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Wild Strawberry *Fragaria vesca L.*: Kinetics of Fruit Drying and Quality Characteristics of the Dried Fruits

Andrzej Krzykowski [1], Dariusz Dziki [1,*], Stanisław Rudy [1], Urszula Gawlik-Dziki [2], Emilia Janiszewska-Turak [3] and Beata Biernacka [1]

[1] Department of Thermal Technology and Food Process Engineering, University of Life Sciences in Lublin, 31 Głęboka St., 20-612 Lublin, Poland; andrzej.krzykowski@up.lublin.pl (A.K.); stanislaw.rudy@up.lublin.pl (S.R.); beata.biernacka@up.lublin.pl (B.B.)

[2] Department of Biochemistry and Food Chemistry, University of Life Sciences in Lublin, 8 Skromna St., 20-704 Lublin, Poland; urszula.gawlik@up.lublin.pl

[3] Department of Food Engineering and Process Management, Institute of Food Sciences, Warsaw University of Life Sciences (SGGW), Warsaw, Nowoursynowska 159c, 02-776 Warsaw, Poland; emilia_janiszewska_turak@sggw.edu.pl

* Correspondence: dariusz.dziki@up.lublin.pl; Tel.: +48-81-445-61-25

Received: 17 September 2020; Accepted: 6 October 2020; Published: 8 October 2020

Abstract: The aim of this study was to determine the effect of the temperature of convection and freeze–drying of wild strawberry *Fragaria vesca* L. fruits on the drying kinetics and on selected quality features of the dried fruits. The process of convection drying was carried out at the temperatures of 25 °C, 40 °C, and 60 °C, whereas freeze–drying was carried out at the temperatures of 20 °C, 40 °C, and 60 °C of the heating shelves and at the pressure of 63 Pa in the lyophilizer chamber. The drying kinetics were best described by the Midilli model for both drying methods. An increase of the drying temperature to 60 °C, for both convection drying and freeze–drying, resulted in a decrease of the total content of phenolic compounds and of the antioxidant activity of the dried fruits. An increase in the temperature of convection drying reduced the lightness of the dried fruits. However, during freeze–drying, these features changed little despite the increase in the drying temperature. The dried fruits with the highest brightness were obtained at a freeze–drying temperature of 60 °C. The method of freeze–drying is proposed as the best because of the resulting color, L-ascorbic acid retention, and antioxidant properties of the dried fruits.

Keywords: wild strawberry; drying; color changes; L-ascorbic acid changes; antioxidant properties

1. Introduction

Wild strawberry (*Fragaria vesca* L.) is a perennial plant about 5–20 cm high, naturally occurring throughout the northern hemisphere. There are reports that it was already known by primitive people, and archaeological studies show that it was also eaten by apes [1–3].

In Poland, wild strawberries can be found all over the country and are also commonly grown in home gardens and allotment areas [2,4]. Despite the fact that well-yielding varieties of strawberries are available, there is no large-scale cultivation of this plant; only small plantations are found in France, Italy, Austria, and Poland [2].

Wild strawberry fruits are valued for their high nutritional content, taste, and dietary value and are a source of antioxidant and antithrombotic compounds essential for our body [5–9]. Their action consists in neutralizing reactive forms of oxygen, thus playing an important role in combating cancer and atherosclerosis [10]. These fruits have been used in folk medicine as a diuretic, an oversleptic agent, and to treat kidney and liver diseases as well as anemia [2,11]. Apart from

monosaccharides and mineral salts, they contain the vitamins C, B, and K, carotene and tannins, pectin, phenolic compounds, flavonoids, and anthocyanins [2].

Wild strawberry fruits are harvested for home use, are used in the pharmaceutical and cosmetic industry, and, due to their specific aroma and taste, are used in confectionery and as an ingredient in jams and liqueurs [12–14].

A hybrid strawberry, also called pineapple strawberry or large-fruit strawberry, was created from the cross of the Chilean strawberry (*Fragaria chiloensis L.*) and the Virginia strawberry (*Fragaria virginiana Duch*.) [15,16]. This strawberry is commonly processed on an industrial scale and has gained the interest of scientists.

Both strawberry and wild strawberry fruits are susceptible to mechanical damage, have a short shelf-life, and therefore require refrigeration or heat treatment to extend the storage period [17–20]. All processing methods cause to a greater or lesser extent a decrease in product quality in relation to the raw material and require different amounts of energy. Freezing results in unfavorable changes in the quality of fruits at the thawing stage [21]; strawberries dried by the most popular convection method have a hard consistency and limited rehydration properties [22]. Freeze–drying, on the other hand, ensures the highest quality of the dried fruits [23].

Despite the facts that wild strawberries are characterized by better taste and aroma compared to strawberries and that their fruits in the form of dried fruits are generally available, the drying kinetics of these fruits has not yet been studied, and the influence of the drying method and the drying temperature on color changes and antioxidant properties of wild strawberries has not been determined. Therefore, the aim of this study was to analyze the parameters of freeze– and convection drying of wild strawberry fruits in relation to the kinetics of the drying process and selected quality characteristics of the dried fruits.

2. Materials and Methods

2.1. Material

Wild strawberry fruits (*Fragaria vesca L.*) came from a naturally growing population in the forest area of Lublin Province (eastern Poland). The raw material was obtained from bushes in full ripeness present in a single location, in June 2019. Selected on the basis of their size, ripe and undamaged fruits were subjected to convection drying immediately after harvesting. Fruits were purchased from (Group of Producers KLASA, Klementowice, Poland). The material intended for freeze–drying was frozen in a freezer chamber chest (Liebherr, GTL-4905, Nussbaumen, Switzerland) at −25 °C, in conditions of free convection.

The dry matter (DM) content of wild strawberry fruits was 13.40 g/100 g of raw material, determined in accordance with the Association of Official Analytical Chemists (AOAC), method 934.06, by drying the tested material at 70 ± 0.1 °C to a constant mass in a Pol-Eko dryer, SLW 53 STD (Wodzisław Śląski, Poland) [24].

2.2. Drying Method

The freeze–drying process was carried out in a lyophilizer Alpha 1-4 (Martin Martin Christ Gefriertrocknungsanlagen GmbH, Osterode am Harz, Germany) with a contact heat supply system, equipped with a scale adapted to work in the vacuum, recording the weight of the raw material during drying with an accuracy of ±0.1 g. The freeze–drying process was carried out at a constant pressure of 63 Pa and at a temperature of the heating shelves of 20 °C, 40 °C, and 60 °C. During freeze–drying, the conditions were selected so to obtain a minimum moisture content of 5%. Changes in the weight of the dried fruit samples were recorded during drying according to a described methodology [25].

Convection drying was carried out using a Promis-Tech dryer (Wroclaw, Poland), which enabled continuous recording of the fruit weight with an accuracy of ±0.1 g. This process was carried out at air temperatures of 25 °C, 40 °C, 60 °C, with a constant air flow of 0.5 $m \cdot s^{-1}$ under the dryer screen. The minimum temperature of convection drying was increased to 25 °C compared to

freeze–drying, because our own research has shown that carrying out this process at 20 °C requires a long time and does not allow achieving the assumed final humidity of the dried fruits of 10%. For both methods of drying, the fruit samples weighed 100 g.

2.3. Modeling of the Drying Curves

To show the kinetics of the drying process, the reduced water content (MR) was calculated from the following formula:

$$MR = \frac{u_t - u_r}{u_0 - u_r}, \quad (1)$$

where u_t is the water content in the course of drying (kg H_2O·kg DM^{-1}), u_0 is the initial water content (kg H_2O·kg DM^{-1}), and u_r is the equilibrium water content (kg H_2O·kg DM^{-1}).

Since the value of u_r is negligible compared to those of u_0 and u, it was omitted. This simplification is widely used and has no major impact on the drying kinetics [26].

In order to select the best mathematical model describing freeze– and convection drying of wild strawberry fruits, seven equations commonly quoted in the literature were analyzed (Table 1).

Table 1. Equations applied to the drying curves.

Model Number	Model Name	Model Equation	References
1	Newton[1]	$MR = \exp(-k \cdot \tau)$	[27]
2	Page	$MR = \exp(-k \cdot \tau^n)$	[28]
3	Henderson and Pabis	$MR = a \cdot \exp(-k \cdot \tau)$	[29]
4	Logarithmic	$MR = a \cdot \exp(-k \cdot \tau) + b$	[30]
5	Wang and Singh	$MR = 1 + a \cdot \tau + b \cdot \tau^2$	[31]
6	Midilli	$MR = a \exp(-k \cdot \tau^n) + b \cdot \tau$	[32]
7	Logistic	$MR = b \cdot ((1 + a \cdot \exp(k \cdot \tau))^{-1}$	[33]

[1] k—Drying coefficient (min^{-1}); a, b—Coefficients of the equations; n—Exponent; τ—Time (min).

2.4. Measurement of Color Coordinates

The color coordinates of the raw and dried materials were determined using the X-Rite 8200 spherical spectrophotometer (X-Rite, Grand Rapids, MI, USA) in the *CIE L*a*b** colorimetric system, which allows determining the brightness L^* and color changes from green to red (a^*) and from blue to yellow (b^*). The homogeneity of the samples was ensured by grinding the material to be tested before taking the measurements, using a GM-200 laboratory mill (Retsch, Düsseldorf, Germany).

On the basis of the experimentally determined color coordinates, the value of the total color difference (ΔE) with respect to the raw material, the color saturation (C), and the hue (HU) of the individual samples were calculated according to the following formulae:

$$\Delta L = L^* - L^*_0, \Delta a = a^* - a^*_0, \Delta b = b^* - b^*_0, \quad (2)$$

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}, \quad (3)$$

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

$$HU = \tan^{-1}\frac{b}{a}, \quad (5)$$

where L_0^*, a_0^*, and b_0^* are the color parameters of the fresh sample.

2.5. L-ascorbic Acid Determination

The content of L-ascorbic acid was determined during titration with the Tillmans method, which consists in the oxidation of L-ascorbic acid to dehydroascorbic acid in an acidic medium with a solution of 2,6-dichloroindophenol. Samples of the grinded raw material and dried fruits weighing 10 g (±0.01g) were quantitatively transferred to a beaker (50 mL); after adding 2% oxalic acid, the

samples were kept in the dark for 15 min. The solution was then filtered through filter paper and brought to 100 mL in a volumetric flask, from which 10 mL of the filtrate was taken and titrated with 2,6-dichlorophenolindophenol solution until a pale pink color appeared, which lasted for 30 s. The total content of L-ascorbic acid was determined in mg/100 g (DM).

2.6. Total Phenolics Content and Antioxidant Activity

In order to determine the total content of phenolic compounds and the antioxidant activity of the raw material before and after drying, extracts from the tested samples were prepared according to a described methodology.

The total content of phenolic compounds was determined in methanolic extracts [34] and was expressed in mg of gallic acid per gram of dry matter (GAE/g DM) [35]. The antioxidant activity of the dried fruits was also determined using four methods based on chelating power (CHEL) [36], antiradical activities (ABTS (2,2′-azinobis (3-ethylbenzothiazoline-6-sulfonate) free radicals [37], DPPH (2,2-diphenyl-1picyclohydrazil) free radicals [38], and reducing power (RED) [39]. The EC_{50} index was used to express the antioxidant activity of the obtained extracts [40].

2.7. Statistical Analysis of the Results

The results of the analyses concerning the kinetics of the freeze– and convection drying processes are presented as a mean of three repetitions, while the remaining analyses concerning the quality of the dried fruits included five repetitions. Experimental data were analyzed for variance at the significance level of α = 0.05; the Tukey's test was used to determine the significance of differences between the mean values (Statistica 13, StatSoft). During the regression analysis of the drying kinetics, the determination factor (R^2), the mean-square error ($RMSE$), and the values of the chi-quadrate test (χ^2) were determined:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(MR_{i,p}-MR_{i,e})^2}{N}}, \quad (6)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}(MR_{i,p} - MR_{i,e})^2}{N-n}, \quad (7)$$

where $MR_{i,p}$ is the predicted value of reduced water content; $MR_{i,e}$ is the experimental value of reduced water content; N is the number of measurements; and n is the number of parameters in the model equation.

3. Results and Discussion

3.1. Drying Kinetics

Changes in the reduced water content (MR) as a function of the duration of the process of freeze– and convection drying of wild strawberry fruits are summarized in Figures 1 and 2. On the basis of the conducted research, it can be concluded that an increase in the drying temperature was accompanied by a decrease in the duration of the process for both analyzed drying methods. At a temperature of 40 °C, freeze–drying was slightly shorter, while at 60 °C, the time of convection drying was much shorter (by 80 min). Increasing the temperature from 20 °C to 60 °C shortened the freeze–drying time by about 40%. Increasing the convection drying temperature from 25 °C to 60 °C shortened the drying time by about 60%. The shortest time was observed in the case of convection drying at 60 °C, which was 250 min.

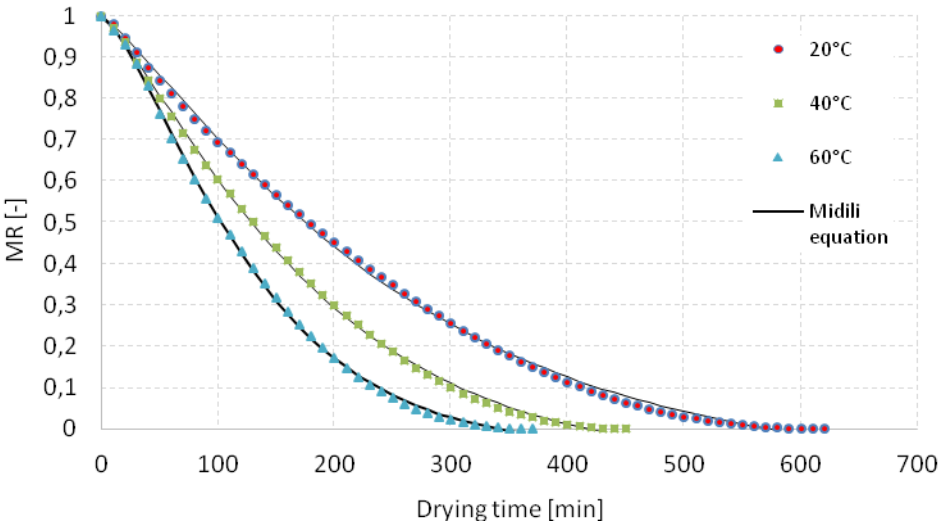

Figure 1. Drying curves of the freeze–drying process of wild strawberry fruits.

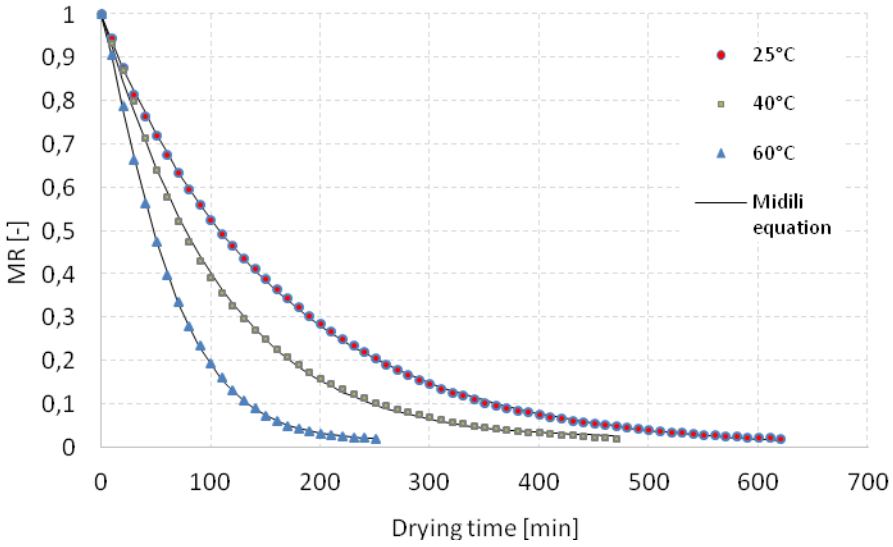

Figure 2. Drying curves of the air-drying process of wild strawberry fruits.

The results of the regression analysis of seven studied models used to describe the kinetics of freeze– and convection drying of wild strawberry fruits are summarized in Tables 2 and 3. It can be concluded on the basis of the analysis of the obtained results that a good match of the experimental data was obtained for each of the analyzed models. The value of the coefficient of determination (R^2) of the equations for both analyzed drying methods ranged from 0.9479 to 0.9999. The mean-square error (*RMSE*) and the value of the reduced test (χ^2) were small, corresponding to 0.0035–0.0608 and 0.00001–0.00385, respectively. In order to standardize, the drying kinetics was modeled using the Midilli model, although slightly better model matching values were obtained using the Wang and Sing models for freeze–drying at 20 °C and 40 °C. For both drying methods, at the three analyzed temperatures, the Midilli model resulted in coefficients of determination (R^2) in the range from 0.999 to 0.9999, and the highest mean-square error (*RMSE*) was 0.0099. Analyzing the results of other researchers, it can be seen that the Midilli model very often gave the best matching results among the empirical models used to describe the processes of freeze– and convection drying [41–43]. In the description of the kinetics of convection and freeze–drying of fruits and vegetables, good results are often obtained using the Page model. However, in the case of wild strawberry fruits, this model did not give such a good match to empirical data as the Midilli model.

Table 2. Analysis of models describing the kinetics of freeze–drying of wild strawberry fruits.

Model	Temperature								
	20 °C			40 °C			60 °C		
	R^2	*RMSE*	χ^2	R^2	*RMSE*	χ^2	R^2	*RMSE*	χ^2
Newton	0.970	0.0526	0.00281	0.969	0.0549	0.00308	0.965	0.06	0.0037
Page	0.995	0.0212	0.00046	0.997	0.0181	0.00034	0.999	0.0123	0.00016
Henderson and Pabis	0.979	0.0439	0.00199	0.979	0.0446	0.00208	0.978	0.0468	0.00231
Logarithmic	0.998	0.0141	0.00021	0.998	0.0153	0.00025	0.995	0.0222	0.00054
Wang and Singh	0.999	0.0029	0.00001	0.999	0.0065	0.00004	0.998	0.0159	0.00027
Logistic	0.998	0.0141	0.00021	0.998	0.0153	0.00025	0.995	0.0222	0.00054
Midilli	0.999	0.0099	0.00010	0.999	0.0078	0.00006	0.999	0.0063	0.00004

Table 3. Analysis of models describing the kinetics of air drying of wild strawberry fruits.

Model	Temperature								
	25 °C			40 °C			60 °C		
	R^2	*RMSE*	χ^2	R^2	*RMSE*	χ^2	R^2	*RMSE*	χ^2
Newton	0.9998	0.004	0.00002	0.9984	0.0106	0.00011	0.9943	0.022	0.0005
Page	0.9998	0.0039	0.00002	0.9985	0.0102	0.00011	0.9995	0.0064	0.00004
Henderson and Pabis	0.9998	0.0038	0.00001	0.9988	0.0091	0.00009	0.997	0.016	0.00028
Logarithmic	0.9998	0.0037	0.00001	0.9993	0.0073	0.00006	0.9976	0.0144	0.00023
Wang and Singh	0.9602	0.0522	0.00282	0.9479	0.0608	0.00385	0.9812	0.0399	0.00172
Logistic	0.9998	0.004	0.00002	0.9987	0.0096	0.0001	0.9994	0.0074	0.00006
Midilli	0.9998	0.0036	0.00001	0.9992	0.0076	0.00006	0.9999	0.0035	0.00001

The coefficients of equations of the analyzed models of kinetics of freeze– and convection drying of wild strawberry fruits are presented in Tables 4 and 5.

Table 4. Values corresponding to different models describing the freeze–drying process of wild strawberry fruits.

Temperature	Equation	Coefficient			
		a	*k* (min^{-1})	*n*	*b*
20 °C	Newton		0.004581		
	Page		0.000699992	1.337876	
	Henderson and Pabis	1.093974	0.004990		
	Logarithmic	1.228606	0.003301		−0.1964
	Wang and Singh	−0.003297			0.000003
	Logistic	−6.25637	−0.00330		−5.09225
	Midilli		0.001386	1.191808	−0.000125
	Equation	**Coefficient**			
		a	*k* (min^{-1})	*n*	*b*
40 °C	Newton		0.006255		
	Page		0.000911	1.367605	
	Henderson and Pabis	1.102569	0.006863		
	Logarithmic	1.237489	0.004581		−0.194121
	Wang and Singh	−0.00451			0.000005
	Logistic	−6.37488	−0.00458		−5.15147
	Midilli		0.001577	1.242171	−0.000142
	Equation	**Coefficient**			
		a	*k* (min^{-1})	*n*	*b*
60 °C	Newton		0.007945		
	Page		0.000921	1.430819	
	Henderson and Pabis	1.121215	0.008836		
	Logarithmic	1.231531	0.006216		−0.163777932
	Wang and Singh	−0.005726			0.000008
	Logistic	−6.10585	−0.00622		−7.51954
	Midilli		0.001263	1.355914	−0.0000931

Table 5. Values corresponding to different models describing the air drying of wild strawberry fruits.

Temperature	Equation	Coefficient			
		a	***k* (min^{-1})**	***n***	***b***
25 °C	Newton		0.006371		
	Page		0.006566	0.994308	
	Henderson and Pabis	0.995310	0.006341		
	Logarithmic	0.996253	0.006286		−0.002644
	Wang and Singh	−0.004315			0.000005
	Logistic	15.47184	0.00653		0.06131
	Midilli		0.006848	0.984885	−0.000008
	Equation	**Coefficient**			
		a	***k* (min^{-1})**	***n***	***b***
40 °C	Newton		0.009089		
	Page		0.008337	1.017652	
	Henderson and Pabis	1.020967	0.009282		
	Logarithmic	1.017365	0.009663		0.011738
	Wang and Singh	−0.005942			0.000009
	Logistic	21.90191	0.00948		0.04288
	Midilli		0.007034	1.058379	0.000041
	Equation	**Coefficient**			
		a	***k* (min^{-1})**	***n***	***b***
60 °C	Newton		0.015674		
	Page		0.008076	1.152685	
	Henderson and Pabis	1.052534	0.016463		
	Logarithmic	1.060778	0.015683		−0.016418
	Wang and Singh	−0.010688			0.000028
	Logistic	1.732845	0.020325		0.359499
	Midilli		0.007181	1.184910	0.000057

3.2. Color Changes

The results regarding the color of the raw material and of the dried wild strawberry fruits are presented in Table 6. The material obtained after the drying process, regardless of the method, was characterized by a higher brightness (L^*) compared to the raw material. In the case of convection drying, an increase in the temperature of the process resulted in a decrease in the brightness of the dried fruits, while during freeze–drying, the color changes were small in the whole temperature range; however, the brightest dried fruits were obtained at the temperature of the heating shelves of 60 °C. The strongest brightness of the freeze–dried fruits compared to the product obtained from convection drying may be related, among other factors, to the lower water content in the lyophilizate.

Table 6. Effect of the drying method on the color of wild strawberry fruits.

MD*	DT	Dimension of Color			
		L*	**C**	**HU**	**ΔE**
RM		35.89 ± 1.16^{a}	27.48 ± 1.15^{b}	21.78 ± 1.25^{a}	0
FD	20 °C	52.78 ± 0.30^{e}	20.18 ± 0.28^{a}	42.83 ± 0.91^{b}	20.34 ± 0.18^{c}
	40 °C	53.54 ± 0.43^{ef}	19.89 ± 0.52^{a}	44.61 ± 0.94^{c}	21.36 ± 0.58^{d}
	60 °C	54.04 ± 0.35^{f}	19.87 ± 0.47^{a}	45.29 ± 0.54^{c}	21.89 ± 0.39^{d}
AD	25 °C	49.37 ± 0.43^{d}	29.33 ± 0.43^{c}	45.92 ± 0.22^{c}	18.17 ± 0.34^{b}
	40 °C	47.14 ± 0.53^{c}	29.40 ± 0.64^{c}	45.92 ± 0.32^{c}	16.60 ± 0.45^{a}
	60 °C	44.18 ± 0.44^{b}	29.85 ± 0.47^{c}	48.30 ± 0.69^{d}	15.86 ± 0.59^{a}

* MD—Method of drying, DT—Drying temperature, RM—Raw material, FD—Freeze–drying, AD—Air drying, L^*—Brightness, C—Color saturation, HU—Color shade, ΔE—Total change in color. ** The values designated by different small letters are significantly different ($\alpha = 0.05$).

An increase in color saturation (*C*) of the dried wild strawberry fruits relative to the raw material was observed in the case of convection drying, while freeze–drying caused a decrease in color saturation. The temperature of the drying process had no statistically significant effect on (*C*) in the case of both freeze– and convection drying.

Both drying methods resulted in an increase in the hue (*HU*) of the dried material compared to the raw material. An increase in the drying temperature produced an increase in (*HU*) regardless of the dehydration method, with changes in this parameter being statistically significant only between the lowest temperature of freeze–drying and the highest temperature of convection drying. Dried wild strawberry fruits with the shade of color closest to that of the raw material were obtained as a result of freeze–drying at the lowest temperature of the heating shelves.

The total change in color of the dried fruits (ΔE) was smaller during convection drying, over the whole temperature range. In the case of freeze–drying, small changes of this parameter were noted, with an upward trend, with an increase in the process temperature, and the direction of the change was the opposite during convection drying. The higher values (ΔE) in the case of dried fruits obtained as a result of freeze–drying were associated, among others, with a greater difference in the brightness (L^*) of the dried fruits compared to the raw material. Although the smallest total difference in color (ΔE) between the raw material and the dried material was recorded as a result of convection drying, the dried material obtained during freeze–drying was characterized by a color similar to pink, visually more attractive and probably more desirable for the consumer.

According to reports of researchers analyzing the drying process of strawberry fruits in relation to the wild strawberry, the unfavorable change in the color of the dried fruits is mainly due to the degradation of anthocyanins, which are unstable compounds, resistant to oxidation and thermal treatment [44,45]. The color of the dried fruits is also affected by pH, content of some metal ions, enzymes, and their associated decomposition reactions [46]. Some researchers found a decrease in the brightness of dried strawberry fruits relative to the raw material in the case of convection drying [47], other researchers showed the opposite result [48].

3.3. L-ascorbic Acid Changes, Total Phenolics Content, and Antioxidant Properties

The average content of L-ascorbic acid (*AC*) in fresh fruits of wild strawberry was 43 mg per 100 g of raw material, which corresponded to 304 mg per 100 g DM. According to other researchers, the content of L-ascorbic acid in the fruits of wild strawberry subjected to drying is similar to the average values of this quality marker in strawberry fruits [47]. The process of drying, regardless of the method and parameters, causes a decrease in the L-ascorbic acid content in the dried fruits. The highest content of L-ascorbic acid in dried wild strawberry fruits was recorded after freeze–drying at the lowest temperature of the heating shelves. An increase in the process temperature caused a decrease in L-ascorbic acid content, regardless of the drying method. In the case of freeze–drying, the loss of L-ascorbic acid compared to the raw material was about 13% at the temperature of of 20 °C of the heating shelves and reached a maximum of about 35% at 60 °C. The process of convection drying resulted in the degradation of L-ascorbic acid by about 78% at the air temperature of 60 °C (Table 7). The results of research concerning L-ascorbic acid content in dried strawberry fruits are inconclusive. As reported by Yurdugu [19], as a result of the freeze–drying process, the L-ascorbic acid content in dried strawberry fruits increased compared to the raw material.

The total content of phenolic compounds (*TPC*) in fresh wild strawberry was 20.5 mg GAE/g DM. Drying caused a decrease in TPC, but the higher the process temperature, the higher the decrease. Convection drying caused a higher decrease in the content of phenolic compounds compared to freeze–drying. TPC were in the range from 15.0 to 19.7 mg GAE/g DM in freeze–dried fruits and from 10.2 to 17.4 mg GAE/g DM in the convection-dried wild strawberry (Table 7). The antioxidant activity of the raw material before drying, measured by different methods, was as follows: 5.2 mg DM/mL (ABTS), 27.5 mg DM/mL (DPPH), 10.3 mg DM/mL, and 10.1 mg DM/mL (RED). Drying at 20 and 40 °C had little effect on the decrease of the antioxidant activity (increase of EC_{50} parameter). On the other hand, the higher process temperature tested (60 °C) already caused a significant decrease in the antioxidant capacity of the extracts obtained from the samples. The

extracts from freeze–dried wild strawberries at the same drying temperature were usually characterized by slightly higher antioxidant activity compared to extracts obtained from convection-dried fruits. Such patterns were observed for each of the methods considered to assess the antioxidant activity (Table 7).

Table 7. L-ascorbic acid content, total phenolics content, and antioxidant activity of wild strawberries.

MD*	DT	*AC*	TPC	ABTS	DPPH	CHEL	RED
		(mg/100g DM)	(mg GAE/g DM)	(EC50; mg DM/mL)			
RM		304 ± 4.08^{d}	21.5 ± 0.96^{f}	5.2 ± 0.33^{a}	27.5 ± 1.12^{a}	10.3 ± 0.75^{a}	10.1 ± 0.31^{a}
FD	20 °C	267 ± 4.44^{a}	19.4 ± 0.58^{e}	6.7 ± 0.42^{b}	31.6 ± 2.23^{bc}	11.5 ± 0.92^{ab}	10.8 ± 0.26^{ab}
	40 °C	228 ± 3.26^{b}	18.3 ± 0.62^{d}	6.2 ± 0.27^{b}	30.2 ± 1.78^{b}	13.2 ± 0.67^{bd}	11.6 ± 0.38^{b}
	60 °C	197 ± 3.75^{c}	15.0 ± 0.69^{b}	8.7 ± 0.61^{c}	33.8 ± 1.07^{c}	16.7 ± 0.42^{ce}	13.2 ± 0.46^{c}
AD	25 °C	123 ± 3.42^{e}	17.4 ± 0.4^{c}	6.2 ± 0.56^{b}	32.3 ± 1.78^{c}	14.1 ± 0.51^{d}	13.6 ± 0.54^{c}
	40 °C	101 ± 3.14^{f}	15.6 ± 0.52^{b}	6.5 ± 0.47^{b}	33.7 ± 0.76^{c}	12.7 ± 0.56^{b}	14.3 ± 0.36^{c}
	60 °C	68 ± 3.21^{g}	10.2 ± 0.36^{a}	9.2 ± 0.51^{c}	36.2 ± 1.29^{d}	15.3 ± 0.47^{c}	16.5 ± 0.22^{e}

* MD—Method of drying, DT—Drying temperature, RM—Raw material, FD—Freeze–drying, AD—Air drying, AC—L-ascorbic acid content, TPC—total phenolics content, ABTS—ability to neutralize free radicals against ABTS, DPPH—ability to neutralize free radicals against DPPH, CHEL—chelating power, RED—reducing power; ** The values designated by different small letters are significantly different ($\alpha = 0.05$).

The literature lacks studies on changes in the antioxidant activity of wild strawberry fruits due to drying. Studies by many authors confirm that temperature, duration, and drying method have the greatest influence on the content of bioactive compounds and the antioxidant potential of dried fruits [45–47,49]. López-Ortiz et al. [44] analyzed changes in the content of bioactive compounds and their activity during convection drying of strawberry fruits at 40, 50, and 60 °C. They found that fruits dried at 40 and 50 °C were characterized by a similar decrease in total content of phenolic compounds and antioxidant activity. However, this decrease was already much higher at the drying temperature of 60 °C. Studies on the convection drying of strawberry fruits at 50 and 60 °C showed that the greatest decrease in antioxidant activity occurred during the first 100 min of the process [45]. Sadowska et al. [50] dried strawberry fruits by various methods (convection drying, freeze–drying, spray drying) and found that the smallest changes in the antioxidant activity and content of bioactive compounds occurred during freeze–drying, while the largest changes were observed after convection drying. Özşen and Erge [51] analyzed changes in the activity of bioactive compounds during the heating of wild strawberry pulp at 60–90 °C in a time from 0 to 80 min. They found that the longer the time and the higher the temperature of the process, the larger the losses of phenolic compounds and anthocyanins.

4. Conclusions

The drying kinetics of two drying methods of wild strawberries was described using the Midilli model, over the entire measuring range. The dried material obtained during freeze–drying was characterized by a color similar to pink, visually more attractive to the consumer, although the smallest total color difference (ΔE) between the raw material and the dried material was recorded as a result of convection drying. The highest content of L-ascorbic acid in dried wild strawberry fruits was recorded in the case of freeze–drying at the lowest temperature of the heating shelves. A drying temperature not exceeding 40 °C had a relatively small effect on the total content of phenolic compounds and on the antioxidant activity of the tested samples. Increasing the drying temperature to 60 °C caused significant drops in TPC and antioxidant activity. Freeze–drying carried out at the same temperatures as convection drying resulted in slightly lower losses of TPC and antioxidant activity compared to convection drying. The best-quality dried fruits were obtained by freeze–drying, with a temperature of the heating shelves not exceeding 40 °C.

Author Contributions: Conceptualization, A.K.; methodology, A.K.; D.D.; validation, S.R. formal analysis, D.D.; investigation, A.K., S.R., U.G.-D., and E.J.-T., data curation, B.B.; writing—original draft preparation, A.K.;

D.D., and S.R.; writing—review and editing A.K. and D.D.; supervision, D.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest

Abbreviations

χ^2	chi-squared test
ABTS	antiradical activity (ability to neutralize free radicals against ABTS)
AC	L-ascorbic acid content
C	color saturation
CHEL	chelating power
DM	dry mass
DPPH	antiradical activity (ability to neutralize free radicals against DPPH)
HU	color shade
MR	reduced water content
RMSE	root mean square error
TPC	total phenolics content
ΔE	total change in color

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