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Influence of Pretreatments and Freeze-Drying Conditions of Strawberries on Drying Kinetics and Physicochemical Properties

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Abstract: The aim of this study is to analyze the effects of pretreatments and drying temperature on the freeze-drying (FD) kinetics, ascorbic acid content, color changes, and antioxidant activity (AA) of strawberries. Experiments were performed at 20 °C, 40 °C, and 60 °C, with a constant pressure of 63 Pa in the FD chamber. The strawberry samples were cut into slices (CS) and pulped (PS) before drying. The drying kinetics was best described using the Midilli or logistic model depending on the strawberry grinding method used and the FD temperature. The FD of strawberries significantly increased the lightness, redness, and yellowness of the dried fruit. The FD temperature and pretreatment methods had little influence on the total phenolic content (TPC) and AA. The lowest TPC was found in strawberry pulps after dehydration at 60 °C, and the highest TPC was observed in strawberry slices dehydrated at the same temperature (18.54 and 22.04 mg of gallic acid equivalent per gram of dry mass, respectively). Furthermore, the ascorbic acid content in dried strawberries was higher for the samples freeze-dried at a higher temperature.

Keywords: strawberry powder; pretreatment; puree; freeze-drying; antioxidant activity; color; ascorbic acid

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1. Introduction

Fruits are important components in everyday nutrition. They are low-calorie food products rich in carbohydrates, including dietary fibers, minerals, and vitamins that regulate the metabolic processes in the human body [1]. Fruits can be consumed either directly or as preserved products. They are also a rich source of polyphenolic compounds, both phenolic acids and flavonoids. Polyphenolic compounds are an important group of antioxidants and protect human cells from oxidative stress [2]. Most fruits have a short shelf-life. Therefore, in most of the scenarios, they require processing, which aids in their preservation [3]. However, many traditional food preservation techniques lead to adverse changes in the nutritional value or sensory characteristics of fruit [4]. Furthermore, the components of biological materials such as fruit are particularly sensitive to increased temperatures.

Strawberry (*Fragaria × ananassa Duchesne*) is a perennial that reaches a height of 15–45 cm. It is cultivated in all temperate countries and in cooler subtropics and is known for its tasty fruit. It is an excellent source of many valuable substances, including minerals (zinc, phosphorus, magnesium, manganese, potassium, and calcium), vitamins (A, B1, B2, B3, B6, B9, E, and in particular C—41.2 mg/100 g) [5], pectins, phytocides, ellagic acid, phenolic acids, flavonoids, fiber (1.63 g/100 g, necessary for the proper functioning of the digestive system), anthocyanins, and bromelain (ripe fruit) [1,6]. It is particularly recommended for people suffering from anemia and all kinds of vitamin-deficiency-related diseases.

One of the significant challenges faced by fruit producers is the emerging microbiological instability of fruit products during storage, manifested not only by unfavorable sensory changes, but most importantly as a danger to the consumer [3]. To limit the adverse changes, seasonal fruits can be converted into useful ingredients. Therefore, preservation techniques that will reduce the quality of this type of product as little as possible are urgently required. Freeze-drying (FD) is one of the best dewatering methods used to minimize the physical and chemical changes in the processed raw material. It is especially recommended for materials containing ingredients that are sensitive to heat treatment. FD results in higher-quality products [4] compared with convection (hot-air) drying [7]. However, the parameters of the FD process and food pretreatment methods have a crucial effect on the properties of the dried products [8].

The impact of the drying process on changes in the properties of plant materials has currently been the subject of many studies. The selection of appropriate methods and parameters of the drying process has a significant impact on the characteristics of the final products, such as color [9,10], physical properties, the content of biological components, and rehydration [11]. In the literature, there are no studies on the effects of pretreatment of fresh strawberries on their FD kinetics and the properties of the dried material by making a puree of them. Thus, this work aimed to study the effect of pretreatments of this fruit and FD temperature on the course of drying and physicochemical properties of a powder obtained from dehydrated strawberries.

2. Materials and Methods

2.1. Materials and Sample Pretreatment

All chemicals used in this study were of analytical grade and were purchased from Sigma Aldrich (St. Louis, MO, USA). A medium-ripening variety of "Senga Sengana" from Poland was used in this study. The fruit was collected from the Auchan Supermarket in Lublin (Poland) in spring 2021 and were cleaned and their stalks removed. The research material consisted of strawberries cut into slices of about a 0.5-cm thickness (I) and triturated into puree strawberries (II). For puree preparation, a blender (Zelmer ZSB4850, Eurogama, Rzeszów, Poland) was used. The prepared strawberries were freeze-dried.

2.2. Drying Method

The FD process was carried out in an ALPHA 1–4 laboratory freeze-dryer (ALPHA 1–4, Martin Christ Gefriertrocknungsanlagen GmbH, Osterode am Harz, Germany) according to the method described by Dziki et al. [12]. The freeze-dryer was integrated with a weight system equipped with a balance (to an accuracy of ±0.1 g) in order to measure the mass of the samples during dehydration [12]. The mass of the fruit was recorded every 5 min during the FD process. The cut samples (CS) and triturated strawberries (PS) (100 g samples) were placed on a stainless steel plate of 21-cm diameter and frozen at −25 °C for 24 h in a freezer (Liebherr GTL4905, Ochsenhausen, Germany) before FD. The FD process was performed at 20 °C, 40 °C, and 60 °C with a constant pressure of 63 Pa. The time from the beginning of the FD process until the mass of the sample stopped changing (when the moisture content reached the level of about 3% (wet basis)) was recorded as FD time. The moisture content of the strawberries before and after drying was determined gravimetrically according to the Association of Official Agricultural Chemists [13].

After the FD process, the material was stored in the dark in tightly closed polyethylene bags at 5 °C until further analyses (for a maximum of 2 weeks). Then, the dried strawberry samples were ground using a laboratory knife mill (Grindomix GM 200, Retsch, Dusseldorf, Germany). The powdered strawberry samples (particles < 0.2 mm) were subjected to further analyses.

2.3. Modeling of Drying Curves

Drying kinetics were presented as the change in the moisture ratio (MR) as a function of drying time (DTI):

$$MR = \frac{u_t - u_r}{u_p - u_r} \quad (1)$$

where u_τ represents the water content at a given measuring point [$kg \cdot kg_{s.s}{}^{-1}$], u_p represents the initial water content [$kg \cdot kg_{s.s}{}^{-1}$], and u_r represents the equilibrium water content [$kg \cdot kg_{s.s}{}^{-1}$].

To describe the FD curves, the seven most commonly used models in the literature were used. The model equations are summarized in Table 1.

Table 1. Models taken advantage for description of course vacuum freeze drying, vacuum, convective and microwave-convective drying.

Number	Model Name	Equation
1	Newton [14]	$MR = \exp(-k \cdot \tau)$
2	Page [15]	$MR = \exp(-k \cdot \tau^n)$
3	Henderson and Pabis [16]	$MR = a \cdot \exp(-k \cdot \tau)$
4	Logarithmic [17]	$MR = a \cdot \exp(-k \cdot \tau) + b$
5	Wang and Singh [18]	$MR = 1 + a \cdot \tau + b \cdot \tau^2$
6	Logistic [19]	$MR = b \cdot ((1 + \mathrm{a} \cdot \exp(k \cdot \tau))^{-1}$
7	Midilli [20]	$MR = \exp(-k \cdot \tau^n) + b \cdot \tau$

k—drying coefficient [min^{-1}]; *a*, *b*—coefficients of the equations; *n*—exponent; τ—time [min]; *MR* moisture ratio.

2.4. Measurement of Color Coordinates

Color coordinates were determined using the CIE L*a*b* system. In this system, color measurement was based on the numerical designation of the three coordinates L*, a* and b*, where L* refers to the lightness of the color, which ranges from 0 for a perfectly black body to 100 for a perfectly white body; a* indicates the color change from green (−a*) to red (a*); and b* indicates the color change from blue (−b*) to yellow (b*). Based on the color coordinates determined, the total color change (ΔE) in relation to the raw material, as well as the values of color saturation (C) and color shade (HU) of the dried material included in the color coordinates, was calculated [6]. The measurements were performed with a CR-200 colorimeter (Konica Minolta, Osaka, Japan).

2.5. Water Activity

The water activity (aw) in the strawberry samples was measured at 20 °C using LabMaster (Novasina AG, CH-8853 Lachen, Switzerland) as described by Serin et al. [21]. Two grams of samples was used for this procedure.

2.6. Total Phenolic Content (TPC) and Antioxidant Activity (AA)

To prepare the extracts, the ground dried sample was extracted with 50% methanol (shaken thrice for 30 min), and the resulting homogenate was centrifuged at 4000 rpm for 10 min at 4 °C [22]. The extraction process was performed twice. The supernatants obtained were pooled and used for further analyses. The TPC in methanolic extracts was determined and expressed in milligrams of gallic acid equivalent per gram of dry matter (GAE/g DM) [23]. Briefly, 0.5 mL of H_2O, 0.5 mL of the sample, and 2 mL of the Folin–Ciocalteu reagent (1:5 H_2O) were mixed. After 3 min, 10 mL of 10% Na_2CO_3 was added to the mixture. The absorbance of the samples was read after 30 min at 725 nm using a UV–Vis spectrophotometer (UV-1900 UV-VIS, Shimadzu, Osaka, Japan).

The AA of the dried fruit was determined based on their ability to scavenge ABTS free radicals (ABTS) following the method of Re et al. [24] and their ability to neutralize DPPH free radicals (DPPH) [25]. These procedures were described in detail by Sujka et al. [26].

The EC_{50} index was used to express the AA of the obtained extracts [10]. As reported in previous studies, the strength of a compound is inversely related to its EC_{50} value, i.e., the lowest EC_{50} value is associated with the strongest effect [27].

2.7. Ascorbic Acid Content

The ascorbic acid content of samples was analyzed using the high-performance liquid chromatography (HPLC) method [28]. It was calculated as the average content of the sum of L-ascorbic acid and L-dehydroascorbic acid in mg/100 g of the product. The analytical procedure was modified as follows: a 0.01% solution of acetic acid in methanol (95/5 $CH_3COOH:CH_3OH$) was used as the eluent instead of a phosphate buffer with the addition of *N*-cetyl-*N*,*N*,*N*-trimethylammonium bromide, which resulted in the destruction of the column stationary phase.

Chromatographic separation was performed on a HPLC system (LaChrom Elite, HITACHI, Merc, Germany). The parameters of the chromatographic analysis were as follows: 22 °C column working temperature; 0.01% acetic acid in methanol (95/5 $CH_3COOH:CH_3OH$) as the mobile phase; 0.7 cm^3/min mobile phase flow rate; and 254 nm wavelength (λ). Under these conditions, the standard solution of L-ascorbic acid (5 μg/cm^3) and the solutions of the tested samples were chromatographed. L-Ascorbic acid was identified by comparing its retention time in the tested samples with that of L-ascorbic acid in the standard solution. The ascorbic acid content in 100 g of product was determined based on the previously proposed formula.

2.8. Statistical Analysis

For each sample, three independent drying steps were performed, and all tests were performed in triplicate for each sample. Mean values and standard deviations were calculated. In addition, one-way and two-way analyses of variance and linear correlation analysis were performed, and significant differences between means were determined by Tukey's test using Statistica software (version 13.1, TIBCO Software, Palo Alto, CA, USA). To determine the coefficient of determination as well as root mean square error (*RMSE*) and reduced test values (χ^2), a drying-kinetics-regression analysis was performed using a nonlinear least squares estimation. *RMSE* and reduced test values (χ^2) were determined using the following equations:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(MR_{i,p} - MR_{i,e}\right)^2}{N}} \tag{2}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{i,p} - MR_{i,e}\right)^2}{N - n} \tag{3}$$

where $MR_{i,p}$ denotes the predicted value of the *MR*, $MR_{i,e}$ denotes the experimental value of the *MR*, *N* denotes the number of measurements, and *n* denotes the number of parameters in the equation of a given model.

All calculations were performed at a significance level of α = 0.05.

3. Results and Discussion

3.1. Drying Kinetics

The changes in the *MR* as a function of the duration of FD of strawberry slices and pulp are presented in Figures 1 and 2. Increasing the heating plate temperature from 20 °C to 60 °C significantly decreased the DTI for both slices and pulp by about 44% and 27%, respectively. In particular, pulping of strawberries before FD significantly reduced the DTI. This tendency was observed for all analyzed temperatures of the heating plates. The DTI of the triturated strawberries constituted 37.5% of the DTI of the strawberry slices when the FD temperature was 20 °C. However, when the FD temperature was 40 °C and 60 °C, the DTI of the strawberry pulp was about twofold shorter than that of the slices. Increasing the FD temperature of strawberries intensified the sublimation process as a result of the high heat and mass transfer during the FD. In addition, grinding of the fruit before FD increases the daring rate as a result of an increase in the surface area of the fruit and damage to their structure. Similar tendencies were observed by Krzykowski et al. [10] when wild strawberries were ground before FD. Other authors [12] have studied the kinetics of the drying process of whole and ground kale leaves. They found that grinding decreased the FD time by 40%. This relationship was also found by Rudy et al. [28] when cranberries were triturated before FD. The results of the regression analysis of the seven proposed models used to describe the kinetics of FD of strawberry slices and pulp are presented in Tables 2 and 3. It can be observed that for each of the analyzed models, a good fit to the experimental data was obtained. The coefficient of determination (R^2) of the equations ranged from 0.960 to 0.999. The *RMSE* value and the value of the reduced test (χ^2) were small, ranging from 0.0054 to 0.0619 and from 0.00003 to 0.00400, respectively. The best fit to the experimental data was obtained in the case of the Midilli and logistic model, depending on the strawberry pretreatment method and the drying temperature. Since the Midilli model R^2 values were the highest in most of the drying curves, though *RMSE* and χ^2 were the lowest, this model was selected for describing the FD process of strawberries (Figures 1 and 2). The Midilli model often produces the best fitting results and is among the most frequently used empirical models for drying fruit and vegetables [29–32].

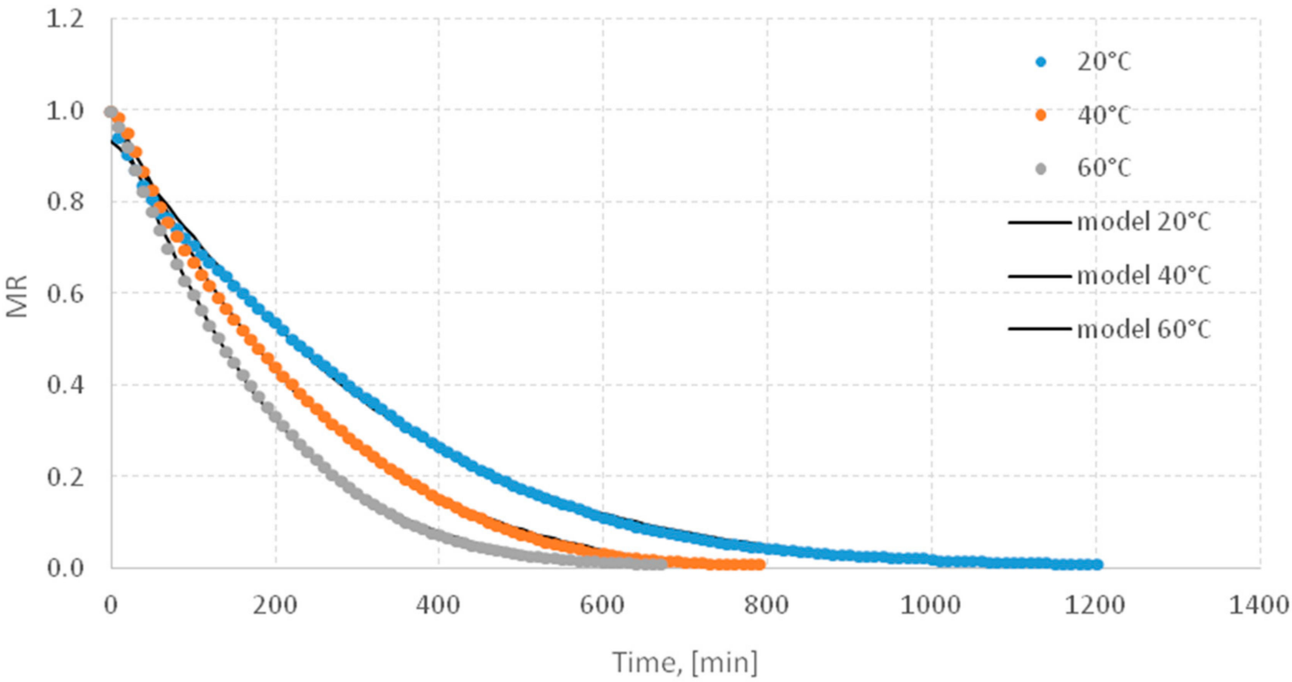

Figure 1. Drying curves of freeze-drying of strawberry slices, *MR*—moisture ratio.

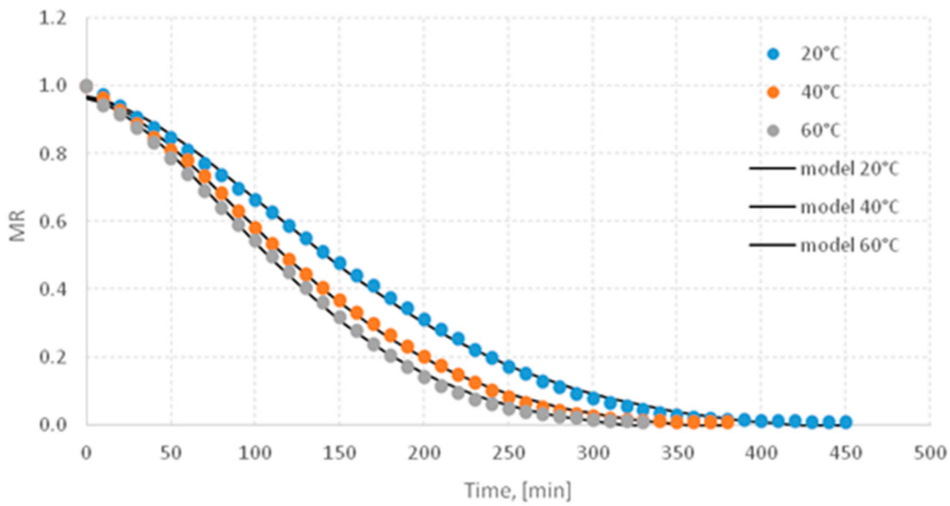

Figure 2. Drying curves of freeze-drying of strawberry pulp, *MR*—moisture ratio.

Table 2. Statistical analysis of models describing kinetics of freeze-drying of strawberry slices.

Model Name	Temperature 20 °C R^2	20 °C *RMSE*	20 °C χ^2	40 °C R^2	40 °C *RMSE*	40 °C χ^2	60 °C R^2	60 °C *RMSE*	60 °C χ^2
Newton	0.9947	0.0193	0.0004	0.9906	0.0277	0.0008	0.9931	0.0234	0.00055
Page	0.9959	0.0168	0.0003	0.9982	0.0120	0.0001	0.9994	0.0069	0.00005
Henderson and Pabis	0.9947	0.0193	0.0004	0.9939	0.0222	0.0005	0.9959	0.0182	0.00034
Logarithmic	0.9974	0.0134	0.0002	0.9989	0.0096	0.0001	0.9987	0.0103	0.00011
Wang and Singh	0.9700	0.0457	0.0021	0.9922	0.0252	0.0007	0.9858	0.0337	0.00117
Logistic	0.9988	0.0093	0.0001	0.9986	0.0106	0.0001	0.9996	0.0055	0.00003
Midilli	0.9983	0.0108	0.0001	0.9992	0.0079	0.0001	0.9996	0.0054	0.00003

R^2—coefficient of determination; *RMSE*—root mean square error; χ^2—reduced test value.

Table 3. Statistical analysis of models describing kinetics of freeze-drying of strawberry pulp.

Model Name	Temperature 20 °C R^2	20 °C *RMSE*	20 °C χ^2	40 °C R^2	40 °C *RMSE*	40 °C χ^2	60 °C R^2	60 °C *RMSE*	60 °C χ^2
Newton	0.9434	0.0781	0.0062	0.9462	0.0761	0.0059	0.9449	0.0767	0.0061
Page	0.9939	0.0257	0.0007	0.9973	0.0169	0.0003	0.9969	0.0183	0.0004
Henderson and Pabis	0.9626	0.0634	0.0042	0.9644	0.0619	0.0040	0.9619	0.0638	0.0043
Logarithmic	0.989	0.0344	0.0013	0.989	0.0344	0.0013	0.9895	0.0335	0.0012
Wang and Singh	0.9915	0.0303	0.001	0.9919	0.0295	0.0009	0.992	0.0293	0.0009
Logistic	0.9987	0.0117	0.0001	0.9991	0.0100	0.0001	0.999	0.0103	0.0001
Midilli	0.9988	0.0111	0.0001	0.9992	0.0094	0.0001	0.9989	0.0107	0.0001

R^2—coefficient of determination; *RMSE*—root mean square error; χ^2—reduced test value.

The values of the coefficients in the seven analyzed regression equations are presented in Table 4 (strawberry fruit slices) and Table 5 (strawberry fruit pulp).

Table 4. Coefficient values in the models describing the freeze-drying of strawberry slices.

Temperature	Equation	Coefficient *a*	*k*	*n*	*b*
20 °C	Newton		0.003404		
	Page		0.002308	1.065620	
	Henderson and Pabis	0.998825	0.003400		
	Logarithmic	1.012891	0.003044		−0.035153
	Wang and Singh	−0.002270			0.000001
	Logistic	1.977956	0.004454		1.111585
	Midilli	0.932817	0.001204	1.161019	−0.000007
40 °C	Newton		0.004463		
	Page		0.001710	1.170589	
	Henderson and Pabis	1.059556	0.004717		
	Logarithmic	1.088395	0.003997		−0.059746
	Wang and Singh	−0.003136			0.000002
	Logistic	2.071080	0.006215		1.083810
	Midilli	0.998372	0.002219	1.115782	−0.000036
60 °C	Newton		0.005747		
	Page		0.002469	1.157272	
	Henderson and Pabis	1.054714	0.006047		
	Logarithmic	1.071121	0.005403		−0.038136
	Wang and Singh	−0.003930			0.000004
	Logistic	2.230434	0.007794		1.237159
	Midilli	0.992444	0.002541	1.147397	−0.000016

Table 5. Coefficient values in the models describing the freeze-drying of strawberry pulp.

Temperature	Equation	Coefficient			
		a	*k*	*n*	*b*
20 °C	Newton		0.006005		
	Page		0.000557	1.444429	
	Henderson and Pabis	1.143041	0.006796		
	Logarithmic	1.335773	0.004172		−0.260742
	Wang and Singh	−0.004311			0.000005
	Logistic	1.148484	0.014077		0.172749
	Midilli	0.967159	0.000192	1.638827	−0.000050
40 °C	Newton		0.007220		
	Page		0.000402	1.562833	
	Henderson and Pabis	1.138669	0.008139		
	Logarithmic	1.314926	0.005141		−0.240099
	Wang and Singh	−0.005199			0.000007
	Logistic	1.166419	0.016613		0.185766
	Midilli	0.970477	0.000286	1.621971	−0.000050
60 °C	Newton		0.007865		
	Page		0.000518	1.544514	
	Henderson and Pabis	1.129497	0.008817		
	Logarithmic	1.359394	0.005180		−0.297120
	Wang and Singh	−0.005643			0.000008
	Logistic	1.145264	0.018421		0.174070
	Midilli	0.964061	0.000309	1.632707	−0.000068

3.2. Color Changes and Water Activity

Strawberry slices and pulp after FD at different temperatures are shown in Figure 3, and the results regarding the color of the raw material and the dried strawberry fruits are presented in Table 6. The average values of the color parameters of fresh strawberry fruits were L* = 30.30, a* = 16.50, and b* = 8.80. The FD process of strawberries significantly increased the lightness (L*), redness (a*), and yellowness (b*) of the dried fruits. Values of L* of the freeze-dried strawberry slices ranged from 35.52 to 43.84 depending on the drying temperature. The freeze-dried samples obtained at 40 °C were characterized by slightly lower L* values than those dried at 60 °C (43.65). However, L* values of the freeze-dried strawberry pulp were lower, ranging from 29.04 to 39.29 (for the drying temperatures of 20 °C and 60 °C, respectively). A similar tendency was observed by other authors in freeze-dried kale leaves. The dried leaves obtained from the lyophilized puree were characterized by lower L* values in comparison with the dried samples obtained from the whole leaves [12].

The decrease in the L* values with an increased FD temperature may be attributable to the degradation of anthocyanins [2]. The a* value of the freeze-dried strawberry slices ranged from 21.66 to 24.66, whereas in the freeze-dried strawberry pulp, it ranged from 24.52 to 34.85. Higher a* values were observed for higher temperatures. A more intense red color was noticeable after drying the strawberry pulp, and the average a* value of the pulp was about 20% higher than that of the strawberry slices. Moreover, in comparison with fresh fruits, the a* value more than doubled in the case of the pulp dried at 60 °C. The b* value of the freeze-dried strawberry slices ranged from 11.10 to 13.19, whereas for the freeze-dried strawberry pulp, it ranged from 12.05 to 15.59. An increase in the FD temperature from 20 °C to 40 ° C had no significant influence on b* values. A significant increase in b* was observed for the triturated fruit freeze-dried at 60 °C. The total color difference (ΔE) of the dried strawberries ranged from 4.30 to 14.97. Both the FD temperature and the pretreatment methods significantly influenced ΔE. The lowest value of ΔE = 4.30 was obtained for the freeze-dried strawberry pulp dehydrated at 40 °C (PSFD40) and the highest (ΔE = 14.97) was obtained for the free-dried strawberry pulp dehydrated at 20 °C (PSFD20).

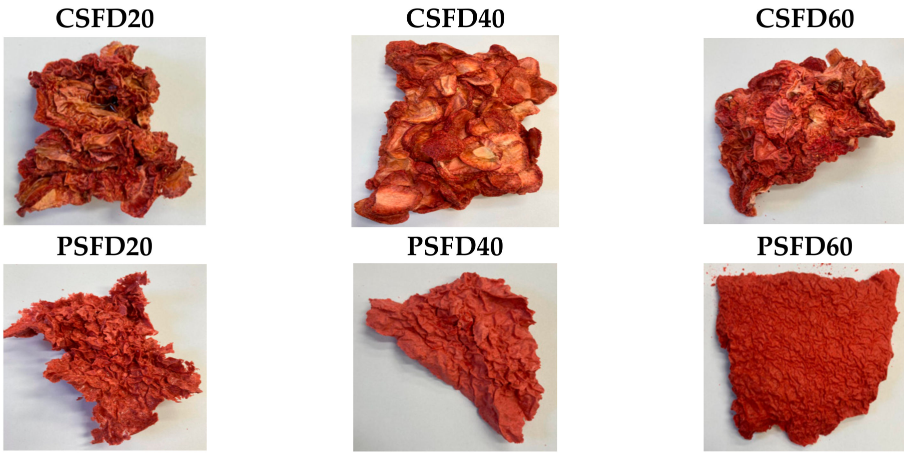

Figure 3. Freeze-dried strawberry slices (CS) dehydrated at 20 °C (CSFD20), 40 °C (CSFD40), and 60 °C (CSFD60), and freeze-dried strawberry pulp (PS) dehydrated at 20 °C (PSFD20), 40 °C (PSFD40), and 60 °C (PSFD60).

Table 6. Color coordinates of raw and freeze-dried strawberries and water activity.

MD *	DT	Color Parameters				Water Activity
		L*	a*	b*	ΔE	
FF		30.30 ± 1.40 [a] ***	16.50 ± 0.20 [a]	8.80 ± 0.50 [a]	-	-
CSFD	20 °C	35.52 ± 3.37 [a,b,c]	21.66 ± 0.40 [b]	11.18 ± 0.78 [b]	8.07 ± 3.14 [b,c]	0.328 ± 0.013 [b]
	40 °C	43.65 ± 6.50 [c,d]	22.69 ± 0.58 [b,c]	11.10 ± 0.51 [b]	8.32 ± 3.52 [b,c]	0.346 ± 0.008 [bc]
	60 °C	43.84 ± 1.47 [d]	24.66 ± 1.41 [c,d]	13.19 ± 0.63 [b]	6.46 ± 2.11 [a,b]	0.335 ± 0.005 [b]
PSFD	20 °C	29.04 ± 1.24 [a]	24.52 ± 1.06 [c,d]	12.05 ± 1.36 [b]	14.97 ± 2.27 [d]	0.358 ± 0.002 [c]
	40 °C	31.97 ± 1.03 [a,b]	26.96 ± 0.79 [d]	12.10 ± 0.46 [b]	4.30 ± 1.27 [a]	0.330 ± 0.003 [b]
	60 °C	39.29 ± 1.04 [b,c,d]	34.85 ± 1.06 [e]	15.59 ± 0.62 [c]	11.44 ± 1.10 [c,d]	0.304 ± 0.004 [a]

* MD—method of drying, DT—drying temperature, FF—fresh fruits, CSFD—cut strawberry after freeze drying, PSFD—pulp strawberry after freeze drying, L*—lightness, a*—redness, b*—yellowness, ΔE—total color difference. *** The values designated by the different small letters ([a–d]) in the columns of the table are significantly different ($\alpha = 0.05$).

Color is one of the most important attributes defining the quality of strawberries and is one of the first parameters evaluated by the consumer, the intensity of the red color being the major quality criterion [3,33]. The color intensity of the final product depends on the variety of the strawberry [6], as well as being highly affected by the drying method [4]. Shishehgarha et al. [34] reported that the strawberries freeze-dried at temperatures lower than 50 °C were of better visual quality, whereas those freeze-dried at higher temperatures seemed to have slightly suffered from excessive heating. Moreover, the pretreatment method followed also has an influence on the color of the final products. Rudy et al. [29] investigated the FD process for whole and triturated cranberries and reported that cranberry puree prior to drying resulted in a dark red end product with a higher AA compared with the whole-fruit FD process.

The water activity of the dried strawberry fruit samples ranged from 0.304 to 0.358 (PSFD60 and PSFD20, respectively) (Table 6). A slightly higher water activity was observed for the sliced strawberries (CS) (0.336), whereas for strawberry pulp (PS), the average water activity was 0.331. In the pulp-dried strawberries, a decrease in water activity was observed with an increasing drying temperature. However, it did not exceed the acceptable limit (0.6) for any of the samples. Water activity is an important parameter that determines the shelf-life of food products [35]. While processing raw materials, either a significant part of the water is removed, or their content is increased. In dried fruits, vegetables, fish, powdered milk, some grain and meat products, concentrated fruit juices, and condensed milk, the amount of water is significantly reduced [36]. However, the amount of water present in the food determines its physical properties [37].

3.3. TPC and AA

The results regarding the TPC and AA of the dried cut and pulp strawberry fruits are presented in Table 7. The FD temperature and the pretreatment method had little influence on the TPC and AA of the dried fruits. The lowest TPC content (18.54 mg GAE/g DM) was found in the strawberry pulp dehydrated at 60 °C (PSFD60), and the highest (22.04 18.54 mg GAE/g DM) was observed in the strawberry slices dehydrated at 60 °C (CSFD60). In particular, the FD temperature (range 20–60 °C) did not have a significant influence on the TPC for both sliced and triturated strawberries. A similar tendency was observed for ABTS. The highest EC_{50} values (the lowest AA) for ABTS were observed in the PSFD20 sample (7.13 mg DM/mL), whereas the highest reduction ability (the lowest EC_{50}) was observed for the CSFD60 sample (5.86 mg DM/mL). In the case of DPPH, the lowest EC_{50} value was recorded for the CSFD40 sample (14.35 mg DM/mL), whereas the highest was recorded for the CSFD20 sample (10.61 mg DM/mL), which was similar to the EC_{50} value observed for DPPH for the PSFD40 sample (10.66 mg DM/mL).

Table 7. Total phenolic content and antioxidant activity of strawberry fruits.

MD *	DT	TPC [mg GAE/g DM]	Antioxidant Activity ABTS [EC_{50}; mg DM/mL]	DPPH [EC_{50}; mg DM/mL]
FF		23.02 ± 0.33 ^{b} **	7.37 ± 0.19 ^{b}	11.78 ± 0.54 ^{a,b}
CSFD	20 °C	20.74 ± 1.39 ^{a,b}	6.64 ± 0.39 ^{ab}	10.61 ± 0.42 ^{a}
	40 °C	19.61 ± 2.25 ^{a,b}	6.44 ± 0.73 ^{a,b}	14.35 ± 1.01 ^{b}
	60 °C	22.04 ± 0.26 ^{b}	5.86 ± 0.19 ^{a}	12.70 ± 0.59 ^{ab}
PSFD	20 °C	18.60 ± 1.12 ^{a,b}	7.13 ± 0.17 ^{b}	12.57 ± 0.60 ^{a,b}
	40 °C	18.73 ± 0.77 ^{a,b}	6.51 ± 0.08 ^{a,b}	10.66 ± 0.98 ^{a}
	60 °C	18.54 ± 0.76 ^{a}	6.43 ± 0.17 ^{a,b}	13.70 ± 0.77 ^{b}

* MD—method of drying, DT—drying temperature, FF—fresh fruits, CSFD—cut strawberry after freeze drying, PSFD—pulps strawberry after freeze drying, TPC—total phenolics content, ABTS—antioxidant activity, DPPH—antioxidant activity. ** The values designated by the different small letters (^{a,b}) in the columns of the table are significantly different (α = 0.05).

Many studies have demonstrated that the drying temperature influences both TPC and AA. Usually, drying destroys biologically active compounds and decreases the AA [38]. However, in FD, these changes are smaller compared with air-drying [39]. Slightly lower values of the TPC were obtained for the triturated strawberries compared with strawberry slices. However, significant differences were found only when the FD temperature was 60 °C. Rudy et al. [29] observed a similar relationship when ground and whole cranberries were freeze-dried.

Krzykowski et al. [10] showed that both the temperature and the method of drying significantly affect the TPC in the dried wild strawberry fruits. Increasing the drying temperature to 60 °C resulted in significant decreases in the TPC and the AA during dehydration. However, FD carried out at the same temperatures as convection drying resulted in a lower degradation of the TPC [10]. Other authors showed that in the case of orange puree, the FD temperature had little influence on the TPC and that the highest TPC was found in fruits freeze-dried at 30 °C and 50 °C [40]. Drying at higher temperatures, on the one hand, intensifies the degradation of biologically active compounds, but on the other hand, significantly reduces the DTI, which often has a positive effect on both TPC and AA. Our results suggest that during FD, the appropriate pretreatment of strawberry fruits can reduce the negative influence of higher temperatures on the AA, because the FD process is faster.

3.4. Ascorbic Acid Changes

Strawberries are a good source of ascorbic acid, which is a powerful natural antioxidant soluble in water but is very sensitive and decomposes quickly under the influence of light, air, and high temperature (thermolabile) [7]. The average content of ascorbic acid in fresh strawberries was 248.70 mg/100 g DM. The FD process, regardless of the method and parameters, caused a decrease in the ascorbic acid content in the dried material (Figure 4). The average ascorbic acid content in the dried strawberries ranged from 74.90 mg/100 g DM to 237.55 mg/100 g DM for the freeze-dried strawberry pulp dehydrated at 20 °C (PSFD20) and freeze-dried strawberry slices dehydrated at 60 °C (CSFD60), respectively. The highest ascorbic acid content in dried strawberry fruit was recorded after the FD process of the slices at the highest temperature of the heating shelves. The ascorbic acid content in the dried fruits depended on the pretreatment method followed before drying. A much higher ascorbic acid content was observed in the case of strawberry slices, on average 226.05 mg/100 g DM, whereas the drying temperature caused a relatively slight decrease. The average ascorbic acid content in the strawberry pulp was 44% lower compared with the slices. Additionally, temperature had a significant influence on the ascorbic acid content in pulp: an increase in the temperature resulted in increased ascorbic acid content.

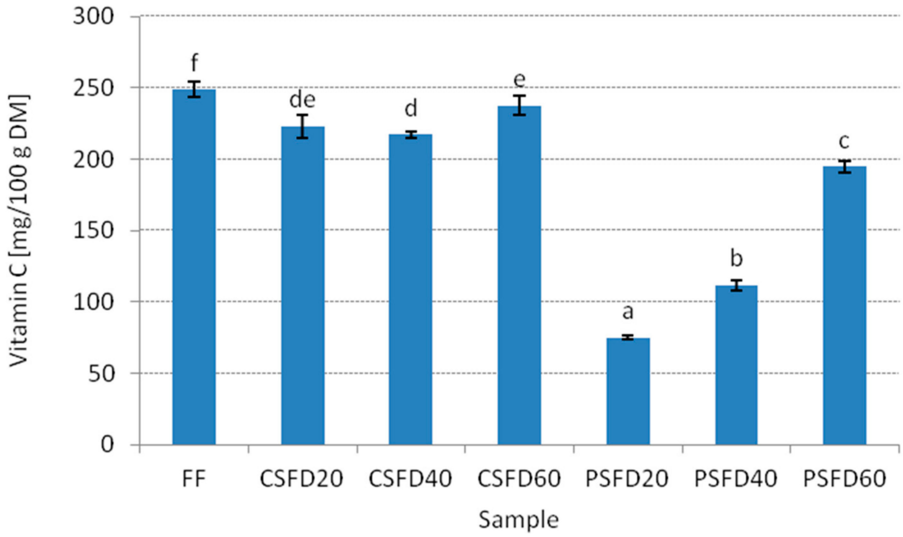

Figure 4. Ascorbic acid content in fresh fruits and freeze-dried strawberry slices (CS) dehydrated at 20 °C (CSFD20), 40 °C (CSFD40), and 60 °C (CSFD60), and freeze-dried strawberry pulp (PS) dehydrated at 20 °C (PSFD20), 40 °C (PSFD40), and 60 °C (PSFD60). The values designated by different lower case letters (a–f) are significantly different (α = 0.05).

Ascorbic acid is a water-soluble vitamin and is highly sensitive to the temperature of the environment in which it dissolves. Heat treatments of food, such as air-drying, lead to an almost complete loss of ascorbic acid. A temperature of 70 °C has a negative effect on the ascorbic acid content [32]. Ascorbic acid is also broken down by oxygen [40]. Wojdyło et al. [38] showed that convection drying decreased the AA and the ascorbic acid content in dried strawberries compared with vacuum drying. However, in the case of FD, a different scenario is observed. Silva-Espinoza et al. also observed similar trends during FD of orange puree. They found that samples freeze-dried at 30 °C were characterized by a significantly lower ascorbic acid content compared with those dehydrated at 40 °C and 50 °C. They attributed this finding to the longer FD time of puree at a lower temperature [40]. On the contrary, according to Krzykowski et al. [10], the highest ascorbic acid content in dried wild strawberry fruit was recorded in the case of FD at the lowest temperature of the heating shelves. However, they lyophilized the whole fruits. In our study, a similar relationship was obtained for sliced fruits. These findings suggest that fruits should be pureed before FD at higher temperatures. The present study also indicated a significant correlation between ascorbic acid content and TPC (r = 0.72, p < 0.05). Similar dependencies were observed by other authors [7] during strawberry drying.

4. Conclusions

The present study demonstrates that both strawberry pretreatments and FD temperature have a crucial influence on the drying kinetics and the physicochemical properties of the dried fruits. Pulping of strawberries and increasing the FD temperature significantly reduces the FD time. In particular, an increase in the drying temperature from 20 °C to 60 °C and pulping of strawberries have little influence on the TPC and AA, but decrease the lightness, redness, and yellowness of the dried fruits. Most importantly, pulping of strawberries before FD reduces the ascorbic acid content in the dried product. However, with the increase in the FD temperature, the ascorbic acid content increases. Taking into account both the time of drying and the quality of the freeze-dried fruits, this study recommends the pulping of strawberries before FD and consequently lyophilization at 60 °C. Such pretreatments and FD temperature lead to a significant reduction in the DTI and obtaining good-quality products. The strawberry powder thus obtained can be used for the fortification of many kinds of food such as ice cream, snacks, cookies, and candies. Future studies will focus on other methods of drying of strawberry puree and assess the changes in the phenolic profile of the dried material.

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