Impact of pre-treatment methods on the drying kinetics, product quality, and energy consumption of electrohydrodynamic drying of biological materials

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Abstract

Electrohydrodynamic (EHD) drying is an energy-efficient drying method. This novel drying technology operates at room temperature, which makes it particularly suitable for drying biomaterials that contain heat-sensitive compounds. It has a higher drying rate than other low-temperature methods, such as solar and freeze-drying. However, its drying rate is not high enough to compete with other conventional thermal methods, such as hot-air drying. For industrial applications requiring high product throughput, the drying rate of EHD drying should be improved. One way to do this is to combine EHD with pre-treatment method. Therefore, this study evaluated the impact of different pre-treatment methods on drying kinetics, energy consumption, and product quality attributes of apple slices dried using EHD drying. Pulsed electric fields (PEF), ultrasound, and blanching are the studied pre-treatment methods. Results show that only PEF pre-treatment could significantly decrease the EHD drying time by 39%. However, it resulted in a 26% higher browning index than the untreated EHD-dried apples, which is not appealing to consumers. The applied pre-treatment methods did not significantly affect other quality attributes, such as antioxidant activity, total phenolics, and rehydration ratio. In conclusion, using the studied pre-treatments for EHD drying is not advised as they increase the complexity of the process, whereas the added values do not exist or do not outweigh the energetic or quality downsides.

Keywords: Food processing; Industrial dryers; Ionic wind; Non-thermal; Batch drying

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1. INTRODUCTION

Fresh fruit and vegetables in long-term storage are at serious risk of spoilage due to enzymic and chemical reactions or the growth and activity of microorganisms such as fungi and bacteria [1]. Preserving methods such as drying, canning, freezing, and vacuum packing inhibit one or more of these conditions and stops their growth. Drying is one of the oldest and the most employed methods for large-scale preservation of solid foods [2]. Drying reduces the product volume and weight, which facilitates easy packing, handling, and storage [3]. However, it is an energy-intensive and time-consuming process due to the high latent heat of evaporation required for drying [4]. Thus, an important challenge of the food processing industry is to reduce the energy consumption of the drying process by upgrading the existing drying methods or developing energy-efficient alternatives.

Electrohydrodynamic (EHD) drying is a novel drying technology with a large potential for complying with both issues of drying, namely high product quality and low energy consumption [5]–[7]. EHD drying relies on airflow generation due to a high voltage difference between two electrodes: an emitter connected to a positive high-voltage power supply and a collector that is usually grounded or connected to a negative high-voltage (Figure 1a). Corona discharge is the primary mechanism for EHD airflow generation (Figure 1 b and c) [8]. This phenomenon happens when the electric field near a conductor is strong enough to ionize the dielectric surrounding it but not too strong to cause an electrical breakdown or arcing between conductors or other components [9]. This results in a self-sustaining ion generation process [10]. These ions move toward the collector due to the electrical forces. Their movement and the momentum transfer due to their collisions with neutral air particles (Figure 1a) results in an airflow from the emitter toward the collector. This airflow, called ionic wind, accelerates the convective moisture removal from the material to be dried (Figure 1d).

Recently, in a comprehensive study, the performance of EHD drying in different aspects was benchmarked against the common conventional drying methods, namely, hot-air, microwave, solar, and freeze-drying [11]. It was found that EHD drying performs significantly better than other studied drying methods in preserving the nutritional content and sensory appeal of dried fruits. It also has less environmental impact and higher energy and exergy efficiencies than others. However, the drying kinetics of fruits using EHD was found to be lower compared to the studied commercial drying methods [11]. This drying method may therefore not be an ideal drying alternative for the food processing industry, which requires high-throughput.

The relevant question now is how do we make EHD a high-throughput sustainable drying method for industrial food processing. It has been reported that different physical pre-treatments such as pulsed electric fields (PEF), ultrasound, and ultraviolet radiation prior to drying can enhance the drying rate [12], [13]. Therefore this study aims to investigate the impact of different pre-treatment methods on the performance of EHD drying from different aspects, namely drying kinetics, product quality, energy consumption, and environmental impact. Pulsed electric fields (PEF), ultrasound, and blanching are the pre-treatment methods considered for this study. PEF pre-treatment leads to electroporation and, consequently, the formation and growth of membrane pores [14]. US pre-treatment creates microscopic channels in the sample by inducing acoustic waves [15]. Blanching was also considered because some existing literature suggested that it can enhance mass transport by changing the water and ion permeability of cell membranes caused by heat stress [16], [17]. The ideal pre-treatment method should significantly enhance the drying rate without compromising product quality. Otherwise, increasing the complexity of the EHD drying process by adding pre-treatment methods cannot be recommended.

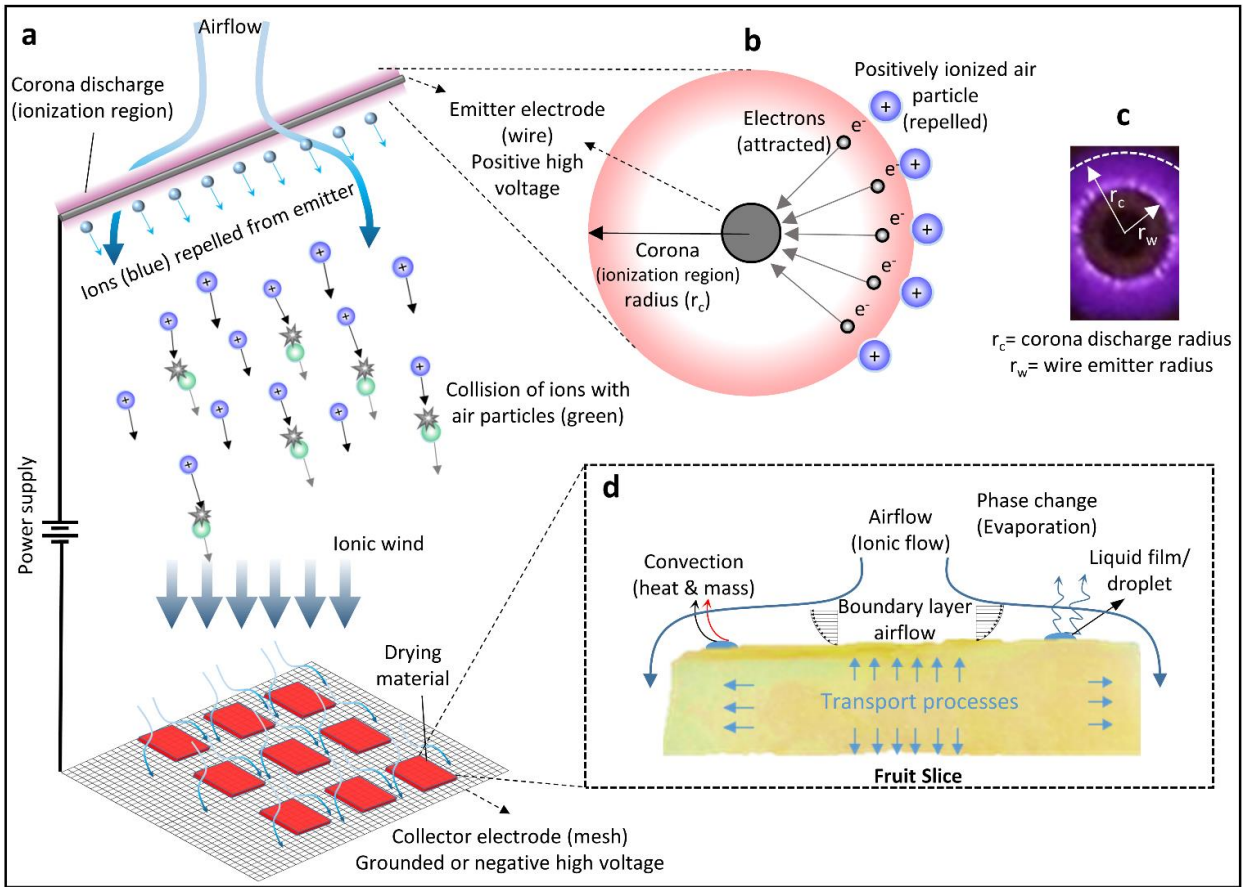

Figure 1 Schematic illustration of EHD drying process (not to scale). a) Schematic of a typical wire-to-mesh EHD drying setup, b) Schematic illustration of Corona discharge region, c) real Corona discharge using circular Dielectric Barrier Discharge (DBD) actuators to mimic the corona discharge conditions around a wire emitter (for more information see [18]), d) fresh apple slice under EHD drying together with dehydration mechanisms.

2. MATERIALS AND METHODS

2.1. Sample preparation and drying experiments

Apples of the Pink Lady cultivar were used for the drying experiments. For each drying test, four cylinders of 3 cm diameter and 5 ± 0.1 cm height were extracted from apple tissues using a cork borer. These cylinders were placed into four containers with 130 ml of distilled water for the control (without pre-treatment), PEF, ultrasound, and blanching pre-treatments. Untreated samples were placed inside the water at the same ratio (i.e., 130 ml of isotonic water) to make samples comparable. After pre-treatments, the surface water of the samples was removed using a paper towel, and the cylinders were further cut into circular disk samples with 3±0.1 mm thicknesses. A total of 24 samples (i.e., six slices from each pre-treatment method and six samples for the control) were randomly chosen, placed in small labeled Petri dishes, weighed, and put into the dryer immediately to reduce surface enzymatic browning. These samples were randomly distributed on the drying surface (collector) and all samples of different pre-treatments were dried together with the untreated samples (Figure 2). EHD drying tests were performed using a lab-scale EHD drying setup. More details about the lab-scale EHD dryer can be found in section 2.2 and [19]. For drying kinetics, the samples were weighted every 10 minutes during the first two hours of drying and every 30 minutes after the first two hours. The initial moisture content MC_{wb} (wet basis) of the untreated samples was estimated by measuring the weight difference after placing them at 105 ± 1 ℃ for 24 hours and was equal to

MC_{wb}=85± 0.7% [g g_{wb}^{-1}] [19]. After treatments, the moisture content of the samples was also determined with the same method, and it was equal to MC_{wb}=88± 2% [g g_{wb}^{-1}]. The higher moisture content in the treated samples is due to the sponge effect, which refers to water gain after treatment due to the formation of microchannels and cavitation inside the food tissue [20].

2.2. EHD drying experimental setup

EHD drying tests were carried out in a lab-scale EHD drying setup (Figure 2) optimized based on the previous simulation and experimental studies [18], [21]. The main components of this upscalable setup are a convective chamber (40×40×70 cm), a digital weighing scale (0.1 g resolution, PG5001-S, Mettler-Toledo, Greifensee, Switzerland), discharge (emitter) wire electrodes and collecting plate electrode, and two high-voltage power supplies of positive and negative polarity (Spellman_SL30PN10, 0～30kV). The emitter wires were positively charged and the plate collector was connected to the negative high-voltage power supply. The samples were placed on the plate collector (Figure 2). The total energy consumption (i.e., overall energy consumed by the dryer) was measured using a plug power meter (MegaPower™, Digiparts, Canada). The discharge energy consumption of the EHD dryer was calculated based on the current and voltage applied between electrodes and monitored using a multimeter (Keysight U1253B, Santa Rosa, CA, USA) and a 1000:1 high-voltage probe (Testec HVP-40, Testec Elektronik GmbH, Germany). A customized test box (1 m ×1 m × 2 m) was built to control the test condition and respect the safety guidelines regarding working in the high voltage environment (i.e., Faraday cage). The EHD drying chamber and all associated equipment were placed in the test box. All the experiments were carried out inside this box. More details about the EHD drying setup are available in [18].

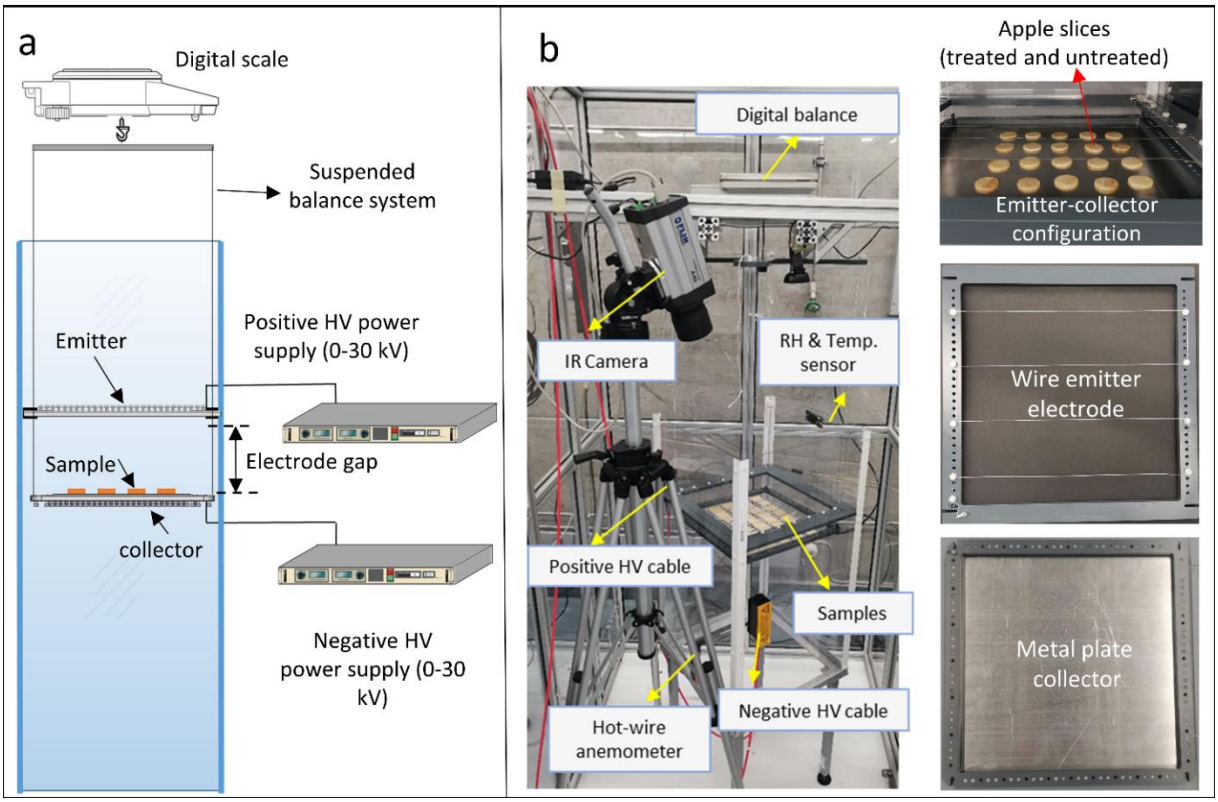

Figure 2 a) Schematic illustration of the experimental setup (not to scale), b) Experimental setup together with the wire-to-plate emitter-collector configurations. The treated and untreated samples are distributed randomly on the collector and their locations are numbered and recorded.

2.3. Pre-treatments

Samples were pre-treated by hot water blanching (HWB), ultrasound (US), and pulsed electric field (PEF) methods before the drying process. The untreated samples were taken as the control. Since applying different drying methods leads to different equilibrium levels for the same material, the samples were dried to reach a certain moisture content in all the drying methods. This enables us to perform the quality test of the dried products under the same conditions. MC_{wb} =15% [g g_{wb}^{-1}] was considered as the cut-off point, and the quality assessment tests on the dried products were performed at this moisture content. MC_{wb} =15% [g g_{wb}^{-1}] was selected because it is below the critical moisture content (for apple slices ~23% [g g_{wb}^{-1}]), which is the averaged moisture content in the sample that corresponds to an equilibrium water activity below which no spoilage occurs [21]. As such, the drying experiments for quality assessment were stopped at different times, depending on when this threshold was reached.

2.3.1. Hot water blanching (HWB)

A 3 cm diameter and 5 ± 0.1 cm height apple tissue cylinder (≈ 33 g) was immersed in a 1000 mL beaker with 130 ml of 60°C distilled water for 3 minutes. The beaker was placed in an oven to keep the temperature constant.

2.3.2. Ultrasound (US) pre-treatment

The apple tissue cylinder (≈ 33 g) was placed in a 1000 mL beaker. 130 mL of distilled water was added to the beaker to reach the recommended 1:4 samples to water weight ratio [22]. The beaker with samples was positioned in an ice water bath (i.e., to maintain the temperature inside the bath at 0 – 4 °C during sonication) and then placed in an ultrasonic bath (20 kHz, UIP1000 HdT, Hielscher, Germany). The US probe was submerged to a depth of 20 mm. The duty cycle was set at 50%, the applied frequency was 20 kHz, and the power was 54 W. The sonication was performed intermittently (5 minutes on and 5 minutes off) for a total sonication time of 10 minutes. The temperature increase after 10 minutes of ultrasound treatment was 12 °C.

2.3.3. Pulsed electric field (PEF) treatment

The apple tissue cylinder (≈ 33 g) mixed with 130 ml of water was placed inside a batch chamber with a 40-mm electrode distance and processed with an HVP-5 (DIL, Quackenbrück, Germany) PEF system. The system was connected to an oscilloscope (Voltcraft, DSO-1062D, Conrad electronics, Hirschau Germany) that was used to monitor the pulses. The samples were treated with 1810 rectangular pulses with 30 µs width at the following conditions: 4.8 kV/cm, 30.5 A, 20 Hz and a temperature that did not exceed 40 °C after the treatment. The motivation for such an intense treatment was being comparable with ultrasound pre-treatment from an input energy perspective and having the same energy applied by both pre-treatments (≈31.8kJ). In addition, if such an intense PEF pre-treatment does not make any difference in the drying kinetics, a less intense PEF cannot significantly affect the drying rate [23]. The specific energy input of PEF pre-treatment $w_{spec.}$ [kJ kg^{-1}] was calculated using the following equation:

$$w_{spec.} = \frac{n}{m_0}\int_0^{\infty} V(t)\cdot I(t)dt \quad (1)$$

Where n is the number of pulses, m_0 (kg) is the mass of the sample, $V(t)$ [V] and $I(t)$ [A] are the voltage and the current as a function of the treatment time, and t [s] is the time.

2.4. Performance indicators and metrics

2.4.1. Critical drying time

The critical drying time (t_{crit}) was considered as the reference drying time for comparing the EHD drying rate with different pre-treatments. Using t_{crit} enables us to have a simple way to compare different drying curves. It is defined as the time needed for the sample to reach the critical moisture content (w_{crit}). w_{crit} is the averaged moisture content in the sample that corresponds to an equilibrium water activity below which no spoilage occurs [21]. For the apple slices, w_{crit} is 37.8 kg m^{-3}.

2.4.2. Specific drying rate (SDR)

The average drying rate [kg_{H2O} h^{-1}] up to the critical drying time was derived from the moisture ratio curves:

$$DR = \frac{evaporated\ water\ mass}{\Delta t} \quad (2)$$

Since the drying rate is dependent on the mass of the wet sample, specific drying rate (SDR) was considered to make the drying rate index comparable for different fruit loading densities. SDR is defined as the drying rate per kilogram of drying material [g_{H2O} $kg^{-1}s^{-1}$]:

$$SDR = \frac{DR}{m_0} \quad (3)$$

where m_0 [kg] is the total mass of the fresh-cut drying products loaded on the dryer.

2.4.3. Specific energy consumption (SEC)

The specific energy consumption (SEC) [J $kg_{H_2O}^{-1}$] is defined as the net energy E [J] used to evaporate a unit mass of water Δm [kg]:

$$SEC = \frac{E}{m_{eva}} \quad (4)$$

m_{eva} is the evaporated water mass. The energy consumption of the drying is calculated as $E = V.I.t_{crit} + E_{PT}$, where V [V] is the applied voltage in EHD, I [A] is the current in EHD, E_{PT} [J] is the energy consumed for pre-treatment. Energy consumptions of the pre-treatment methods are calculated using the standard formulation provided in [12], [20], [24].

2.4.4. Color change measurements (CIE-LAB color parameters)

The surface color of apple slices was measured prior to pre-treatment and after the drying using a Minolta chroma meter (CM-2600D, Konica Minolta Inc., Japan) with CIELab system, illuminant D_{65} (daylight), SCE (specular component excluded) mode, and 10° observer angle. Before the color acquisition, the colorimeter was calibrated using a standard white plate.

The overall color change, ΔE, was calculated using the following equation [25], [26]:

$$\Delta E = \sqrt{(L_0^* - L^*)^2 + (a_0^* - a^*)^2 + (b_0^* - b^*)^2} \quad (5)$$

where L^*, a^*, and b^* are the parameters of the CIE color coordinate system defined by the Commission Internationale de l'Eclairage (CIE). Overall, six samples from each untreated and treated batch were tested three times each and the mean value and standard deviation are reported in this paper.

2.4.5. Rehydration ratio

Rehydration ratio is defined as the drained weight of the rehydrated sample to the weight of the dry sample. For rehydration measurements, the samples were first weighed, then 10 ml of hot tap water at 75° C were pipetted into the apple samples in their Petri dishes. They were then placed in an oven at 75° C for 90 min. The samples were drained over a mesh for two minutes, followed by gently blotting with paper tissue 3–4 times to absorb and remove the surface water and then reweighed to calculate the water absorption.

2.4.6. Total phenolic content measurements

To determine antioxidant capacity and total phenolic content (TPC), the amount of water previously lost during drying was added to the samples. This allowed us to treat our samples as fresh-weight samples. 1 ml of deionized water was added to the samples in order to obtain sufficient supernatant for the measurements. The samples were centrifuged at 14000 rpm for 20 min and the supernatant was collected. Folin-Ciocalteu method [27] using chlorogenic acid as a standard was used for the TPC analysis. To this end, 1 ml of extract was mixed with 5 ml Folin reagent (1 N) and after 5 min, 4 ml of Na_2CO_3 solution (3%) was added to stop the reaction and let for 1 h at room temperature in the dark. Then the absorbance was measured at 765 nm. Twenty-four samples from two different drying batches were tested for each drying method. TPC was calculated and expressed as µg chlorogenic acid equivalent (CAE) equivalent per 1 g of apples.

2.4.7. Trolox equivalent antioxidant capacity (TEAC)

The obtained extract from the dried samples described in section 2.4.6 was used for estimating the antioxidant activity. Twenty-four samples from two different drying batches were tested for each drying method. To evaluate the total antioxidant capacity of the dried products, Trolox Equivalent Antioxidant Capacity (TEAC) assay described by [28] has been used.

2.4.8. Fruit microstructure

Three apple slices were randomly chosen from control, PEF, US, and HWB pre-treatments for microstructural analysis. A scanning electron microscope (SEM) (Phenom Elektronenmikroskop, Phenom-World BV, NL-5652 AM Eindhoven, Netherlands) was used to examine the structural changes of apple slices during drying qualitatively. SEM images were later captured using magnification from 59× to 2150×.

2.5. Statistical analysis of the data

All experiments were repeated twice. Measurements were carried out with three replications. The results were expressed as average ± standard deviation. Data that did not follow a normal distribution were normalized before the analysis.

Statistical differences among means of data obtained for samples were analyzed using a one-way analysis of variance (ANOVA) with the least significant difference comparison test (*t*-test) and accepted at a significance level of p-value < 0.05. Randomization was used in all the measurements to assure the independence of the error. All the statistical analyses were performed in R [29].

3. Results

3.1. Energy consumption and drying kinetics performance

This section compares the drying kinetics and specific energy consumption (SEC) of the untreated and treated apple slices dried by the EHD drying method. The results are shown in Table 1 and Figure 3. The drying kinetics of PEF-treated samples are significantly different ($p<0.05$) from the control. The critical drying time ($t_{crit.}$) of untreated samples was 155 min (Figure 3a and Table 1). PEF pre-treatment reduced the $t_{crit.}$ from 155 min to 95 min (39% reduction). Consequently, it increased the specific drying rate from 0.26 [g_{H2O} $kg^{-1}s^{-1}$] (untreated) to 0.48 [g_{H2O} $kg^{-1}s^{-1}$] and resulted in a 17% lower specific energy consumption (SEC) than the control (Figure 3b). Note that SEC accounts for energy consumed by the EHD dryer and the pre-treatments.

Ultrasound and blanching pre-treatments do not significantly ($p>0.05$) affect the drying curves (Figure 3a). Although these pre-treatments did not significantly improve the drying time ($p>0.05$), they increased the SEC, which in the case of US+EHD this difference was statistically significant (28% increase, $p<0.05$), Figure 3b). Accordingly, ultrasound and blanching pre-treatments increased the energy consumption of the process without improving the drying rate. Blanching was also considered because some existing literature suggested that it can enhance mass transport by changing the water and ion permeability of cell membranes caused by heat stress [16], [17]. However, based on our results, we can conclude that its impact on permeability was not sufficient to increase the drying rate significantly. Overall, from drying kinetics and energy consumption perspectives, only PEF pre-treatment shows an added value compared to the untreated samples.

Table 1 Energy consumption and drying kinetics performance of EHD drying with different pre-treatments for drying apple slices.

Method	**Indicator**		
	$t_{crit.}$ [min]	**SEC [MJ kg^{-1}_{H2O}]**	**SDR [g_{H2O} $kg^{-1}h^{-1}$]**
EHD	155	19.52	0.26
PEF+EHD	95	16.18	0.48
US+EHD	145	24.99	0.28
HWB+EHD	140	21.31	0.30

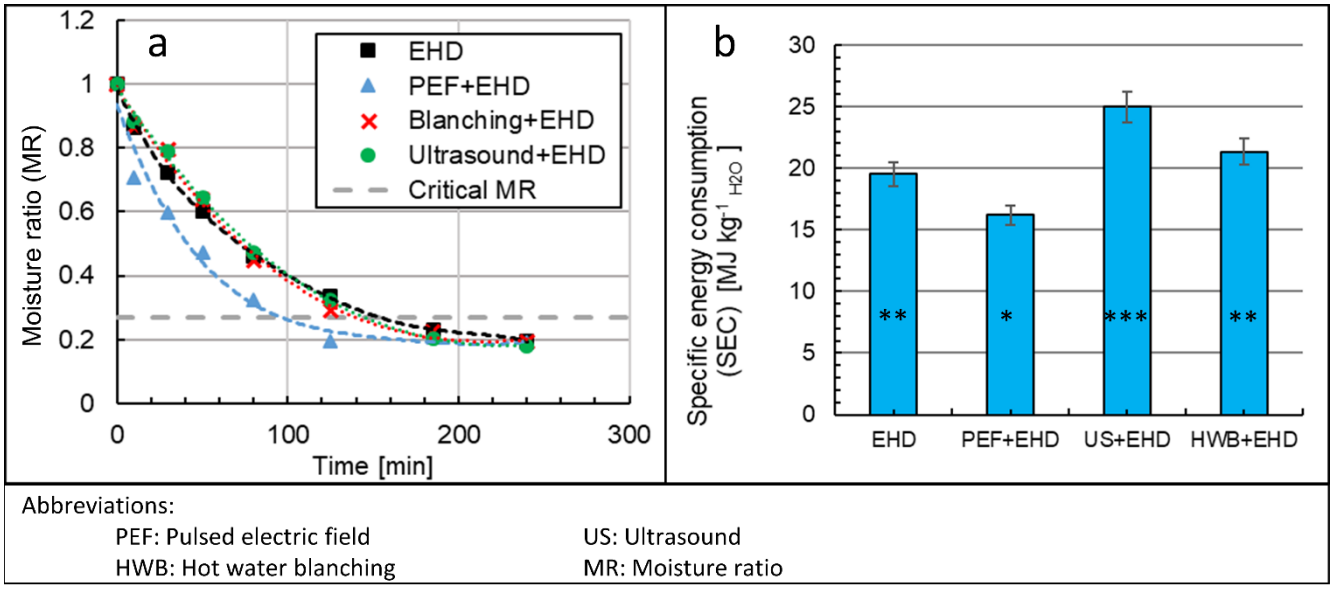

Figure 3 Drying kinetics and energy consumption performance for dehydrating the untreated and treated apple slices by EHD drying; a) Drying kinetics (moisture ratio vs. time), b) Specific energy consumption (SEC). The number of stars on the bars shows the statistical difference between the methods. Values with a similar number of stars are not significantly different (statistically P > 0.05). Error bars correspond to the standard error of means obtained for multiple replicates.

3.2. Quality attributes

This section compares the quality attributes of the untreated and treated apple slices dried by the EHD drying method. The results are shown in Figure 4 and detailed in Table 2 and Table 3. Antioxidant capacity and TPC were not significantly affected by pre-treatment methods ($p>0.05$) (Figure 4b and c). Consumers prefer visible quality; therefore, color degradation is a major quality attribute in dried food products. PEF pre-treatment resulted in a lower total color change than the control. However, the PEF-treated samples had a significantly higher (26%, $p<0.05$) browning index than untreated samples, which shows increased oxidation of phenolics (Figure 4a and Table 2). Having browning on the dried products is not appealing to consumers. L^* value indicates the light-dark spectrum ranging from 0 (black) to 100 (white). L_0^* culomn in Table 3 indicates that samples became darker by PEF pre-treatment before starting the drying process. a^* value shows the red-green spectrum ranging from -60 (green) to 60 (red) and b^* value indicates the yellow–blue spectrum ranging from -60 (blue) to 60 (yellow) of the samples. These values were also different in PEF-treated samples before starting the drying.

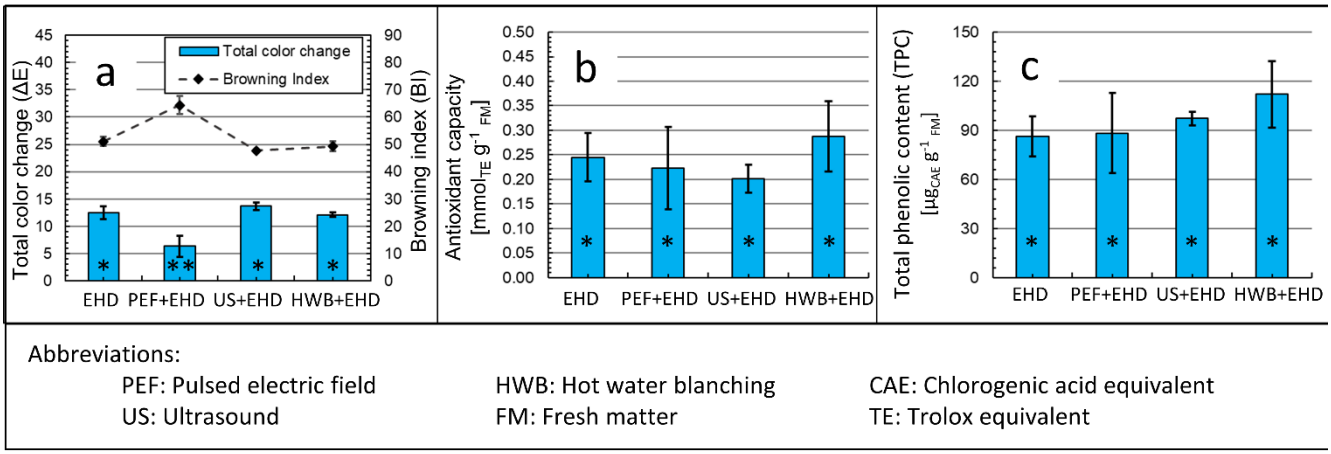

Figure 4 Quality indices performance for dehydrating the untreated and treated apple slices by EHD drying; a) Total color change and browning index, b) Antioxidant capacity, c) Total phenolic content. The number of stars on the bars shows the statistical difference between the methods. Values with a similar number of stars are not significantly different (statistically P > 0.05). Error bars correspond to the standard error of means obtained for multiple replicates.

Table 2 Physicochemical quality attributes for apple slices dried by EHD drying with different pre-treatments*,**.

Method	Quality indices				
	Rehydration ratio	Antioxidant capacity	TPC	ΔE	BI
EHD	3.69±0.4[a]	0.25±0.05[a]	86.22±12.2[a]	12.51±1.19[a]	51.10±1.71[a]
PEF+EHD	4.08±0.4[a]	0.22±0.08[a]	88.36±24.6[a]	6.32±1.96[b]	64.42±3.22[b]
US+EHD	3.86±0.6[a]	0.20±0.03[a]	97.23±4.1[a]	13.66 ±0.64[a]	47.76±0.45[a]
HWB+EHD	3.63±0.3[a]	0.29±0.07[a]	112.12±20.3[a]	12.11±0.44[a]	49.23±1.83[a]

*The values indicate mean±standard error of ten measurements in two different sets of experiments.

**Values within the same column with similar letters are not significantly different (statistically P > 0.05).

Table 3 CIE L*a*b* color coordinates for apple slices dried by EHD drying with different pre-treatments.

Method	Color coordinates[1]					
	L_0*	a_0*	b_0*	L*	a*	b*
EHD	74.59	-0.17	17.49	76.04	6.59	27.85
PEF+EHD	62.16	7.54	25.86	67.14	10.02	28.11
US+EHD	75.61	-1.33	15.51	77.21	5.77	27.05
HWB+EHD	74.06	-0.38	17.96	76.62	6.36	27.22

[1] L_0^*, a_0^*, and b_0^* are the color measurements of the samples after pre-treatments and before drying and L^*, a^*, and b^* are the color measurements of the same slices after drying.

The rehydration of dried samples depends on the microstructure changes caused by drying and processing [30]. Figure 5a shows the rehydration ratio of the EHD-dried samples with different pre-treatment methods. The differences are statistically insignificant ($p>0.05$). This can be explained by microstructural changes in samples after drying, which are presented in Figure 5b. The microstructure of dried samples was observed under a scanning electron microscope (SEM). Although microstructures in the PEF-treated samples are slightly different than others, the overall structures are similar. This could be the reason for the not significantly different rehydration ratio in the PEF-treated samples compared to others.

Overall, the results showed that only PEF pre-treatment could enhance the drying rate, however, with the drawback of having higher browning in dried samples.

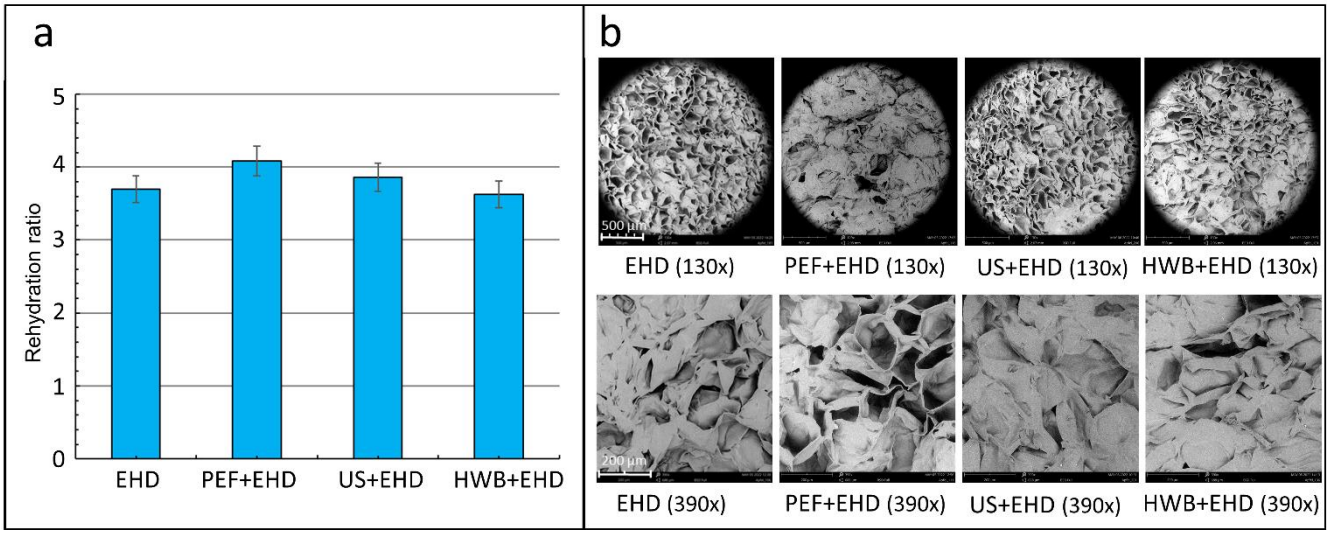

Figure 5 a) Rehydration ratio for EHD-dried apple slices with different pre-treatments, b) Scanning electron microscopy (SEM) images of EHD-dried apple slices with different pre-treatments at different magnifications (130X and 390X). Error bars correspond to the standard error of means obtained for multiple replicates.

4. Discussion and outlook

The reason for the different impacts of the pre-treatment methods on the specific drying rate could be attributed to their underlying physics. Although EHD drying is a convective-based drying method, transmembrane flow due to cell electroporation is the second major dehydration mechanism during EHD drying [31]. The contribution of other dehydration mechanisms is negligible compared to these two mechanisms, namely convection and transmembrane flow. PEF pre-treatment leads to electroporation and, consequently, the formation and growth of membrane pores [14]. This effect increases the transmembrane flow, the second major dehydration mechanism in EHD drying. Therefore, the significant impact of the PEF pre-treatment on the drying rate, shown in the results, could be attributed to the enhancement of the transmembrane flow. The same hypothesis could explain the statistically insignificant ($p>0.05$) impact of the US and HWB pre-treatments on the drying rate; The impact of these pre-treatments on the drying rate was insignificant because they did not improve the two major dehydration mechanisms of EHD drying. As mentioned before, US pre-treatment creates cavitation and microscopic channels in the sample by inducing acoustic waves [15]. Based on the SEM results, similar pores are observed in US-treated and untreated samples that show cavitations did not result in destroying the cellular structure. Blanching can enhance mass transport by changing the water and ion permeability of cell membranes caused by heat stress

[16], [17]. However, based on our results, we can conclude that its impact on permeability was not sufficient to increase the drying rate significantly. Nevertheless, further studies are required to verify these hypotheses and unravel the actual reasons for these observations.

Since the contribution of other dehydration mechanisms is negligible compared to convection [31], increasing the airflow rate for the same energy input should be the focus of future process optimization studies. In this regard, EHD air amplifier [32], [33] is a new promising concept with a high potential to be employed in an EHD dryer. It can increase the airflow, hence the convective drying rate, without compromising the promising characteristics of an EHD dryer.

Other studies have also reported that PEF pre-treatment of apple tissue can lead to enzymatic browning due to the release of substrates for enzyme activity [34], and nonenzymatic browning due to the promotion of Maillard reaction products [35], [36]. The promotion of Maillard reaction products occurs when an electric field at a high intensity (>30 kV/cm) is applied [35]. Therefore, in this study, the browning is mainly enzymatic because the PEF pre-treatment is applied at an intensity of 4.8 kV/cm. The enzymatic browning can be inhibited by using an ascorbic acid solution (1%) to control the phenol oxidase activities [37]. In this way, the drawbacks of PEF pre-treatment can be reduced, making it a good option to increase the drying rate of the EHD drying process without compromising the quality of the dried products.

Only one operating condition for each pre-treatment method was selected based on previous experiences to reduce the experimental time and costs. This was one of the main limitations of this study. Nevertheless, based on similar studies on employing these pre-treatments for convective-based drying methods, applying more intense treatments likely will not change the overall conclusion of this study. For instance, Nowacka et al. [38] applied US pre-treatment with a frequency of 35 kHz and for 30 minutes (40% increase in applied frequency and three times longer processing than this study) and could increase the drying rate by a maximum of 31% compared to the untreated samples. Changing the treatment time from 10 min to 20min and 30 min did not affect the drying time significantly.

5. Conclusion

The impact of PEF, ultrasound, and blanching pre-treatments on the drying kinetics, energy consumption, and quality attributes of EHD-dried apple slices are studied. The results showed that only PEF pre-treatments could significantly reduce the drying time and energy consumption compared to EHD drying alone. The applied PEF treatment resulted in 50% less overall color changes but significant browning (26%) of the dried samples. Moreover, after the treatment temperature of the samples increased from 20°C to 40°C, which can affect the heat-sensitive compounds of the drying material. However, it is questionable that achieving a maximum 39% decrease in drying time by using a PEF pre-treatment worth increasing the process complexity and the operation cost or not. Since product quality is a major aspect of food processing, this study concludes that applying pre-treatment methods to increase the EHD drying rate without compromising the nutritional content and sensory appeal of dried fruits is non-viable under the tested conditions and for the tested fruit. In conclusion, future studies should consider further options to increase the drying rate of the EHD drying without compromising its promising characteristics, namely the low-temperature processing, low energy consumption, high product quality, simple design, and low-cost operation.

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7. Authors contributions

Kamran Iranshahi: Conceptualization, Methodology, Investigation, Experimentation, Project administration, Writing-Original draft, Review & Editing. **Marios Psarianos**: Experimentation, Review & Editing. **Donato Rubinetti**: Review & Editing. **Daniel Onwude**: Review & Editing. **Oliver K. Schlüter**: Methodology, Review & Editing. **Thijs Defraeye**: Conceptualization, Methodology, Supervision, Project administration, Review & Editing.

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