processes

MDPI

Article

Impact of Pulsed Electric Field Treatment on the Process Kinetics and Selected Properties of Air and Dehumidified Air-Dried Mushrooms

Magdalena Dadan, Alicja Barańska, Aleksandra Matys, Katarzyna Rybak, Dorota Witrowa-Rajchert, Artur Wiktor and Małgorzata Nowacka *

Department of Food Engineering and Process Management, Institute of Food Sciences, Warsaw University of Life Sciences (WULS-SGGW), 02-787 Warsaw, Poland; magdalena_dadan@sggw.edu.pl (M.D.); alicja_baranska@sggw.edu.pl (A.B.); aleksandra_matys@sggw.edu.pl (A.M.); katarzyna_rybak@sggw.edu.pl (K.R.); dorota_witrowa_rajchert@sggw.edu.pl (D.W.-R.); artur_wiktor@sggw.edu.pl (A.W.)

* Correspondence: malgorzata_nowacka@sggw.edu.pl

Abstract: The study examined the effects of pulsed electric field treatment on the kinetics and properties of convective-dried mushrooms using different drying agents. Increasing the drying air temperature reduced drying time, while the use of dehumidified air resulted in faster water removal. PEF treatment, depending on the parameters, shortened the drying time maximum by 12% or extended the drying time. The physical (dry matter content, rehydration properties, hygroscopic properties, and color) and chemical (polyphenols content and anti-oxidant activity) properties were analyzed. The dry matter contents of the mushrooms were influenced by the drying temperature, while PEF pre-treatment did not influence the rehydration and hygroscopic properties in both cases of drying using air humidity. However, the color parameters were affected by the drying method and energy input, with higher energy input leading to decreased lightness, increased redness, and color saturation. The chemical analyses revealed that the anti-oxidant compounds in the dried mushrooms were influenced by various factors, with PEF treatment and drying non-dehumidified air polyphenol content increasing, whereas dehumidified air caused more phenolic degradation if it was combined with PEF treatment. Anti-oxidant activity varied depending on the drying agent, with non-dehumidified air generally exhibiting better properties. The highest total polyphenol content and best anti-oxidant properties were obtained for the PEF pre-treated with 3 kJ/kg of energy and dried with non-dehumidified air at a temperature of 70 °C.

Keywords: mushrooms; pulsed electric field; convective drying; dehumidified air; bioactive compounds; rehydration rate

Citation: Dadan, M.; Barańska, A.; Matys, A.; Rybak, K.; Witrowa-Rajchert, D.; Wiktor, A.; Nowacka, M. Impact of Pulsed Electric Field Treatment on the Process Kinetics and Selected Properties of Air and Dehumidified Air-Dried Mushrooms. *Processes* **2023**, *11*, 2101. https://doi.org/10.3390/pr11072101

Academic Editor: Jan Havlík

Received: 13 June 2023
Revised: 7 July 2023
Accepted: 12 July 2023
Published: 14 July 2023

1. Introduction

Non-thermal technologies, such as a pulsed electric field (PEF), are increasingly becoming an alternative to conventional food processing methods. The use of PEF technology is economical, environmentally friendly, and allows for the inactivation of micro-organisms and enzymes. Furthermore, the use of a pulsed electric field in food processing improves mass transfer, minimizes the loss of nutrients during processing, and can also extend shelf life [1]. Moreover, when using PEF, it is possible to modify the texture and, thus, design the properties of the material [2].

The mechanism of action of PEFs is based on subjecting products to short-term electric impulses with a high-strength electric field, usually from 10 kV/cm [3]. The mutual interaction of electric charges causes local structural changes in the material, breaking or damaging the continuity of the cell membrane of the raw material. The main mechanism of PEF action is called electroporation or permeabilization and is based on the electrically

induced formation of pores in a membrane, causing its increased permeability [4,5]. The impact of a PEF is dependent on the parameters, such as electric field strength and the shape and number of pulses, as well as their width and frequency [5,6]. Electroporation can be reversible or irreversible, depending, e.g., on the size of cells [6]. The irreversible electroporation causes permanent and irreversible disruption to the cell membrane and, therefore, has a positive effect on mass exchange or the inactivation of micro-organisms and can improve the drying process by accelerating the removal of water from the raw material [7].

Dellarosa et al. [8] analyzed the impact of a PEF on water distribution and loss in mushroom stalks. They reported that the PEF significantly disintegrated the tissue causing the redistribution of water from the intracellular to the extracellular compartments, which was comparable to the case of thermal treatment. Furthermore, the morphology and molecular weight of the polysaccharides in the cell wall of the mushrooms were modified due to PEF treatment. Many scientific papers have proven the acceleration of the drying process via pulsed electric field treatment. Depending on the matrix, a shortened drying time in the range of 8 to 30% was generally achieved [9]. In the work of Mirzaei-Baktash et al. [10], the drying time of mushroom slices was reduced by 7–25% for hot air drying and by 16–28% for the electrohydrodynamic method when a PEF was applied before the drying. However, the effect of a PEF is dependent not only on the PEF parameters but also on the drying method and drying conditions, and thus, both factors should be considered to guarantee a shorter drying time while also retaining the bioactive component contents.

Food drying is one of the oldest methods of food preservation, which plays a very important role in food processing. Due to the reduced water content and, thus, reduced water activity in a product, the growth of micro-organisms and the course of biochemical reactions are inhibited [11–13]. In the food industry, convective drying (air drying) is the most commonly used method on an industrial scale, which, according to numerous studies, is considered one of the most unfavorable methods of heat treatment. The material dried by convection is characterized by large physicochemical changes that affect the nature of chemical compounds and the structures of cells. Moreover, the energy consumption of this process is relatively high due to, e.g., the low thermal efficiency of dryers [13,14]. Nevertheless, this technique has many advantages, such as simplicity, low cost (of the dryers), and ease of process control [14], and is also frequently used in mushroom drying [15]. As Marçal et al. [15] summarized, mushrooms subjected to high-temperature drying are characterized by a change in their phenolic and organic acid profile and a decrease in polysaccharide content due to their conversion into oligosaccharides and Maillard reactions.

Conventionally, during convective drying, the material is dried by means of air of ambient humidity, which is heated to the set temperature. However, the problem is the lack of repeatability. Moreover, the course of the drying process is affected by the water content in the drying air. As a result of the reduced water content (dehumidified air), the potential of the heating medium to take moisture from the dried material increases, and due to the benefits that the use of dehumidified air can bring, it is, nowadays, more and more frequently used in experimental works [12].

Until now, the use of dehumidified air to support convective drying has not been studied in detail. The work of Matys et al. [12] showed some of the benefits of using dehumidified air, such as a reduction in drying time, significantly higher total phenolic content, and significantly better anti-oxidant activity. However, the authors noted this effect at a lower air temperature (55 °C and, in some cases, also 70 °C), and at 85 °C, the opposite effect was observed. Some properties and the shortening of the drying time were more pronounced when ultrasound treatment was carried out before drying with dehumidified air. Therefore, more studies need to be conducted concerning the combination of drying with dehumidified air and other pre-treatments, e.g., pulsed electric fields.

To the best of our knowledge, the combined influence of PEF treatment and drying with dehumidified air has not been investigated yet. Therefore, the aim of this study was to assess the possibility of using a PEF prior to convective drying with or without

dehumidified air based on the drying kinetics and selected properties of mushrooms. The physicochemical properties (such as hygroscopic properties, rehydration properties, color, and dry matter content), as well as the chemical properties, were measured to analyze the influence of both the PEF and dehumidified air on the different properties of a material. Many publications have confirmed that mushrooms exhibit anti-oxidant potential due to the phenolic compound content, and this affects the nutritional value of dried mushrooms [16]. Furthermore, color is a crucial factor that has an impact on the acceptance of a product by consumers. A good rehydration ratio is important to obtain a soft, well-rewatered dried sample. Additionally, in order to obtain a stable product during storage, hygroscopic properties should not increase. What is important regarding PEF treatment—due to the electroporation phenomenon—is the leakage of the content of cells can increase the browning reactions, causing undesirable changes in color [17], which can significantly impact the acceptance of the product by consumers. Therefore, the maintenance or increase (in the case of bioactive components or rehydration properties) in these parameters is important.

2. Materials and Methods

2.1. Material

The white mushrooms (champignons) were purchased in a unit package of 500 g at a market in Warsaw. The purified raw material, without stems, was kept at room temperature and was used for further research.

2.2. Pulsed Electric Field (PEF) Pre-Treatment

Before drying, the raw material was pre-treated with a pulsed electric field using the PEF Pilot reactor (ELEA GmBH, Quakenbrück, Germany). The pre-treatment parameters were selected on the basis of the preliminary studies, during which the changes in the conductivity of the material CDI (cell disintegration index) were analyzed after PEF treatment [18], as is presented in Figure 1.

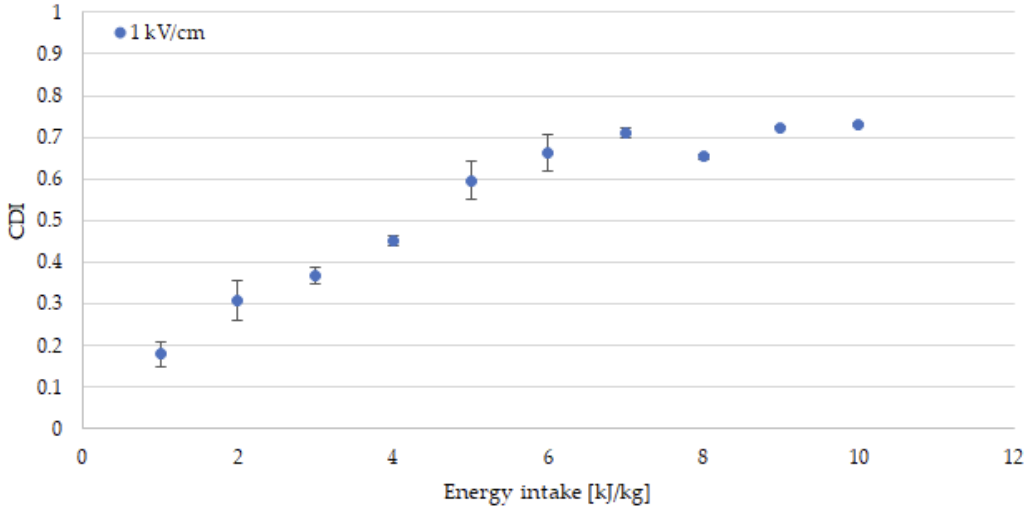

Figure 1. Cell disintegration index (CDI) after PEF treatment of mushrooms.

A range of specific energy input between 1 and 5 kJ/kg was selected for optimization, as it causes an increase in the CDI value but is below the "saturation" level; after exceeding this, the increase in energy intake does not significantly increase the CDI. The parameters of the pulsed electric field were set at the following values: the electrode voltage equaled 24 kV; the electric field strength stood at 1 kV/cm; the pulse frequency was at 20 Hz; the pulse width took the value of 7 µs. The number of rectangular pulses varied concerning the amount of supplied energy. According to the preliminary studies, the following energy values were set: 1, 3, and 5 kJ/kg due to the electroporation phenomenon. In order to set

the appropriate PEF value, the mushroom caps were placed in an electrical treatment cell. The structure of the electrical treatment cell included a set of two parallel stainless-steel electrodes, which were distanced from each other by 24 cm. Then, the mushrooms were flooded with tap water (21 ± 1 °C, which served the function of a conductive medium) to a weight of 1 kg. The system prepared in this way was placed inside the reactor. After the treatment, the excess water from the mushrooms was removed using tissue paper, and the mushroom cups were cut into 5 mm-thick slices.

2.3. Convective Drying

The samples were dried in a laboratory convective dryer, which was integrated into an air dehumidification system, as was presented in the work by Matys et al. [12]. The air dehumidifier was composed of a cooling unit (MTA, TAEevo TECH020, Tribano, Italy) and a condensation-adsorption unit (ML270, Munters, Kista, Sweden). Air humidity after dehumidification was 1.5 g/m^3. The drying air temperature and velocity were set to 55, 70, and 85 °C and 2 m/s, respectively. The air flowed parallel to the layer of the mushrooms, which were laid on the sieve. The load on the sieve was 0.96 kg/m^2. The change in the mass (±0.1 g) of the sample was measured and recorded every minute. The process lasted until the samples reached a constant mass. The drying was performed in duplicate.

The drying curves were plotted as a relationship between the relative (dimensionless) water content and the time (MR = f(τ)), based on the recorded changes in the mass of the samples during drying:

$$MR = \frac{M_\tau}{M_0}, \quad (1)$$

where M_τ and M_0 correspond to the water content of the sample during drying [kg H_2O/kg d.m.] and the initial water content [kg H_2O/kg d.m.], respectively.

The drying time was defined by obtaining MR = 0.02 [19]. The change in drying time was calculated as a percentage change in the time of convective drying (CD) and convective drying with dehumidified air (DA).

2.4. Dry Matter Content

The dry matter content was determined via the gravimetric method at 70 °C for 24 h, according to the method of AOAC [20]. The measurement was performed for two repetitions.

2.5. Hygroscopic Properties

In order to determine the hygroscopic properties of the dried mushroom slices, a water vapor adsorption test was carried out. For this purpose, the dried mushrooms were weighed on an analytical scale and were then placed in a desiccator with a sodium chloride solution, giving a water activity of 0.75 [21]. The mass of the samples was remeasured after 1, 24, 48, and 72 h. The hygroscopic properties were determined as the mass of the sample over adsorption time in relation to the initial mass of the dried material. The measurement was performed for three replicates.

2.6. Rehydration Properties

Half a slice of the dried mushroom was placed in a beaker filled with 100 mL of distilled water. The beaker and all of its content were kept at room temperature (approx. 20 °C) for 1 h. After this time, the water was filtered through a sieve, and the rehydrated mushroom was slightly blotted and weighed. Then, the dry matter content was determined according to the methodology described in Section 2.4. The analysis was performed for three replicates.

The rehydration properties were determined on the basis of relative mass gain (Δm) and relative dry matter content (SSL) according to the following formulas:

$$\Delta m = \frac{m_\tau}{m_0}, \quad (2)$$

$$SSL = \frac{m_\tau dm_\tau}{m_0 dm_0}, \quad (3)$$

where m_τ is the mass of the rehydrated mushroom [g], m_0 stands for the mass of the sample before rehydration [g], $d_{m\tau}$ is the dry matter content in the rehydrated mushroom [%], and d_{m0} is the dry matter content in the sample before rehydration [%].

2.7. Color

The fresh and dried samples were analyzed with a colorimeter (CR-5, Konica-Minolta, Tokyo, Japan) in order to determine their color in CIE L*a*b*system (light source: D65; standard observer: 2°; diameter: 8 mm). Each sample was analyzed over 10 replications. The total color difference (ΔE) and chroma (C*) were calculated based on the L*a*b* color parameters [13]:

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}, \quad (4)$$

$$C^* = \sqrt{(a^*) + (b^*)}, \quad (5)$$

where L* is the lightness, a* is redness/greenness, b* is yellowness/blueness of the samples, and ΔL*, Δa*, Δb* are the differences in the color parameters between the fresh and dried mushrooms.

2.8. Total Phenolic Content (TPC)

The determination of total phenolic content was carried out using the Folin-Ciocalteu method [18]—gallic acid was served as the standard. Grounded dried mushrooms were extracted with 80% ethanol solution in order to obtain polyphenolic compounds. In order to determine the TPC, 4.92 mL of distilled water, 0.18 mL of extract, and 0.3 mL of Folin-Ciocalteu's reagent were added to the test tubes. After 3 min, 0.6 mL of a supersaturated sodium carbonate solution was dispensed. The samples were mixed and then stored in the dark for 1 h. Finally, the absorbance at 750 nm was measured on a UV-VIS spectrophotometer (Heλios γ, Thermo Scientific) against a blank, i.e., extract-free. The results are expressed as milligrams of gallic acid per 1 g of dry matter. The analyses were performed in duplicate.

2.9. Anti-Oxidant Activity (DPPH and ABTS Assays)

Anti-oxidant activity was assessed on the basis of the degree of scavenging of the synthetic $DPPH^\bullet$ radicals and the $ABTS^{\bullet+}$ radical cations by the anti-oxidants extracted from the samples. For the procedure, the same ethanol extracts were used for the determination of total phenolic content. In order to perform the chemical analyses, free radical solutions and solutions for the measurements were prepared according to the methodology described in [11].

Ethanol extracts were placed in glass test tubes in the amount of 0.1, 0.2, 0.3, and 0.5 mL. The tubes were then filled up to a total volume of 2 mL with 80% ethanol solution. Then, 2 mL of DPPH solution was added and mixed thoroughly. After 30 min (room temperature, dark place), the absorbance was measured at a wavelength of 515 nm (Heλios γ spectrophotometer, Thermo Scientific) against an 80% ethanol solution. The analysis was performed twice.

The test tubes were dosed with ethanol extracts in the following volumes: 0.025, 0.05, 0.075, and 0.1 mL, and then 3 mL of ABTS solution was added thereafter. Everything was mixed and left for 6 min in a dark place. Subsequently, the absorbance was measured at a wavelength of 734 nm (Heλios γ spectrophotometer, Thermo Scientific) against an 80% ethanol solution. The analysis was conducted over two replications.

Anti-oxidant activity was expressed as the EC_{50} for the DPPH and the ABTS radical methods. This indicator determines the dry matter content in the extract (mg d.m./mL) necessary to scavenge 50% of the initial amount of free radicals.

2.10. Statistical Analysis

The statistical analysis was performed using Statistica 13.3 software (TIBCO Inc., Palo Alto, CA, USA). The one-way analysis of variance (ANOVA) with Tukey's tests at a significance level of $\alpha = 0.05$ were used for this purpose. For the selection of the optimal temperature and PEF energy for non-dehumidified and humidified air, the DOE method was used (Statistica 13.3, TIBCO Inc., USA).

3. Results and Discussion

3.1. Drying Kinetics

Figures 2 and 3 show the kinetics of drying for the untreated and PEF-pre-treated mushrooms, from which water was removed with non-dehumidified and dehumidified air, respectively. As can be seen, the drying efficiency decreased over time. This phenomenon was related to the progressing difficulties in the water removal procedure [19]. By increasing the temperature of the drying air and therefore intensifying the water evaporation process [20,21], the drying time of the mushrooms was reduced (Table 1). For example, the drying time of the 85CD sample was 26% shorter than that of the 70CD sample. On the other hand, drying the 70CD sample to MR = 0.02 took 43% less time than the drying process of the 55CD sample (to the same relative water content). When comparing the two types of drying agents to each other—non-dehumidified and dehumidified air—it can be concluded that the use of air with reduced humidity ensured faster water removal than the non-dehumidified air. This phenomenon can be explained by the greater potential of the dehumidified air to absorb water from the given material [11]. So far, the effect of dehumidified air on convective drying has been investigated on fruit such as apples [11,22], kiwi [23], and quince [24]. The results appear to be consistent: reducing the humidity of the drying air reduces the drying time of a given product, which results from increasing the gradient of water vapor pressure between the drying air and the surface of the dried material. Moreover, a higher percentage reduction in drying time is achieved at lower air temperatures. For example, the drying time of the 55DA sample was 38% shorter than that of the 55CD sample. However, after increasing the temperature to 70 and 85 °C, the reduction was 26 and 10%, respectively. A pulsed electric field (PEF) is often used as a pre-treatment before drying. It is applied to, for example, maximize the efficiency of removing water from a given material. The application of a PEF did not reveal any distinct tendencies in the duration of the subsequent drying of the mushrooms. The highest reduction in drying time (14% in relation to the material untreated with a PEF and dried in the same conditions) was noted after providing energy at the amount of 3 kJ/kg to the mushrooms and then drying them with non-dehumidified air at 55 °C. It is consistent with the values obtained in the literature, in which the drying time reduction was in the range of 8–30% [9]. On the other hand, the drying time of the PEF3_55DA sample was 37% longer than that of the 55DA sample. By increasing the permeability of the cell membrane due to electroporation, the pulsed electric field led to a reduction in the convective drying time of parsnips, carrots [25], potatoes [26], onions [27,28], and red peppers [29]. The effectiveness of a PEF depends not only on the physical properties of a given material [30] but also on the applied parameters and method of drying. Therefore, both the PEF and the drying parameters should be adjusted to obtain a positive effect. Further research is necessary in this area.

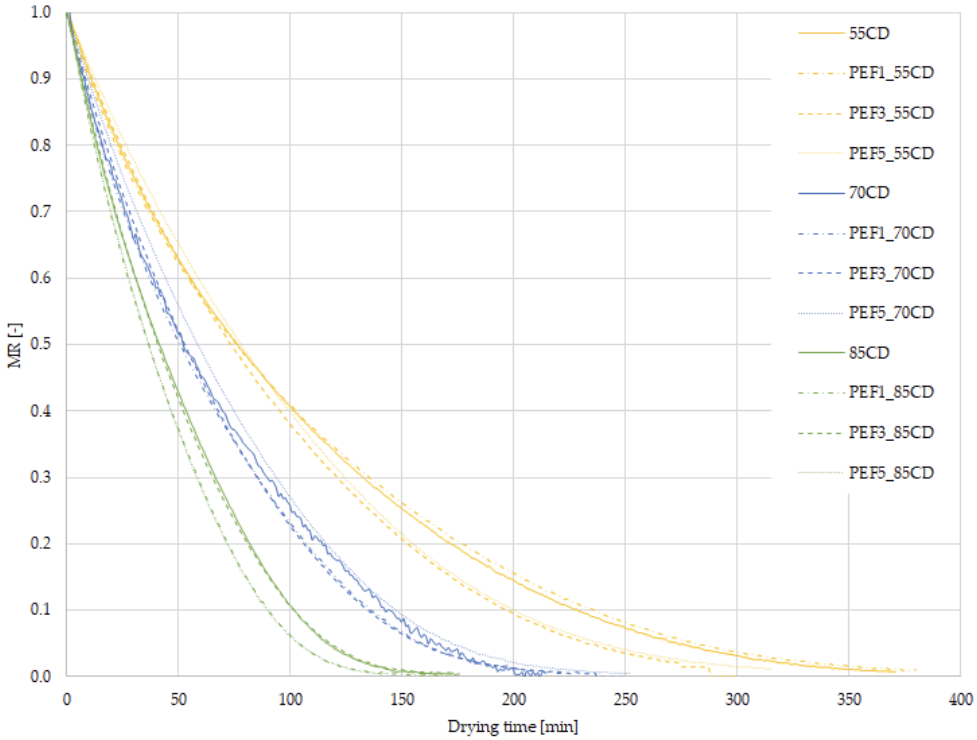

Figure 2. Drying kinetics of mushrooms obtained using the convective method with non-dehumidified air subjected to (or not) PEF.

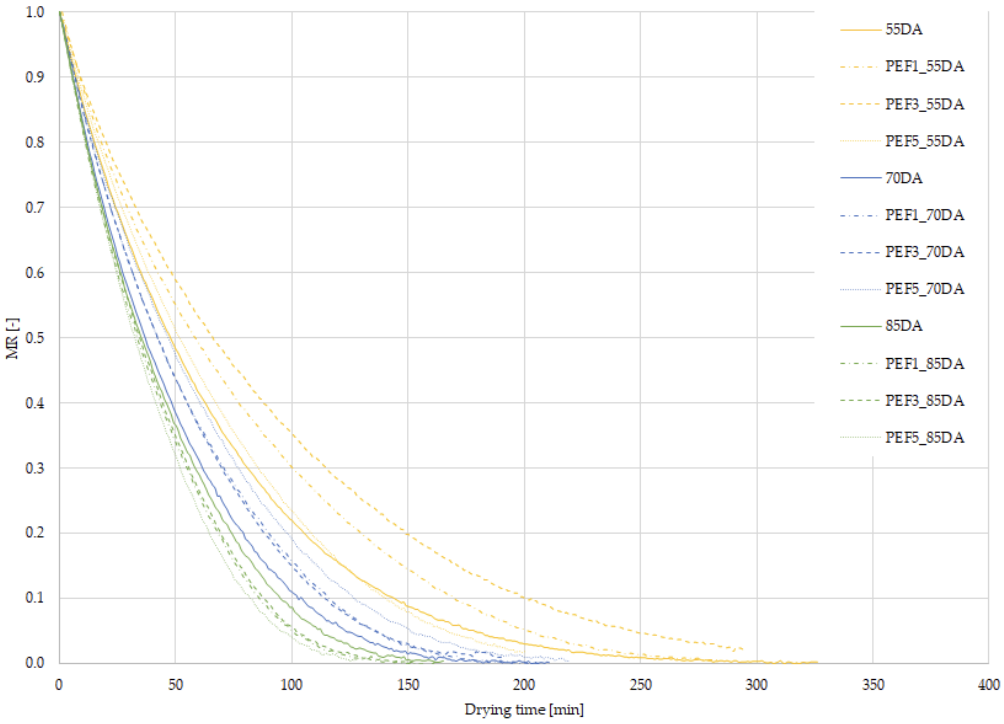

Figure 3. Drying kinetics of mushrooms obtained using the convective method with dehumidified air subjected to (or not) PEF.

Table 1. Drying time to MR = 0.02 of the convective-dried (CD) and dehumidified convective-dried (DA) mushrooms, including PEF pre-treatment and drying temperature. The drying time change was calculated as a percentage time change between CD and DA.

Temperature [°C]	PEF Input [kJ/kg]	Drying Time [min]		Drying Time Change [%]
		CD	DA	
55	0	336	209	38
	1	351	227	35
	3	288	287	3
	5	301	190	37
70	0	191	142	26
	1	194	152	22
	3	207	152	27
	5	212	173	18
85	0	140	126	10
	1	126	112	11
	3	139	115	17
	5	123	108	12

3.2. Dry Matter Content

The dry matter content of dried mushrooms with non-dehumidified air that were subjected to (or not) PEF treatment varied from 89.1 to 96.8% (Figure 4). It can be observed that both the temperature of drying and PEF pre-treatment significantly influenced the parameter. When comparing the non-treated samples to the PEF-treated samples at the same temperature of drying, it was observed that PEF affected the dry matter content, but the significance of this effect was dependent on the air temperature. Increasing the drying temperature improved the water evaporation rate, which resulted in higher dry matter content. However, regarding the lowest drying temperature (55 °C), PEF significantly decreased the dry matter content, irrespective of the energy input setting. In the case of the middle set of temperatures, the pre-treated samples were characterized by significantly lower dry matter content when compared to the non-treated samples, but only when 3 and 5 kJ/kg was applied. For the highest drying temperature, the application of the PEF to the sample did not significantly influence the dry matter content. Interestingly, there were no significant differences in dry matter content between the different energy input levels of the PEF-treated samples (1–5 kJ/kg), irrespective of the temperature. When taken together, these results suggest that drying temperature had a greater effect on this parameter than the use of the PEF.

The results of the dry matter content of the mushrooms dried with the application of the dehumidified air with or without PEF pre-treatment are presented in Figure 5, and they ranged from 83.9 to 97.6%. Similar to the variants dried with non-dehumidified air, the drying temperature had a significant effect on the dry matter content of the obtained mushrooms. However, it should be underlined that the temperature had the most significant influence on this parameter when 3 kJ/kg of energy was applied. When comparing the PEF-treated and the intact dried samples, it can be seen that the significant difference was noted only with the use of 3 kJ/kg when drying at 55 and 70 °C. With regard to the different energy inputs of the PEF pre-treatments, the only significant differences were observed for the mushrooms dried at the lowest drying temperature of 55 °C—the middle value of energy caused a significant decrease in dry matter content. For the other energy values—the results were statistically the same as for the non-treated sample.

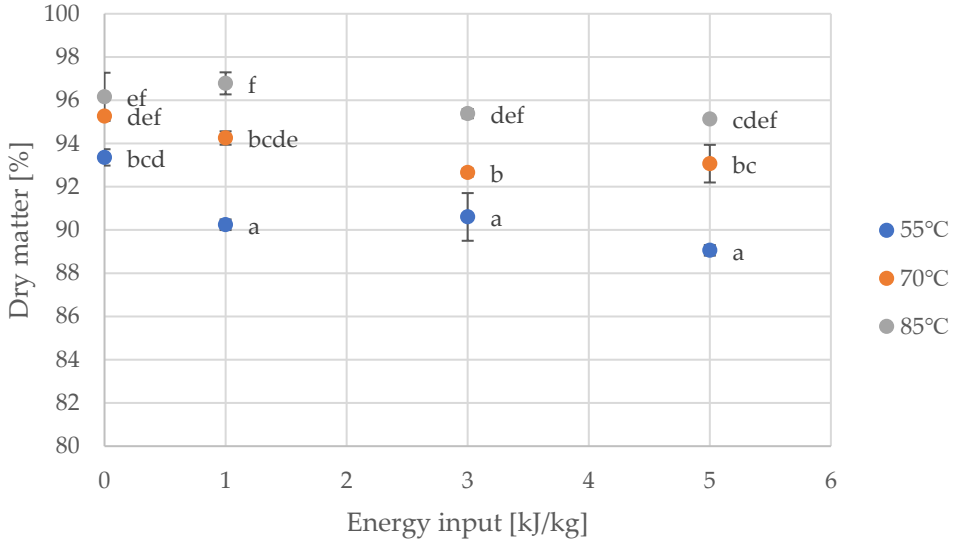

Figure 4. Dry matter [%] of mushrooms obtained using the convective method with non-dehumidified air subjected to (or not) PEF. The same letters (a–f) represent the homogeneous groups (α = 0.05).

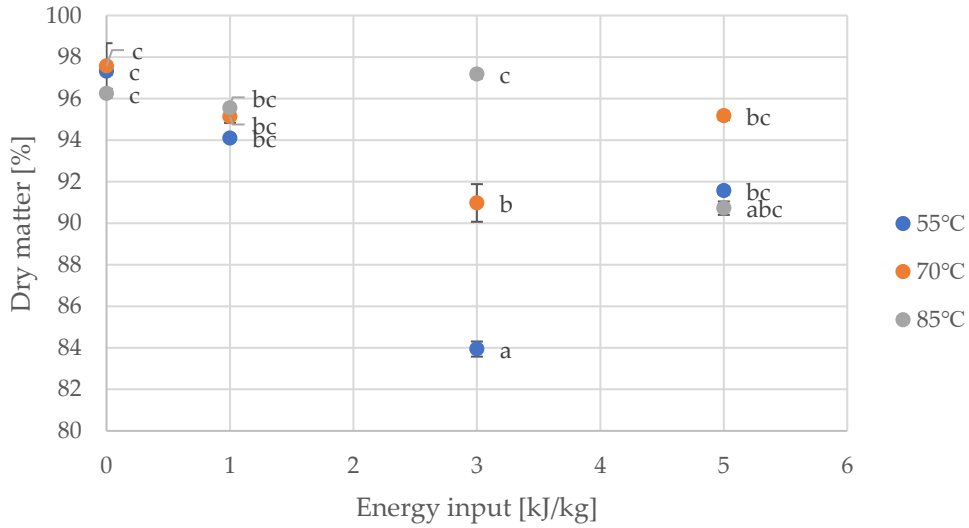

Figure 5. Dry matter [%] of mushrooms obtained using the convective method with dehumidified air subjected to (or not) PEF. The same letters (a–c) represent the homogeneous groups (α = 0.05).

The results of the dry matter content of the dried white button mushrooms presented in this study follow the data presented in the literature [31].

3.3. Hygroscopic Properties

The gain in mass of the dried white button mushrooms with non-dehumidified air after 72 h of moisture adsorption was significantly affected by drying temperature, and it ranged from 1.05 to 1.19 (Figure 6). Generally, with increasing drying temperature, the gain in mass of the samples increased. Moreover, the PEF pre-treatment did not have a significant effect on the mushrooms' hygroscopic properties, with the exception of the sample dried at the highest drying temperature and pre-treated with the highest energy input (85 °C, 5 kJ/kg), as well as with 3 and 5 kJ/kg and drying at 55 °C. In that case, the PEF-treated material was characterized by lower water vapor adsorption. The obtained results concur well with the findings of Wiktor et al. [32], who reported no difference in the hygroscopic properties of dried apples subjected to PEF pre-treatment. However, the results presented in this research are in contrast to the research of Rybak et al. [33], who freeze-dried PEF-treated red bell peppers and observed increased hygroscopic properties

regarding the material after pre-treatment. Lammerskitten et al. [34] reported, on the other hand, that PEF pre-treatment decreased water vapor absorption in freeze-dried apples, as the sugar distribution profile of the samples changed as a result of electroporation.

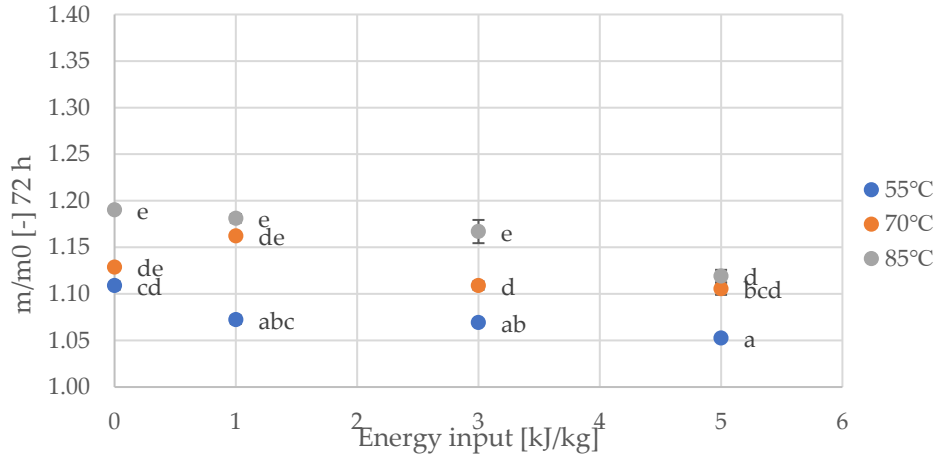

Figure 6. Hygroscopic properties (m/m_0) of mushrooms obtained using the convective method with non-dehumidified air subjected to (or not) PEF. The same letters (a–e) represent the homogeneous groups ($\alpha = 0.05$).

The gain in mass of the mushrooms after 72 h of treatment, which was obtained under low drying air humidity, significantly differed when dried at different drying temperatures, which is similar to the samples dried with non-dehumidified air (Figure 7). However, it should be underlined that the energy input of 3 kJ/kg had the greatest effect on the hygroscopic properties of the mushrooms dried at the lowest temperature, as the gain in mass of the sample was the lowest. Only in the case of this sample was the impact of the PEF significant. It can be concluded that, in general, the PEF energy value (1–5 kJ/kg) did not influence the hygroscopic properties in both cases of drying air humidity, and in most cases, the use of the PEF (when compared to the untreated mushrooms) did not change the hygroscopic properties. In fact, the unchanged or decrease in mass gain after water vapor adsorption is desirable, as the product can be stable during storage (does not adsorb as much moisture from the environment).

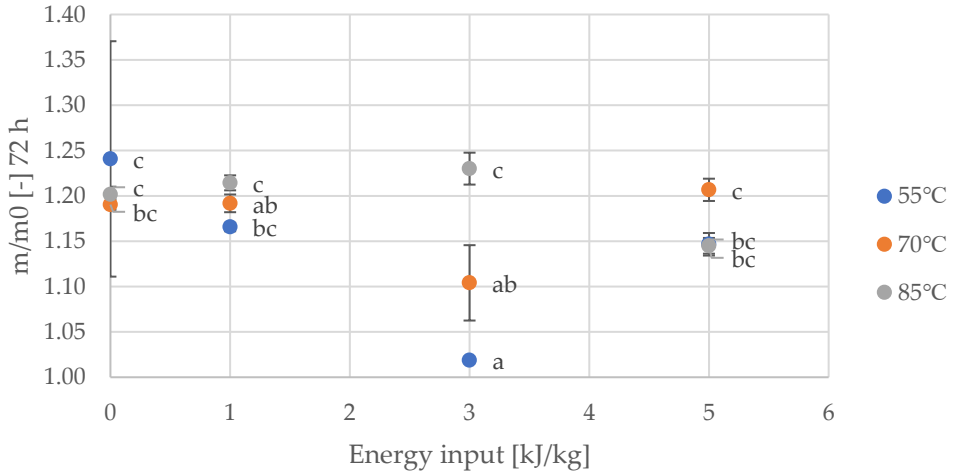

Figure 7. Hygroscopic properties (m/m_0) of mushrooms obtained using the convective method with dehumidified air subjected to (or not) PEF. The same letters (a–c) represent the homogeneous groups ($\alpha = 0.05$).

3.4. Rehydration Properties

The determination of the rehydration properties was performed in order to establish the ability of the drying sample to be re-imbibed with water [35,36]. On this basis, it can be determined, e.g., via the magnitude of the chemical and structural changes caused by the processing of the material [37,38]. Figure 8 shows the relative gain in mass (Δm) of the untreated and PEF-treated mushrooms dried with non-dehumidified air. As one can observe, all the analyzed samples did not differ statistically. On the other hand, Figure 9 shows the values of Δm of the untreated and PEF-pre-treated mushrooms dried with dehumidified air. A significant difference was noted only between the PEF3_55DA and PEF5_55DA samples. The PEF5_55DA sample exhibited a higher Δm. The different temperatures of the drying air and the variable amount of energy supplied to the mushrooms during PEF pre-treatment (except for the above-mentioned exception) did not lead to a clear, straightforward tendency in the relative mass-gain values.

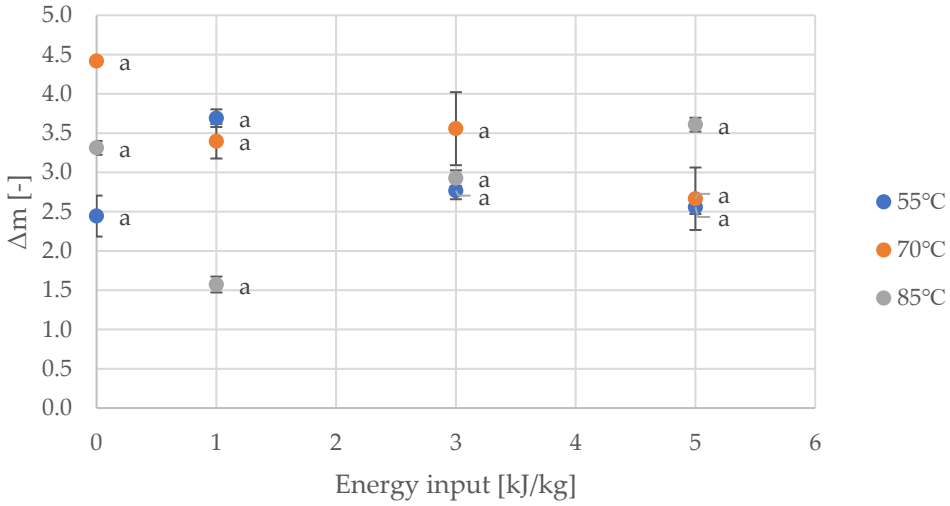

Figure 8. Relative gain in mass (Δm) of mushrooms obtained using the convective method with non-dehumidified air subjected to (or not) PEF. The same letter (a) represents the homogeneous groups (α = 0.05).

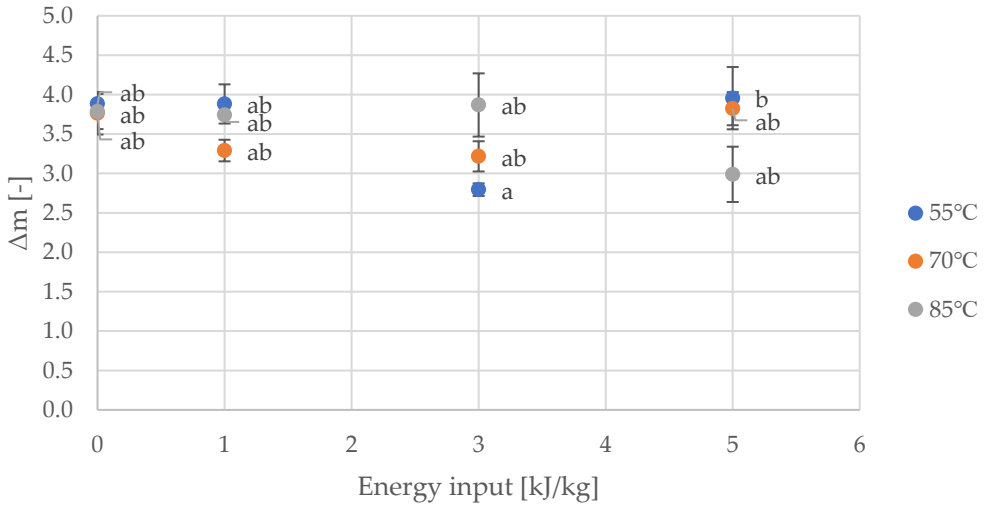

Figure 9. Relative gain in mass (Δm) of mushrooms obtained using the convective method with dehumidified air subjected to (or not) PEF. The same letters (a,b) represent the homogeneous groups (α = 0.05).

During rehydration, in addition to the water absorption process, the material tends to swell. The leaching of soluble solids into surrounding water takes place as well [35,39]. Figures 10 and 11 show the relative dry matter content after rehydration (to a dried mushroom before rehydration (SSL)) of the untreated and PEF-treated mushrooms dried by non-dehumidified and dehumidified air, respectively. The different temperatures of the drying air and the variable amount of energy supplied to the mushrooms during the PEF pre-treatment did not lead to a clear, straightforward tendency in the relative dry matter content. In most of the analyzed cases, the usage of dehumidified air resulted in obtaining dried mushrooms with higher SSL values. It means that the materials dried with dehumidified air lost less dry matter than those obtained with non-dehumidified air. Samples 55DA and PEF1_70DA were an exception to this; their non-dehumidified air-dried counterparts (55CD and PEF1_70CD) exhibited higher relative dry matter content.

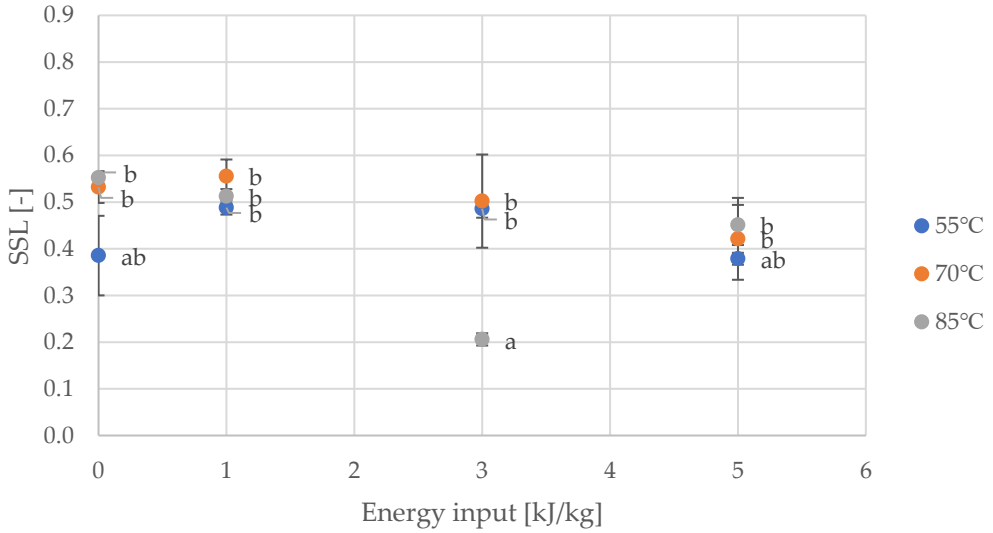

Figure 10. Relative dry matter content (SSL) of mushrooms obtained using the convective method with non-dehumidified air subjected to (or not) PEF. The same letters (a,b) represent the homogeneous groups ($\alpha = 0.05$).

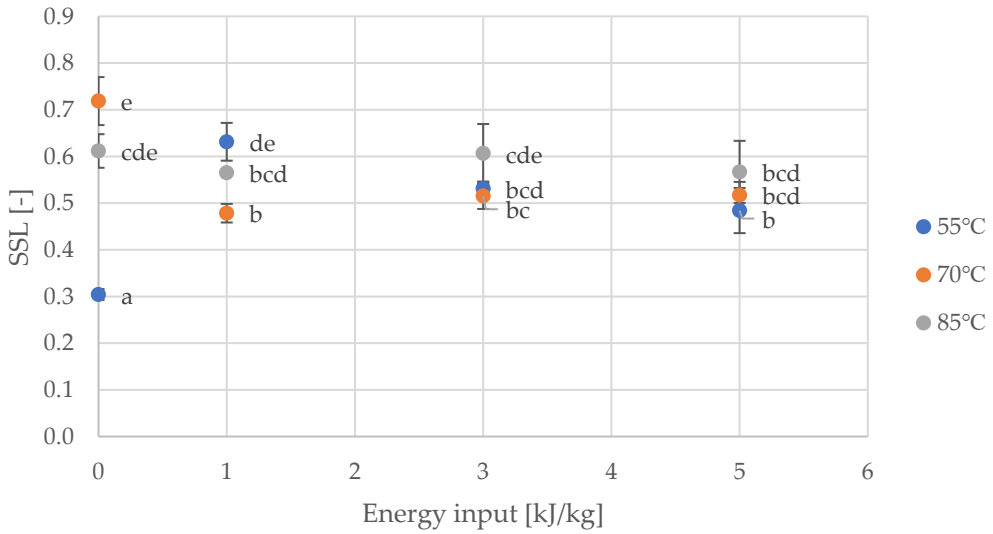

Figure 11. Relative dry matter content (SSL) of mushrooms obtained using the convective method with dehumidified air subjected to (or not) PEF. The same letters (a–e) represent the homogeneous groups ($\alpha = 0.05$).

3.5. Color

Table 2 presents the color parameters of the analyzed mushrooms. The L* color parameter describes the lightness of the samples and ranged from 46.2 ± 3.1 to 79.9 ± 3.2 for those mushrooms dried using the convective method with non-humidified air. The significant effect of energy input was noted. The input of 1 kJ/kg did not affect any of the samples in comparison to the control. These results were the highest, indicating the lightest of all the samples. However, the increasing value of energy decreased the lightness of the samples dried at each of the drying temperatures. This is in agreement with Wiktor et al. [40], who observed the same relationship for dried carrots pre-treated with a PEF. Alam et al. [25] noted, as well, the darkening of the PEF pre-treated dried carrots and parsnips [25]. Electroporation, which led to leakages of the cellular content, such as enzymes, could well be responsible for this phenomenon. In contradiction to these observations, Won et al. [29], who applied PEF before drying red peppers, reported that the energy input did improve the color parameters of the samples. In general, the temperature of drying with non-dehumidified air did not affect the lightness; the only exception was the PEF_3_55C sample, which was characterized by significantly lower lightness than that of analogous samples dried at different temperatures. With regard to the samples dried with dehumidified air, the L* parameter varied from 58.7 ± 8.3 to 87.6 ± 3.2. In general, for this drying method, the effect of energy input was insignificant, as the variants pre-treated with the PEF did not differ (except for PEF1_55DA sample). However, the mushrooms subjected to the PEF were darker in comparison to the control samples, which, as aforementioned, was a result of the electroporation.

Table 2. The color parameters of the mushrooms obtained using the convective method with non-dehumidified air or dehumidified air subjected to (or not) PEF. The same letters ($^{a–d}$ and $^{A–D}$) in the columns represent the homogeneous groups ($\alpha = 0.05$).

Material	L*	a*	b*	C*	ΔE
55CD	79.9 ± 3.2 ^{d}	−0.6 ± 0.5 ^{a}	17.1 ± 0.9 ^{a}	17.1 ± 0.9 ^{a}	10.3 ± 2.8 ^{a}
PEF1_55CD	77.8 ± 2.4 ^{d}	+2.0 ± 0.6 ^{b}	24.9 ± 1.4 ^{c}	25.0 ± 1.4 ^{bc}	16.4 ± 2.4 ^{a}
PEF3_55CD	50.5 ± 3.5 ^{a}	+6.4 ± 1.5 ^{de}	21.3 ± 1.6 ^{bc}	22.3 ± 1.8 ^{bc}	40.5 ± 3.5 ^{d}
PEF5_55CD	44.9 ± 8.1 ^{a}	+7.0 ± 0.6 ^{de}	21.6 ± 2.2 ^{bc}	22.7 ± 2.2 ^{bc}	46.2 ± 7.4 ^{d}
70CD	75.1 ± 8.2 ^{cd}	−0.8 ± 0.5 ^{a}	12.3 ± 1.5 ^{a}	12.3 ± 1.5 ^{a}	14.5 ± 8.3 ^{ab}
PEF1_70CD	78.7 ± 6.5 ^{d}	+0.1 ± 0.4 ^{ab}	15.5 ± 0.7 ^{a}	15.5 ± 0.7 ^{a}	11.1 ± 6.4 ^{a}
PEF3_70CD	61.9 ± 6.5 ^{bc}	+4.2 ± 1.8 ^{b}	21.0 ± 2.9 ^{b}	21.5 ± 3.0 ^{b}	29.1 ± 6.9 ^{c}
PEF5_70CD	46.2 ± 3.1 ^{a}	+8.0 ± 1.0 ^{f}	22.1 ± 2.2 ^{bc}	23.6 ± 2.2 ^{bc}	45.1 ± 3.0 ^{d}
85CD	77.6 ± 7.1 ^{d}	−0.7 ± 0.3 ^{a}	13.9 ± 0.7 ^{a}	13.9 ± 0.7 ^{a}	11.9 ± 7.1 ^{a}
PEF1_85CD	70.8 ± 6.6 ^{cd}	+1.3 ± 0.5 ^{ab}	16.8 ± 1.9 ^{a}	16.9 ± 2.0 ^{a}	19.2 ± 6.7 ^{ab}
PEF3_85CD	64.3 ± 6.1 ^{c}	+4.9 ± 1.7 ^{cd}	23.0 ± 2.5 ^{bc}	23.5 ± 2.5 ^{bc}	27.6 ± 5.9 ^{bc}
PEF5_85CD	52.8 ± 3.0 ^{ab}	+7.7 ± 1.0 ^{f}	24.1 ± 2.9 ^{bc}	25.3 ± 3.0 ^{c}	39.2 ± 3.1 ^{d}
55DA	87.1 ± 1.5 ^{B}	+0.2 ± 0.4 ^{A}	14.3 ± 0.5 ^{A}	14.3 ± 0.5 ^{A}	2.9 ± 1.4 ^{A}
PEF1_55DA	81.9 ± 3.4 ^{B}	+0.6 ± 0.4 ^{A}	17.0 ± 1.1 ^{AB}	17.0 ± 1.1 ^{ABC}	8.5 ± 3.5 ^{AB}
PEF3_55DA	61.6 ± 4.5 ^{A}	+4.5 ± 1.0 ^{BC}	21.3 ± 3.2 ^{B}	22.2 ± 3.4 ^{C}	29.1 ± 4.8 ^{CD}
PEF5_55DA	60.6 ± 6.9 ^{A}	+3.7 ± 1.4 ^{BC}	18.4 ± 1.6 ^{AB}	18.6 ± 1.9 ^{ABC}	29.7 ± 7.9 ^{CD}
70DA	87.6 ± 3.2 ^{B}	0.0 ± 0.6 ^{A}	14.3 ± 2.8 ^{A}	14.3 ± 2.8 ^{A}	3.9 ± 2.4 ^{A}
PEF1_70DA	68.8 ± 7.4 ^{A}	+3.4 ± 1.3 ^{B}	18.0 ± 1.5 ^{AB}	18.3 ± 1.6 ^{ABC}	21.7 ± 7.4 ^{C}
PEF3_70DA	59.4 ± 9.8 ^{A}	+5.4 ± 1.6 ^{BC}	20.9 ± 6.0 ^{B}	20.7 ± 5.5 ^{BC}	32.8 ± 9.5 ^{D}
PEF5_70DA	68.5 ± 7.2 ^{A}	+3.0 ± 1.7 ^{B}	16.4 ± 2.6 ^{AB}	15.8 ± 1.9 ^{AB}	18.8 ± 3.1 ^{BC}
85DA	84.3 ± 1.9 ^{B}	+0.4 ± 0.3 ^{A}	15.9 ± 0.8 ^{AB}	15.9 ± 0.8 ^{AB}	5.9 ± 1.8 ^{A}
PEF1_85DA	58.7 ± 8.3 ^{A}	+4.3 ± 1.5 ^{BC}	16.3 ± 1.6 ^{AB}	16.9 ± 1.8 ^{ABC}	31.4 ± 8.5 ^{CD}
PEF3_85DA	64.5 ± 4.2 ^{A}	+3.2 ± 0.4 ^{B}	16.2 ± 1.6 ^{AB}	16.5 ± 1.5 ^{ABC}	25.5 ± 4.1 ^{CD}
PEF5_85DA	67.1 ± 3.1 ^{A}	+3.1 ± 0.6 ^{B}	18.5 ± 0.9 ^{AB}	18.8 ± 0.8 ^{ABC}	23.3 ± 2.8 ^{CD}

The redness of the samples (a*) varied from −0.8 ± 0.5 to +8.0 ± 1.0 and was significantly affected by the energy input of PEF pre-treatment with regards to the mushrooms

dried conventionally. It can be observed that increasing the energy input increased the a* parameter, which indicated a higher saturation of red in the samples. This implies that enzymatic browning occurred as a result of the leak of the cellular content, which was the effect of electroporation. These observations correlate favorably with Wiktor et al. [40] and Alam et al. [25], who noted the same effect of PEF pre-treatments on carrot tissue and parsnips, respectively [25,41]. However, in another piece of research by Wiktor et al. [41] on carrots, the authors reported the opposite relationship between the energy input of the PEF and the a* color parameter [41]. As for the mushrooms dried with the application of dehumidified air, the values of the a* parameter ranged from 0.0 ± 0.6 to +5.4 ± 1.6, and the effect of the PEF on this parameter was similar to the effect on lightness: PEF had less impact on the redness of the mushrooms. The effect of temperature and PEF energy on yellowness (b*) in the case of both drying media was similar to the case of the a* value.

The chroma (C*) of the samples dried using convective drying was significantly affected by PEF pre-treatment. It was observed that, with increasing energy input, C* increased, which underlined the importance of PEF pre-treatment, as C* defines the saturation of the color. However, with regard to the samples dried using dehumidified air, the PEF pre-treatment did not significantly influence C*. According to Tiwari et al. [42], samples that are characterized by a ΔE of higher than 2 have differences that are visible to an untrained observer. By taking this relationship into consideration, for all of the dried mushrooms, the changes in the colors were considered visible to the observer. Moreover, it can be noted that, with an increasing PEF pre-treatment energy input, ΔE increased as well, which was due to more prominent electroporation and, thus, enzymatic browning.

When taken together, these results suggest that the color parameters were significantly affected by PEF pre-treatment for both drying methods. It can be concluded that, in comparison to the previous data reported on PEF application to dried materials, the effect of this technique depends on the type of dried material and the parameters of both the drying and PEF.

3.6. Total Phenolic Content and Anti-Oxidant Activity

Table 3 presents the results of the chemical analyses concerning the content of anti-oxidant bioactive compounds in the obtained dried mushrooms. Polyphenols are unstable compounds that are prone to reacting with some factors and/or degradation. Their stability depends on enzymes, light, metal ions, oxygen, pH, and proteins, as well as temperature. In addition, they may interact with some food constituents [43]. Nevertheless, no straightforward tendency was observed concerning the TPC values and the temperature of the drying air. Interestingly, the introduction of a preliminary treatment in the form of a PEF led to, in some cases, a significant increase in TPC in the mushrooms dried with non-dehumidified air. The effect of a PEF on enzymes is not clear-cut. Depending on the treated matrix and the parameters applied, the PEF may both decrease and increase their activity [44]. Moreover, the extraction capacity of PEF-treated samples as a result of the structural damage of the cells may also increase [17]. However, in the case of drying with the second type of medium—air with reduced humidity—a slightly lower content of polyphenols was observed in the PEF-treated samples. The utilization of dehumidified air caused higher phenolic degradation during the drying process. It may be related to the higher partial pressure of oxygen present in the drying medium, which served as better conditions for enzymatic degradation. Among all the obtained dried materials, the PEF3_70CD sample showed the highest TPC (17.6 mg GAE/g d.m.).

Table 3. Total phenolic content (TPC) and anti-oxidant activity (EC_{50} DPPH and EC_{50} ABTS) of mushrooms obtained using the convective method with non-dehumidified air or dehumidified air subjected to (or not) PEF. The same letters ($^{a–d}$ and $^{A–E}$) in the columns represent the homogeneous groups ($\alpha = 0.05$).

Material	TPC [mg GAE/g d.m.]	EC_{50} DPPH [mg d.m./mL]	EC_{50} ABTS [mg d.m./mL]
55CD	11.5 ± 0.5^{abc}	0.84 ± 0.02^{bcd}	0.19 ± 0.00^{ab}
PEF1_55CD	12.4 ± 0.6^{abcd}	0.71 ± 0.03^{ab}	0.26 ± 0.00^{cd}
PEF3_55CD	12.0 ± 0.2^{abc}	0.76 ± 0.02^{ab}	0.27 ± 0.01^{d}
PEF5_55CD	12.7 ± 0.1^{bcd}	0.71 ± 0.01^{a}	0.25 ± 0.00^{cd}
70CD	10.9 ± 0.7^{ab}	0.76 ± 0.02^{ab}	0.21 ± 0.01^{abc}
PEF1_70CD	12.7 ± 0.5^{bcd}	0.78 ± 0.01^{ab}	0.24 ± 0.01^{bcd}
PEF3_70CD	17.6 ± 0.7^{e}	0.70 ± 0.01^{a}	0.18 ± 0.02^{a}
PEF5_70CD	13.9 ± 0.7^{d}	0.79 ± 0.01^{abc}	0.23 ± 0.00^{bcd}
85CD	10.6 ± 0.2^{a}	0.74 ± 0.03^{ab}	0.21 ± 0.02^{abc}
PEF1_85CD	13.1 ± 0.3^{cd}	0.75 ± 0.00^{ab}	0.23 ± 0.00^{bcd}
PEF3_85CD	13.2 ± 0.1^{cd}	0.97 ± 0.03^{d}	0.24 ± 0.01^{cd}
PEF5_85CD	13.2 ± 0.2^{cd}	0.91 ± 0.05^{cd}	0.26 ± 0.01^{cd}
55DA	12.1 ± 0.1^{C}	0.60 ± 0.02^{A}	0.26 ± 0.05^{A}
PEF1_55DA	9.0 ± 0.1^{ABC}	0.98 ± 0.03^{CDE}	0.73 ± 0.04^{BCD}
PEF3_55DA	5.6 ± 0.1^{A}	0.97 ± 0.01^{CDE}	1.11 ± 0.00^{D}
PEF5_55DA	8.8 ± 0.0^{ABC}	0.98 ± 0.00^{CDE}	0.76 ± 0.04^{BCD}
70DA	12.3 ± 0.0^{C}	0.60 ± 0.02^{AB}	0.61 ± 0.04^{ABC}
PEF1_70DA	5.9 ± 0.1^{AB}	1.26 ± 0.05^{E}	0.81 ± 0.07^{BCD}
PEF3_70DA	10.1 ± 1.9^{C}	0.65 ± 0.17^{AB}	0.52 ± 0.21^{AB}
PEF5_70DA	6.0 ± 0.3^{AB}	1.18 ± 0.05^{DE}	0.96 ± 0.07^{CD}
85DA	11.1 ± 0.2^{C}	0.69 ± 0.01^{ABC}	0.69 ± 0.06^{ABCD}
PEF1_85DA	9.7 ± 0.2^{BC}	0.90 ± 0.00^{ABCD}	0.71 ± 0.02^{ABCD}
PEF3_85DA	10.1 ± 0.2^{C}	0.96 ± 0.01^{BCDE}	0.76 ± 0.02^{BCD}
PEF5_85DA	5.7 ± 0.2^{AB}	1.13 ± 0.01^{DE}	0.96 ± 0.03^{CD}

Table 3 also shows the calculated EC_{50} values (DPPH and ABTS), which are used to interpret the anti-oxidant activity of the obtained dried mushrooms. The lower the values of these indicators, the higher the ability to scavenge free radicals [45]. As in the case of TPC, there was no straightforward tendency between the values of the EC_{50} DPPH coefficient and the temperature of the drying air. When taking into account the type of the drying agent, in the vast majority of cases, the mushrooms dried with non-dehumidified air showed better anti-oxidant properties (lower EC_{50} DPPH values) than the samples dried with dehumidified air. The exceptions were the mushrooms untreated with PEF before drying and the sample to which 3 kJ/kg of energy was applied before drying at 70 °C. In these cases, air with reduced humidity turned out to be more efficient. Most of the dried mushrooms obtained after the application of a pulsed electric field and drying with dehumidified air (55, 70, and 85 °C) exhibited lower anti-oxidant activity than the untreated samples dried under the same conditions. When the non-dehumidified air was used, a significant decrease was noted only for the PEF3_85CD and PEF5_85CD samples. The use of PEF treatment is connected to the risk of generating free radicals and reactive oxygen species [44], which can explain the observed tendency. Lower EC_{50} DPPH values (better anti-oxidant properties) were reported for the PEF-pre-treated samples dried with non-dehumidified air at 55 °C (relative to the untreated sample: 55CD).

Additionally, in the case of the ABTS assay, no clear trend was observed between the values of the EC_{50} ABTS coefficient and the temperature of the drying air. Nevertheless, the type of drying agent had a clear influence on the anti-oxidant activity. After the implementation of the air dehumidification system, the dried mushrooms with reduced anti-oxidant activity (with even four times higher EC_{50} ABTS values) were obtained. As mentioned above, such drying conditions may have enforced the enzymatic degradation

of the material. The application of the pulsed electric field did not affect or even slightly worsen the anti-oxidant activity of the samples after drying them with both types of drying agents. However, it seems that the simultaneous use of PEF and dehumidified air favored the loss of anti-oxidant potential. The best scavenging activity against ABTS radicals was demonstrated by the PEF3_70CD sample (0.18 mg d.m./mL), for which the highest TPC was also noted. The EC_{50} ABTS values of samples 55CD, 70CD, and 85CD did not differ statistically from the value obtained by the PEF3_70CD sample (Table 3).

4. Cluster Analysis

A cluster analysis was conducted to compare the various technological variants based on process kinetics and product quality parameters (Figure 12). The analysis revealed three major groups: the first contains the mushrooms obtained using the convective method with dehumidified air, subjected to (or not) a PEF; the second group contains the samples obtained using the convective method with non-dehumidified air, subjected to (or not) PEF, as well as one with 55DA; the third group contains mixed samples. The results suggest that using the convective method with different humidity can affect the quality of the samples.

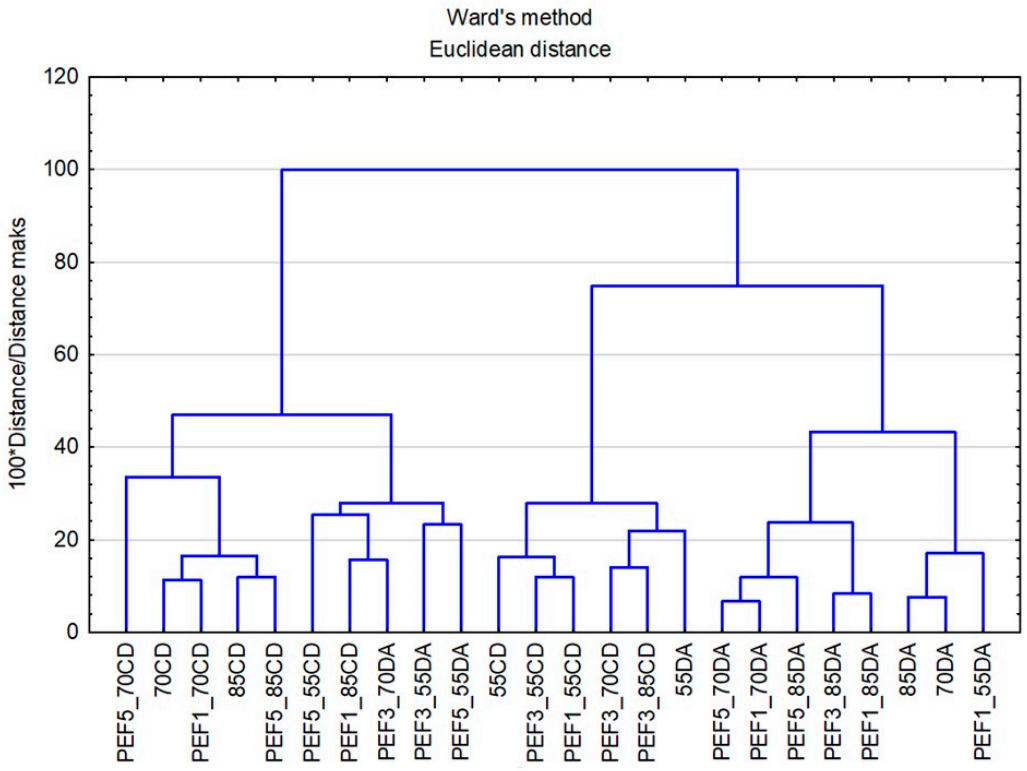

Figure 12. Cluster analysis of mushrooms obtained using pulsed electric field treatment and air or dehumidified air-dried mushrooms.

On the basis of the obtained results, statistical approximation profiles of the dried mushrooms obtained using the convective method with non-dehumidified and de-humidified air subjected to (or not) PEF, as well as its usability for obtaining the product over a short time and low ΔE values and high polyphenol content were made (Figures S1 and S2). The optimal properties for obtaining high-quality dried material over a short time were analyzed. For drying with non-dehumidified air, the best parameters were a PEF pre-treatment energy input of 3.5 kJ/kg and an air temperature of 77.5 °C, while for drying with dehumidified air, a PEF pre-treatment energy input of 1 kJ/kg and drying at 73 °C.

5. Conclusions

The study presents the impact of pulsed electric field treatment on process kinetics and the selected physical and chemical properties of convective-dried mushrooms. Furthermore, two types of drying media using non-dehumidified and dehumidified air were applied. Increasing the temperature of the drying air reduced drying time. Additionally, the use of dehumidified air resulted in faster water removal, from 10–37%. However, the use of PEF treatment, depending on the parameters, shortened the drying time maximum by 12% or extended the drying time. This means that, in the case of the use of 1–5 kJ/kg of specific energy input for PEF treatment, the parameters must be selected accordingly. However, in future work, the mushroom tissue should be subjected to treatment with higher PEF energies, and for this research, the effect of the treatment on the drying kinetics and quality of the final product must also be considered.

The physical parameters were dependent on different parameters. The dry matter content of the mushrooms was significantly influenced by drying temperature. The rehydration properties generally showed no significant differences between the untreated and PEF-pre-treated mushrooms dried with non-dehumidified or dehumidified air. The hygroscopic properties were also unaffected by the PEF, and a decrease in relative mass was noted, which means that this product can be stable during storage. However, the color parameters of the analyzed mushrooms were influenced by the drying method and energy input, with higher energy input resulting in decreased lightness (L*) and increased redness (a*), yellowness (b*), and chroma (C*) values, indicating enzymatic browning and greater color saturation. The effect of pulsed electric field (PEF) pre-treatment on the color parameters varied depending on the drying method and the specific characteristics of the mushrooms, with the PEF leading to a darker color. The results highlight the complex relationship between PEFs, drying, and color changes in different materials.

The results of the chemical analyses of the anti-oxidant compounds in the dried mushrooms depended on various factors. The use of pulsed electric field (PEF) treatment and drying with non-dehumidified air led to a slight increase in total polyphenol content, while dehumidified air caused higher phenolic degradation, especially when it was combined with PEF treatment. The PEF-treated samples under 3 kJ/kg of energy and dried with non-dehumidified air at a temperature of 70 °C had the highest total polyphenol content and the best anti-oxidant properties. The anti-oxidant activity of the dried mushrooms varied depending on the drying agent, with non-dehumidified air generally exhibiting better anti-oxidant properties.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/pr11072101/s1, Figure S1. Approximation profiles and usability for dried mushrooms obtained using convective method with non-dehumidified air (CD) subjected or not to PEF. Figure S2. Approximation profiles and usability for dried mushrooms obtained using convective method with dehumidified air (DA) subjected or not to PEF.

Author Contributions: Conceptualization, A.W., M.D. and M.N.; methodology, K.R., A.W., M.D., M.N. and D.W.-R.; software, A.M.; validation, K.R. and M.D.; formal analysis, A.B. and M.D.; investigation, K.R., M.D., A.M., A.B., A.W. and M.N.; resources, D.W.-R.; data curation, A.M., A.B. and K.R.; writing—original draft preparation, M.D., A.B., A.M., K.R. and M.N.; writing—review and editing, M.D., M.N., A.W. and D.W.-R.; visualization, A.B.; supervision, A.W. and D.W.-R.; project administration, M.N.; funding acquisition, A.W. All authors have read and agreed to the published version of the manuscript.

Funding: This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 817683 (acronym FOX).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available upon request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Arshad, R.N.; Abdul-Malek, Z.; Roobab, U.; Munir, M.A.; Naderipour, A.; Qureshi, M.I.; Bekhit, A.E.-D.; Liu, Z.W.; Aadil, R.M. Pulsed electric field: A potential alternative towards a sustainable food processing. *Trends Food Sci. Technol.* **2021**, *111*, 43–54. [CrossRef]
2. Löffler, M.J. Generation and Application of High Intensity Pulsed Electric Fields. In *Pulsed Electric Fields Technology for the Food Industry*; Raso, J., Heinz, V., Eds.; Springer: Berlin/Heidelberg, Germany, 2022; pp. 55–106.
3. Mahnič-Kalamiza, S.; Miklavčič, D. The Phenomenon of Electroporation. In *Pulsed Electric Fields Technology for the Food Industry*; Raso, J., Heinz, V., Eds.; Springer: Berlin/Heidelberg, Germany, 2022; pp. 107–141.
4. Dellarosa, N.; Tappi, S.; Ragni, L.; Laghi, L.; Rocculi, P.; Rosa, M.D. Metabolic response of fresh-cut apples induced by pulsed electric fields. *Innov. Food Sci. Emerg. Technol.* **2016**, *38*, 356–364. [CrossRef]
5. Nowacka, M.; Dadan, M.; Janowicz, M.; Wiktor, A.; Witrowa-Rajchert, D.; Mandal, R.; Pratap-Singh, A.; Janiszewska-Turak, E. Effect of nonthermal treatments on selected natural food pigments and color changes in plant material. *Compr. Rev. Food Sci. Food Saf.* **2021**, *20*, 5097–5144. [CrossRef] [PubMed]
6. Mahnič-Kalamiza, S.; Vorobiev, E.; Miklavčič, D. Electroporation in food processing and biorefinery. *J. Membr. Biol.* **2014**, *247*, 1279–1304. [CrossRef]
7. Dellarosa, N.; Frontuto, D.; Laghi, L.; Rosa, M.D.; Lyng, J.G. The impact of pulsed electric fields and ultrasound on water distribution and loss in mushrooms stalks. *Food Chem.* **2017**, *236*, 94–100. [CrossRef]
8. Wiktor, A.; Parniakov, O.; Witrowa-Rajchert, D. Drying Improving by Pulsed Electric Fields. In *Pulsed Electric Fields Technology for the Food Industry*; Raso, J., Heinz, V., Eds.; Springer: Berlin/Heidelberg, Germany, 2022; pp. 385–397.
9. Mirzaei-Baktash, H.; Hamdami, N.; Torabi, P.; Fallah-Joshaqani, S.; Dalvi-Isfahan, M. Impact of different pretreatments on drying kinetics and quality of button mushroom slices dried by hot-air or electrohydrodynamic drying. *LWT* **2022**, *155*, 112894. [CrossRef]
10. Chen, X.D.; Mujumdar, A.S. Food drying fundamentals. In *Drying Technologies in Food Processing*; Chen, X.D., Mujumdar, A.S., Eds.; Blackwell Publishing Ltd.: Singapore, 2008; pp. 1–7.
11. Matys, A.; Wiktor, A.; Dadan, M.; Witrowa-Rajchert, D. Influence of Ultrasound and the Conditions of Convective Drying with Dehumidified Air on the Course of the Process and Selected Properties of Apple Tissue. *Foods* **2021**, *10*, 1840. [CrossRef]
12. Dadan, M.; Nowacka, M.; Wiktor, A.; Sobczynska, A.; Witrowa-Rajchert, D. Ultrasound to improve drying processes and prevent thermolabile nutrients degradation. In *Design and Optimization of Innovative Food Processing Techniques Assisted by Ultrasound*; Barba, F.J., Cravotto, G., Chemat, F., Lorenzo Rodriguez, J.M., Munekata, P.E.S., Eds.; Academic Press: London, UK, 2021; pp. 55–110. [CrossRef]
13. Dadan, M.; Nowacka, M. The assessment of the possibility of using ethanol and ultrasound to design the properties of dried carrot tissue. *Appl. Sci.* **2021**, *11*, 689. [CrossRef]
14. Marçal, S.; Sousa, A.S.; Taofiq, O.; Antunes, F.; Morais, A.M.M.B.; Freitas, A.C.; Barros, L.; Ferreira, I.C.F.R.; Pintado, M. Impact of postharvest preservation methods on nutritional value and bioactive properties of mushrooms. *Trends Food Sci. Technol.* **2021**, *110*, 418–431. [CrossRef]
15. Sledz, M.; Wiktor, A.; Rybak, K.; Nowacka, M.; Witrowa-Rajchert, D. The impact of ultrasound and steam blanching pre-treatments on the drying kinetics, energy consumption and selected properties of parsley leaves. *Appl. Acoust.* **2016**, *103*, 148–156. [CrossRef]
16. Association of Official Analytical Collaboration International. *Official Methods of Analysis of AOAC International*, 17th ed.; The Association of Official Analytical Chemists: Rockville, MD, USA, 2002.
17. Śledź, M.; Nowacka, M.; Wiktor, A.; Witrowa-Rajchert, D. Selected chemical and physico-chemical properties of microwave-convective dried herbs. *Food Bioprod. Process.* **2013**, *91*, 421–428. [CrossRef]
18. Rybak, K.; Wiktor, A.; Witrowa-Rajchert, D.; Parniakov, O.; Nowacka, M. The Quality of Red Bell Pepper Subjected to Freeze-Drying Preceded by Traditional and Novel Pretreatment. *Foods* **2021**, *10*, 226. [CrossRef] [PubMed]
19. Delgado, J.M.P.Q.; da Silva, M.V. Food Dehydration: Fundamentals, Modelling and Applications. In *Transport Phenomena and Drying of Solids and Particulate Materials*; Delgado, J.M.P.Q., Barbosa de Lima, A.G., Eds.; Springer: Berlin/Heidelberg, Germany, 2014; pp. 69–94. [CrossRef]
20. Lebovka, N.I.; Shynkaryk, N.V.; Vorobiev, E. Pulsed electric field enhanced drying of potato tissue. *J. Food Eng.* **2007**, *78*, 606–613. [CrossRef]
21. Liu, C.; Pirozzi, A.; Ferrari, G.; Vorobiev, E.; Grimi, N. Effects of Pulsed Electric Fields on Vacuum Drying and Quality Characteristics of Dried Carrot. *Food Bioprocess Technol.* **2020**, *13*, 45–52. [CrossRef]
22. Kaya, A.; Aydın, O.; Demirtaş, C. Drying Kinetics of Red Delicious Apple. *Biosyst. Eng.* **2007**, *96*, 517–524. [CrossRef]
23. Kaya, A.; Aydın, O.; Kolaylı, S. Effect of different drying conditions on the vitamin C (ascorbic acid) content of Hayward kiwifruits (*Actinidia deliciosa* Planch). *Food Bioprod. Process.* **2010**, *88*, 165–173. [CrossRef]
24. Kaya, A.; Aydin, O.; Demirtas, C.; Akgün, M. An experimental study on the drying kinetics of quince. *Desalination* **2007**, *212*, 328–343. [CrossRef]
25. Alam, M.R.; Lyng, J.G.; Frontuto, D.; Marra, F.; Cinquanta, L. Effect of Pulsed Electric Field Pretreatment on Drying Kinetics, Color, and Texture of Parsnip and Carrot. *J. Food Sci.* **2018**, *83*, 2159–2166. [CrossRef]

26. Liu, C.; Grimi, N.; Lebovka, N.; Vorobiev, E. Convective air, microwave, and combined drying of potato pre-treated by pulsed electric fields. *Dry. Technol.* **2019**, *37*, 1704–1713. [CrossRef]
27. Ostermeier, R.; Giersemehl, P.; Siemer, C.; Töpfl, S.; Jäger, H. Influence of pulsed electric field (PEF) pre-treatment on the convective drying kinetics of onions. *J. Food Eng.* **2018**, *237*, 110–117. [CrossRef]
28. Ostermeier, R.; Parniakov, O.; Töpfl, S.; Jäger, H. Applicability of Pulsed Electric Field (PEF) Pre-Treatment for a Convective Two-Step Drying Process. *Foods* **2020**, *9*, 512. [CrossRef]
29. Won, Y.-C.; Min, S.C.; Lee, D.-U. Accelerated Drying and Improved Color Properties of Red Pepper by Pretreatment of Pulsed Electric Fields. *Dry. Technol.* **2015**, *33*, 926–932. [CrossRef]
30. Yamada, T.; Yamakage, K.; Takahashi, K.; Takaki, K.; Orikasa, T.; Kamagata, J.; Aoki, H. Influence of Drying Rate on Hot Air Drying Processing of Fresh Foods Using Pulsed Electric Field. *IEEJ Trans. Electr. Electron. Eng.* **2020**, *15*, 1123–1125. [CrossRef]
31. Sharma, B.H.P.D. Drying Characteristics of Button Mushroom. *Int. J. Curr. Microbiol. Appl. Sci.* **2021**, *10*, 503–512. [CrossRef]
32. Wiktor, A.; Landfeld, A.; Matys, A.; Novotná, P.; Dadan, M.; Kováříková, E.; Nowacka, M.; Mulenko, M.; Witrowa-Rajchert, D.; Strohalm, J.; et al. Selected Quality Parameters of Air-Dried Apples Pretreated by High Pressure, Ultrasounds and Pulsed Electric Field—A Comparison Study. *Foods* **2021**, *10*, 1943. [CrossRef] [PubMed]
33. Rybak, K.; Parniakov, O.; Samborska, K.; Wiktor, A.; Witrowa-Rajchert, D.; Nowacka, M. Energy and Quality Aspects of Freeze-Drying Preceded by Traditional and Novel Pre-Treatment Methods as Exemplified by Red Bell Pepper. *Sustainability* **2021**, *13*, 2035. [CrossRef]
34. Lammerskitten, A.; Wiktor, A.; Mykhailyk, V.; Samborska, K.; Gondek, E.; Witrowa-Rajchert, D.; Toepfl, S.; Parniakov, O. Pulsed electric field pre-treatment improves microstructure and crunchiness of freeze-dried plant materials: Case of strawberry. *LWT* **2020**, *134*, 110266. [CrossRef]
35. Witrowa-Rajchert, D.; Lewicki, P.P. Rehydration properties of dried plant tissues. *Int. J. Food Sci. Technol.* **2006**, *41*, 1040–1046. [CrossRef]
36. Sacilik, K.; Elicin, A.K. The thin layer drying characteristics of organic apple slices. *J. Food Eng.* **2006**, *73*, 281–289. [CrossRef]
37. Khraisheh, M.A.M.; McMinn, W.A.M.; Magee, T.R.A. Quality and structural changes in starchy foods during microwave and convective drying. *Food Res. Int.* **2004**, *37*, 497–503. [CrossRef]
38. Ashtiani, S.-H.M.; Sturm, B.; Nasirahmadi, A. Effects of hot-air and hybrid hot air-microwave drying on drying kinetics and textural quality of nectarine slices. *Heat Mass Transf.* **2018**, *54*, 915–927. [CrossRef]
39. Dehghannya, J.; Farshad, P.; Heshmati, M.K. Three-stage hybrid osmotic–intermittent microwave–convective drying of apple at low temperature and short time. *Dry. Technol.* **2018**, *36*, 1982–2005. [CrossRef]
40. Wiktor, A.; Nowacka, M.; Dadan, M.; Rybak, K.; Lojkowski, W.; Chudoba, T.; Witrowa-Rajchert, D. The effect of pulsed electric field on drying kinetics, color, and microstructure of carrot. *Dry. Technol.* **2016**, *34*, 1286–1296. [CrossRef]
41. Wiktor, A.; Sledz, M.; Nowacka, M.; Rybak, K.; Chudoba, T.; Lojkowski, W.; Witrowa-Rajchert, D. The impact of pulsed electric field treatment on selected bioactive compound content and color of plant tissue. *Innov. Food Sci. Emerg. Technol.* **2015**, *30*, 69–78. [CrossRef]
42. Tiwari, B.K.; Patras, A.; Brunton, N.; Cullen, P.J.; O'Donnell, C.P. Effect of ultrasound processing on anthocyanins and color of red grape juice. *Ultrason. Sonochem.* **2010**, *17*, 598–604. [CrossRef] [PubMed]
43. Deng, J.; Yang, H.; Capanoglu, E.; Cao, H.; Xiao, J. Technological aspects and stability of polyphenols. In *Polyphenols: Properties, Recovery, and Applications*; Woodhead Publishing: Swaston, UK, 2018; pp. 295–323. [CrossRef]
44. Wiktor, A.; Pratap-Singh, A.; Parniakov, O.; Mykhailyk, V.; Mandal, R.; Witrowa-Rajchert, D. PEF as an alternative tool to prevent thermolabile compound degradation during dehydration processes. In *Pulsed Electric Fields to Obtain Healthier and Sustainable Food for Tomorrow*; Barba, F.J., Parniakov, O., Wiktor, A., Eds.; Academic Press: Cambridge, MA, USA, 2020; pp. 155–202. [CrossRef]
45. Matys, A.; Witrowa-Rajchert, D.; Parniakov, O.; Wiktor, A. Application of pulsed electric field prior to vacuum drying: Effect on drying time and quality of apple tissue. *Res. Agric. Eng.* **2022**, *68*, 93–101. [CrossRef]