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# EFFECT OF ELECTROHYDRODYNAMIC, OVEN, AND HOT-AIR DRYING METHODS ON PROPERTIES OF BANANA SLICES

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## ABSTRACT

Banana slices were dried using electrohydrodynamic (EHD) at 6, 8, and 10 kV $cm^{-1}$; oven at 50, 60, and 70 $^oC$; and hot-air at 50, 60, and 70 $^oC$ at a constant air velocity of 1.5 m $s^{-1}$. ANOVA showed that drying method had a significant effect on drying time, rehydration capacity, shrinkage, and color parameters (L*, a*, b*, and $\Delta E$). Oven drying led to a greater color change than did hot-air. In addition, no significant difference was observed between the color change parameter $\Delta E$ for EHD and hot-air dried samples. EHD is not fast; however, its advantages of less energy requirement, lower shrinkage, and great rehydration capacity make it a good choice for convection drying.

***Keywords**: Corona wind, EHD, Shrinkage, Rehydration.*

## INTRODUCTION

The qualities of fresh banana deteriorate rapidly after harvesting. Drying is the most common method of food preservation which increases the food shelf-life and reduces packaging, storage, and transportation costs. Dried fruits and vegetables have gained commercial importance and their growth on a commercial scale has become a main part of the agricultural industry [1]. In electrohydrodynamic (EHD) drying, a high electric field is used for drying fruits and vegetables. The principal mechanism in EHD drying is convective, without the need for direct heat application, which makes it useful for drying heat sensitive materials. EHD drying depends on the strength of the ionic wind which impinges on the sample to produce turbulent, vortex-like motions and enhances the mass transfer rates of liquid and volatile components [2]. Asakawa performed a pioneering research on the promotion and retardation of heat transfer in terms of electric field [3]. Application of electrical treatments that increases the speed of mass and heat transfer during the convective drying process has seen a sustained progress in recent decades in the food industry and agricultural productions [4].

Application of multiple-point-to-plate electrodes with AC high voltage for drying apple slices showed that EHD accelerated the initial drying rate by 4.5 times compared to that achieved in ambient air-dried samples [2]. The drying wheat treated with a high voltage electrostatic field (HVEF) showed that multiple points to plate corona discharge electrode improved the average drying rate to 2.1, 2.0, and 1.7, for 10, 7.5, and 5 kV $cm^{-1}$ electric field strength, respectively [5].

Tomato slices dried with EHD, which consumed only 16.5 mJ $g^{-1}$ of electric power, exhibited a better appearance with a lower surface temperature than those dried with ambient air and oven drying methods [6]. The present study was conducted to compare drying rate, energy consumption, rehydration capacity, shrinkage, and color parameters of dried banana slices subjected to eletrohydrodynamic, oven, and hot-air drying methods.

### Theoretical Considerations of EHD Drying

The mechanism used for enhancing heat and mass transfer by an electric field arises from the EHD induced secondary flow when a high electric field is applied to the ambient air. The EHD induced secondary flow is known as the corona wind, which can be thought of as a micro jet of fluid issued from the charged electrode to the ground surface. The total effect of this secondary flow is additional mixing of fluids and instability of the boundary layer, leading to substantial increase in heat and mass transfer coefficients [7]. A detailed mathematical description of EHD drying is quite complex. The presence of gaseous, liquid, and solid phases in the material being dried makes theoretical treatment even more complex due to the different dielectric properties of these phases. If the medium of an EHD system is air, a space charge of singly charged $N_2^+$, $O_2^+$, $N^+$, $O^+$, and $O_2^-$ ions are known to form which combine with water molecules to constitute small air ions having a certain range of mobility [8]. As calculation of the segregated columbic forces between a large number of charges is difficult, the abstract principle of a volume force (F) was introduced as in equation (1) [9].

$$F = E.\rho_i + \frac{1}{2}.\varepsilon_0 . \left[ \nabla \left( E^2.\rho_a . {dk}/{d\rho_a} \right) - E^2.\nabla k \right] \quad (1)$$

The first term is the columbic force, which results from an interaction between the free charges and the imposed electric field. The second term designates the polarization forces, which are created when pairs of charges transmit the electric force to the medium. More specifically, it results from a no uniformity of the dielectric constant. The third term is the electrostatic force resulting from a non-uniform electric field and a variation in the density of the medium. Using isothermal conditions with a small electrode gap, the contribution of the second and third terms can be considered small and, hence, neglected. Therefore, the volume force is dependent on the electric field strength and charge density of ions. The drying rate in EHD depends on the strength of the electric wind, which impinges on the wet material being dried and produces turbulent, vortex like motions, thereby enhancing the mass transfer rates of volatile components such as liquid. Thus, EHD drying results from a conversion of electrical to mechanical energy [2]. The ionic wind velocity ($\upsilon$) induced in terms of EHD set up can be calculated from the following equation derived from the conservation of energy and Gaussian laws [10].

$$\upsilon = E.\frac{\varepsilon_0}{\rho_a} \quad (2)$$

## MATERIALS AND METHODS

Banana samples with an initial moisture content of 275% to 300% dry basis were purchased from a local market during spring 2011 and stored in the refrigerator at 4 °C. Prior to the drying experiments and after 4 h stabilization at the laboratory temperature (25 °C), the samples were hand peeled and sliced to pieces 3 mm thick using a sharp knife on a cut board. In order to select samples of the same stiffness, Fruits Stiffness Tester (model OSK-10576 Ogawa Seiki, Japan, accuracy 0.01 kg) was used. The samples were weighted rapidly at regular time intervals using an electronic balance (AND, model GF-400, Japan, accuracy 0.001 g). All the experiments were carried out at the laboratory temperature (25 °C) with a relative humidity of 30%. The moisture content of each sample was measured using the oven drying method at 103 ºC for 24 h [11]. A complete randomized design was used with three replications and statistical analyses were accomplished using the MINITAB (State College Pennsylvania; Minitab Inc.) and MSTAT-C (Michigan State University). Means were compared using the LSD test ($P$<0.05). In order to investigate the effect of various drying methods, an orthogonal contrast analysis with a completely randomized arrangement (CDR) was used. A multiple point to plate high voltage electric field system was manufactured to conduct the drying experiments. In order to produce the electric field, a high voltage power supply (Heinzinger Electric GmbH, PNC 4000-5, Rosenheim, Germany) was used with a maximum output voltage of 40 kV at 5 mA. The cathode of the power supply was connected to a stainless steel square plate, 150×150 mm as the positive corona ($EHD^+$). Comparison of the different polarities has revealed that the positive corona discharge is more effective than the negative one at lower applied voltages [12]. In addition, positive corona drying has been found to consume less energy than its negative counterpart [13]. In order to improve the electric discharge, 25 needle-point electrodes each 2.5 mm in diameter were placed on the square plate. The distance between needle-point electrodes was 34.6 mm to overlap discharge by 50% based on the famous Warburg equation for the positive corona [14]. A square aluminum plate (150×150 mm) was attached to the ground at a distance of 20 mm from the needle-points of the electrodes to obtain a powerful electrostatic field between the plate and the needle-point electrodes (Fig. 1). Samples were also dried using an oven (Behdad 3490, Zanjan, Iran) and a hot-air dryer. The hot-air dryer used in this study consisted of a backward curved blade centrifugal fan (driven by a 2 hp motor, maximum rotation speed of 2800 rpm), an electrical heater (consisting of 8 thermal elements, the power of each being 800 W), and a drying chamber as shown in Figure 2 [15]. The air velocity was fixed at 1 m $s^{-1}$ by installing a frequency inverter (model CV7300, TECO, Taiwan) to control the rotation speed.

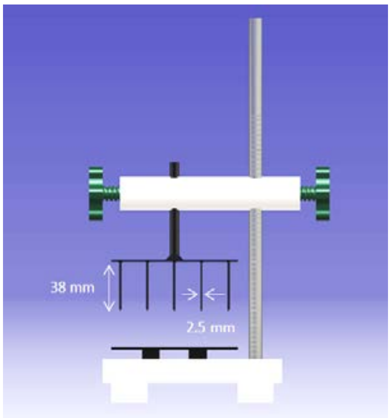


Fig. 1: A schematic of the multiple points to plate electrohydrodynamic (EHD) system.

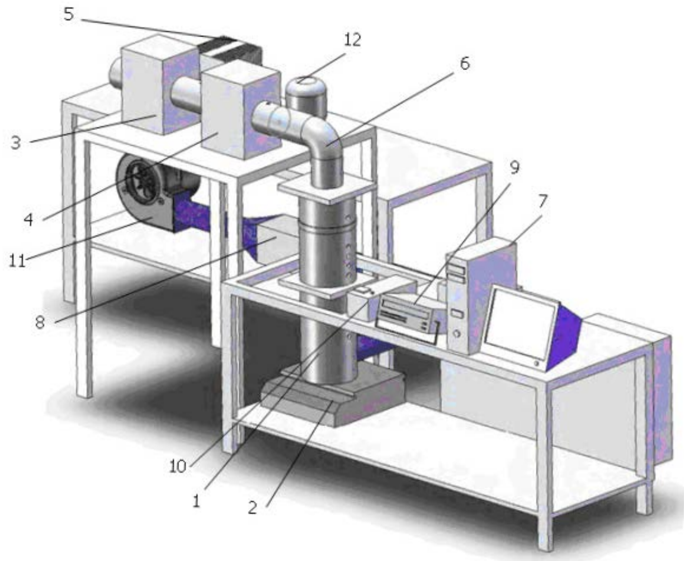


Fig. 2: A schematic of the convective hot-air dryer setup: (1) drying chamber, (2) digital scale, (3) condenser, (4) evaporator, (5) external condenser, (6) flexible tube, (7) PC, (8) electrical heater, (9) digital multi-meter, (10) frequency inverter, (11) centrifugal fan and (12) compressor.

Samples of banana slices with a thickness 3 mm were dried in a EHD system where the samples were exposed to different electric fields of 6, 8, and 10 kV $cm^{-1}$. The voltage levels applied were 12, 16, and 20 kV and the gap between the electrode points and plate was set to 20 mm (Fig. 1). In addition, some other samples were dried in an oven (50, 60, and 70 $^{o}C$) and some in a hot-air dryer (50, 60, and 70 $^{o}C$) at a constant air velocity of 1 m $s^{-1}$. The samples were weighed rapidly at regular intervals using an electronics balance; the initial sample weight was constant at 20 g. The initial moisture content was reduced to 17.5% dry basis. The drying treatments were evaluated in terms of drying time, consumed energy, rehydration capacity, shrinkage, and color parameters ($L^*$, $a^*$, $b^*$, and ΔE).

To evaluate the rehydration ratio of the dried samples, 6 g of the dried samples was immersed in 300 ml of distilled water at 25 ºC for 15 min at the end of each test. The samples were then drained and weighed. The rehydration ratio was determined using eq. 3 [16].

$$W_r(\%) = \frac{W_t - W_d}{W_d} \times 100 \quad (3)$$

Color was measured in terms of the hunter $L^*$, $a^*$, and $b^*$ values of fresh and dried samples using color difference meter (Texflash, DC 3881, Switzerland) According to which, Positive $a^*$ and $b^*$ values indicate redness and yellowness, negative values indicate greenness and blueness, and the $L^*$ value indicates visual lightness [17]. Color difference, ΔE, describes color changes during drying (eq. 4). A larger value of ΔE indicates a greater color change from the reference material. The subscript 0 designates initial samples.

$$\Delta E = \left( \left( L^*_0 - L^* \right)^2 + \left( a^*_0 - a^* \right)^2 + \left( b^*_0 - b^* \right)^2 \right)^{1/2} \quad (4)$$

Shrinkage was determined using a digital caliper (model KT, China, accuracy 0.01 mm) to measure the diameter of the X-Y plane of the slices before and after drying. The reduction at surface area was calculated using eq. 5:

$$\Delta A = \left( 1 - \frac{A_f}{A_i} \right) \times 100 \quad (5)$$

where, $A_f$ and $A_i$ are the initial and final surfaces of the banana slices.

## RESULTS AND DISCUSSION

Moisture removal values obtained for the banana slices dried in each of the three systems of EHD at 6, 8, and 10 kV cm$^{-1}$; oven; and hot-air at 50, 60, and 70 °C are presented in Figures 3, 4, and 5, respectively. Drying time decreased with increasing electric field strength in the EHD; in the oven and hot-air drying systems though, it increased with increasing air temperature.

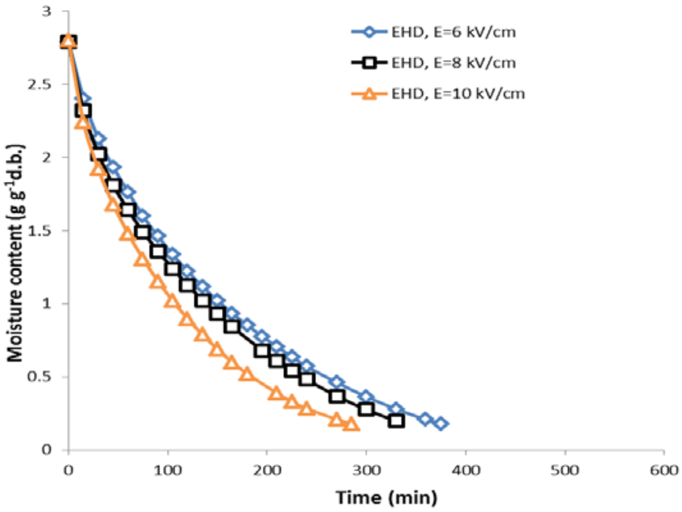


Fig. 3: Electrohydrodynamic (EHD) moisture removal for banana slices.

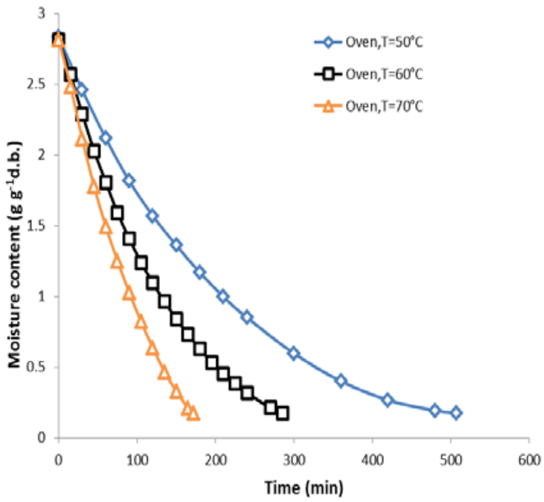


Fig. 4: Oven drying moisture removal for banana slices.

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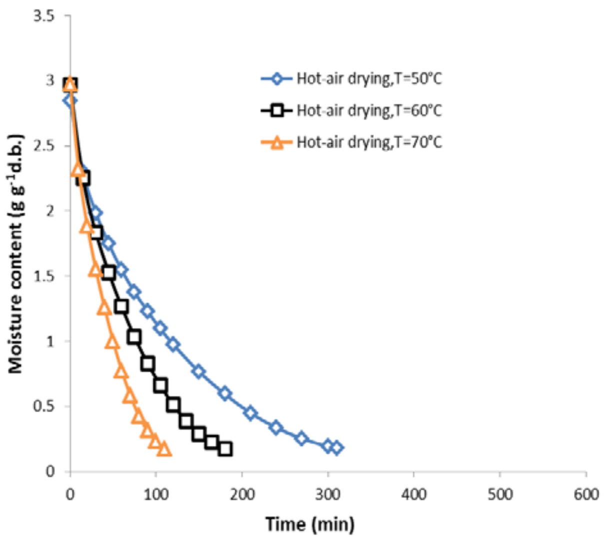


Fig. 5**:** Hot-air drying moisture removal for banana slices.

Drying rates obtained for bananas slices dried in the EHD at 6, 8, and 10 kV $cm^{-1}$; oven; and hot-air at 50, 60, and 70 °C. The mean values of drying rate were 0.88, 1.02, and 1.72 g $_{H2O}$/g $_{DM}$ min for EHD, oven, and hot-air drying methods, respectively. A constant rate period was not observed in the EHD; hence, the entire drying process occurred in the falling rate period. It has been reported that the drying of almost all biological products takes place in the falling rate period [18]. During the first period of the EHD drying process, evaporation rate was high, but it reduced with time. The drying rate was observed to reduce linearly as moisture content reached 200% d.b. EHD drying rates recorded at electric field strengths of 6, 8, and 10 kV $cm^{-1}$ were 0.78, 0.86, and 0.99 g $_{H2O}$/g $_{DM}$ min, respectively. The drying rates observed in the oven experiment at 60 and 70 °C may be divided into the three periods of a warming up and two falling rates. The drying rates were almost constant during the warming up period while the moisture content decreased below its initial value. The second falling rate period of the oven dried samples started at a moisture content of 60% dry basis. Drying rate decreased linearly at temperatures of 50, 60, and 70 °C in the two falling rate period. Two different drying periods were observed to occur in the first and second falling rate periods for hot-air drying at 50, 60, and 70 °C and oven drying at 50 °C. The drying rate curves in these Figures show the typical drying behavior for those agricultural products that possess porous or cellular structures [19]. In the present experiment, the drying rate decreased following a non-linear pattern with decreasing moisture content up to 70% dry basis during the first falling rate period of the hot-air method but the decrease pattern changed to a slower, linear one after the second falling rate started.

ANOVA showed that all treatments had significant differences in their drying times at 1% confidence level. Hot-air drying at 70 °C and oven drying at 50 °C had maximum and minimum drying times, respectively. Significant differences were observed in the drying times of samples dried by EHD at 6, 8, and, 10 kV $cm^{-1}$. It was found that EHD drying rate increased with increasing electric field strengths from 6 to 10 kV $cm^{-1}$, while drying time decreased from 372 to 292 minutes with increasing drying rate. The drying rates of wheat, tomato slices, rough rice, and radish have been reported to increase with increasing electric field strength [5, 6, 20, 21]. It seems that there is an optimum field strength for EHD drying [2, 13]. In the oven and hot-air processes, drying rate increased with increasing air temperature. These results are in good agreement with those reported in the literature [22, 23, 24]. CRD orthogonal contrast analysis showed that the drying method used had a significant effect on the drying time parameter ($P<0.01$). The mean values of drying times up to a moisture content of 17.5% were 335.8, 321.3, and 199.7 minutes in the EHD, oven, and hot-air processes, respectively, with the maximum value belonging to the EHD and the minimum to the hot-air process. The EHD drying time was found to be 1.68 and 1.05 times greater than those of the oven and hot-air processes, respectively. This may be ascribed to differences between the mechanism of EHD drying and those of convective drying methods. EHD drying rate enhancement may be mainly due to the corona wind induced by the high voltage electrostatic field as the predominant driving force [25]. The electric wind impinges on the wet sample, enhancing mass transfer to improve the drying rate. Oven drying rate enhancement is due to the heat, which penetrates into the central part of the sample and causes water movement to the surface due to the difference between the pressure of the ambient air vapor and fluid pressure within the sample. In the hot-air drying, however, heat and air flow are the main parameters involved in the enhanced drying rate. Air flow in this process helps to remove the surface moisture; hence, the higher drying rate in the hot-air process than those in the EHD and oven processes.

Rehydration of dried samples is widely used as a quality index. Rehydration is a complex process and indicates the physical and chemical changes caused as a result of the drying process [26, 27]. ANOVA showed that the treatment used has a significant effect on the rehydration capacity of the dried banana slices ($P<0.01$). Samples treated with EHD at 10 kV $cm^{-1}$ had the maximum rehydration capacity with a mean value of 84.52% (water absorbed per 100 kg of dried sample), while the samples treated with hot-air at 70 °C recorded the minimum with a mean value of 78.10%. No significant differences were observed between the samples treated with the oven and hot-air processes. CRD orthogonal contrast analysis showed significant differences between the rehydration capacity of EHD samples (83.1%) and those of the oven (79.52%) or hot-air (79%) treated samples ($P<0.01$). However, no significant differences were observed in the rehydration capacity of samples treated with the oven and hot-air processes. A similar behavior has been reported for Japanese radishes treated with the EHD and oven processes [28]. The lower rehydration value of the latter two processes is evidence for the high shrinkage caused at severe heating resulting in irreversible physical and chemical cellular changes. These changes seemed to be minimized in the EHD dried samples. The non-thermal nature of EHD might be the main factor responsible for the greater water absorption capacity. ANOVA showed that the treatments had a significant effect on the shrinkage percentage of the dried banana slices ($P<0.01$). Maximum and minimum values of shrinkage percentage were recorded for hot-air drying at 70 °C and for EHD drying at 10 kV $cm^{-1}$, respectively. However, no significant differences were observed in the shrinkage percentage of EHD at 6, 8, and 10 kV $cm^{-1}$. No significant differences have either been reported for the shrinkage percentage of EHD dried tomato slices at different electric field strengths [6]. CRD orthogonal contrast analysis showed that significant differences between sample shrinkage in the three drying methods investigated ($P<0.01$). Shrinkage mean values were measured at 20.67%, 26.18%, and 30.59% for the EHD, oven, and hot-air processes, respectively. These findings are in agreement with those reported for apple, Japanese radish, and carrot slices, respectively [2, 28, 13]. The extensive shrinkage in the samples dried by the oven and hot-air processes may be associated with cellular collapse probably due to heat damage of the cell wall and membrane [28].

Color is a main attribute of food materials, affecting the product's appearance and consumer acceptability. Unusual colors cause the product to be rejected by consumers and lose customer satisfaction. The color of fruits changes during the drying process due to the formation of browning, which has often been associated with the Millard reaction [29]. The color parameters of fresh and dried banana slices investigated in the present study. ANOVA showed that treatments had significant effects on $a^*$, $b^*$, $L^*$, and $\Delta E$ color parameters of the dried samples ($P<0.01$). EHD at 6 kV $cm^{-1}$ yielded the highest $L^*$ and $b^*$ but the lowest $\Delta E$ and $a^*$. In addition, oven drying at 50 °C yielded the highest values of $\Delta E$ and $a^*$ but the lowest of $L^*$ and $b^*$. Desirable samples are those closest in color to the original fresh fruit. Significant differences were observed in total color change ($\Delta E$) among the samples treated with EHD at 6, 8, and 10 kV $cm^{-1}$. Those treated at 6 kV $cm^{-1}$ had the least $\Delta E$ value; hence, the best quality. CRD orthogonal contrast analysis showed significant differences between $L^*$ and $a^*$ values of the hot-air dried samples compared to the EHD and oven dried ones. The mean values of $L^*$ and $a^*$ were 67.40-6.06, 65.25-5.87, and 70.30-4.34 for the EHD, oven, and hot-air processes, respectively. Hot-air treated samples had a higher brightness value (higher $L^*$ value) and a lower redness value (lower $a^*$ value) than did the ones dried by the EHD and oven processes. Enzyme degradation is better achieved with long term drying methods such as the EHD; however, no significant differences were observed between the $\Delta E$ values of the EHD and hot-air dried samples. A significant difference was observed between the $b^*$ values of the samples dried by EHD and those by hot-air; the EHD process yielded higher mean values of $b^*$. The discoloration during drying is related to no enzymatic browning [27]. The mean values of color changes, $\Delta E$, were measured to be 21.25, 23.91, and 19.86 for EHD, oven, and hot-air processes, respectively. This means that the hot-air process leads to less color changes than the oven process does (Fig. 9). Thus, temperature and drying time seem to be the main parameters involved in color change during the drying process. The lower discoloration of the hot-air dried samples may be due to its greatly shorter drying time. Compared to oven dried samples, EHD dried ones have been reported to exhibit minimal color changes and to remain more similar in color to fresh fruits [2, 28, 30, 13].

## CONCLUSIONS

The drying period of the EHD process was found to be longer than those of the oven and hot-air processes. Moreover, the EHD method has a better performance as regards its consumed energy as well as such product qualities as shrinkage percentage and rehydration capacity. Therefore, electrohydrodynamic methods may be recommended as suitable alternatives to convectional drying methods. Energy consumption in the EHD drying is negligible compared to that of the oven or hot-air drying. It has been reported that EHD energy consumption for drying tomato slices at 3, 4, and 5 kV cm$^{-1}$ was 4.4-16.5 kJ g$^{-1}$ while that for oven drying of the same product at 55 °C was 3600 kJ g$^{-1}$[6]. Energy consumption for drying carrot slices in the EHD at 5.2 kV cm$^{-1}$ and oven drying at 55 °C over a period of 5 hours were reportedly 1.25 and 1700 kJ g$^{-1}$, respectively [13]. It seems that conventional drying methods such as hot-air or oven drying are energy intensive and, thereby, cost intensive, whereas the electrohydrodynamic method is inherently energy efficient. The conventional drying methods are energy intensive and, hence, cost-intensive. The EHD$^{+}$ drying is, in contrast, inherently energy efficient. A constant rate period was not observed in EHD, the entire drying process occurring during the falling rate period. Air flow helps to remove the surface moisture and the drying rate of hot-air is found to be greater than those of the EHD and oven processes. EHD drying needs no heat input and the temperature of the samples does not increase during the drying process; hence, it may be regarded as one of the most suitable methods for dehydrating heat-sensitive materials. Since EHD drying is most effective on the surface of the fruit, combined auxiliary heating mechanisms have been proposed to combine with EHD in order to enhance its advantages.

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