Electrohydrodynamic (EHD) Drying of Grape Pomace

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The objective of this research was to find the industrially-accepted processing method of the currently underutilized wet grape pomace prior to subsequent extraction of natural ingredients. Due to high moisture content (2.5-3.0 kg/kg db), thermal drying of pomace is an expensive and time-consuming operation. Therefore, the energy efficiency of non-thermal electrohydrodynamic (EHD) technology as applied for grape pomace drying was extensively studied. The experiments on EHD drying at temperature 20°C revealed excellent quality of the dry product. Superior energy efficiency of the EHD drying ranging from 600 to 1580 kJ per kg of evaporated water as reported in topical literature was confirmed in our experimental study. These preliminary experiments on the lab-scale showed benefits of EHD drying of heat-sensitive grape pomace to be further transformed into food additives, skin powder and grape oil.

Keywords: quality, energy, non-thermal drying, by-product, waste

1. Introduction

Grapes are the world’s largest fruit crop with more than 70 million tons produced annually [1]. Approximately 15 million tons leftover from wine production gives rise to solid waste “pomace” [2]. Grape pomace is a fibrous material that consists of seeds (30-40% dry matter), skin (60-70% dry matter) and water. Grape seeds contain valuable oil and oligomeric procyanidins (OLP), whereas the grape skin is a rich source of bioactive compounds, such as polyphenols, flavonoids and dietary fibers [2]. Extensive research has demonstrated that the extracts from grape seeds and skin have several potentially beneficial effects on human health, owing to antioxidative and radioprotective compounds [3], anti-hyperglycemic effects [4], prevention of hypertriglyceridemia by improving insulin sensitivity [5], and anti-inflammatory action [6]. Due to unique health–beneficial properties, grape oil, skin and seed extracts are highly demanded on the global market.

Available technologies for fruit pomace drying have extensively been reviewed by Jangam et al. [7] and Shalini [8]. Solar drying is inexpensive, but could not guarantee the required product quality [9] whereas the osmotic dehydration modifies usually the biochemical composition [10]. Freeze-drying is too expensive and justified only for high-value biomaterials [11]. Hot air convective drying is still a commonly used industrial method of fruit pomace drying, even though the heat negatively affects product quality [12, 13].

Electrohydrodynamic (EHD) drying regarded as non-thermal technology suitable for dewatering heat-sensitive biomaterials. The EHD exploits the phenomenon of electrically-induced mass transfer in a strong external electric field [14]. Compared to osmotic dehydration, hot air or freeze-drying, the EHD technology offers lower production cost along with superior product quality [15]. Previous research documented the effectiveness of EHD for apples, potato, tomato, mushrooms, spinach, rape-seed and wheat drying [16]. So far, however, the EHD drying has never been studied for fruit pomace drying.

Our preliminary research revealed that fruit pomace, processed with EHD, had exceptionally high nutritional and antioxidant value, which offers a commercial advantage compared to other products available on the market. Energy-related calculations showed that the application of this novel technology for fruit pomace can double the energy efficiency of traditional thermal drying. We anticipate that the use of EHD for fruit pomace drying will endow with novel bioproducts, such as dried grape skin and grape seeds, which could further be processed into grape seed oil and grape skin/seed powder. The EHD drying offers reduced investment and operating costs for the extraction of nutraceutical and functional food ingredients from winery wastes. It will open the opportunities...
for supply chain development of new bioproducts for both the food and nutraceutical sectors.

2. Methodology

2.1 Materials

The wet pomace of grapes variety L’Acadie Blanc, harvested in 2015, was obtained from L’Acadie Vineyards, Nova Scotia in November 2015 just after cold press juicing. For the cycle of drying experiments (3 months) it was stored in a freezer at -20°C in plastic bags. One day before each drying experiment, the required mass of grape pomace was removed from the freezer and thawed in the cooler at temperature 4-6°C. Initial moisture content of grape pomace was in the range from 2.5 to 3.2 kg/kg db (dry basis).

2.2 Experimental apparatus

A small-scale convective chamber, equipped with electrode system, was used for EHD drying of grape pomace (Fig. 1).

It consists of a multi-pin electrode, real-time mass and electric current measurement system, an industrial blower (Fantech, Model K4, Canada), an electric heater for experiments with elevated temperature, and an AC/DC high voltage converter unit (SPELLMAN, Model RHR20P10, USA). The 40×20×20 cm drying chamber made from transparent plastic sheets had two air vents 10.2 cm in diameter on both ends of the chamber. High voltage was set at 15 kV DC, which was below the electric breakdown to avoid avalanche ionization. Air stream velocity was set at 1.0 m/s, as measured by thermo-anemometer (model HD300, Extech Instruments, USA). The multi-pin discharge electrode 10×9 cm was formed from 1.5 cm long carbon steel sharp needles located in the nodes of the rectangular grid. Two kinds of discharge electrodes were used in this study: the one with needles arranged in 9×10 rows of 1 cm square cells (#1), and another one with needles arranged in 5×4 rows of 2 cm square cells (#2). Discharge electrode was connected to positive pole of the high-voltage source. The collecting 20×10 cm aluminum plate electrode was connected to the ground of the high voltage power unit. The gap between discharge and grounded electrodes was set constant at 3.5 cm. In this study we used the one-factorial experimental design with repeated measurements. Both the applied voltage and discharge current between the electrodes were displayed on the control panel of the high voltage source. The values of all measured parameters were acquired and stored for further processing using LabView2012 (National Instruments, USA) data acquisition system with USB-6120 interface and desktop computer.

2.3 Drying experiments

The effect of high-voltage electric field on the kinetics of grape pomace drying was evaluated from drying experiments at temperature of 20±1°C maintained by the laboratory air conditioning system. In each experiment, approximately 25-30 g of fresh pomace was placed as a 5-7 mm layer in the center of the aluminum plate under discharge electrode. Duration of each experiment was set at 20 hours with EHD, and 35 hours without EHD. Mass of the sample was determined by weighing on the digital balance HCB1002 (Adam Equipment, Danbury, CT, USA) with 0.01 g resolution. Instantaneous moisture content X was calculated from the continuous recording of the sample mass, whereas mass of the bone dry solid m, was determined by oven drying at 105°C for 24 h.

2.4 Effective moisture diffusivity

The sample of grape pomace was considered as an infinite slab, because the thickness of the layer (5-7 mm) was much smaller than the size of the tray (20×10 cm). Thus, the moisture diffusivity for the infinite slab was calculated from the following relationship [17]:

\[ MR = \frac{X_i - X_e}{X_o - X_e} = \frac{8}{\pi^2} \exp\left(-\frac{\pi^2 D_{eff} t}{4L^2}\right) \]

where \(D_{eff}\) is the effective diffusivity (m²/s), \(L\) is the thickness of the slab (m), \(X_i\), \(X_e\), and \(X_o\) represent the initial, instantaneous and equilibrium moisture content (kg/kg db), and \(t\) is the running time (s). The assump-
tion of constant thickness of the slab during EHD drying was confirmed experimentally through measurements of the fresh and dry layers of the grape pomace.

The effective moisture diffusivity was calculated from re-arranged equation (1) as:

$$D_{eff} = D_e \exp \left( -\frac{E_a}{RT} \right)$$

where

$$E_a = R \cdot \ln \left( \frac{D_2}{D_1} \right) \cdot \frac{T_1 T_2}{T_2 - T_1}$$

Equation (2) allowed estimation of instantaneous diffusion coefficient, which was calculated from the slope of ln $MR$ versus dehydration time $t$.

### 2.5 Activation energy

Energy of activation $E_a$ represents the minimum energy required for water molecules to migrate within the food during drying. It has been reported [7, 8] that the effect of dehydration temperature on the moisture effective diffusivity follows the Arrhenius relationship:

$$D_e = \frac{D_0}{e^{E_a/RT}}$$

where

$$E_a = RT \ln \left( \frac{T_1}{T_2} \right)$$

Activation energy is useful characteristics of drying, indirectly indicating the state of water in the food sample.

### 2.6 Ionic wind

The ionic wind velocity $u_e$ is directly proportional to the electric field strength $E$ (V/m) and can be calculated from the following relationship [18]:

$$u_e = E \sqrt{\frac{\varepsilon_0}{\rho}}$$

where $\varepsilon_0$ is the dielectric permittivity of free space ($8.85 \times 10^{-12}$ F/m) and $\rho$ is the air density (1.204 kg/m$^3$ at 20$^\circ$C and 0.1 MPa atmospheric pressure).

The interaction between ionic wind and convective air flow was quantified by a dimensionless EHD number, which represents the ratio between ionic wind velocity $u_e$ and cross-flow convective air velocity $u$ [19]:

$$N_{EHD} = \frac{u_e}{u}$$

The EHD number quantifies interaction of two orthogonal forces: electric force of ionic wind and inertial force of air cross-flow.

### 2.7 Color measurements

The pictures of dried pomace samples were captured by a digital CCD camera (Oscar F-810C, Canada) with light intensity of approximately 395 lux and recorded by imaging software (Vision Assistant 8.5, National Instruments, USA). A color measurement procedure was developed on LabVIEW 2013 (National Instruments, USA) to determine the color with RGB color space output, which was further converted into CIE 1976 ($L^*, a^*, b^*$) color space, using standard conversion matrix [20]. In the CIELAB coordinate system, color values expressed as $L^*$, ranging from 0 (darkness) to +100 (whiteness or brightness), $a^*$ (redness to greenness), and $b^*$ (yellowness to blueness) were determined for each sample. Color changes $\Delta E$ were then calculated, using the following equation [13]:

$$\Delta E = \sqrt{(L^* - L^*o)^2 + (a^* - a^*o)^2 + (b^* - b^*o)^2}$$

where $L_o^*$, $a_o^*$, and $b_o^*$ are the initial values of wet pomace samples.

### 2.8 Energy efficiency

Energy efficiency of drying was quantified through the specific energy consumption representing the amount of energy needed to evaporate unit mass of water in kJ/kg [21]. This index, further termed as energy efficiency $\eta$, was determined from measurable variables, namely the power (kW) and the drying rate (kg/s):

$$\eta = \frac{V * f}{\Delta m} \Delta t$$

Equation (8) was used to calculate both energy efficiency of EHD drying and total energy efficiency of EHD electrical setup.

### 2.9 Statistical analysis

Measurements were carried out in triplicate and results were expressed as means ± standard deviation. Changes in drying rate were analyzed using one-way
analysis of variance (ANOVA). Model assumptions (normality and constant variance) were verified by examining the residuals as described in Montgomery [22]. All statistical procedures were performed using Minitab 15.0 software (Minitab Inc., USA). Statistical significance was determined using least significant difference (LSD) t-tests and accepted at p < 0.05.

3. Results

Results of grape pomace drying at 20°C with and without EHD are presented in Fig. 2. EHD drying to moisture content 0.22–0.25 kg/kg db took about 20–25 hours, whereas convective drying at 20°C and air velocity of 1.0 m/s without EHD required 30–35 hours. It follows that EHD significantly accelerated drying kinetics. First period of EHD drying (about 1 hour) was characterized by almost linear drying kinetics, which corresponds to previous findings [23]. This behavior could be explained by evaporation of free water, available on the surface of the drying material. In contrast, samples dried without EHD, followed classic exponential behavior, which is the evidence of diffusion-limited drying. Experiments on hot-air drying of grape pomace indicated that diffusivity increased significantly with temperature from $0.14 \cdot 10^{-10}$ m$^2$/s at 20°C to $1.8 \cdot 10^{-10}$ m$^2$/s at 80°C. Activation energy of grape pomace drying was calculated as 26890 J/mol·K, which indicates that water in the sample was mostly in unbound (free) liquid form.

An analysis of instantaneous diffusivity shows drastic difference between two treatments. Namely, diffusivity in convective drying without EHD was almost constant during the entire drying period (about $0.22 \cdot 10^{-10}$ m$^2$/s). In contrast, diffusivity in EHD drying was significantly higher in the first 5 (electrode #1) or 15 (electrode #2) hours of drying. It indicates the possible existence of another mechanism of drying, different from the diffusion. This mechanism, obviously, depends on the geometry of discharge electrode but this requires further investigation.

It is important to note that the electrode #2 with low packing density of discharge pins provided more efficient drying of grape pomace than the electrode #1 with the high packing density of discharge pins. In both cases, the ionic wind velocity calculated with Equation (3), was the same and equal to 1.16 m/s. The EHD num-

![Fig. 2 Moisture content and diffusivity of grape pomace with EHD electrode #1 (red squares), electrode #2 (black circles) and without EHD (grey triangles) at temperature 20°C and air velocity 1 m/s.](image1)

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ber was above 1.0. This unexpected effect of the pin packing density on the drying rate requires further experimental investigation. Qualitative results of EHD drying are presented in Fig. 3.

Convective drying at temperature 20°C with EHD was by 1.5 to 1.7 faster than without EHD. To separate possible effects of drying time and temperature, low-temperature drying was taken as a reference. It was found that kinetics of EHD drying at 20°C was comparable with the kinetics of thermal drying at 40°C. It is important to mention that organoleptic properties of EHD dried grape skin, such as texture, color and flavor, were superior as compared to thermally-dried samples. The samples of EHD-dried grape pomace featured significantly brighter color and an attractive raisin-like flavor, which makes such a pomace suitable to food industry for the use as a food ingredient or natural source of fiber. Color measurements showed significant difference between EHD-dried, dried without EHD and thermally-dried (40°C) grape pomace (Table 1).

It follows that drying mostly affected the $L^*$ and $a^*$ parameters. Significant difference in total color change $\Delta E$ between EHD and non-EHD drying indicates negative effect of prolonged exposure of a dried material to convective airflow. Total color change was two times smaller in EHD drying compared to thermal drying. Negative effect of thermal drying could be explained by intensive browning due to thermal oxidation. Better appearance of the grape pomace after EHD drying can be attributed to minimal effect of EHD on quality degradation.

Calculation of energy efficiency was based on the measurements of energy consumption and mass reduction over 5 hours of drying. The magnitude of energy, factually used in EHD drying, was calculated from direct measurements of voltage and discharge current. The energy consumed was independent of the environmental conditions (temperature, air velocity), but depended on the configuration of discharge electrode (Table 2).

Energy efficiency (kJ/kg) was calculated from the factual energy consumption (kJ) and water evaporated over 5 hours of drying (kg) (Table 3).

From calculations presented in Table 3, it follows that energy efficiency of EHD was almost independent of electrode configuration. This methodology of calculation of energy efficiency in EHD drying is used in most of reported research [14, 16, 19], and sometimes it is referred to as “exergy efficiency” [24].

Practical considerations, however, often require estimation of total energy efficiency from total energy consumption [15]. In our study total energy consumption in

| Table 1 | Effect of drying technology on color ($L^*$, $a^*$, $b^*$) of grape pomace. |
|---------|------------------|-----------------|-----------------|-----------------|
|         | $L^*$            | $a^*$           | $b^*$           | $\Delta E$     |
| Initial material | 53.02±3.41       | 2.39±0.34       | 23.64±1.21      |
| Drying with EHD   | 37.18±2.42       | 13.30±0.95      | 20.14±0.79      | 19.40±2.86     |
| Drying without EHD (20°C) | 25.83±2.65       | 11.76±1.55      | 24.34±1.67      | 28.77±1.71     |
| Thermal drying (40°C) | 20.91±1.63       | 15.59±1.16      | 19.13±1.34      | 35.01±4.11     |

| Table 2 | Energy used in EHD drying, kJ. |
|---------|-----------------|-----------------|-----------------|
| Electrode | Voltage, kV | Current, mA | Power, W | Energy consumed in 5 hours, kJ |
| #1       | 15            | 0.018         | 0.27       | 4.86                        |
| #2       | 15            | 0.032         | 0.48       | 8.64                        |

| Table 3 | Energy efficiency of EHD drying, kJ/kg. |
|---------|-----------------|-----------------|-----------------|
| Electrode | Water evaporated, kg | Energy consumed, kJ | Energy efficiency, kJ/kg |
| #1       | $7.58 \cdot 10^{-3}$ | 4.86           | 641.2          |
| #2       | $14.15 \cdot 10^{-3}$ | 8.64           | 610.6          |
EHD drying was determined from the electric power of all powered equipment, namely high-voltage power supply and air blower. Energy consumption by the high-voltage power supply ranged from 55 to 75 W, depending on high voltage output. This power could be translated into 900 to 1350 kJ of energy consumed in 5 hours. Energy consumed by convective blower at 1.0 m/s air velocity was 90 kJ. Hence, the total energy consumption of electric equipment, used in EHD drying, was in the range from 990 to 1440 kJ. Total energy efficiency, recalculated from total energy consumption (990–1440 kJ), gave quite different numbers, namely 8610 kJ/kg for electrode #2, and 15140 kJ/kg for electrode #1. In this case, the electrode (#2) offers better energy efficiency. This example clearly illustrates that the methodology of calculation of energy efficiency in EHD drying requires further investigation and standardization.

Comparison of electric discharge energy (4.86–8.64 kJ) with total energy consumption (990–1440 kJ) shows the extremely low (below 1%) overall energy efficiency of EHD setup. This contrasts the extremely high energy efficiency of EHD drying quoted in literature that however is based on the sole discharge energy. The efficiency is mostly limited by the high-voltage converter, which consumes by two orders more energy, than it is factually used for EHD drying. We can conclude that with a more efficient high-voltage converter it would be possible to achieve better energy efficiency of EHD drying.

4. Conclusions

This research demonstrated that EHD drying is advantageous for heat-sensitive biomaterials, such as grape pomace. Analysis of organoleptic properties of EHD-dried pomace samples showed superior quality as compared to thermally dried samples. It opens the opportunity for using the pomace from grapes and other fruits in food industry as a natural food ingredient. With respect to discharge electrode geometry, the experimental drying rate was the highest with 2×2 electrode configuration. Regarding energy issues, a significant (two orders) difference was found between energy used for EHD drying and overall energy consumption of auxiliary equipment. With a more efficient high-voltage converter it would be possible to achieve better efficiency of EHD drying.

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