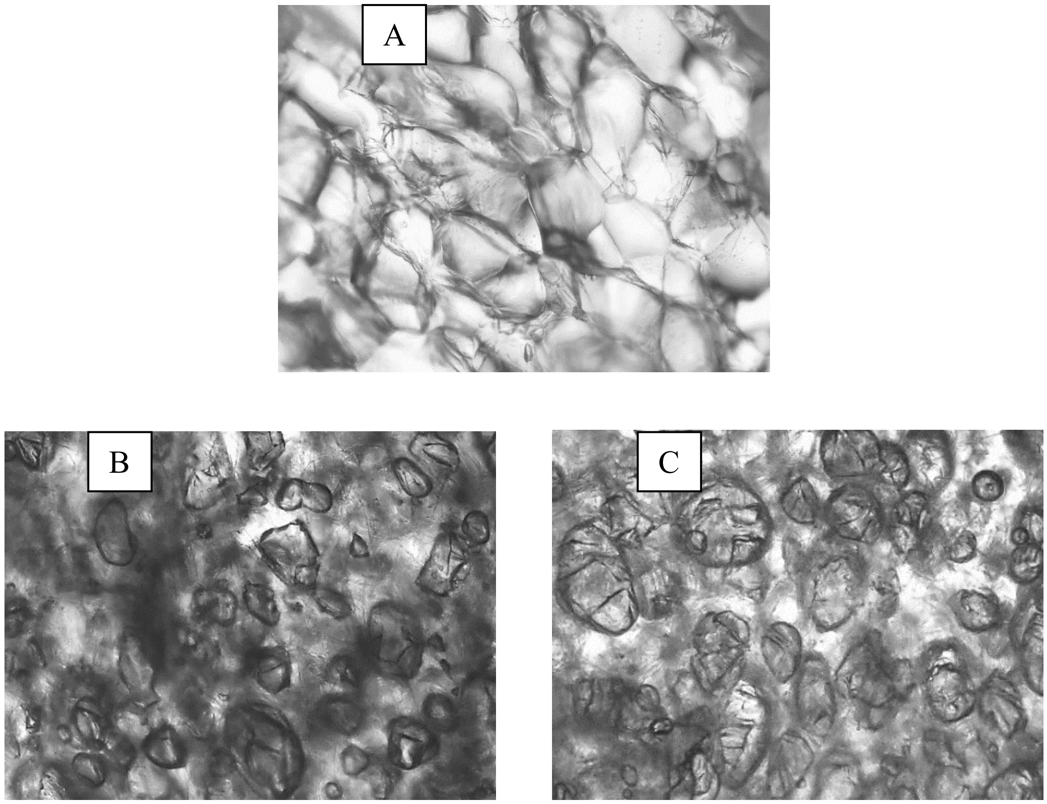


Figure 5.3: Microscopic images of (A) Fresh, (B) EHD dried, and (C) Hot air-dried apple slices (100x magnification)

The cross sections of apple slices were taken only from the outer layer of 4 mm apple slices, as it was challenging to obtain cross sections from thinner slices. From Figure 5.3, the apple parenchymal cells were clearly visible in the fresh. In contrast, the cells were shrunken in both EHD and hot air-dried samples, and the cells appeared to be more ruptured in the hot air-dried apple slices. This was in accordance with the surface morphological changes observed in goji berry upon EHD and thermal drying (Ni et al., 2020a; Ni et al., 2020c). The study reported visible cracks on the thermal dried compared to small perforations on EHD dried goji berries from the scanning electron microscopic images.

5.4 CONCLUSIONS

The textural properties of EHD and hot air-dried apple slices were analyzed in a texture analyzer. The comparative study revealed a significant effect of final moisture content on the textural properties. However, the textural properties were not affected by the thickness of the apple slices or the drying technique. The microscopic images showed lesser cellular rupture and damage in EHD than in hot air-dried apple slices. Furthermore, the cellular shrinkage was almost similar in both cases.

CHAPTER 6 GENERAL CONCLUSIONS AND FUTURE RECOMMENDATIONS

Electrohydrodynamic drying is a novel and non-thermal drying technique that has been explored for over 20 years in the field of food and agriculture. This promising dewatering technique is awaiting to be commercialized for industrial purposes. Researchers have reported several benefits of EHD drying over conventional high-temperature drying techniques because of its simple design, low energy consumption (approximately 1000 kJ/kg), and quality retention. However, there are several challenges yet to be addressed. The significant factors affecting EHD drying include electrical parameters, electrode configuration, material properties, and environmental conditions. The food drying characteristics like drying kinetics, effective diffusivity, energy efficiency, and dry product quality depend on these factors.

From the literature review (Chapter 2), it follows that most studies on the EHD drying of fruits and foods, in general, proved the efficacy of EHD over ambient or oven drying techniques. Most of the works focused on the effect of electric field intensities and electrode configuration on the drying characteristics and quality. However, the influence of material properties and environmental conditions was underexplored. At the same time, evaluating energy and quality aspects is essential for commercializing the EHD drying technique and improving consumer acceptance of dried fruits.

The primary objective of this thesis was to design a multifactorial experiment to evaluate the main and interaction effects of material properties and environmental conditions on the EHD drying of fruits. Therefore, a preliminary analysis was conducted to evaluate the effect of the material and environmental factors affecting EHD drying with a particular focus on slice thickness (Chapter 3). Considering the industrial relevance, two fruits - apples and strawberries were selected for the drying experiments. The drying kinetics, energy consumption, and quality attributes like shrinkage and color of EHD and hot air-dried fruit slices were compared.

The study revealed that the EHD induced drying flux and effective diffusivity didn't change with slice thickness. However, the drying rate constant significantly decreased with thickness, which increased the drying time. The specific and total energy consumption also increased with the increase in thickness. A significant impact of relative humidity on the EHD drying kinetics was also observed during the drying trials, where the drying flux was substantially reduced at higher humidity. The area shrinkage and discoloration were considerably reduced in EHD dried compared to hot air-dried fruit slices. The shrinkage and color were determined through image analysis, and it was difficult to determine the color of strawberry slices because of the non-uniform color distribution. The results obtained from this preliminary study were further used to design the multifactorial experiment.

Based on the preliminary results, a multifactorial experiment was designed with slice thickness in the range 1-3 mm, load density of 50 and 100%, external airflow in the range of 0-1 m/s, and relative humidity as the independent factors with randomized experimental runs in Minitab 19 statistical software (Chapter 4). A new EHD dryer was designed with the dimensions of the multipin discharge electrode same as that of the collecting electrode for full coverage. The drying kinetics, specific energy consumption, and quality of EHD and hot air-dried apple slices were determined. The results of the multifactorial experiment confirmed that the drying flux in the constant rate period of drying was independent of thickness but significantly changed with slice load density and relative humidity. The drying flux was higher at 50% load density and low (40-50%) relative humidity. Significant interactions between thickness-load and load-airflow on the drying flux were also observed.

The drying rate constant and effective diffusivity significantly increased with the external airflow. Additionally, the drying rate constant decreased with increase in thickness. The specific energy consumption depended on the load density, with low energy efficiency at 50% compared to 100% load. This decrease in energy efficiency invalidates the positive effect of low load density on drying, showing that the faster drying kinetics might not be economical.

The range of factors studied did not significantly affect the quality, except for the shrinkage and rehydration ratio, which were significantly affected by the slice thickness. The area and volumetric shrinkage were the smallest for 1 mm thick slices, while the rehydration ratio was the highest at 1 mm. As observed in the preliminary analysis, EHD dried apple slices had smaller area shrinkage and color changes than hot air-dried apple slices. The disintegration index was slightly smaller in EHD drying with a slightly higher polyphenolic content.

The comparison of textural properties of EHD and hot air-dried apple slices in Chapter 5 confirmed a significant dependence of texture on the final moisture content. The textural properties were not affected by the thickness of the apple slices or the drying technique (EHD/hot air). The microscopic images revealed the microstructural changes demonstrating less cellular rupture and damage in EHD than in hot air-dried apple slices.

Besides, the cellular shrinkage was almost similar in both cases. Hence, EHD drying has been confirmed to be an effective drying technique with low energy consumption and better product quality compared to hot air drying. Moreover, the quality changes in apple slices based on the factors considered were minimal.

Key contributions and practical applications

- The existing studies on EHD drying of foods predominantly compared EHD with ambient air or oven drying techniques. There were no studies on the EHD operating conditions affecting the dry product quality to date, except for the influence of electric field intensities. This study provides an insight into the influence of material and environmental factors affecting the EHD drying of fruit slices.
- Strawberries were chosen for drying experiments considering the market demand. Strawberry slices were dried using EHD for the first time, and the experiments showed significantly low energy consumption by retaining quality of the product.
- The main and interaction effects of slice thickness, load density, and external airflow were thoroughly evaluated on the drying efficiency and quality of EHD dried apple slices. The optimal humidity range for higher drying flux was found to be 40-50% RH. This data is crucial for designing an EHD dryer and industrial upscaling of the EHD drying technique.
- In our study, the specific energy consumption in the EHD dryer was 12-20 times smaller than in the hot air dryer, and the energy consumption was relatively smaller at 100% load density. The low energy requirements make EHD drying an industrially favorable and environmentally sustainable technique. It also makes the EHD drying technique affordable to small-scale farms and fruit processing industries.

- Maintaining the quality is essential for consumer acceptance of dry products. Consequently, industries focus on adapting nonthermal drying techniques for heat-sensitive food products. In this study, the considered factors didn't impact the quality attributes in EHD drying. Moreover, EHD drying has better-retained product quality than hot air drying.
- Since the research on the effects on EHD on the textural properties dry foods is very scarce, this study compared the textural properties of EHD and hot air-dried apple slices without any pre- or post-treatment. The correlation of texture with moisture content was confirmed, and textural changes were independent of the drying technique in the drying conditions used.

Future recommendations

- The relative humidity was uncontrollable in this study and was used as a covariate in the statistical analysis. It was found that RH > 65% was negatively influencing the drying kinetics. Hence, focused studies on the impact of relative humidity are essential for optimizing the EHD drying technique and designing an industrial-scale EHD dryer.
- The sensory attributes of the EHD dried fruit slices could be further explored through manual and instrumentation techniques.
- Consumer surveys and sensory panel evaluations should be done to evaluate the acceptance of the public for the new food drying technique and dried products.
- The optimization studies are more complex in the food and agriculture industry as the drying conditions may vary depending on the raw material. Hence, more research must be performed on EHD drying for industrial upscaling.

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APPENDICES

Appendix A

A1

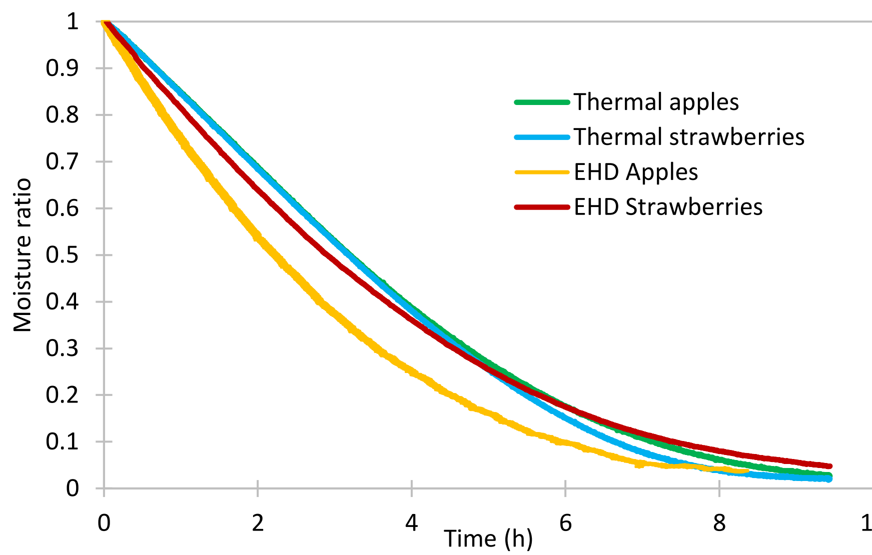

Figure a: Drying kinetics of EHD (22 kV and 4 cm) and hot air (40°C and 0.15 m/s) dried apple and strawberry slices

Table a: Drying rate constant and effective diffusivity in tray (hot air) drier at different temperatures for 2 mm apple slices

Temperature (°C)	**Relative humidity (%)**	**Airflow (m/s)**	**Average drying rate constant, k (h^{-1})**	**Effective diffusivity (x10^{-11} m^2/s)**
40	16	0.15	1.328	1.15
35	36	0.15	0.648	0.706
32	40	0.15	0.501	0.544
30	49	0.15	0.228	0.285

A2

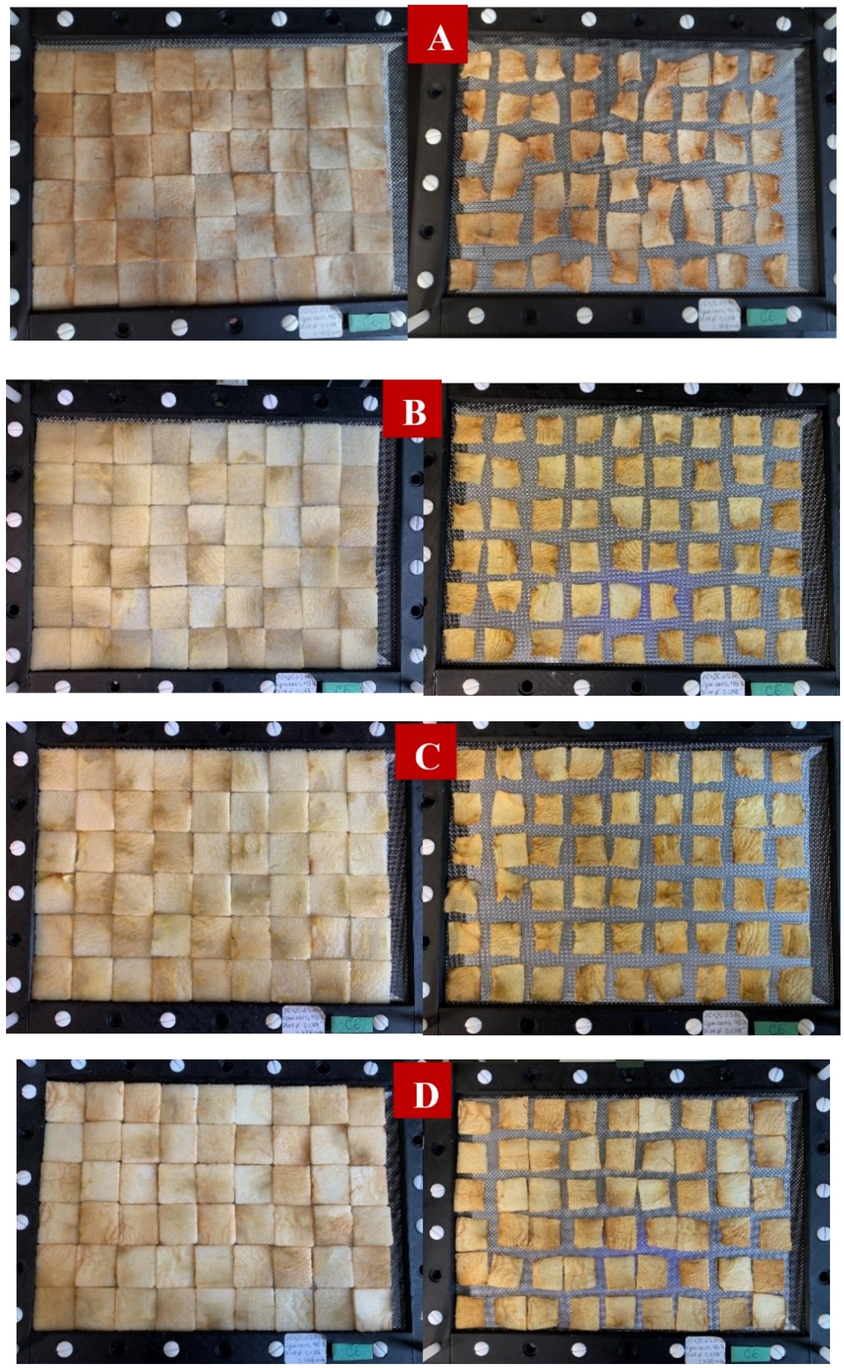

Figure b: Apple slices 1-mm (A), 2-mm (B), 3-mm (C), and 4-mm (D) before (left) and after (right) EHD drying

A3

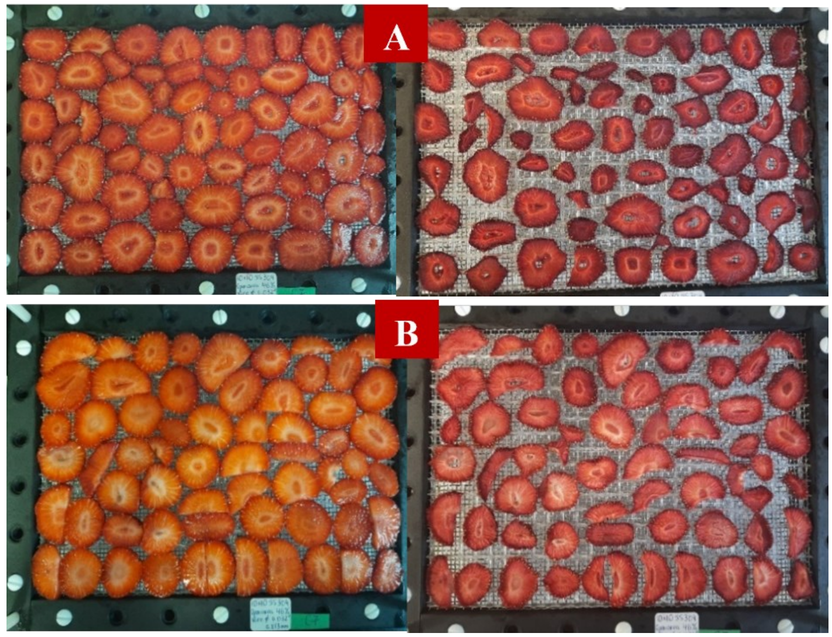

Figure c: Strawberry slices 3-mm (A) and 4-mm (B) before (left) and after (right) EHD drying

A4

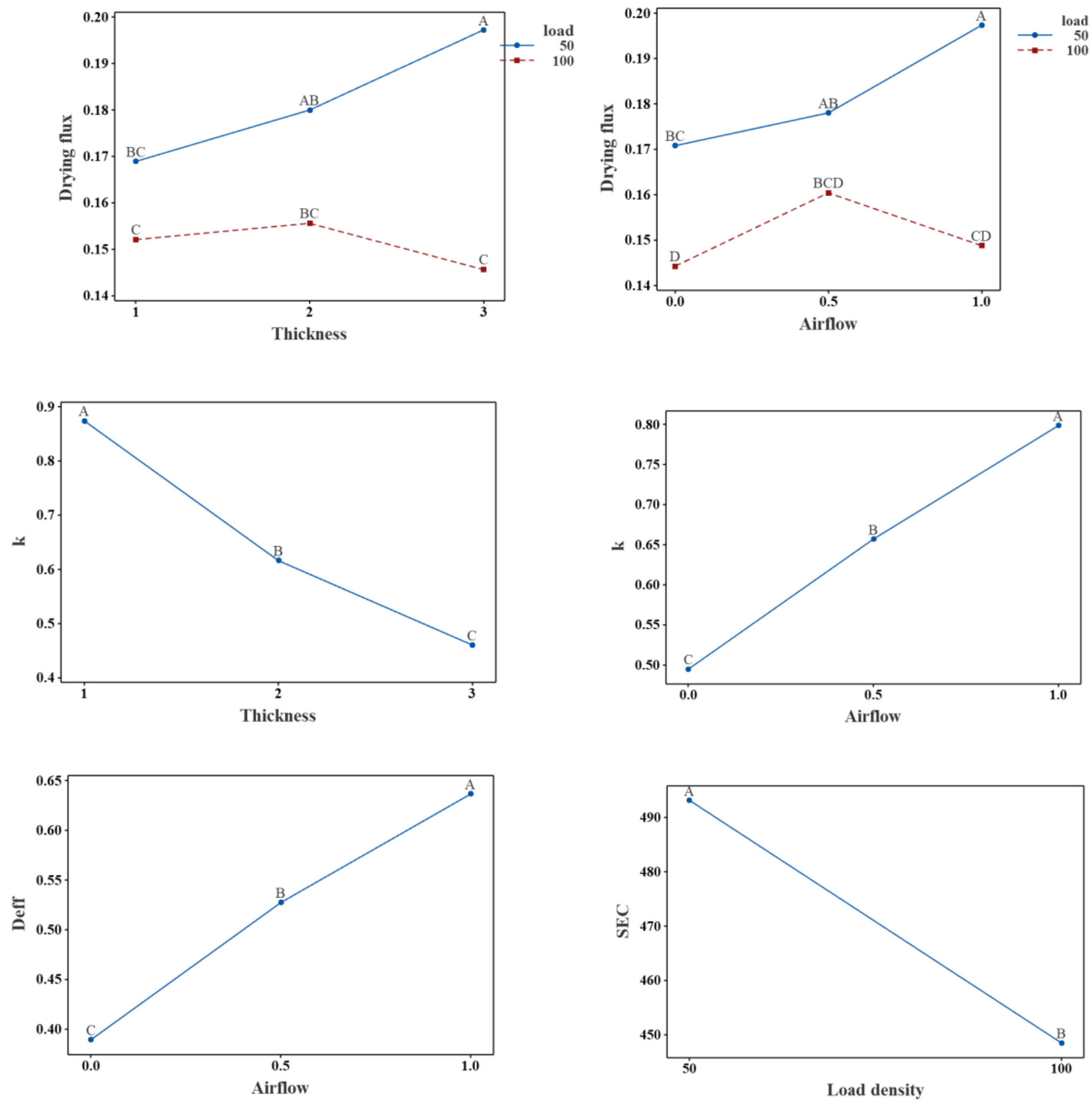

Figure d: Main and interaction effects of input factors on drying characteristics

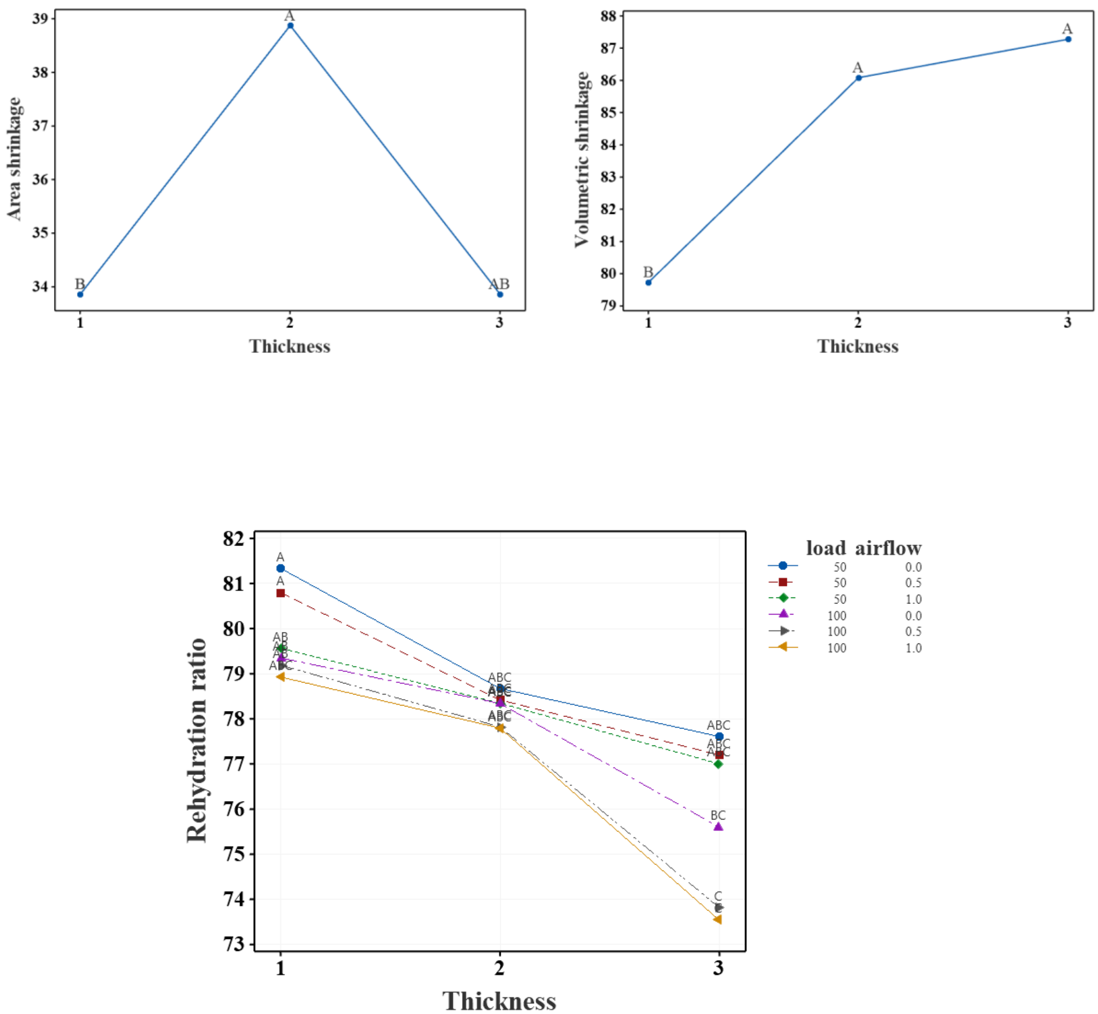

Figure e: Main and interaction effect of input factors on quality

A5

Table b: Textural properties of EHD and hot air-dried apple slices

Drying technique	**EHD**			**Thermal**			**Thermal**		
Final moisture content (g/g)	0.4	0.4	0.4	0.4	0.4	0.4	0.25	0.25	0.25
Thickness (mm)	2	3	4	2	3	4	2	3	4
Hardness (kPa)	697.17±271	717.93±167	660.08±185	957.32±278	767.29±137	691.31±198	1226.31±125	1118.77±127	954.05±66
Adhesiveness (gs)	-0.029±0.55	0.058±0.44	0.193±0.51	-0.175±0.33	-0.382±0.12	0.101±0.66	-0.193±0.50	-0.278±0.31	-1.558±0.46
Resilience (%)	29.96±8.01	32.36±9.79	25.24±1.23	29.22±8.98	32.26±7.15	29.11±4.19	23.74±2.58	29.24±4.57	46.88±2.57
Cohesiveness	0.799±0.04	0.795±0.05	0.765±0.02	0.745±0.05	0.724±0.08	0.746±0.04	0.691±0.02	0.739±0.03	0.824±0.02
Springiness (%)	90.70±2.35	88.09±8.13	82.99±2.90	81.71±5.34	84.07±3.56	87.66±7.19	81.51±5.69	71.97±5.81	73.09±3.13
Gumminess	1184.35±505	1183.66±283	1042.02±265	1460.57±345	1175.47±327	1079.81±339	1759.35±159	1725.96±269	1630.97±75
Chewiness	1069.68±456	1029.21±222	857.12±190	1186.27±255	999.91±317	931.72±269	1426.86±82	1226.49±93	1192.37±80

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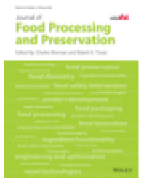

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