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Impact of Different Dehydration Methods on Drying Efficiency, Nutritional and Physico-Chemical Quality of Strawberries Slices (*Fragaria ananassa*)

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Abstract

This study aimed to evaluate the drying kinetics, microstructural features, moisture content, color, pH, aw, texture, acidity, rehydration capacity, and sensorial attributes of strawberry slices processed by different drying methodologies. Strawberry samples were processed by hot air-drying (HA, 60 °C, 0.5 m/s), freeze-drying (FD, 0.055 mbar), and pulsed electric field (PEF)-assisted freeze-drying (PEFFD, 1 kV/cm and 3.2 kJ/kg). PEF pre-treatment significantly increased cell membrane permeability by forming micropores, which led to a significant reduction in the moisture content of up to 8.87% and improved the drying efficiency. Nonetheless, this pre-treatment did not significantly alter the drying rate due to the inherent constraints of the freeze-drying process. PEFFD samples better retained their shape, volume, and visual quality, and exhibited a maximum rehydration capacity of 64.90%. The ascorbic acid retention was found to be higher in the FD and PEFFD when compared to HA. FD and PEFFD samples had an increase in both red and yellow hue. PEF shows promise as a pre-treatment technique, improving both the drying efficiency and strawberry quality. Further studies are needed to assess PEFFD's industrial scalability and economic feasibility.

Keywords: strawberry; PEF; freeze-drying; drying models; mathematical model

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1. Introduction

Strawberries (*Fragaria* × *ananassa*) are widely appreciated as a seasonal red fruit in several countries. FAOSTAT reported that the worldwide area harvested and the production of strawberries in 2022 were around 39,760 ha and 9.6 million tonnes (t), respectively [1], with Asia accounting for 48% of the total output. Within the European Union, strawberry production represented 18.6% of the global market. In Portugal, the harvested area of strawberries reached 523 ha in 2022, while production reached 18.09 t, and apparent consumption reached 29.39 t in the same year. When compared to 2018, this represents an increase of 200 ha, 7.73 t, and 3.35 in harvest area, production, and apparent consumption, respectively [2].

Strawberries have interesting functional properties, unique sensorial attributes, high vitamin C content, and antioxidant potential. In addition, this fruit contains over 93% water and is low in carbohydrates and fats (≈5%) (wet basis) [3]. These characteristics contribute to their nutritional value and health benefits, while also leading to a greater tendency to

deteriorate rapidly throughout the post-harvest period, resulting in a rather limited shelf life [4,5].

Processed strawberries, such as dried fruit, are a great alternative for increasing shelf-life while maintaining their quality as close as possible to fresh fruit. Currently, dried food is used as a component of convenience foods (tertiary processed foods), which are ready-to-cook or ready-to-eat [6].

In the industry of dried fruits and vegetables, hot air-drying is the most used method; nonetheless, it normally causes a significant change in the sensorial attributes and physicochemical profile of the product [7]. Freeze-drying provides significant advantages in terms of minimizing the loss of sensorial quality and nutrient products, compared to hot air-drying [5]. However, the long processing times of these methods contribute to extremely energy-consuming operation and high processing costs [5,8].

Due to the drawbacks of the industrial treatments and increasing demand for fruit snacks with premium quality and more sustainable food production, it is essential to find and provide new methods or synergies between technologies capable of improving efficiency and reducing the time and cost of the drying process, while guaranteeing product quality.

Recently, several thermal and non-thermal innovative approaches have been studied as pre-treatments before drying processes, in order to enhance drying efficiency, preserve quality, and extend the shelf life of fruits and vegetables. These include high pressure processing (HPP) at 50–250 MPa for 5 min followed by vacuum freeze-drying [4]; ultrasound (US) at 200 W for 25 min followed by vacuum freeze-drying [3,5]; freeze–thaw blanched in boiling water for 2 min, frozen at −20 °C and thawed at 25 °C for 3 h, followed by microwave-vacuum drying [9]; closed-cycle modified atmosphere drying at 60 °C, drying air/gas velocity of 3 m/s, and drying medium oxygen level of 9.47% [7]; freezing at −20 °C for 20 h and ultrasound at 30 kHz and 180 W for 16 min pre-treatments, alone and combined, followed by infrared technology at 60 °C combined with hot air impingement drying [10]; and pulsed electric field (PEF) at a range of pulses from 0 to 160 and E = 800 V/cm [8,11].

Among non-thermal pre-treatments, PEF offers a distinctive advantage by enabling rapid and controlled electroporation, enhancing mass transfer while preserving the structural and nutritional integrity of the final product [6,8,12]. In contrast, US and HPP often require longer processing times and may introduce thermal effects [3–5]. HPP also demands plastic packaging during processing, raising sustainability and operational concerns, while the US faces scalability challenges and high equipment costs at an industrial scale. PEF systems, on the other hand, are already commercially available for continuous flow applications [13], making this technology more suitable for integration into industrial freeze-drying processes. Nonetheless, the PEF method is not devoid of disadvantages since the food's electrical conductivity is a critical property that influences the process efficiency. Another critical aspect of PEF technology is the lack of a standardized way of reporting treatment conditions [12].

Therefore, this study aimed to evaluate the effectiveness of dehydration, hot air drying, freeze-drying, and pulsed electric field-assisted freeze-drying methods, and to compare their effects on physicochemical, sensorial, and structural changes in strawberry slices.

2. Materials and Methods

2.1. Raw Material

Fresh strawberries (var. Savana) were produced in semi-hydroponic conditions and manually harvested at an industrial unit (Horta Grande Agrifood Company) in Abrançalha de Cima, Abrantes, Portugal. Fresh "Red face" strawberry fruits (≈10 kg) were cleaned and

sliced 5 mm thick before drying. For samples subjected to the PEF-assisted freeze-drying process, slicing was performed after the PEF pre-treatment.

2.2. Drying Processes

Strawberry slices were dried using three drying methodologies: (i) hot air-drying (HA), (ii) freeze-drying (FD), and (iii) PEF-assisted freeze-drying (PEFFD), as described below. The conditions for both the PEF and drying processes (Table 1) were established through preliminary tests performed by the authors [13] and on literature references [6,8,11]. Samples were prepared in triplicate for all treatments.

Table 1. Parameters for the drying methods used on the strawberry samples.

Drying Methods	PEF Pre-Treatment	Freezing Temperature (°C)	Freezing Duration (h)	Condenser Temperature (°C)	Vacuum Pressure (mBar)	Drying Temperature (°C)	Air Flow ($m \cdot s^{-1}$)
HA	None	-	-	-	-	60 ± 2	0.5
FD		−40	4	−67	0.055	-	-
PEFFD	1 kV/cm, 27 A, 3.2 kJ/kg						

HA—Hot air-drying, FD—Freeze-drying, PEFFD—Pulse electric field-assisted freeze-drying, PEF—Pulse electric field.

- Hot air-drying (HA)

The hot air-drying process was performed in a food dehydrator (Klarstein, Master Jerky 32, Berlin, Germany). This process was carried out at a temperature of 60 ± 2 °C, with a constant air flow of 0.5 $m \cdot s^{-1}$. Along the process, the samples were weighed until weight stabilization between successive weighings.

- Freeze-drying (FD)

Strawberry slices, uniformly spread on trays as single layers, were frozen at −40 °C for 4 h. The freeze-drying process was conducted in a vacuum freeze-dryer (LabConco, Freezone 6 plus, Kansas City, MO, USA). The condenser temperature was −67 °C with 0.055 mBar vacuum pressure.

- PEF-assisted freeze-drying (PEFFD)

PEF pre-treatment was applied to whole strawberries using PEF equipment (EPULSUS®-LBM3B-15; Energy Pulse Systems; Lisbon, Portugal). The equipment includes a 9 kW generator that produces bipolar squared electric pulses up to 15 kV and 400 A. The treatment was applied in batches (1 L capacity) with the following settings: voltage (10 kV); positive pulse width (15 µs); negative pulse width (15 µs); frequency (60 Hz); number of pulses (60). Output parameters included field strength (1 kV/cm); current (27 A); specific energy (3.2 kJ/kg). After the PEF treatment, samples were sliced and dried by freeze-drying under the same conditions used for FD samples.

2.3. Scanning Electron Microscopy (SEM)

Microstructural images of dried strawberry slices were obtained using a desktop scanning electron microscope (Phenom-World BV, Eindhoven, The Netherlands). The sample was held in aluminum cylinders with electrically conductive carbon adhesive tape (PELCO Tabs™, Ted Pella Inc., Redding, CA, USA) and coated with a layer of 20 Å gold to improve conductivity. SEM analyses were performed under high vacuum conditions at an acceleration voltage of 5 kV and 230-fold magnification to assess the porosity of dried samples.

2.4. Physico-Chemical Analysis

- Moisture Content

Moisture content was measured by the gravimetric method. The air oven method was used for measuring the moisture content of the strawberries. The work temperature was 105 °C, and the measurement was performed until constant weight was obtained. It was calculated using Equation (1), in which M_0 and M_2 are the sample weights (g) before and after the air oven process, respectively.

$$\% \text{ MC} = \frac{M_0 - M_2}{M_0} * 100 \quad (1)$$

- Rehydration capacity

The rehydration ratio (RC) was determined by immersing 3 ± 0.01 g of the dried sample in a glass beaker filled with 400 mL of distilled water at 20 °C (±1 °C). The samples were drained at 60 min, blotted with tissue paper, and the weights of the samples were measured using a digital balance (Mettler Toledo, ML 204, Columbus, OH, USA) with an accuracy of ±0.01 g. The RC was calculated using Equation (2), in which M_0 and M_3 are the sample weights (g) before and after rehydration, respectively.

$$\text{RC} = \frac{M_3 - M_0}{M_0} \quad (2)$$

- pH, titratable acidity, and water activity (a_w)

The pH of strawberries was measured potentiometrically, using a glass electrode pH meter (Consort, C931, Topac Inc., Brussels, Belgium) calibrated against buffers of pH 4.01 and 7.00.

The titratable acidity was determined by titrating a 5 g homogenized sample, diluted in 50 mL water with 0.1 N NaOH, and expressed as mg citric acid/100 g. Phenolphthalein (one to two drops) was used as an indicator, and titration was performed until a pale pink color (pH 8.2) was achieved. Water activity (a_w) was measured with an Aqualab 4TE (Decagon Instruments, Pullman, WA, USA) with an accuracy of ±0.001.

- Ascorbic acid content

The dye solution needed for the ascorbic acid measurement was prepared by dissolving 100 mg of 2,6-dichlorophenolindophenol (blue dye) in 100 mL of distilled water. The mixture was diluted 4 fold, filtrated, and stored at 4 °C for further use. A total of 100 mg standard L-ascorbic acid was dissolved in 50 mL of 20% glacial acetic acid and diluted to 100 mL with distilled water. Afterwards, 10 mL of the L-ascorbic acid solution was titrated with the dye solution. The dye in contact with the L-ascorbic acid solution changed color from blue to pink. The endpoint was reached when the pink color lasted for 15 s.

- Texture

Cutting tests were performed at a velocity of 0.55 mm per second using texture analyzer equipment (TA. XT Plus, Stable Microsystems, Surrey, UK) equipped with a knife edge probe (size: 7 cm width, 10 cm height, and 1.2 mm thickness, HDP/BS probe) and a load cell of 5 kg. The cutting strength is the maximum force applied by the blade (N) during the cutting path through the entire strawberry slice.

- Color Parameters

The color measurements were performed with a Minolta reflectance colorimeter (Minolta Chroma Meter CR-400, Minolta, Osaka, Japan). The color values were defined as lightness (L*), redness/ greenness (a*), and yellowness/blueness (b*). Calibration of the

colorimeter was carried out using a standard white plate before measuring the color values. The difference in color between the samples was evaluated using Equation (3).

$$\Delta E^*_{ab} = \sqrt{(L^*_2 - L^*_1) + (a^*_2 - a^*_1) + (b^*_2 - b^*_1)} \quad (3)$$

2.5. Analysis of the Drying Kinetics

In this work, the experimental drying curves were fitted with 5 commonly used drying equations (Table 2):

Table 2. Drying models adopted for the mathematical modeling of the drying kinetics of quince.

No	Model Name	Model	References *
1	Page	$MR = \exp(-kt^n)$	
2	Two Term	$MR = a\exp(-k_0t) + b\ \exp(-k_1t)$	
3	Two Term Exponential	$MR = a\exp(-kt) + (1-a)\exp(-kat)$	[14]
4	*Diffusion* Approach	$MR = a\exp(-kt) + (1-a)\exp(-kbt)$	
5	*Midilli* et al	$MR = a\exp(-kt^n) + bt$	

* Table was adapted from [14].

The moisture ratio (MR) and drying rate (DR) were determined using Equations (4) and (5):

$$R = \frac{M_t - M_e}{M_0 - M_e} \quad (4)$$

$$DR = \frac{M_{t+dt} - M_t}{dt} \quad (5)$$

In these equations, M_t is the instantaneous dry basis moisture content at a given time, M_0 is the initial dry basis moisture content at the beginning, M_e is the equilibrium dry basis moisture content, M_{t+dt} is the moisture content at t + dt, and t is the drying time (min). As the values of M_e are relatively smaller than M_t or M_0, the moisture ratio formula was simplified in line with the following Equation (6):

$$MR = \frac{M_t}{M_0} \quad (6)$$

2.6. Sensory Evaluation

The sensory evaluation was carried out to observe its sensory acceptance. Nineteen panelists were asked to score the samples in terms of color, aroma, texture, flavor, overall appreciation, and purchase intent using a hedonic scale from 1 (very unpleasant) to 9 (very pleasant).

2.7. Statistical Analysis

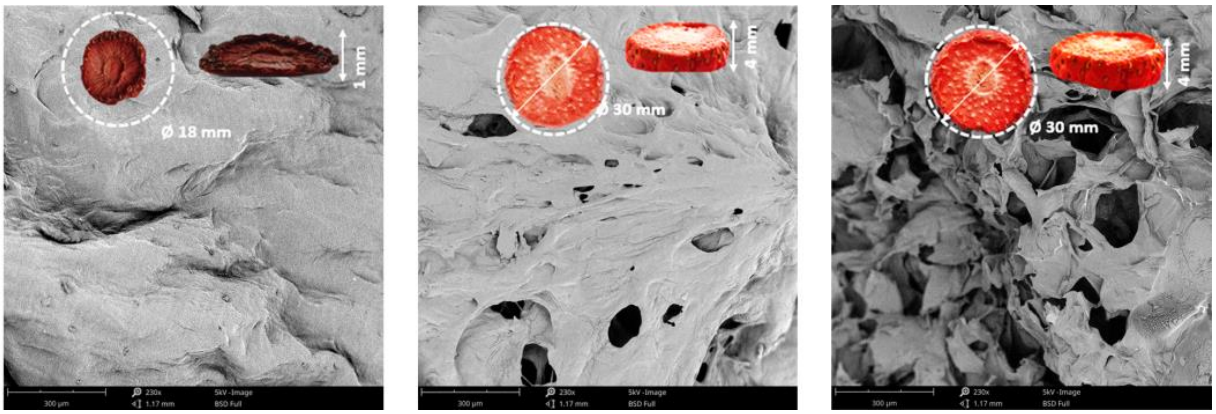
The drying experiments were conducted using a completely randomized design (CRD), with three drying treatments (HA, FD, PEFFD). Texture and color analyses were conducted in ten replicates for each sample; however, all other evaluated parameters were assessed in triplicate.

Analysis of variance (one-way ANOVA) was used to assess significant differences between samples at a significance level of 95% ($p \leq 0.05$). Multiple comparisons were performed by Tukey's test (physicochemical analysis) and Friedman's test (sensory evaluation) using the GraphPad Prism v9. The results are presented as mean ± standard deviation.

3. Results and Discussion

3.1. Effect of Different Dehydration Methods on Microstructure

Scanning electron microscopy images of strawberry samples dried by hot air, freeze-drying, and freeze-drying pre-treated with PEF are presented in Figure 1.



(**A**) (**B**) (**C**)

Figure 1. Microstructure images of strawberries dried by different methods: (**A**) hot air-drying; (**B**) freeze-drying; (**C**) PEF + freeze-drying.

Strawberries dried by the hot air process (Figure 1A) revealed high density and tissue shrinkage. This occurs because the high temperature in the drying process creates a moisture gradient within the fruit. The center retains more moisture compared with the surface, leading to internal stress. This stress can cause cell walls to merge and collapse, resulting in significant structure changes that are observable in SEM images. The strawberry sample dried by freeze-drying, as shown in Figure 1B, has higher porosity compared with the sample processed by air drying. In the freeze-drying process, water is removed via sublimation under vacuum, a process that preserves the integrity of cell walls. As a result, the microstructure is preserved, and the density is lower compared with convective drying.

The sample with the highest porosity was treated with PEF before freeze-drying (Figure 1C). The visible impact of PEF might be due to electroporation of the cell walls, a phenomenon that occurs when electric fields are applied [6,12]. The phenomenon does not require high power consumption, and it increases the industrial attractiveness of PEF treatment [6].

3.2. Effect of Different Dehydration Methods on Physical–Chemical Characteristics

- Moisture, rehydration, and a_w

Moisture content varied significantly between drying treatments (Table 3). HA strawberry samples had the highest moisture content, with an average of 13.79%. This can be attributed to the changes that the hot air-drying process causes in the food structure, namely significant deformation, including shrinkage of the product, which dramatically reduces the water diffusivity by reducing the diffusion area [15]. The decrease in water diffusivity makes it difficult to reduce water by evaporation, leading to higher moisture content in the dehydrated product.

Table 3. Physical–chemical characteristics of strawberries dried by hot air, freeze-drying, and freeze-drying with PEF pre-treatment.

Characteristics		HA	FD	PEFFD
Color (ΔE)	HA	0	9.66	10.49
	FD	9.66	0	6.96
Moisture content (%)		13.79 ± 0.01 a	9.49 ± 0.27 b	8.87 ± 0.09 c
a_w		0.290 ± 0.00 a	0.286 ± 0.00 b	0.284 ± 0.01 c
Cutting strength (N)		59.3 ± 7.9 a	19.9 ± 3.4 b	14.0 ± 3.2 c
Rehydration (%)		53.11 ± 0.12 c	60.42 ± 0.08 b	64.90 ± 0.10 a
pH		3.61 ± 0.01 a	3.53 ± 0.01 a, b	3.39 ± 0.09 b
Titratable acidity (mg/100 g)		27.03 ± 0.15 b	30.07 ± 0.35 a	30.35 ± 0.26 a
Ascorbic acid (mg/100 g)		6.48 ± 0.17 c	44.63 ± 0.16 a	36.99 ± 0.10 b

Different letters on the same row indicate a significant difference at $p \leq 0.05$.

On the other hand, strawberries treated with freeze-drying and freeze-drying with PEF had a moisture content of 9.49% and 8.87%, respectively. During freeze-drying, the food's structure is mostly preserved, which creates a greater area of diffusion and, consequently, the food's moisture is further reduced. The PEF treatment, despite not significantly increasing the diffusion area, provides less water retention due to cell electroporation [16]. The increase in permeabilization in strawberry cell walls results in higher rates of water movement, which improves water diffusivity, leading to a decrease in the final moisture content of the dried food [16].

Since water diffusion is the main force in both drying and rehydration, higher diffusivity typically results in better rehydration [17]. The results support this theory, as HA samples had the lowest rehydration percentage at 53.11%. In contrast, FD showed a 13.76% higher rehydration, and PEFFED achieved the highest rehydration, a 22.19% increase compared to HA. The higher rehydration level in samples pre-treated with PEF indicates that the pores formed during electroporation effectively facilitated mass transfer between the surrounding medium and the intracellular matrix during the rehydration process. The rehydration percentage is a crucial economic metric in the food reconstitution industry, as it affects the production yield, specifically the amount of product produced relative to the raw materials used. Therefore, freeze-dried strawberries, especially with PEF pre-treatment, can offer significantly higher yields in the reconstitution process and partly offset the higher cost of freeze-drying, compared with the hot air-drying process. Rehydration is also an important factor in the firmness, mechanical properties, and taste of freeze-dried products and should be considered when producing premium dried products [18].

Considering a_w values (Table 3), all treatments had significant differences. In hot air-drying, the a_w value was the highest at 0.290; in freeze-drying, it was 0.286, and in freeze-drying with PEF, it was 0.284. Nonetheless, these results showed that all treatments were efficient in preventing or limiting microbial growth, since most food microorganisms grow between 0.85 and 1, including pathogenic bacteria [19].

- pH, titratable acidity, ascorbic acid

Strawberries, like most fruits, are rich in organic acids and therefore naturally acidic [20]. Strawberry drying does not affect the total amount of organic acids; however, it does affect their concentration, which in turn considerably increases the strawberry acidity.

Freeze-drying processing with and without PEF pre-treatment increased strawberry acidity compared to HA. The titratable acidity in PEFFD and FD samples (Table 3) was approximately 12.3% and 11.2% higher, respectively, than in HA samples. The difference between treatments can be attributed to the disparity in moisture content. Freeze-drying reduces the strawberries' moisture content, leading to a higher concentration of organic acids in the dried product. The degradation of heat-sensitive organic acids might also substantially influence the acidity of the product.

A significant reduction in the ascorbic acid content was observed in the HA-treated samples compared to FD and PEFFD samples, with values of 6.48 mg/100 g, 44.63 mg/100 g, and 36.99 mg/100 g, respectively (Table 3). This reduction is due to thermal exposure during the HA process. In contrast, the freeze-drying process, which does not involve the application of heat, preserved higher levels of ascorbic acid.

In vacuum conditions, the lack of oxygen also reduces the photooxidation of ascorbic acid [21] and consequently contributes to the high levels of ascorbic acid in freeze-dried samples. The significant difference in ascorbic acid levels between FD and PEFFD treatments can be attributed to multiple factors. The electroporation of cell membranes, induced by PEF treatment, could result in the release of soluble compounds in water from inside the cells [6]. Part of the released ascorbic acid can end up in the water bath, used as a conducting medium in PEF, which is subsequently discarded without further analysis [22]. Additionally, ascorbic acid is unstable in aqueous solutions; once released from the cells and under aerobic conditions, it is easily oxidized. While this oxidation is typically reversible in vivo, the process becomes irreversible once the ascorbic acid is outside of the cell [23].

Food acidity is an important metric in the product's sensory characteristics and in the respective consumer acceptance. Ascorbic acid is considered a taste marker, indicating the product's freshness and taste retention [24]. Moreover, maintaining the level of this acid is crucial for the functional properties of the product, given its significant role as an antioxidant in human metabolism. Therefore, freeze-dried strawberries with and without PEF are richer in ascorbic acid, with a higher sense of freshness, compared with strawberries dried by hot air.

One of the factors that exerts a great selective effect on the microflora development in food is pH. The highest pH value was found in the strawberries processed with HA, followed by freeze-drying and freeze-drying with PEF (Table 3). Microorganisms have different pH tolerance levels, and the pH level that can prevent their growth varies depending on the type of microorganism. Generally, acidic conditions with a pH between 3 and 4 can inhibit the growth of many pathogenic bacteria such as *Escherichia coli* and *Salmonella* [25]. Nonetheless, acidophilus bacteria, spores, molds, and yeasts can survive and grow in acidic conditions. As a result, controlling pH may not be sufficient to prevent microbial growth in dried strawberries, and other barriers should be maintained, such as low a_w.

- Texture

Cutting force refers to the resistance measured during slicing of the food sample. It represents the pressure required to divide food materials with a cutting blade and can be measured with a texturometer. This parameter is important in the food industry, as it can affect consumer acceptance and the quality of the final product. Particularly in dried products, it is a relevant parameter to evaluate since it reflects in the ease of chewing and influences the food's organoleptic characteristics.

It was observed (Table 3) that HA strawberries had the highest cutting force, with 59.3 N. On the other hand, FD strawberries had considerably lower cutting forces (19.9 N), with PEFFD resulting in even lower cutting forces (14.0 N). Generally, rigid foods have higher cut force values and require more force to be cut, while softer foods require less force to be cut. The SEM images (Figure 1) may provide an explanation for the results obtained in the texture—in hot air-drying, the tissue shrinkage is responsible for an increase in the structure rigidity, leading to a higher cutting force and greater food hardness. On the contrary, freeze-drying preserves the microstructure by maintaining the intercellular spaces previously occupied by water, which remain empty after treatment. The structure of freeze-dried strawberry samples, due to the pronounced intercellular spaces, is less robust compared to HA samples, resulting in a significant reduction in cutting force. Pre-treating the strawberries with PEF enlarges the intercellular spaces and consequently, the reduction

in the structure robustness is enhanced. The obtained results are aligned with previous studies where applying pre-treatments that reduce the food matrix density also reduces the hardness of the product [10].

- Color

The color of dehydrated products is a key factor in determining product quality, as it can significantly influence consumer purchasing decisions, since visual appearance plays a crucial role in consumer perception.

Considering the color difference (ΔE) between the drying methods (Table 3), the sample pre-treated with PEF before freeze-drying (PEFFD) exhibited the smallest color change when compared to the freeze-dried sample (FD), with a ΔE of 6.96. Conversely, the largest color difference was observed between the hot air-dried (HA) and PEFFD samples, showing a ΔE of 10.49. The color difference between the HA and FD samples was also notable, registering a ΔE of 9.66. The difference in color between freeze dried with and without PEF and hot air-dried samples could be attributed to enzymatic oxidations, Maillard reactions, caramelization reactions, and pigment degradations that can occur in processes that resort to high temperatures to treat food [26]. It is also possible to conclude that pre-treatment with PEF also influences the color of freeze-dried samples, as significant differences were measured in all the evaluated parameters (L*, a*, b*). This is likely the result of the PEF pre-treatment being administered in a water bath: when PEF is applied, the electroporation might promote the release of pigments into the medium, which is discarded at the end of the process.

3.3. Drying Kinetics

An overview of the moisture ratio (MR) during the freeze-drying, freeze-drying with PEF, and hot air-drying is presented in Figure 2. The results show that the hot air-drying duration to obtain approximately 0 MR is much lower compared with freeze-drying with and without PEF. In hot air-drying, the MR is close to 0 after just 25.45 h; in contrast, freeze-drying with and without PEF obtained a MR of 0 after 49 h.

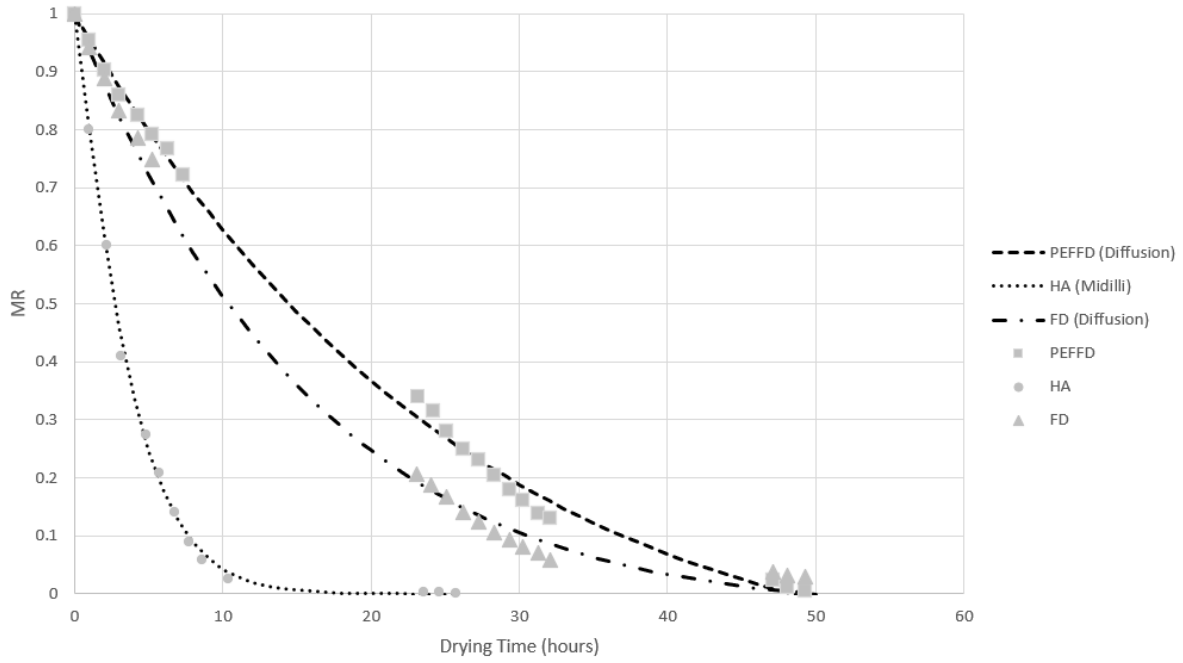


Figure 2. Drying curves of strawberries dried by freeze-drying (FD), hot air (HA), and freeze-drying with PEF (PEFFD) with the best fitting model analyzed.

Between the freeze-drying with and without PEF, there are also significant differences in the drying curve; with PEF, the curve slope is lower until a MR of 0.2 and higher between a MR of 0.2 and 0. Considering that strawberries treated with freeze-drying with PEF have a lower final moisture of 8.87% compared with 9.49% in freeze-drying without PEF, and both have the same drying time to reach a MR around 0, it is possible to conclude that PEF as a pre-treatment enhances drying efficiency by increasing cell membrane permeability and facilitating moisture diffusion.

Drying models were selected based on both statistical fit and their relevance considering physical drying mechanisms: *Midilli* for hot air-drying, *Diffusion* for freeze-drying, and Diffusion for freeze-drying with PEF, as shown in Figure 2. This selection was not solely based on statistical indicators, presented in Table 4, but also on the model assumptions fitting the specific drying behavior.

Table 4. Statistical data obtained from 5 drying models.

Model	Treatment								
	HA			FD			PEFFD		
	R2	X2	RMSE	R2	X2	RMSE	R2	X2	RMSE
PAGE	0.999	0.00002	0.01323	0.998	0.00003	0.01564	0.994	0.00009	0.02753
TwoTerms	0.998	0.00003	0.01616	0.997	0.00005	0.02011	0.997	0.00005	0.01825
TwoTermsExp	0.998	0.00002	0.01342	0.996	0.00008	0.02133	0.994	0.00008	0.02692
Diffusion	0.998	0.00034	0.01654	0.997	0.00005	0.02035	0.997	0.00004	0.01824
Midilli	0.999	0.00021	0.01321	0.998	0.00003	0.01481	0.997	0.00004	0.01846

For hot air-drying (HA), *Midilli* (RMSE = 0.01321) demonstrated the best statistical fit with R^2 values of 0.999 and an RMSE of 0.01321. Additionally, *Midilli* is a semi-empirical model that offers flexibility to accurately capture the complex and often non-linear drying behavior typical of hot air processes, making it a robust choice despite the minimal statistical difference from Page. The addition of one parameter (bt) in the *Midilli* model in relation to the Page model, offers the ability to adapt to a wider range of drying behaviors, including in constant and falling rate stages.

In the case of freeze-drying (FD) without PEF, despite the *Midilli* model having a slightly better statistical fit (*Midilli* R^2 = 0.998, RMSE = 0.01481; Diffusion's R^2 = 0.997, RMSE = 0.02035), the *Diffusion* model is better suited to explain the drying behavior in FD samples. While empirical models like *Midilli* offer slightly higher statistical accuracy, the Diffusion model's assumptions align well with the primary mechanism of moisture removal in freeze-drying, especially during the falling rate phase, which involves the sublimation of ice followed by vapor diffusion through the dried porous layer. This makes the Diffusion model mechanistically relevant for understanding the underlying mass transfer phenomena in this process.

Conversely, for freeze-drying with PEF (PEFFD), the Diffusion model was identified as the best fit. It showed the strongest statistical performance (R^2 = 0.997, RMSE = 0.01824) compared to other models, including *Midilli*. Crucially, the selection of the *Diffusion* model is justified by its statistical fit and its physical assumptions aligning with the observed impact of PEF treatment in the SEM images. The structural preservation observed in SEM images directly facilitates the internal movement of moisture, thereby making diffusion one of the predominant impact mechanisms of water removal.

3.4. Sensory Analysis

Strawberries must meet certain quality criteria to be accepted by consumers, including a uniform bright red color, consistent size and shape, firmness, and a fresh flavor that is perceived through a combination of taste and aroma [27]. The drying process, with freeze-drying or HA, significantly alters the organoleptic characteristics of strawberries

(Figure 3). Usually, the main factors contributing to this change are the concentration of the present compounds, change in the structure, and chemistry reactions that modify or degrade the compounds responsible for aroma, color, or taste. In hot air-drying, these alterations are more pronounced because the use of heat for long periods of time can induce enzymatic oxidations, Maillard, and caramelization reactions that not only alter the color of strawberries, as explained before, but are also responsible for aroma and taste changes [27,28]. Since freeze-drying does not apply temperatures above 40 °C to dry the product, the organoleptic characteristics are more identical with fresh strawberries and, based on the analyzed bibliography, these characteristics offer more acceptance by consumers when compared with products processed with hot air-drying. The results obtained in this work support the conclusions of these studies.

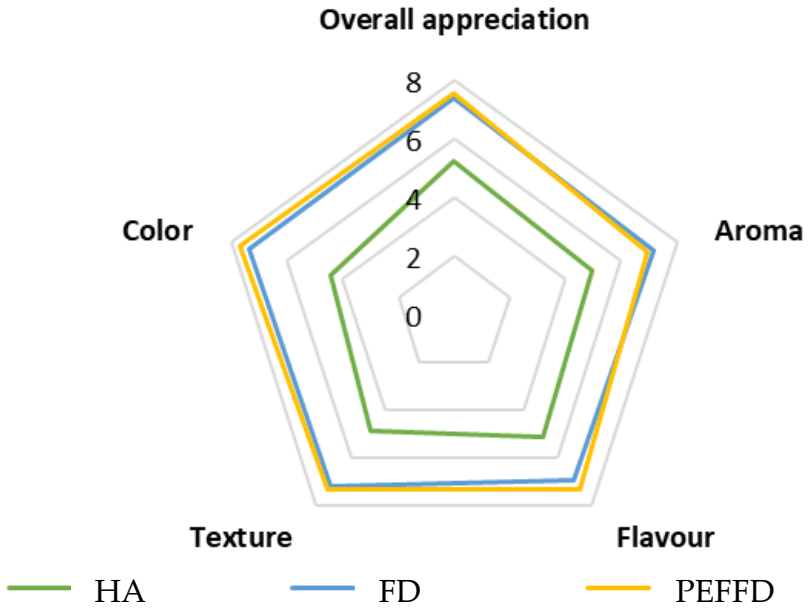


Figure 3. Sensory analysis data of strawberries dried by hot air-drying, freeze-drying, and freeze-drying with PEF.

Strawberries processed with freeze-drying with and without PEF had significantly higher ratings in all attributes evaluated, such as color, aroma, texture, flavor, and overall appreciation. Therefore, it is evident that consumers tend to prefer products with fresh-like characteristics, which can only be naturally present when low-impact processes are applied, such as freeze-drying and PEF.

Comparing freeze-drying samples with and without PEF, it is possible to observe that the rankings were almost similar. Samples treated with PEF showed slightly higher scores in overall acceptance (7.6), flavor (7.3), texture (7.3), and color (7.7) compared to samples without PEF (7.4; 6.9; 7.2; 7.4, respectively), but these differences were not statistically significant ($\alpha = 0.05$). Further studies involving a larger number of participants are recommended to determine whether the application of PEF has a significant impact on the organoleptic properties of the product.

4. Conclusions

In conclusion, the combined application of a pulsed electric field (PEF) and the freeze-drying process has demonstrated its potential to create samples with significantly lower moisture content. This technique not only enhances the efficiency of the freeze-drying process but also yields distinct textural characteristics in comparison to traditional hot air-drying. PEF treatment further amplifies the reduction in cutting force by preserving

the strawberry structure. Moreover, the organoleptic characteristics are notably improved when freeze-drying is applied with or without PEF pre-treatment when compared with hot air-dried. On the other hand, the hot air-drying method improves process time by 48% compared with freeze-drying and freeze-drying with PEF, with both having the same process time. The study outcomes also enhance the importance of selecting appropriate drying methods for predicting the drying curve of different drying methods. The performance of the *Midilli* model has stood out as a suitable choice for hot air-drying and freeze-drying, while the *Diffusion* model is the most suitable when PEF is applied.

While not the main focus of this study, a qualitative economic comparison can provide additional insight. The hot air-drying process is the most cost-effective method, with low equipment costs and short processing time (≈25.5 h). However, it usually results in a final product with significant quality loss. Freeze-drying and PEF-assisted freeze-drying processes require higher capital investment and energy consumption (≈49 h) but result in premium-quality products. PEF-assisted freeze-drying introduces a moderate equipment complexity but enhances rehydration and structure, which may justify the higher cost in applications targeting high-value markets.

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