# Electrohydrodynamic drying of kiwi (*Actinidia Chinensis*) slices

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**Abstract:** Electrohydrodynamic (EHD) enhanced drying of kiwi slices using multiple point-to-plate electrode arrangements under a DC voltage was carried out in an experiment to compare with those of oven drying at 60ºC and ambient-air at 25ºC. The EHD was run at a high electric field of 375 V mm$^{-1}$ using thirteen ionizing needles to a plate electrode. The effects compared included drying rate, temperature, energy consumption, color, and shrinkage. Samples dried by the EHD and oven showed nearly the same values of moisture content, whereas that of the air-dried sample was 3.5 times higher at the end of a 7-hour drying. The sample subjected to EHD preserved the same temperature during the drying. Compared with oven drying, EHD's energy consumption was negligible. EHD and ambient-air drying rarely developed undesirable changes in color, whereas the oven-dried sample color underwent a significant change in color. Finally, slices underwent almost the same final shrinkage in volume in both EHD and oven drying.

**Keywords:** EHD; non-thermal; drying rate; color.

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## 1 Introduction

Food drying is widely used for food preservation. It is a complex that may lead to changes in product quality. Conventional drying methods at high temperatures typically produce undesirable changes in the physical, chemical, and biological properties of the dried materials. One of the most important physical changes the food material undergoes during drying is the decrease in volume, or shrinkage, which leaves a negative impact on the quality of the dried product. Changes in shape, loss of volume, and increased hardness are mostly associated with a negative impression on the consumer (Mayor and Sereno, 2004). Similarly, undesirable chemical or biochemical reactions may produce changes in texture, flavor, nutrients, color, and other properties of the food product. The most common changes in kiwi, for instance, include pigment degradation, especially carotenoids and chlorophyll browning reactions such as Maillard condensation of hexoses and amino items or oxidation of ascorbic acid (Maskan, 2001). High temperature is the one reason for potential adverse nutritional changes in the dried product (Kaya et al., 2008). It is, therefore, essential to dry such products at desirably low temperatures to preserve their nutritional value. Removal of water from a solid, however, needs heat energy. Drying has been reported to account for anywhere from 12% to 20% of the energy consumption in the industrial (Raghavan et al., 2005). Obviously, novel methods of drying need to be developed, which are reducing energy consumption, improving shrinkage, and keeping color and the associated properties of the product. Rapid drying, as made possible by electrohydrodynamic (EHD), is undoubtedly a solution where the increased drying rate is of practical importance to the food processing and similar industries. This novel method enhances mass transfer

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rates with more desirable product quality at lower energy costs (Hashinaga et al., 1999; Esehaghbeygi et al., 2014).

A novel, innovative drying is based on the generation of most ions by a corona discharge in a strong electric field. Air ions of $N^{2+}$, $O^{2+}$, $N^+$, $O^+$, and $O^-$ are produced by a corona discharge using a single- or multiple-point to plate electrode. The ions streaming away from the electrode collide with the neutral air molecules, a process called 'ion drag'. Part of the electric force is used to speed up the ions while the rest overcomes the resistance offered by the air molecules, thus causing an ion drag. Because of the momentum transfer from the ions to the neutral air molecules, a flow is created, which resembles a jet. This jet flow is called the corona, or ionic wind. The impingement of the corona wind on wet substances produces an impact in the form of wind pressure, turbulence, and vortex motion, which enhances the mass transfer rate of water (Taghian dinani et al., 2014). However, further development for industrial use needs to dehydrate biomaterials (Defraeye and Martynenko, 2018) while, the geometry of the multi pins discharge electrode could reduce the adverse effect of interference between neighboring ionic jets and makes the EHD dryer to industrial practice (Martynenko et al., 2017b).

Many investigators have experimented with EHD for better drying of vegetables, fruits, and food products (Bai and Sun, 2011). High-performance liquid chromatography (HPLC) analyzes by Hashinaga et al. (1999) showed no chemical substances formed in their EHD-dried apple slices, which also kept lighter colors with fewer browning than those dried in an oven or in the surrounding air. Xue et al. (1999) studied the direct effects of EHD on the physical and chemical properties of whey protein and remarked that EHD produced insignificant amounts of heat compared with conventional drying methods. The corona discharge produced by a multiple point-to-plate high voltage electrical fields (HVEF) was used by Dalvand et al. (2013) showed needles number on drying rate had a significant effect and the drying rate of kiwi fruit reduced with increasing in needles number. Bajgai and Hashinaga (2001) studied the EHD drying of radish slices and spinach. Compared with oven drying, the process led to reduced solid losses, lower shrinkage, the better color of radishes, and almost intact color of spinach. Bajgai et al. (2006) found that EHD drying produced superior quality food products of the high nutritional value as well as natural color and textural characteristics. EHD is energy efficient and environmentally friendly drying method when compared with the energy-intensive and environmentally unsound conventional drying methods (Alemrajabi et al., 2012).

Kiwi is a fruit of high nutritional value because of its high vitamin C content and strong antioxidant owing to its great number of phytonutrients, including carotenoids, lutein, phenolic, flavonoids, and chlorophyll (Cassano et al., 2006). Preservation of its natural qualities is, therefore, appealing to consumers. The present study aims to study the effects of drying rate, energy consumption, and drying temperature in a try to find out the best electrical field strength for EHD drying of kiwi slices. In addition, comparisons will be made among EHD, oven drying at 60ºC, and ambient-air at 25ºC used to dry kiwi slices in terms of their drying rates and temperatures as well as their qualitative (color and shrinkage) and quantitative (energy consumption) effects.

## 2 Materials and methods

Fresh kiwi was randomly chosen from the local market, washed, peeled, and cut into round slices 4 mm thick and 35-45 mm across on a single layer. Samples of approximately 45 g were randomly chosen from the lot and spread uniformly on a stainless steel plate. Actually, different parts of the kiwi fruit were not almost equally dense; however, we assumed the volume and surface area of the slices were taken to be the same. A high-voltage DC power supply (*Heinzinger* electric GmbH, PNC 40000-5 Rosenheim, Germany) was used. Thirteen needles 2 mm in diameter with sharp tips of 0.1 mm were installed on a circular stainless steel plate 130 mm in diameter. The plate was connected to the positive pole of the high voltage power supply as a multiple-pointed electrode (Hashinaga et al., 1999; Alemrajabi et al., 2012). The kiwi samples were spread on an electrically grounded stainless steel plate 135 mm in diameter. An adjustable stand was used to set the gap between the multiple-pointed electrodes and the plate.

Three different methods were used to dry the kiwi slices, namely, ambient-air, oven drying, and EHD dries. Kiwi slices with the initial moisture content of 88% wet base were weighed (AOAC, 1996). A set of preparatory experiments with three-electrode gaps (40, 50, and 60 mm) and three electric voltages (15, 17.5, and 20 kV) were performed to find out the best electrical field strength for EHD drying. The main EHD drying tests were performed with positive polarity; both electrodes had the same dimensions, at a room temperature of 25ºC±1ºC and relative humidity of 25%±0.5%. The oven- and ambient-air experiments were carried out at 60ºC and 25ºC, respectively. Comparison of performing different polarities revealed the positive corona discharge was more effective than the negative one at lower applied voltages (Lai and Sharma, 2005). In addition, it was found that positive corona drying consumed less energy than the negative corona drying process (Alemrajabi et al., 2012). The oven used in the oven-drying was fan type *Behdad* 1200 watts, accuracy ±1ºC, Zanjan, Iran. Temperature measurement of the center of kiwi slices was performed during the experiments using a K-type contact thermocouple (sheathed flexible thermocouple) and a digital thermometer (standard ST-612, accuracy 5%). The K-type thermocouple has the advantage that temperature changes in the presence of a high electrical field are avoided. Each experiment was continued for 7 hours, and sample measurement was done each hour. Moisture loss of the kiwi slices was obtained as Equation 1.

$$M = \frac{W_O - W_d}{W_d} - W_O \tag{1}$$

Where $M$ is moisture loss, $W_o$ and $W_d$ are the initial weight of the sample (kg) and the weight of the dried sample (kg), respectively. In addition, the drying rates of the kiwi slices were calculated using Equation 2:

$$DR = \frac{M_t - M_{t+\Delta t}}{\Delta t} \tag{2}$$

Where $DR$ is drying rate, $M_{t+\Delta t}$ is moisture content (d.b. %) at $t+\Delta t$, $t$ is a time (min), and $\Delta t$ is time difference, minute.

Color measurements ($L^*$, $a^*$, and $b^*$) of the kiwi samples were carried out three times before and after drying using a color difference meter (*Texflash* DC 3881, Switzerland). $L^*$, $a^*$, and $b^*$ values showed the brightness/darkness, redness/greenness, and yellowness/blueness, respectively. In addition, the total color difference ($\Delta E^*$) was calculated from the $L^*$, $a^*$, and $b^*$ features using Equation 3 (the subscript '0' names fresh samples):

$$\Delta E^* = (\Delta a^{*2} + \Delta b^{*2} + \Delta L^{*2})^{1/2} \tag{3}$$

where

$\Delta a^* = a^* - a^*_o$, $\Delta b^* = b^* - b^*_o$, $\Delta L^* = L^* - L^*_o$

Chroma ($C$) showed color saturation, which is proportional to color intensity. The hue angle is another feature used to characterize color in food products. An angle of 0 or 360° represents a red hue, and angles of 90°, 180°, and 270° represent yellow, green, and blue hue, respectively. Hue angle and Chroma were calculated as follows;

$$h = \tan^{-1}(b^*/a^*) \tag{4}$$

$$C = (a^{*2} + b^{*2})^{½} \tag{5}$$

Another color feature used was the browning index *(BI)*, which represents the purity of brown color. It is reportedly an important feature in processes where enzymatic and no enzymatic browning takes place (Palou et al., 1999); *BI* is calculated as follows;

$$BI = [100\,(x - 0.31)]\,/0.17 \tag{6}$$

Where,

$x = (a^* + 1.75L^*)/(5.645L^* + a^* - 3.012b^*)$

The values of these features for Fresh kiwi samples (namely, $L^*_o$= 52.263, $a^*_o$= -4.483, $b^*_o$= 18.021, $h_o$=103. 960, $C_o$=18. 571, and $BI_o$=34. 199) were used as reference values to compare with those gained from the dried samples.

Shrinkage shows changes in sample volume ($v_i$) on its initial volume ($v_o$) and is calculated using Equation 7. Toluene (*Merck* Chemicals, Germany) was used for shrinkage measurements.

$$\text{Shrinkage percentage} = (1 - (v_i/v_o)) \times 100 \tag{7}$$

The consumptive energy per unit of reduced mass is obtained from Equation 8:

$$E_c = V.I.t\cos\phi \Big/ m_i - m_f \tag{8}$$

where $E_c$ is specific consumed energy (J $g^{-1}$) run on a full capacity of each dryer; $V$, the voltage of the power supply (V); $I$, the consumed current (A); $\phi$, the angle of phase variance (deg.); and $m_i$ and $m_f$ are the initial and final mass values of the samples, (g) at the time interval $t$ (s), respectively.

## 3 Results and discussion

The effect of electric field strength on moisture loss was investigated for two- and five-hour drying periods at preliminary tests (Figure 1) only to remark similar trends with respect to Moisture loss in both sets of experiments. Other researchers have also reported a similar sigmoid trend at different electric field strengths (Hashinaga et al., 1999; Yang and Ding, 2016). An electric field strength of 375 V mm$^{-1}$ (15 kV at 40 mm electrode gap) led to maximum moisture loss, which was selected as the best field strength and applied in the remaining EHD drying experiments. The rate of moisture loss in kiwi slices is shown in Figure 2 for EHD, oven drying, and ambient-air processes. The results show that the samples subjected to EHD and oven drying showed faster drying kinetics than those air-dried. Based on Figure 3, the drying rates of EHD- and oven-dried samples were almost constant and higher than that of the air-dried ones. The mean values of drying rate were 0.88 and 1.02 g $_{H2O}$/g $_{DM}$ min for EHD and oven drying methods, respectively. A constant rate period was not observed in the EHD; therefore, the entire drying occurred in the falling rate period. It has been reported drying almost all biological products takes place in the falling rate period (Raghavan et al., 2005). The samples were monitored for their temperature variations throughout all the preparatory EHD drying tests. As shown in Figure 4, enhanced convective heat and mass transfer resulted in temperatures even lower than the ambient temperature. In other words, during the first hours of drying, the evaporation rate was high, and the latent heat of evaporation was leading to a decrease in temperature. Reportedly, the surface temperature of carrot slices never exceeded the ambient temperature in EHD drying (Alemrajabi et al., 2012). However, material surface characteristics were attributed to different hydrodynamic conditions (Martynenko et al., 2017a). On the other hand, oven-dried samples are exposed to a high temperature, which may adversely affect product quality (Hashinaga et al., 1999). Therefore, the non-thermal drying of EHD can be considered as an advantage over conventional drying methods, which are based on heating; therefore, heat-sensitive materials are good candidates for EHD drying.

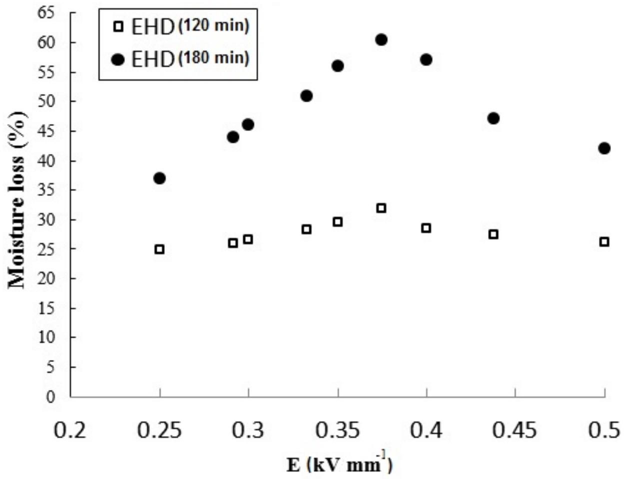


Figure 1 Moisture loss versus electric field strengths of kiwi slices by EHD for two periods of time

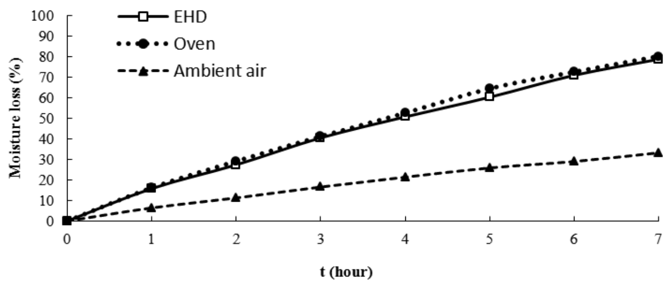


Figure 2 Moisture loss versus time for kiwi slices by EHD, oven, and ambient-air drying method

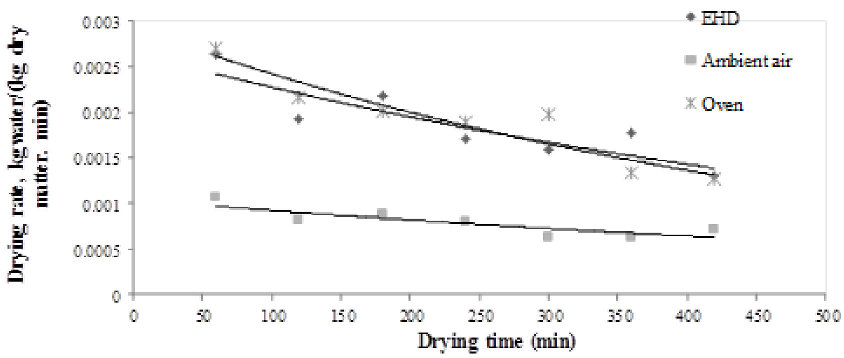


Figure 3 Variation of drying rate of kiwi slices by EHD, oven, and ambient-air drying method

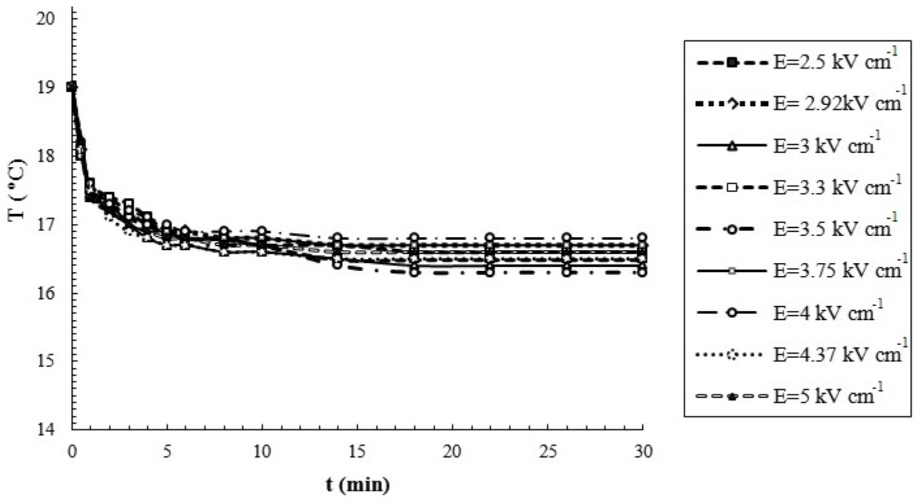


Figure 4 Variation of temperature in center of kiwi slices versus time for different field intensity at room temperature of 25ºC±1ºC

## 3.1 Color changes

The results for color features that existed from the three drying methods are shown in Figs. 5, 6, and 7 for $L^*$, $a^*$, and $b$; $h$, C, and $BI$; and $\Delta E$ values, respectively (mean value plus standard deviation).

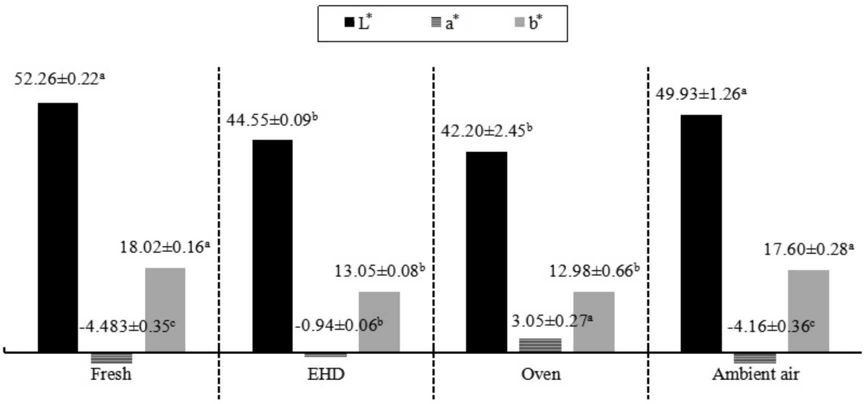


Figure 5 Color parameters $L^*$, $a^*$, and $b^*$ for kiwi slices dried by EHD, oven, and ambient-air drying method (mean values plus standard deviation)

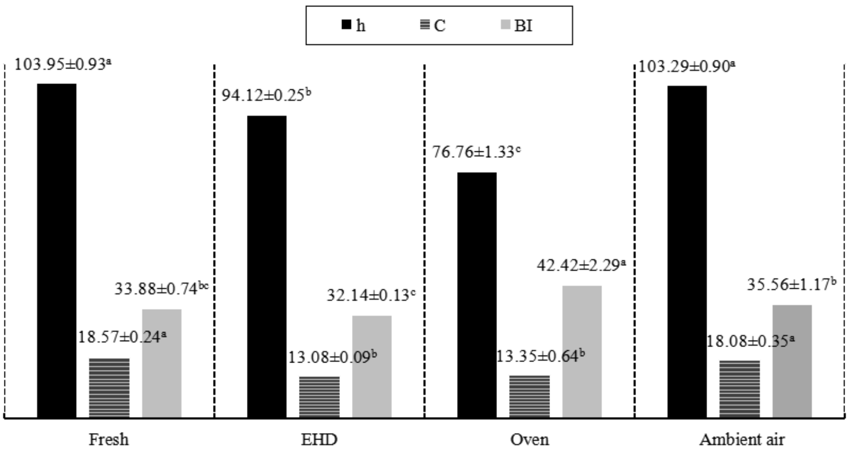


Figure 6 The color parameters of *h*, *C*, and *BI* for kiwi slices (mean values plus standard deviation)

In general, the development of discoloration of samples during any drying may be related to pigment destruction, ascorbic acid browning, and no enzymatic Maillard browning (Maskan, 2001). The $L^*$, $a^*$, and $b^*$ values in Figure 5 revealed that kiwi color was affected regardless of the drying method used. The $L^*$ value decreased in all the three drying methods, whereas it was most and least influenced by the oven and air-dried, respectively. This falling value shows the samples were turning darker. Variation in the brightness of dried samples can be taken as a measure of browning. A similar trend was observed in the increase of $a^*$-value and in the decrease of $b^*$-value. Initially, samples showed a negative $a^*$-value showing greenness, while this feature increased gradually during drying. The final $a^*$-value for oven drying became positive. Oven-dried samples lost their greenness and turned more reddish during the drying. In addition, $b^*$-values shifted towards lower values, showing fewer yellowness in the dried samples. These changes may be because of decomposing chlorophyll and carotenoid pigments and forming brown pigments (Maskan, 2000). Chroma, which points to the stability of yellow color in kiwi, decreased during drying and closely followed the $b^*$-values. The hue angle values also decreased in the samples subjected to each of the three drying methods. Expectedly, the maximum decrease occurred in the oven-dried samples, decreasing from about 103.960 (green, Hue >90°) to 76.675 (red, Hue <90°). Browning index decreased by EHD drying but increased in the oven- and air-dried samples. These results revealed that oven drying strongly affects the color quality of kiwi and produces a more brownish compound. The increase in $a^*$-values support this result. A larger $\Delta E$ denotes a color change greater than that in the ambient-air dried. Figure 7 shows that color features were most and least influenced by the oven and ambient-air drying, respectively.

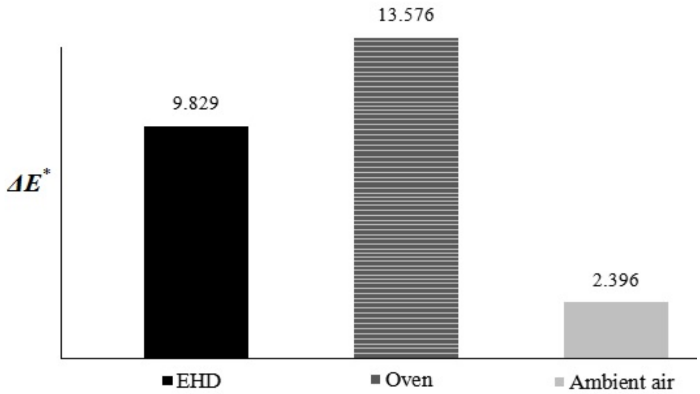


Figure 7 The total color difference ($\Delta E^*$) of dried kiwi slices by EHD, oven, and ambient-air drying method

### 3.2 Shrinkage

Shrinkage occurred in all the drying methods employed. Figure 8 shows the effects of different drying methods on the shrinkage of kiwi samples. Using Equation 5, sample shrinkage values in the oven, EHD$^-$, and ambient-air after 7 hours were calculated at 79.44%, 64.74%, and 20.98%, respectively. Ambient-air drying made minimum shrinkage; however, the moisture content was the highest among the three methods of drying, meaning that a longer drying period is needed and the product has more time to shrink gradually (Maskan, 2000).

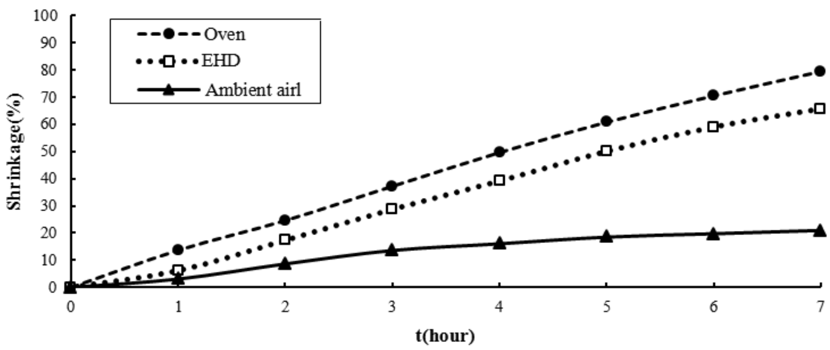


Figure 8 Shrinkage patterns for EHD, oven, and ambient-air drying of kiwi slices

Drying in the oven was rapid. Since that hot air in the oven has a higher potential to absorb humidity, thus speeding up the removal of water from the tissues in the samples. Shrinkage may increase resistance to water transport by diffusing from the outer parts of the slice. According to Figure 8, in all drying methods, shrinkage followed the pattern of the drying curves depicted in Figure 2, with high shrinkage initially and gradual leveling off towards the end of drying so the final size and shape of samples were fixed before drying was completed. Similar behavior has been observed by others (Maskan, 2000).

### 3.3 Energy consumption

Energy consumption per unit reduced mass of the samples subjected to EHD and oven drying run on a full capacity of each dryer is shown in Table 1. Oven drying is more energy-intensive because the energy consumed in oven drying is partly used to compensate for the heat lost from the oven to the ambient-air (Esehaghbeygi and Basiry, 2011). It may be concluded the energy consumed in EHD drying is more efficiently used for moisture removal. Esehaghbeygi and Basiry (2011) have reported that oven drying of tomato slices used 200-800 times more energy than EHD drying of similar slices.

**Table 1 The specific consumed energy of kiwi slice dried by different drying method (run on a full capacity of dryers)**

| Drying method | Temperature (°C) | Electrical field (kV cm$^{-1}$) | Specific energy (kJ g$^{-1}$) |
|---|---|---|---|
| EHD | 25 | 3 | 2.45$^{b}$ |
| EHD | 25 | 4 | 2.65$^{b}$ |
| EHD | 25 | 5 | 2.90$^{b}$ |
| Oven | 60 | - | 470$^{a}$ |

Note: $^{a-b}$ Means in the same column followed by different superscripts are significantly different as determined by *LSD* ($P$ <0.05).

## 4 Conclusions

EHD-enhanced drying of kiwi slices using multiple point-to-plate electrodes under a DC voltage was carried out experimentally, and the results were compared with those of oven drying and ambient-air. The results can be summarized as follows:

- The drying rate of kiwi slices in EHD was near to that of oven drying.
- Energy consumption in the EHD drying is low.
- The original color of EHD-dried samples remained almost intact while great browning was observed in those dried in an oven.
- EHD-dried samples exhibit a lower shrinkage percentage compared to oven-dried ones.
- The temperature of the samples in the EHD drying does not increase during the drying; therefore, it may be regarded as one of the most suitable methods for dehydrating heat-sensitive materials.

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