The Impact of Pulsed Electric Field Treatment and Shelf Temperature on Quality of Freeze-Dried Pumpkin

Oleksii Rastorhuiev 1, Aleksandra Matys 2,*, Artur Wiktor 2,*, Katarzyna Rybak 2, Alica Lammerskitten 3, Stefan Toepfl 3, Wolfram Schnäckel 1, Ewa Gondek 2 and Oleksii Parniakov 3

1 Department of Food Science and Nutrition, Faculty of Agriculture, Ecotrophology, and Landscape Development, Anhalt University of Applied Sciences, Strenzfelder Allee Str. 28, 06406 Bernburg, Germany; oleksijrastorguev@gmail.com (O.R.); wolfram.schnaeckel@hs-anhalt.de (W.S.)
2 Department of Food Engineering and Process Management, Institute of Food Sciences, Warsaw University of Life Sciences, 02-776 Warsaw, Poland; katarzyna_rybak@sggw.edu.pl (K.R.); ewa_gondek@sggw.edu.pl (E.G.)
3 Elea Technology GmbH, Prof. von Kützing Str. 9, 49610 Quakenbrück, Germany; a.lammerskitten@elea-technology.com (A.L.); s.toepfl@elea-technology.com (S.T.); o.parniakov@elea-technology.com (O.P.)
* Correspondence: aleksandra_matys@sggw.edu.pl (A.M.); artur_wiktor@sggw.edu.pl (A.W.)

Abstract: Pulsed electric field (PEF) treatment is known as a method that can intensify heat- and mass-transfer-based processes such as osmotic dehydration, drying, or freeze-drying. However, the literature about its impact on quality of freeze-dried products is limited to a few raw materials. The aim of this study was to analyze the effect of PEF on the cell disintegration index, selected bioactive compounds, and physical quality parameters of freeze-dried pumpkin. The final quality of the freeze-dried product was evaluated by residual moisture content, color analysis, total phenolic content, total carotenoid content, sugars content, and hygroscopic properties. The application of PEF treatment induced the disintegration of pumpkin cells even at low energy input (0.11 kJ/kg), and the saturation level of electroporation was reached after 4 kJ/kg. PEF treatment at 2 kJ/kg allowed 40% more total carotenoids to be retained in comparison to the untreated sample. Furthermore, all PEF-treated freeze-dried pumpkin samples exhibited lower sucrose content but had higher glucose and fructose contents in comparison to the reference samples. However, this effect was more pronounced when the shelf temperature was equal to 40 °C.

Keywords: PEF; electroporation; lyophilization; freeze drying; pumpkin

1. Introduction

Drying is one of the oldest and most commonly applied operations in food processing. The aim of drying is the reduction in both the water content and water activity of the product, which results in a prolonged shelf life of food [1,2]. There are many different methods of water removal by drying, starting with the convection (hot air) drying method as the most popular. Despite its simplicity, convection drying is associated with many drawbacks, which is why unconventional techniques were implemented such as microwave-assisted drying, microwave–vacuum drying, and infrared drying. Among all water removal methods, freeze-drying is considered as a benchmark technology since it allows high-quality dried products to be obtained. Due to the reduced amount of free water and the low temperature during the process, suppressed microbiological activity can be achieved. In addition to this, the primary shape and structure of the product can be maintained due to ice formation and its further sublimation [3–6]. The dissolution of the phenolic compounds in the plant materials is affected by material processing. The relatively low drying temperature during freeze-drying allows for increased retention of phenolic compounds in the dried material and has a positive effect on their bioaccessibility. There
are also processes that can modify the polyphenol profile. One of them is fermentation, during which, as a result of microbiological activity and enzymatic decomposition, the concentration of some metabolites may increase, while that of others may fall [7,8]. Despite several advantages in quality, the high operating and maintenance costs make freeze-drying one of the most expensive methods of dehydration. These costs result from the long drying time under continuous vacuum and the need for freezing the material before drying [9]. Thus, freeze-drying is mainly used for high-quality products. To increase its efficiency, different emerging technologies can be used such as pulsed electric field treatment.

Pulsed electric field (PEF) technology opens new horizons for existing applications in the field of unit operations, which aim towards water removal. It has been previously demonstrated that PEF treatment enhances convection drying [10–13], vacuum drying [14–16], and microwave drying [17,18]. Moreover, it has been proven that application of PEF enhances freeze-drying time and it can eliminate the need for external freezing of the raw material before freeze-drying since the product can be frozen by the vacuum method during pressure drops inside the drying chamber [19,20].

The reason why PEF treatment intensifies dehydration is associated with its impact on cellular systems. The mechanism of PEF can be explained by the electroporation phenomenon [21]. Electroporation depends on the formation of pores across the cell membrane owing to the application of very short pulses characterized by very high electric field intensity. The pores are formed when the transmembrane potential of the cell exceeds a critical value. The process of pore formation can be irreversible and generally lead to permanent damage to or the death of the cell, or reversible when the cell can restore its normal functionality. The nature of the process depends on the processing parameters and properties of the treated material [11,22,23].

The beneficial effect of PEF pretreatment on the mechanical, thermal, optical, and microstructural properties of freeze-dried plant material was demonstrated, using mainly apples and strawberries as matrices. The obtained results showed that due to the electroporation phenomenon of PEF, a more homogenous distribution of sugar and water inside tissue leads to more uniform drying. Moreover, texture and acoustic analyses stated that the PEF-treated material has a greater porosity and crispness compared to the untreated one [24]. However, the literature about the quality of freeze-dried products produced with the assistance of PEF is limited.

Therefore, the objective of this work is to evaluate the impact of PEF application on the chemical and physical quality parameters of freeze-dried pumpkin. The treatment protocol was established by the measurements of the cell disintegration index. The effect on the freeze-drying process was analyzed by comparing the residual moisture level for untreated and PEF-treated tissues. The product quality of freeze-dried samples was investigated in terms of color analysis, total phenolic content, total carotenoid content, and sugars content. Finally, the hygroscopic properties of the untreated and PEF-treated freeze-dried pumpkin were evaluated.

2. Materials and Methods

2.1. Raw Materials

Commercial fresh pumpkins (Cucurbita maxima) were purchased from a local supermarket (Quakenbrück, Germany). The material was stored at 12 °C in a dark place until required and washed before each trial. The measurements of dry matter content in the raw material were carried out according to AOAC 920.15 [25]. The initial moisture content was 89.8 ± 1.34%. After the PEF treatment, pumpkin was cut into cubes of 10 × 10 × 10 mm$^3$ (length × width × height), with 1000 mm$^3$ of volume.

2.2. PEF Treatment

The application of pulsed electric field was carried out in a batch reactor (PEF Pilot™, Elea Technology GmbH, Quakenbrück, Germany) using an electric field intensity of 1.07 kV/cm and a specific energy input of 0.1–4 kJ/kg. The monopolar exponential
decay pulse length was set to 40 µs and the interval between pulses was equal to 0.5 s. The material was placed in the treatment cell which consisted of two stainless steel parallel-plate electrodes and insulator material. The distance between electrodes was equal to 28 cm. Afterwards, the chamber was filled with potable water (5000 g, \( \sigma = 222 \mu S/cm \), and \( T = 19 \pm 1 \degree C \)) so that the whole pumpkin was covered in order to provide contact between electrodes. Specific energy input (kJ/kg) was controlled by adjusting the number of applied pulses.

The specific energy input \( W_p \) was computed using the following Equation (1):

\[
W_p = \frac{U \cdot C^2 \cdot n}{2 \cdot m}
\]

where \( n \) is the number of pulses; \( m \) is the mass of the treated samples (kg); \( U \) is the voltage (kV); and \( C \) is the capacitance (1 µF).

2.3. Determination of Cell Disintegration

The cell disintegration index, \( Z_p \), was determined based on the measurement of electrical conductivity of the untreated, PEF-treated, and totally destroyed material, according to Equation (2) [26]:

\[
Z_p = \frac{\sigma - \sigma_i}{\sigma_d - \sigma_i}
\]

where \( \sigma \) is the electrical conductivity of the sample, and subscripts \( i \) and \( d \) refer to the conductivities of the intact and completely damaged tissue, respectively.

The measurements were performed at 20 \degree C using a conductometer (PEF Control, Elea Technology GmbH, Quakenbrück, Germany). The electrical conductivity of totally destroyed pumpkin (\( \sigma_d \)) was achieved using following treatment: \( W_p = 64 \text{ kJ/kg;} \ E = 1.07 \text{ kV/cm.} \) Application of higher energy input did not lead to significant increment in electrical conductivity of the sample.

2.4. Freezing

Before freeze-drying, cut untreated or PEF-treated pumpkin was frozen in a shock freezer (Alpeninox SF 10-CW, Alpeninox, Pordenone, Italy). The air temperature was set to \(-33 \degree C \) and its velocity was equal to 2 m/s. During freezing, the temperature of the sample was monitored continuously using a fiber optical temperature sensor placed in the geometrical center of the material. The process was stopped when the temperature inside the product reached \(-33 \degree C \), which happened after 15 min.

2.5. Freeze-Drying

Freeze-drying of pumpkin was carried out in a laboratory unit (Alpha 1–4 LSCplus, Martin Christ Gefriertrocknungsanlagen GmbH, Osterode am Harz, Germany) at a pressure of 1 mbar and a temperature of the ice condenser of \(-55 \degree C \). The temperature of the plates was set at 40 and 60 \degree C. Freeze-drying lasted until the samples reached shelf temperature, which was then maintained for 60 min.

2.6. Water Activity

Water activity was measured with the usage of a hygrometer (AquaLab CX-2, Decagon Devices, Pullman, WA, USA) in three repetitions.

2.7. Color Analysis

Optical properties of freeze-dried pumpkins were measured in a laboratory colorimeter working in a CIE L*a*b* system (CM-5, Konica-Minolta, Tokyo, Japan) using D65/10\(^{b}\) illumination type. The freeze-dried pumpkin was ground for 10 s using a laboratory shredder. Afterwards, powder was put into a special Petri dish which completely covered
the measurement zone (30 mm). The measurements were repeated six times for each variant of the experiment.

Total color difference (ΔE) was calculated using Equation (3) [27]:

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}$$  \hspace{1cm} (3)

where ΔL*, Δa*, and Δb* are differences for average values of L*, a*, and b* measured for the intact and PEF-treated samples.

In turn, browning index (BI) was computed based on following Equations (4) and (5) [27]:

$$BI = 100 \cdot (x - 0.31) / 0.172$$  \hspace{1cm} (4)

$$x = \left( a^* + 1.75 \cdot L^* \right) / \left( 5.645 \cdot L^* + a^* - 3.012 \cdot b^* \right)$$  \hspace{1cm} (5)

2.8. Total Phenolic Content (TPC)

2.8.1. Extract Preparation for TPC Measurements

Extracts were prepared by homogenization of 2 g of dried pumpkin with 25 mL of 80% (v/v) ethanol (POCH, Gliwice, Poland) and further boiling. After extraction, samples were cooled down and filtrated to volumetric flasks (50 mL) and filled up with 80% ethanol. From each obtained material, three independent extracts were prepared.

2.8.2. TPC Measurements

Total phenolic content was determined using the Folin–Ciocalteau (F-C) method [28]. Determination of TPC was performed by mixing 0.18 mL of extract with 0.3 mL of F-C reagent (Sigma-Aldrich, St. Louis, MO, USA) and 4.92 mL of distilled water. After 3 min of incubation, 0.6 mL of sodium carbonate was added and the whole system was stirred well, and then left in darkness for 1 h. Afterwards, the samples’ absorbance was measured at 750 nm against blank sample using spectrophotometer (Helios, Thermo Spectronic, Waltham, MA, USA). All extracts were measured in duplicate and the results were expressed as mg of gallic acid equivalents per 100 g of dry matter (d.m.).

2.9. Total Carotenoid Content (TCC)

Total carotenoid content in the freeze-dried pumpkin was measured following the spectrophotometric method presented previously in [29]. Before extraction to 1 g of the shredded sample, 1 mL of Carrez I and II solutions were added. Extraction of the carotenoids was carried out using acetone and petroleum ether until the precipitate turned white. The absorbance of the extracted sample was measured at 450 nm using a spectrophotometer (Helios, Thermo Spectronic). TCC was expressed as mg β-carotene equivalents per 100 g d.m., and it was calculated following Equation (6):

$$TCC = \frac{A \cdot y \cdot 10^6}{A_{1cm}^% \cdot 1000 \cdot m}$$  \hspace{1cm} (6)

where A is the absorbance of the sample; y is the volume of extract (mL); $A_{1cm}^%$ is the extinction coefficient of carotenoids in petroleum ether solution; and m is the mass of dry substance (g).

2.10. Sugars Content

Sugars content, i.e., glucose, fructose, and sucrose, was analyzed by the chromatographic method using an HPLC unit equipped in a refractive index detector (Waters, Milford, MA, USA) [30]. The extracts for analysis were prepared by homogenizing dried pumpkins with redistilled ultra-pure water (MilliQ) at 80 °C and centrifuging them at 2000 rpm for 10 min. Afterwards, supernatant was passed through 0.22 µm PTFE syringe filters and submitted to HPLC analysis using Sugar-Pak I column (Waters, Milford, MA,
USA). Ultra-pure redistilled water was used as a mobile phase and the column was kept at temperature of 90 °C. The results were computed based on calibration curves prepared for each compound separately and expressed in g/100 g d.m. Two extracts were prepared for each sample, and the analysis was carried out in a duplicate for each extract.

2.11. Hygroscopic Properties

Hygroscopic properties of freeze-dried pumpkin were analyzed by studying the kinetics of water vapor adsorption after 1, 3, 6, 9, 12, and 24 h. Samples were placed in a desiccator over the supersaturated sodium chloride water solution (RH = 75%) at constant temperature of 25 ± 1 °C. Such conditions provided a water activity of 0.75. The measurements were repeated three times for each investigated variant. The hygroscopic properties (H) were expressed using the following equation:

\[ H = \frac{m_t - u_t}{m_0 - u_0} \]  

(7)

where \( m_t \) and \( u_t \) are the mass and water content of the sample at the \( \tau \) time of analysis; \( m_0 \) and \( u_0 \) are the initial mass and water content of the analyzed material.

2.12. Statistical Analysis

The obtained results were subjected to statistical analysis using ANOVA, MANOVA, and Pearson’s correlation methods at \( \alpha = 0.05 \) in STATISTICA 13 (TIBCO, Palo Alto, CA, USA). Homogenous groups were determined using the Tukey test. All measurements were repeated three times, unless specified differently.

3. Results and Discussion

3.1. Electroporation Efficiency

Figure 1 presents the cell disintegration index of pumpkin treated with different specific energy inputs (\( W_p = 0–64 \) kJ/kg). The application of PEF even at a low energy of 0.1–1 kJ/kg induces the disintegration of pumpkin cells. The application of PEF treatment with a specific energy higher than 4 kJ/kg practically did not increase \( Z_p \), as a so-called plateau was reached. These data are in good correspondence with previously reported findings for other different fruits and vegetables that suggest that plant matrices can achieve a so-called saturation level of electroporation [31,32]. Relying on the values of \( Z_p \), the PEF treatments at low and medium intensities (0.1, 0.5, 1, and 2 kJ/kg) were selected for further freeze-drying, later referred as PEF1, PEF2, PEF3, and PEF4, respectively.

![Figure 1. Cell disintegration index of pumpkin, \( Z_p \), treated at different PEF specific energy inputs, \( W_p \).](image-url)
3.2. Residual Moisture Content and Water Activity

The freeze-drying technique is one of the drying methods that allows low residual moisture to be reached in the final product. Figure 2 shows the residual moisture content, RM, of freeze-dried pumpkin that was untreated and PEF-treated with different specific energies. As it can be seen, the RM content in the untreated pumpkin dried at 60 °C is lower than that of the one dried at 40 °C. That can be explained by the enhancement of sublimation due to the increased heat flow from the heating plate of the freeze-dryer, resulting in deeper water removal from pumpkin tissue. What is interesting is that the application of PEF in the case of drying at 40 °C resulted in a reduction of RM by 20% compared to the untreated sample. However, the PEF2, PEF3, and PEF4 treatments did not show any additional reduction of RM. The opposite behavior has been observed for pumpkin dried at 60 °C. In this case, PEF1 treatment increased the RM of samples after freeze-drying by approx. 3-fold. What is more, the PEF2, PEF3, and PEF4 treatments were able to reduce RM by approx. 45, 11, and 5%, respectively, compared to the untreated freeze-dried samples. A similar reduction of RM induced by PEF treatment has been reported previously for apples [19]. The water activity of all investigated samples varied between 0.143 and 0.149. Lower values of water activity were found for samples dried at 60 °C, but no clear impact of energy input during PEF application was found. However, samples pretreated with 2 kJ/kg, PEF4, exhibited the lowest values, 0.145 and 0.143 for 40 and 60 °C, among other materials dried at the same temperature.

Figure 2. Residual moisture content (RM) of untreated and PEF-treated freeze-dried pumpkin depending on the specific energy input \( W_p \). Different heating plate temperatures of 40 and 60 °C have been used. a-c Different letters indicate significant statistical differences (Tukey’s HSD, \( p < 0.05 \), \( n = 3 \)).

3.3. Color

The optical properties of the freeze-dried pumpkin samples are presented in Table 1. The biggest changes in color parameters were observed when PEF treatment was carried out at energy intakes of 0.5 kJ/kg (PEF2) and higher, and it was the most visible for the \( a^* \) and \( b^* \) chromaticity coordinates. For instance, the \( a^* \) values of samples subjected to PEF4 treatment and then freeze-dried at 40 and 60 °C were equal to 22.86 and 19.43, respectively. For comparison, the untreated freeze-dried sample exhibited redness values of 18.92 and 17.95 when the process was conducted at 40 and 60 °C, respectively. Similar observations can be made for the yellowness parameter \( (b^*) \). The application of PEF1 did not cause any relevant, from a statistical point of view, changes in the redness and yellowness of the samples when compared to the reference material. Most PEF-pretreated samples also
exhibited lower $L^*$ values. Only the materials treated with PEF demonstrated a brighter color than the untreated pumpkins, regardless of the freeze-drying temperature.

Table 1. Color parameters ($L^*$, $a^*$, $b^*$), total color difference ($\Delta E$, in comparison to untreated dried material), and browning index (BI) of freeze-dried pumpkin samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$L^*$</th>
<th>$a^*$</th>
<th>$b^*$</th>
<th>$\Delta E$</th>
<th>BI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Drying at 40 °C</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U—0 kJ/kg</td>
<td>76.68 ± 0.05</td>
<td>18.82 ± 0.15</td>
<td>72.77 ± 1.31</td>
<td>-</td>
<td>202.4</td>
</tr>
<tr>
<td>PEF1—0.1 kJ/kg</td>
<td>77.31 ± 0.31</td>
<td>18.59 ± 0.07</td>
<td>72.69 ± 0.96</td>
<td>0.68</td>
<td>198.7</td>
</tr>
<tr>
<td>PEF2—0.5 kJ/kg</td>
<td>76.03 ± 0.67</td>
<td>20.51 ± 0.59</td>
<td>74.66 ± 1.56</td>
<td>2.62</td>
<td>216.9</td>
</tr>
<tr>
<td>PEF3—1 kJ/kg</td>
<td>76.66 ± 0.36</td>
<td>19.48 ± 0.14</td>
<td>74.15 ± 0.90</td>
<td>1.53</td>
<td>210.1</td>
</tr>
<tr>
<td>PEF4—2 kJ/kg</td>
<td>74.25 ± 0.21</td>
<td>22.86 ± 0.09</td>
<td>75.32 ± 0.42</td>
<td>5.35</td>
<td>232.7</td>
</tr>
<tr>
<td><strong>Drying at 60 °C</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U—0 kJ/kg</td>
<td>77.66 ± 0.13</td>
<td>17.95 ± 0.17</td>
<td>73.76 ± 0.70</td>
<td>-</td>
<td>201.8</td>
</tr>
<tr>
<td>PEF1—0.1 kJ/kg</td>
<td>77.79 ± 0.14</td>
<td>17.89 ± 0.02</td>
<td>73.67 ± 0.12</td>
<td>0.17</td>
<td>200.6</td>
</tr>
<tr>
<td>PEF2—0.5 kJ/kg</td>
<td>77.07 ± 0.06</td>
<td>18.86 ± 0.12</td>
<td>74.86 ± 0.42</td>
<td>1.55</td>
<td>211.1</td>
</tr>
<tr>
<td>PEF3—1 kJ/kg</td>
<td>76.57 ± 0.41</td>
<td>18.38 ± 0.39</td>
<td>79.06 ± 0.55</td>
<td>5.43</td>
<td>236.7</td>
</tr>
<tr>
<td>PEF4—2 kJ/kg</td>
<td>76.22 ± 0.07</td>
<td>19.43 ± 0.19</td>
<td>78.28 ± 1.11</td>
<td>4.97</td>
<td>235.1</td>
</tr>
</tbody>
</table>

The same letters in columns indicate homogeneous groups (Tukey’s HSD, $p < 0.05$, $n = 6$).

The BI shows in a complex way the browning pattern of the investigated samples. Based on this parameter, it can also be stated that PEF treatment with the lowest energy input, regardless of the freeze-drying temperature, resulted in a less brown color in comparison to the reference pumpkins. However, the application of higher energy resulted in a browner color—the values of BI significantly correlated with energy input for samples dried at 40 °C ($r = 0.911$) and 60 °C ($r = 0.885$). Two-way ANOVA for average values showed that energy input had a bigger impact than temperature ($\eta^2 = 0.825$ and 0.377, respectively) on the variability in the BI, although the effect was not significant ($p = 0.175$ and 0.387) on the assumed level of confidence. Nevertheless, the samples dried at a higher temperature in general exhibited higher values of BI, which may be attributed to the surface release of sugars and caramelization reactions which can also take place at lower temperatures between 45 and 65 °C [33], and to Maillard’s reaction, which may occur at a temperature of 60 °C [34]. The total color difference in the PEF-treated samples, as calculated regarding the untreated freeze-dried material dried at the same temperature, ranged from 0.17 to 5.53. What is interesting is that, when comparing the effect of freeze-drying temperature, in general $\Delta E$ was higher for materials dehydrated at 40 °C, which means that the effect of PEF was more pronounced in that case.

3.4. Total Phenolic Content and Total Carotenoid Content

As pumpkin is an excellent source of bioactive compounds including β-carotene [35], it is worth observing the retention of this compound after freeze-drying. Figure 3a presents the total phenolic content (TPC) in untreated and PEF-treated freeze-dried samples. In general, better retention of TPC has been observed in the samples dried at 60 °C than at 40 °C. It could be due to the shorter drying time at higher temperatures, which might have reduced the degradation of bioactive ingredients in the dried pumpkins [36]. Moreover, at higher temperatures, the enzymes responsible for the oxidation of these compounds could be denatured [37]. In the case of TPC, PEF treatment has not shown a positive trend in the enhancement of its retention. The only significant increase in TPC content has been observed in the case of samples pretreated with PEF2 and PEF3 and dried at 40 °C. The high variability in the results may also be attributed to the presence of substances which may interfere with the phenolics’ determination and which are naturally present or are formed in the pumpkin during its processing, such as the before-mentioned products of nonenzymatic browning reactions [38,39].
may interfere with the phenolics’ determination and which are naturally present or are formed in the pumpkin during its processing, such as nonenzymatic browning reactions [38,39].

The sugars content in untreated and PEF-treated freeze-dried pumpkin is presented in Figure 4. In general, regardless of the freeze-drying temperature, the untreated material contained significantly more sucrose. Furthermore, the amount of glucose and fructose in the PEF-treated pumpkin was in most cases significantly higher. For example, the sucrose content of intact freeze-dried pumpkin was equal to 6.32 and 4.60 g/100 g d.m., for 40 and 60 °C, respectively. In turn, the PEF-treated material exhibited 3.89–5.55 g/100 g d.m. when the shelf temperature was set to 40 °C, and 2.99–4.28 g/100 g d.m. when it was set to 60 °C. At the same time, the levels of glucose and fructose content for PEF-treated samples were higher by 11.0–44.2% and 0.3–30.2%, respectively.

Figure 3b shows the total carotenoid content (TCC) in untreated and PEF-treated freeze-dried pumpkin at 40 and 60 °C. The TCC content in the samples dried at 60 °C is decreasing with an increase in PEF intensities, from 98.16 to 86.72 mg β-carotene/100 g d.m. for untreated and PEF samples, respectively. This can be explained by the fact that PEF treatment enhances heat and mass transfer in the plant tissue. Therefore, the more the cells are open (high Zp, see Figure 1), due to PEF, the more exposed the bioactive compounds are to the heat. Completely different behavior can be observed for the samples dried at 40 °C. With an increase in PEF intensities from 0 to 2 kJ/kg, the TCC is increasing, reaching a 40% increase in the sample pretreated with 2 kJ/kg. Similar behavior has been observed for carrot subjected to combined PEF and ultrasound treatment before hot-air drying [40].

3.5. Sugars Content

The sugars content in untreated and PEF-treated freeze-dried pumpkin is presented in Figure 4. In general, regardless of the freeze-drying temperature, the untreated material contained significantly more sucrose. Furthermore, the amount of glucose and fructose in the PEF-treated pumpkin was in most cases significantly higher. For example, the sucrose content of intact freeze-dried pumpkin was equal to 6.32 and 4.60 g/100 g d.m., for 40 and 60 °C, respectively. In turn, the PEF-treated material exhibited 3.89–5.55 g/100 g d.m. when the shelf temperature was set to 40 °C, and 2.99–4.28 g/100 g d.m. when it was set to 60 °C. At the same time, the levels of glucose and fructose content for PEF-treated samples were higher by 11.0–44.2% and 0.3–30.2%, respectively.
Several studies explained this phenomenon by sucrose inversion. The α-1,2-glycosidic bond, which combines glucose and fructose, can be broken in several ways, for instance, by applying a high temperature, chemicals, or enzymes. As a result of the hydrolysis process, sucrose can be broken into fructose and glucose monosaccharides [41]. PEF application can apparently have an influence on the inversion process of sucrose. In this case, enzymatic hydrolysis at low pH takes place. Due to the electroporation of the cells, PEF facilitates the internal diffusion of sugars and other substances, e.g., enzymes. Considering that enzymes can reach the substrate more easily, in this case sucrose, enzymatic hydrolysis happens faster. The existing literature also demonstrates that PEF treatment may increase the activity of native and even denaturized sucrose invertases [42]. Moreover, the kinetics of most chemical and biological processes are faster at higher temperatures. Also, the activity of sucrose invertases was reported to depend positively on temperature [43]. That could explain the lower sucrose content in the samples dried at 60 °C. It is worth emphasizing that an enhancement of sucrose inversion was also found because of ultrasound utilization [44].

Two-way ANOVA proved that energy input, temperature, and the interaction between those parameters alike had significant (p < 0.05) effects on sucrose and glucose content, whereas the fructose amount was influenced only by temperature and energy input. What is interesting, in the case of fructose content, is that the value of η² found for the effect of energy was much lower (0.774) than for temperature (0.909), while for sucrose it oscillated between 0.961 and 0.982, and for glucose between 0.861 and 0.882.

### 3.6. Hygroscopic Properties

The hygroscopic properties of the freeze-dried pumpkins depended strongly on the drying temperature (Figure 5). In all cases, the samples dried at 60 °C were characterized by a higher ability of water vapor adsorption in comparison to the materials dried at the lower temperature. Also, the energy input played an important role. However, its effect

Figure 4. Content of sugars, sucrose ( ), glucose ( ), and fructose ( ) in untreated and PEF-treated pumpkin freeze-dried at (a) 40 °C and (b) 60 °C depending on the specific energy input \( W_p \). ** Different letters indicate significant statistical differences (Tukey’s HSD, \( p < 0.05 \), \( n = 3 \)).
also depended on the freeze-drying temperature. For instance, the samples subjected to PEF treatment exhibited greater hygroscopicity when dried at 60 °C but lower when dried at 40 °C, in comparison to the respective reference materials. A reverse pattern has been stated for materials pretreated with PEF and then dried at 40 and 60 °C. The different ability of water vapor adsorption for the PEF and untreated samples seem to depend on many different factors. One of them is the sugars content—and especially the content of reducing sugars, which have a higher sorption capacity than non-reducing sugars [45].

![Figure 5](image-url)  
**Figure 5.** Kinetics of moisture adsorption ($H$) of untreated and PEF-treated pumpkin freeze-dried at (a) 40 °C and (b) 60 °C depending on time ($t$). Untreated (■), PEF1 (▲), PEF2 (▼), PEF3 (●), PEF4 (▶).

4. Conclusions

The application of PEF treatment even at low specific energy input (0.1–1 kJ/kg) induced the disintegration of pumpkin cells. Moreover, the further increase in specific energy input to values higher than 4 kJ/kg did not result in an increase in $Z_p$. PEF treatment showed a positive effect on the reduction of the residual moisture of the freeze-dried pumpkin. However, the higher temperature of drying, 60 °C, resulted in a lower residual moisture of the sample compared to that dried at 40 °C. In the case of retention of bioactive compounds, for the pumpkin dried at 40 °C, PEF treatment at 2 kJ/kg allowed 40% more...
total carotenoids to be retained compared to the untreated sample. An interesting finding has been observed that in all PEF-treated samples, the content of sucrose was reduced, while the content of glucose and fructose was increased. Finally, it has been shown that the different ability of water vapor adsorption for the PEF and untreated samples seem to depend on many different factors, for example, sugars content and composition.

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