

Article

Foam-Mat Freeze Drying of Kiwiberry (*Actinidia arguta*) Pulp: Drying Kinetics, Main Properties and Microstructure

Radosław Bogusz , Małgorzata Nowacka * , Katarzyna Rybak , Dorota Witrowa-Rajchert  and Ewa Gondek

Department of Food Engineering and Process Management, Institute of Food Sciences, Warsaw University of Life Sciences—SGGW, Nowoursynowska 159c, 02-776 Warsaw, Poland; radoslaw_bogusz@sggw.edu.pl (R.B.); katarzyna_rybak@sggw.edu.pl (K.R.); dorota_witrowa-rajchert@sggw.edu.pl (D.W.-R.); ewa_gondek@sggw.edu.pl (E.G.)

* Correspondence: malgorzata_nowacka@sggw.edu.pl

Featured Application: Consumers are becoming more conscious of how their eating habits influence their health, and they are more inclined to incorporate fruits and vegetables into their regular meals. In addition, they are exploring for novel raw materials with potential health benefits. Kiwiberry fruits include bioactive components such as vitamin C, carotenoids, chlorophylls, anthocyanins and phenolic acids, which contribute to their antioxidant activity. They also include lots of dietary fiber. However, they are seasonal and have a short shelf life. As a result, it is essential to adopt processing methods that ensure their availability at all times. To do this, they can be processed into a variety of products, including jams, juices, dry snacks and food powders, which can be used as components in a variety of other food and pharmaceutical items.

Abstract: The kiwiberry is an interesting source of bioactive compounds (micronutrients, polyphenols vitamins and pectins) and enzyme actinidine but has limited durability. The aim of this study was to determine the impact of shelf temperature (10 °C, 25 °C and 40 °C) during freeze drying on the foam-mat kiwiberry pulp drying process and the quality of the obtained material based on analyses such as moisture content, water activity, hygroscopicity, solubility, microstructure and spectral measurement using the FTIR method. The use of higher shelf temperatures during freeze drying positively influenced the drying process, reducing its duration by up to 40.7%. The shelf temperature caused changes in the dry matter content (97.2–99.6%), water activity (0.159–0.221), structure and hygroscopic properties (1.41–4.41 g water/100 g d.m.) of the kiwiberry foam mats. Foam-mat drying at 40 °C exhibited a significantly lower water activity, total porosity and hygroscopicity, providing properties favorable for good microbiological and functional stability during storage. Furthermore, this temperature applied during freeze drying resulted in an increase in the solubility of the obtained material, which indicates its possible use in the matrix of other food products.

Keywords: *Actinidia arguta*; foam-mat freeze drying; drying kinetics; structure; hygroscopic properties; quality



Citation: Bogusz, R.; Nowacka, M.; Rybak, K.; Witrowa-Rajchert, D.; Gondek, E. Foam-Mat Freeze Drying of Kiwiberry (*Actinidia arguta*) Pulp: Drying Kinetics, Main Properties and Microstructure. *Appl. Sci.* **2024**, *14*, 5629. <https://doi.org/10.3390/app14135629>

Academic Editor: Wojciech Kolanowski

Received: 6 June 2024

Revised: 20 June 2024

Accepted: 25 June 2024

Published: 27 June 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The kiwiberry (*Actinidia arguta*), also known as mini kiwi, baby kiwi or hardy kiwifruit, is a small, grape-sized fruit with a thin, edible smooth and hairless skin and therefore may be eaten whole without peeling [1,2]. This fruit is rich in over 20 bioactive components, e.g., vitamin C, minerals, dietary fibre, phenolic acids, flavonoids, anthocyanins and pigments [3,4]. The shelf life of kiwiberry fruits is limited; that is, under refrigerated conditions they may be stored for up to six weeks at the harvesting maturity stage and for up to one week after reaching the eating maturity stage [5]. During storage, their quality decreases due to a reduction in their content of the bioactive components, loss of firmness and hardness, and also changes in colour [2,4]. The results of these changes contribute

to consumers' lower acceptability and direct consumption of kiwiberry fruits. Therefore, some processing methods are required, and drying seems to be the most promising option.

Drying is one of the oldest and most common methods of food preservation, during which water is removed from the dried material via evaporation to the surrounding environment. The effect is a product with reduced water activity and an elongated shelf life [6,7]. However, drying may result in undesirable changes in the physical and chemical properties of dried products, e.g., shrinkage, reduction in rehydration capacity, loss of bioactive compounds or non-enzymatic browning [8–10]. The food industry is therefore seeking to solve these problems by using new drying methods or optimizing the known ones to achieve minimum nutrient loss, reduce adverse texture changes and retain the best sensory properties at the lowest possible processing cost [11,12]. The combination of foaming and freeze drying seems to be a promising method for powdered food production.

Foam-mat drying consists of foaming the material with foaming and stabilizing agents and then drying it [13,14]. The obtained porous structure provides more efficiency in heat and mass transfer, and so lower temperatures can be used, and better properties of the resulting product can be maintained [13,15]. In addition, the dried product may be crushed into a powder form, which makes it much easier to transport, store as well as manage in other branches of the food industry. For example, fruit and vegetable powders can be used as an ingredient in baby food, confectionery fillings, ice cream, soups, cakes, extruded cereal products, yogurt, dietary supplements and many other food products [16–18]. Therefore, some increasing trends in the foaming of fruit and vegetable pulps, purees, concentrates and juices are observed. This is due to their low-molecular-weight substances and low glass transition temperature (T_g), e.g., 33.1 °C for freeze-dried apple puree powder [17], freeze-dried mango puree 48.9 °C [19] or −18.3 °C for freeze-dried kiwi powder [20]. Drying this type of product in an unchanged form by employing commonly used techniques can lead to a gel or gum layer and, as a result, makes further processing and industrial application impossible [17,21]. Some unfavourable changes occurring during the traditional drying methods promote the application of other drying methods such as, e.g., freeze drying.

Freeze drying, also known as lyophilization, is a technique that dehydrates a product by removing water from it through sublimation and desorption [22,23]. It is a time-consuming and uneconomical method of drying [24]; however, it allows the obtaining of a high-quality product. Thanks to the use of low temperatures and vacuum conditions during the process, the obtained product retains its colour, aroma, flavour and valuable nutrients, and has good reconstitution properties and a long shelf life [25,26]. Due to its high energy consumption and thus expensiveness, some modifications are used for obtaining high-quality food powders, e.g., foaming before the freeze-drying process [24]. Based on the literature, this technique has been used to dry tomato paste [27], grapefruit puree [28], raspberry pulp [29], date pulp [30,31], raspberry puree [32], blueberry juice [13,24], grape juice [33] and also aloe vera [34].

To the best of our knowledge, kiwiberry pulp has been processed using spray drying [35,36] and foam-mat convective drying [15] so far. There is no information about the foam-mat freeze drying of kiwiberry pulp, and this work is the first one that describes the impact of the process parameters of freeze drying on the drying kinetics and selected quality aspects. Therefore, the purpose of this work was to determine the effect of the freeze-drying process, performed at different shelf temperatures, on the microstructural changes of foam-mat dried kiwiberry pulp and the physical properties of powders.

2. Materials and Methods

2.1. Materials

The research material used in this study was the kiwiberry (*Actinidia arguta*) of the Bingo cultivar, purchased from a commercial plantation under the supervision of scientists from the Department of Environmental Protection at Warsaw University of Life Sciences (WULS-SGGW, Poland). Kiwiberry fruits with a similar maturation stage (before reaching eating maturity), colour and without visual alteration were collected. The kiwiberry fruits

were stored under refrigerated conditions without exposure to light for one day before processing. The ovalbumin powder (Basso, Toruń, Poland) was used as a foaming agent.

2.2. Technological Processing

2.2.1. Foam Preparation

The kiwiberry fruits were crushed using a Thermomix® TM6 (Vorwerk, Madrid, Spain) and then the pulp was passed through a metal sieve (mesh diameter of 3.5 mm) to avoid larger particles. After that, the kiwiberry pulp was foamed using a 2% (*w/w*) of ovalbumin powder. The mixture was stirred for 10 min using a laboratory planetary robot (KitchenAid, 5KSM150, 300W, Benton Harbor, MI, USA) at the maximum rotation speed. The prepared foam was then spread onto aluminium cylindrical trays. The thickness of the layer of the drying material was 10 mm, and the aluminium trays used in this experiment had a diameter of 200 mm and a height of 20 mm.

2.2.2. Drying Process

The trays with prepared kiwiberry foam were firstly shock frozen using a Shock Freezer HCM 51.20 (Irinex, Treviso, Italy) at a temperature of $-45\text{ }^{\circ}\text{C}$ for 2 h. Then, the frozen samples were transferred to a Christ Gamma 1–16 LSC laboratory freeze-dryer (Martin Christ Gefriertrocknungsanlagen GmbH, Osterode am Harz, Germany) and then dried at three different shelf temperatures of 10, 25 and $40\text{ }^{\circ}\text{C}$ using a condenser temperature of $-55\text{ }^{\circ}\text{C}$ and pressure of 63 Pa. During the process, the changes in the mass were recorded continuously every 5 min for the first 120 min and every 15 min by means of a measuring system (SWL0125, Mensor, Warsaw, Poland) situated inside the drying chamber and connected to a specially designed scale positioned outside the chamber. Drying was performed until a constant weight was reached in two repetitions. The dried foams were packed and stored in barrier bags (PET12/Al8/PE100) to perform further analysis.

Freeze-drying curves were plotted as dimensionless water content (MR) as a time function. The relative moisture ratio was calculated according to the equation [15]:

$$\text{MR} = \frac{u_{\tau}}{u_0}, \quad (1)$$

where u_{τ} is the moisture content during each moment of the drying process (g water/g d.m.), and u_0 is the initial moisture content (g water/g d.m.).

The simplified Fick's second law for an infinite flat plate was used to calculate the effective water diffusion coefficient (D_{eff}) of the freeze-drying process, assuming that the volume of material did not change during the drying process [15]:

$$\text{MR} = \frac{8}{\pi^2} \exp \left[\frac{-D_{\text{eff}} \pi^2 \tau}{4L^2} \right], \quad (2)$$

where L is half of the kiwiberry foam thickness (m), and τ is the freeze-drying time (s).

2.3. Quality Assessment

2.3.1. Dry Matter Content and Water Activity

The dry matter content was measured using the oven method at a temperature of $70 \pm 1\text{ }^{\circ}\text{C}$ for 24 h [21]. The water activity was measured using a HygroLab C1 hygrometer (Rotronic, Bassersdorf, Switzerland) at a temperature of $25 \pm 1\text{ }^{\circ}\text{C}$ [35]. The measurement was performed in three repetitions for each sample.

2.3.2. Hygroscopicity

The hygroscopic properties were measured using the desiccator method under a saturated NaCl solution ($a_w = 0.75$) at room temperature ($22 \pm 1\text{ }^{\circ}\text{C}$). The weight changes were measured after up to 72 h [35]. The results were expressed in grams of adsorbed water

via 100 g of dry matter (g water/100 g d.m.). The measurement was performed in three repetitions for each sample.

2.3.3. Water Solubility Index and Water Absorption Index

The water solubility index (WSI) and water absorption index (WAI) were evaluated according to the methodology described by Dehghannya et al. [16]. Each measurement was conducted in three repetitions. The water solubility index (%) was denoted as the ratio of solids in the dried supernatant to the dry weight of the initial sample and the water absorption index was denoted as the ratio of the remaining wet solids after centrifugation to the dry weight of the initial sample.

2.3.4. Fourier-Transform Infrared Spectroscopy (FTIR)

The FTIR spectra of freeze-dried kiwiberry foams were determined by using a FTIR spectrophotometer Cary 630 (Agilent Technologies Inc., Santa Clara, CA, USA) with an incorporated single-bounce attenuated total reflectance (ATR) diamond crystal interface. Spectral measurements were taken in the wavelength range of 650–4000 cm^{-1} , at the resolution of 4 cm^{-1} , with 32 scans on the spectrum [37].

2.3.5. Microstructure

Scanning Electron Microscopy (SEM)

The microstructure of the freeze-dried kiwiberry foams was analyzed via a scanning electron tabletop microscope, namely TM3000 (Hitachi, Tokyo, Japan). The samples were sprayed with a layer of gold, and then put into the measuring chamber. The surface was observed at a magnification of 100 and the cross-section was observed at a magnification of 50.

X-ray Micro-Computed Tomography (XRCT)

The microstructure and porosity were measured using a Microtomograph Skyscan 1272 system (Bruker, Kontich, Belgium). The system performs two primary functions: data acquisition and image reconstruction. X-ray scans were performed at a 40 kV source voltage and 193 μA current, with a rotation step of 0.3° and a resolution of 25 μm [37]. NRecon software v. 1.6.10.5 (Bruker, Kontich, Belgium) was used to generate 3D images from μCT projections. The determination of porosity and the distribution of the structural thickness of the pores and walls was performed after reversed binarization processing using CTAn software v. 1.23.0.2 (Bruker, Kontich, Belgium).

2.4. Mathematical Modelling

The kinetics of water vapour sorption of the freeze-dried kiwiberry foams were described via the solution of the second Fick's law for transient diffusion using the Table Curve 2D v5.01 software (SYSTAT Software, Inc., Chicago, IL, USA) via the following equations [17]:

$$A \exp(-K\tau) = \frac{u - u_e}{u_0 - u_e}, \quad (3)$$

$$K = \frac{D_{eff}}{L^2}, \quad (4)$$

where u_τ is the water content during each moment of the drying process (g water/100 g d.m.), u_e is the equilibrium water content (g water/100 g d.m.), u_0 is the initial water content (g water/100 g d.m.), A is the shape factor, K is the coefficient linked to water diffusion ($1/\text{min}$), τ is the sorption time (s), D_{eff} is the effective moisture diffusivity (m^2/min) and L is half of the kiwiberry foam thickness (m).

Fitting Fick's kinetic model to the hygroscopicity data was performed using the Table Curve 2D v5.01 software (SYSTAT Software, Inc., Chicago, IL, USA). The coefficient of

determination (R^2), the reduced chi-squared statistic (χ^2) and the root mean square (RMS) were used to evaluate the goodness of fit of Fick's kinetic model:

$$R^2 = 1 - \frac{\sum_{i=1}^N (u_p - u_e)^2}{\sum_{i=1}^N (u_e - \bar{u}_e)^2}, \quad (5)$$

$$\chi^2 = \frac{\sum_{i=1}^N (u_p - u_e)^2}{N - n}, \quad (6)$$

$$\text{RMS} = \sqrt{\frac{\sum_{i=1}^N \frac{(u_e - u_p)^2}{u_e}}{N}}, \quad (7)$$

where u_e is the experimental water content during each moment of the adsorption process (g water/100 g d.m.), u_p is the predicted water content during each moment of the adsorption process (g water/100 g d.m.), $\bar{u}_e$ is the mean predicted water content during each moment of the adsorption process (g water/100 g d.m.), N is the number of observations and n is the number of constants in the model equation.

2.5. Statistical Analysis

The one-way ANOVA procedure was used to assess the impact of the shelf temperature. Tukey's HSD test was used to determine the homogenous groups. Statistical analysis was performed using the Statistica 13.3 (TIBCO Software, Palo Alto, CA, USA) software at $\alpha = 0.05$.

3. Results and Discussion

3.1. Drying Kinetics

The freeze-drying kinetics of foam-mat kiwiberry pulp are presented in Figure 1. The results show that the shelf temperature influenced the exhibited different patterns of water removal, and thus the drying curves. As expected, a shorter drying time was obtained for samples dried at the higher temperatures. The foam mat dried at 25 °C and 40 °C dried faster by 37.3 and 40.7%, respectively, compared to the sample dried at 10 °C (885 min). For instance, after 60 min of freeze drying, the MR outcomes ranged to 0.86 for the foam mat dried at 10 °C and 0.80–0.82 for the foam mats dried at 25 °C and 40 °C. Moreover, for the sample dried at 25 °C, the MR value was the lowest, which means that, in this case, the temperature of 40 °C did not cause an increase in the drying progress. This can be explained by the disruption of sublimation and dissolution of the material during the process.

The results of this study are in accordance with those of other studies. In general, increasing the temperature of the drying air intensified the process course, which was found for foamed tomato puree dried at the layer of 15 mm in thickness via a vacuum and air-drying methods at temperatures of 50, 60 and 70 °C [27], foamed papaya pulp with different foaming agents (methyl cellulose, glycerol monostearate, egg albumin) using air-drying methods at temperatures of 60, 65 and 70 °C [38,39], foamed mango pulp with different levels of egg albumin dried at temperatures of 65, 75 and 85 °C [40], foamed cocoa powder at the layer of 4 mm in thickness dried at temperatures of 50, 60 and 70 °C [11], foamed kiwiberry pulp dried at the layers of 4, 8 and 12 mm in thickness at temperatures of 50, 60 and 70 °C [15] and grapefruit puree freeze dried at room temperature and 40 °C [28].

The effective water diffusion coefficient was determined via the simplified Fick's second law and the relationship between the shelf temperature and the D_{eff} values is presented in Figure 1. The effective water diffusion coefficient of the freeze-dried samples varied from 2.47×10^{-9} to 4.51×10^{-9} m²/s. The higher values were noted for samples dried at a higher shelf temperature, and it was also found that the shelf temperature affected the D_{eff} values. This means that at a higher drying temperature, the water molecules can move faster, and thus provide a higher moisture diffusivity [41].

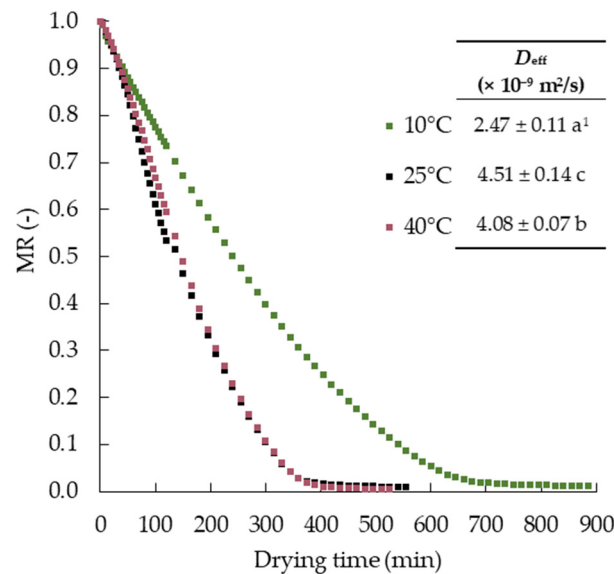


Figure 1. Drying kinetics of freeze-dried foam-mat kiwiberry pulp. ¹ Different letters within column for effective water diffusion coefficient (D_{eff}) indicate the statistical difference (Tukey's HSD, $p < 0.05$).

The D_{eff} parameter is a significant indicator of the optimization and evaluation of the drying processes and is primarily concentrated via the internal moisture movement, especially mass transfer mechanism and molecular and hydrodynamic diffusion [42]. For food, the value of this parameter should vary from 10^{-11} to $10^{-9} \text{ m}^2/\text{s}$ [7]. The obtained results are in good accordance with the data presented in the literature, which show the tendency to increase the D_{eff} values with increased drying temperature. For instance, this tendency was noted by Wilson et al. [40], who dried foam-mat mango pulp with 3% egg white using a convective drying method at three different temperatures (65, 75 and 85 °C). It was stated that an increase in temperature resulted in an increase in D_{eff} values, which were $1.68 \times 10^{-8} \text{ m}^2/\text{s}$ and $2.48 \times 10^{-8} \text{ m}^2/\text{s}$ for 65 and 85 °C, respectively. Bogusz et al. [15] stated the same tendency in D_{eff} values after the convective drying of foam-mat kiwiberry pulp with 2% ovalbumin. For example, at the layer of 4 mm in thickness, the D_{eff} value increased from 5.58×10^{-10} to $16.02 \times 10^{-10} \text{ m}^2/\text{s}$ when the temperature increased from 50 to 70 °C. This trend was maintained for each layer thickness.

3.2. Dry Matter Content and Water Activity

The dry matter content of dried materials is one of the main factors determining their overall quality, nutritional value and storage stability. The dry matter content of freeze-dried foam-mat kiwiberry pulp is summarized in Table 1. The average values ranged from 97.2 to 99.6%, with the lowest value for the sample dried at 10 °C. The differences in dry matter content may be related to the capillary diffusion of the water molecules within the material. At a higher temperature the higher driving force of the heat exchange process occurs, caused by the higher difference in temperature between the material and the heat source [23,43].

Table 1. Dry matter content and water activity of freeze-dried foam-mat kiwiberry pulp.

Drying Temperature (°C)	Dry Matter Content (%)	Water Activity (-)
10	97.2 ± 0.1 a ¹	0.221 ± 0.003 c
25	98.2 ± 0.1 b	0.180 ± 0.003 b
40	99.6 ± 0.1 c	0.159 ± 0.005 a

¹ Different letters within columns indicate the statistical difference (Tukey's HSD, $p < 0.05$).

The dry matter content determined in our study is consistent with the results of other studies. Salahi et al. [43] showed that under a constant thickness of layer, the dry matter

content of powders increased with the increase in air-drying temperature. For instance, foam-mat cantaloupe powder dried at 40, 55 and 70 °C at the layer of 3 mm in thickness resulted in a dry matter content, respectively, from 91.9 to 95.4%. In another study, the dry matter content of the cocoa powder increased from 95.7 to 98.5% with an increase in the air-drying temperature from 50 to 70 °C [11]. In turn, Cól et al. [44] noted the dry matter content of 92.7% for foam-mat freeze-dried bacaba powder.

The water activity affects the factors that determine the sustainability of food such as microbial growth, enzymatic and chemical activity, and the course of the non-enzymatic browning reaction [43]. The values of water activity were in the range of 0.159 to 0.221 (Table 1) with a descending trend with an increasing shelf temperature. All the samples had water activity values below 0.6, which is important for microbial stability during storage [8]. The water activity corresponding to the monolayer moisture content ($a_w < 0.25$) of the material ensures its durability and high-quality properties, while exceeding this value causes undesirable changes in the product [45,46]. According to Darniadi et al. [13], the low water activity values of the foam-mat dried samples were probably related to the loss of water due to their porous structure. The water activity determined in the current study is in line with the results of other studies, for instance, from 0.147 to 0.288 for foam-mat dried cantaloupe powder dried at temperatures of 40, 55 and 70 °C [43], from 0.120 to 0.190 for foam-mat yacon juice dried at temperatures of 50, 60 and 70 °C [47], from 0.110 to 0.789 for foam-mat bacaba powder dried at temperatures of 50, 60 and 70 °C and 0.533 for foam-mat freeze-dried powder [44].

3.3. Hygroscopicity

Hygroscopicity is linked to the ability to absorb water from an environment and affect the physical, chemical and microbiological stability of the dried materials. The knowledge of the hygroscopic properties of these products is very important mainly when it comes to establishing the drying, packaging and changes in the product during storage [30,47].

The changes in the hygroscopicity of kiwiberry foam mats are shown in Figure 2. The hygroscopic kinetics present a different pattern, depending on the shelf temperature. The foam mats dried at 10 °C and 20 °C presented higher hygroscopicity in comparison to the sample dried at 40 °C during the measurement. After 72 h, the samples were characterized by hygroscopicity of 4.07 g water/100 g d.m. (10 °C), 4.41 g water/100 g d.m. (25 °C) and 1.41 g water/100 g d.m. (40 °C). The opposite trend with increasing drying temperature was observed for the foam-mat-dried banana pulp [21] and foam-mat-dried cantaloupe pulp [43].

Hygroscopic properties are mainly related to chemical composition, structure, enzymatic and chemical reactions [8,10] as well as the structure of the dried materials [48]. For example, Jedlińska et al. [35] observed that the spray-dried kiwiberry powders with a lower moisture content were more hygroscopic. The explanation is linked to an increasing water gradient between the analyzed material and surrounding environment in a desiccator. The current study contradicts this explanation. That is why the higher hygroscopicity of kiwiberry foam mats dried at lower temperatures (10 and 25 °C) is related to better structure preservation and higher porosity (see Section 3.6) as well as evenly distributed thin-walled pores, which affect the better ability to absorb water vapour [21,48]. The hygroscopic properties of the tested foam mats were affected by the shelf temperature during freeze drying. For practical reasons, a low hygroscopicity is preferable, reducing the adverse changes during storage of the dried material. These expectations were met by the foam mat dried at 40 °C.

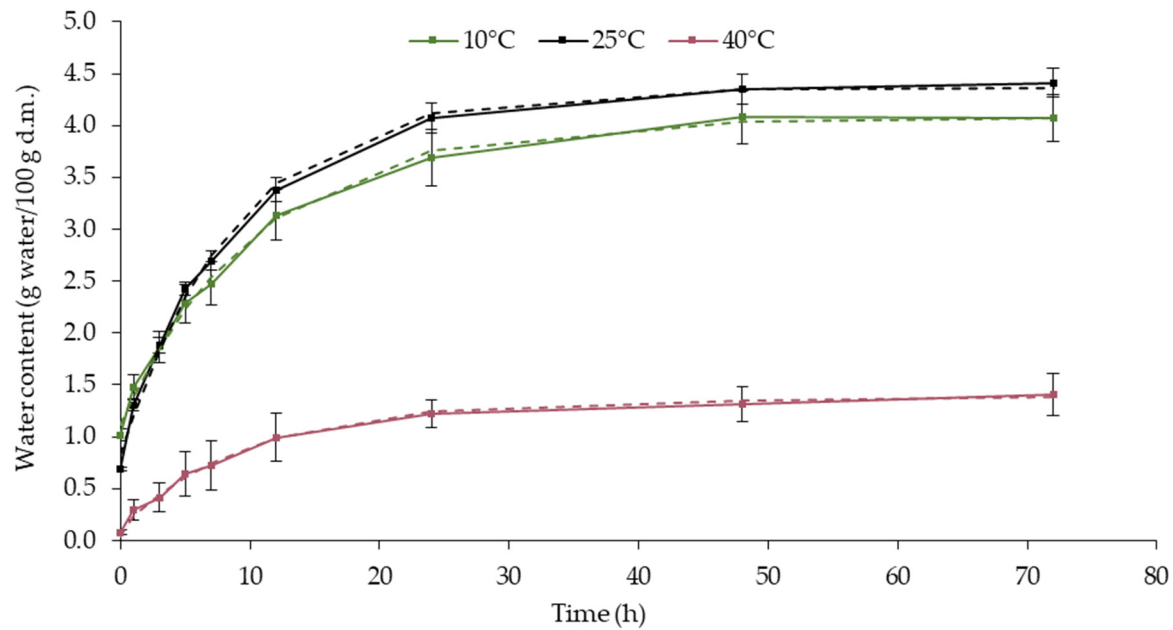


Figure 2. Hygroscopic kinetics of freeze-dried foam-mat kiwiberry pulp. Dotted lines represent values obtained from the mathematical modelling.

The results of the hygroscopic kinetics modelling showed that the solution of Fick's second law is suitable and satisfying for adjusting the experimental data of freeze-dried foam-mat kiwiberry pulp based on the high correlation coefficient (R^2) values ranging from 0.993 to 0.997 and the root mean square (RMS) values ranging from 4.20 to 13.11% (Table 2). The increasing shelf temperature during freeze drying caused a significant lowering of the equilibrium moisture content of the foam-mat kiwiberry pulp. It seems that the higher shelf temperatures provided the dry foam mats with a more collapsed and less porous structure, which resulted in a worse adsorption capacity. On the other hand, a low adsorption capacity is favourable for storage purposes and better rehydration properties [46].

Table 2. Parameters of sorption kinetics of freeze-dried foam-mat kiwiberry pulp.

Drying Temperature (°C)	Equilibrium Water Content (g water/100 g d.m.)	Effective Moisture Diffusivity (m ² /min)	R^2	χ^2	RMS (%)
10	4.07 ± 0.24 b ¹	$0.97 \times 10^{-9} \pm 0.10$ a	0.997	0.005	4.20 ± 0.15
25	4.37 ± 0.20 b	$1.17 \times 10^{-8} \pm 0.10$ b	0.997	0.007	7.17 ± 0.60
40	1.59 ± 0.25 a	$1.06 \times 10^{-8} \pm 0.01$ a	0.993	0.001	13.11 ± 5.29

¹ Different letters within columns indicate the statistical difference (Tukey's HSD, $p < 0.05$).

3.4. Water Solubility Index and Water Absorption Index

The reconstitution properties of powders are one of the most important and the best quality indicators commonly used to evaluate the changes occurring during the drying process. These parameters are also essential for the future utilization as food components [49,50]. For example, higher water absorption index (WAI) values indicate that a powder may retain more moisture, improving its utility and preventing dryness during storage [47].

The water solubility index (WSI) of freeze-dried foam-mat kiwiberry pulp was significantly influenced by shelf temperature (Table 3). The WSI value increased by 7.8% as the shelf temperature increased from 10 to 40 °C. A similar trend was also observed by other authors during the convective drying of foamed fruit materials [16,21,51]. Dehghan-nya et al. [16] and Watharkar et al. [21] were provided a comparable WSI for foam-mat convective-dried lime juice (69.07–69.53%) and banana pulp (57.13–62.09%), respectively.

Table 3. Water solubility index (WSI) and water absorption index (WAI) of freeze-dried foam-mat kiwiberry pulp.

Drying Temperature (°C)	Water Solubility Index (%)	Water Absorption Index (-)
10	62.68 ± 1.05 a ¹	1.53 ± 0.03 a
25	64.31 ± 0.67 ab	1.55 ± 0.06 a
40	67.55 ± 3.38 b	1.73 ± 0.10 b

¹ Different letters within columns indicate the statistical difference (Tukey's HSD, $p < 0.05$).

The results for the water absorption index (WAI) of freeze-dried foam-mat kiwiberry pulp were in the range of 1.53 to 1.73 (Table 3). A significantly higher WAI value was observed for the sample dried at 40 °C. The increasing WAI as the temperature increases was also found reported in the literature [21,47]. In comparison to our results, other researchers for foam-dried materials have presented higher WAI, e.g., from 2.46 to 3.90 for mango pulp [52], 4.18–4.97 for muskmelon pulp [51] and 5.31–5.97 for banana pulp [21] or a comparable WAI, e.g., 1.47–1.73 for lime juice [16] or 1.48–1.81 for yacon juice [47].

The increased values of WSI and WAI in our study may be due to the total porosity and structural changes, which occurred during drying. In general, freeze-dried products are characterized by a higher porosity which allows the rapid adsorption of water, thus enhancing the solubility of water-soluble compounds. The kiwiberry is rich in these compounds, e.g., sugars, dietary fibre as well as some protein [3,53]. The samples dried at higher shelf temperatures exhibited a more damaged structure and lower total porosity (see Section 3.6), which may promote enhanced water adsorption and solubility of the components. Moreover, a decrease in the total porosity of the samples may provide better contact between the powder and water, resulting in the enhancement of the WSI and WAI values [21]. Another explanation for the increased solubility (WSI) is linked to the breakage of the molecular bonds in sugars due to a decrease in moisture content [21]. Some other interesting and promising explanations could be related to the statement by Panato et al. [54]. The collapsing of bubbles during drying may promote the compaction of the foam structure and decreased susceptibility to water interaction, thus resulting in a lower water-solubility. Unfortunately, this theory does not hold true for the results obtained.

3.5. FTIR Spectra

The FTIR spectra shown in Figure 3 were measured to observe the changes in chemical structure of the freeze-dried kiwiberry foam mats. The broad band found in the region of wave number 3600–3000 cm^{−1} is characteristic of the stretching vibrations of the –OH hydroxyl group of water molecules, phenolic compounds, carbohydrates and organic acids [35,55] as well as the N–H stretching bond of free amino acids [56]. In the analyzed region, a medium peak with a wave number around 3260 cm^{−1} is associated with the –OH stretching vibrations of proteins [57] added during the foaming of egg ovalbumin. The bands in the region of 2950–2855 cm^{−1} correspond to the asymmetric and symmetric stretching vibrations of C–H bonds (alkyl and aromatic) in –CH₂ and –CH₃ aliphatic groups [58,59], assigned to cellulose [60], carbohydrates [35] as well as carboxylic acids [14,35]. The next band in the region of the wave number around 1718 cm^{−1} is associated with the stretching vibrations of the C=O carbonyl group, assigned to pectin with esters [60]. The amide I peak observed in the region of the wave number around 1645 cm^{−1} results from the C=O bond stretching vibrations, while the amide II detected in the region of the wave number around 1550 cm^{−1} results from the C–N stretching and N–H bending bond vibrations, assigned to proteins [58] added during the foaming of egg ovalbumin. The band in the region of the wave number around 1650 cm^{−1} predominantly belongs to the C=C bond vibrations of phenolic and aromatic ingredients [61] and the –OH hydroxyl group's deformation vibrations in water molecules [56]. The variation in the fingerprint region between 1470 and 650 cm^{−1} is related to the stretching vibrations of the C–O, C–C and C–H bonds, and the bending vibrations of the C–H bond present in the chemical structure of carbohydrates. In some cases, these bands may also originate from organic acids and carotenes [35,56].

The vibrations in the region of the wave number around 1420 cm^{-1} are due to the O-CH and C-C-H group deformation vibrations in carbohydrate structures [35]. In the region $1400\text{--}1170\text{ cm}^{-1}$, weak bands of C-O stretching vibrations of different aromatic esters [14] and polyphenols and antioxidative components [35] from kiwiberry fruits are visible. Moreover, a strong peak of C-O and C-C bond stretching vibrations in the range from 900 to 1150 cm^{-1} is observed, which contribute to different carbohydrate groups, such as glucose, fructose and sucrose [62]. In turn, the vibrations observed at around 1240 cm^{-1} may be attributed to C-N stretching in proteins [60]. The region below 900 cm^{-1} indicates the conformational changes in material and is characteristic of the anomeric region vibrations in carbohydrates or C-H and C-C bonds' deformation [14,56]. The highest discrepancies are visible for the foamed kiwiberry pulp dried at 40°C probably due to the heat treatment and water content in the tested samples.

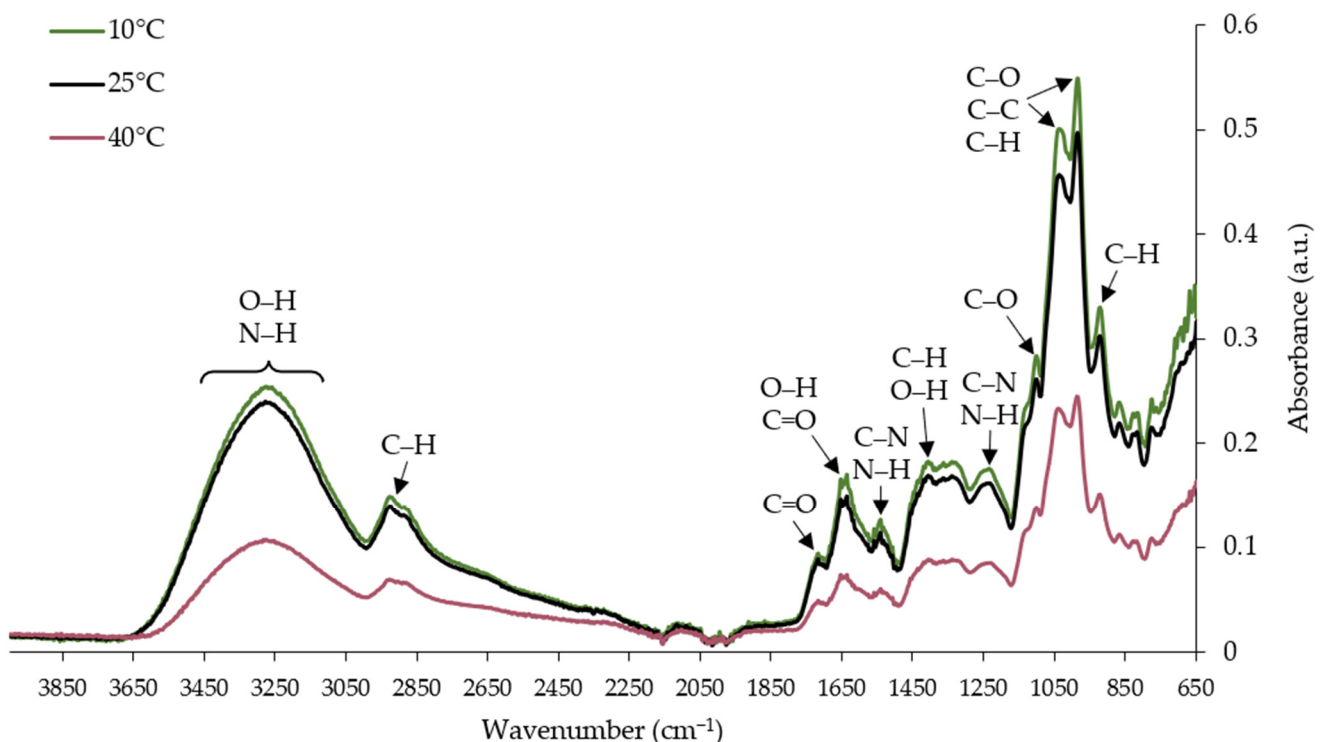


Figure 3. FTIR spectra of freeze-dried foam-mat kiwiberry pulp.

3.6. Microstructure

The structure is one of the main factors determining the total quality of foods and also plays the key role in sensory evaluation. The SEM images of the cross-section and surface of dried kiwiberry foam mats are shown in Figure 4. As can be seen, the shelf temperature affected the structure. It has been stated that the foam mat structure dried at lower temperatures (10°C and 25°C) was more uniform compared to the sample dried at 40°C . Overall, with increasing shelf temperature of freeze drying, the porosity and uniformity of the pore size distribution of the dried material decreased. The microstructure of the sample (10°C) was characterized by a higher number of small pores compared to the others. A higher number of big and elongated cavities and, thus, a very low-density and uncompacted structure could be found for the samples dried at 25°C and 40°C . This phenomenon might be explained by the fact that at higher temperatures, the sublimation rate is generally higher, which may result in the collapse of the dried material and loss of the pore structure created by the freezing process. Moreover, with an increasing drying temperature and thus, enhanced heat and mass transfer, the combination of adjacent bubbles and therefore, collapse of the foam structure, may occur intensively, and also structural changes such as shrinkage [23] as well as decreasing of the material's complex viscosity, resulting in a decrease in porosity and structural collapse [18].

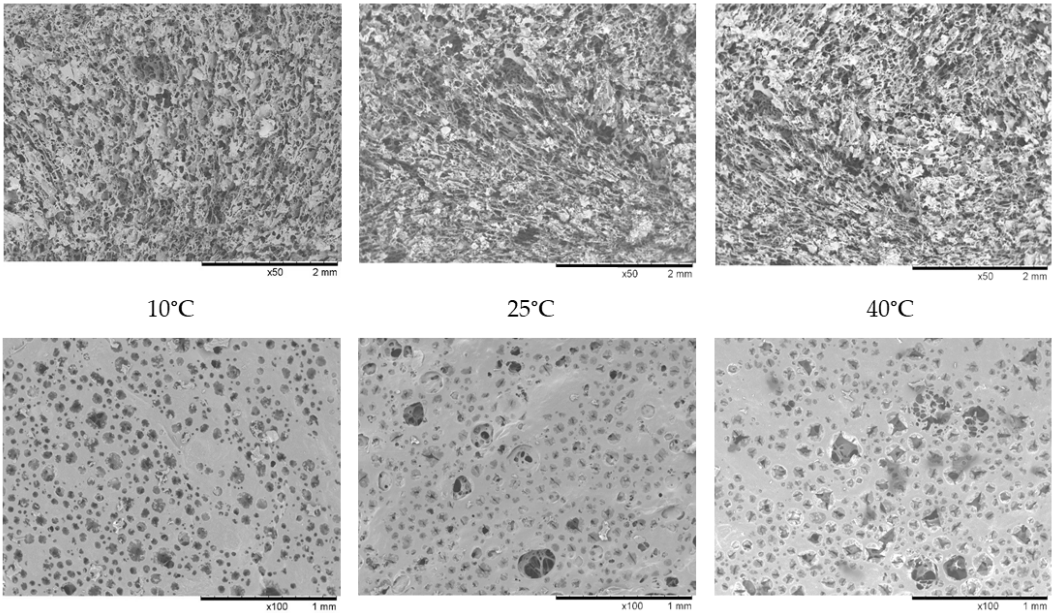


Figure 4. SEM microstructure of cross-section (top row, magnification 50×) and surface (down row, magnification 100×) of foam-mat dried kiwiberry pulp.

It was previously reported that the temperature influences the porosity of samples. Egas-Astudillo et al. [28] showed that by increasing the shelf temperature from room temperature to 40 °C during the freeze drying of grapefruit puree promoted a slight increase in the porosity and the mean area of pores. Salahi et al. [43] stated that foam-mat cantaloupe pulp dried at 55 and 70 °C had a higher number of pores compared to foam-mat cantaloupe pulp dried at 40 °C. Azizpour et al. [63] observed the same relationships in the microstructure after drying of foam-mat shrimp at various drying temperatures (45, 60, 75 and 90 °C). Due to the shorter drying time at a higher temperature, the extent of collapse and coalescence of adjacent bubbles decreased and, as a result, caused more porosity and uniformity of the pore size distribution.

Evaporated water during the drying process can cause various textural and structural changes. The total porosity of freeze-dried foam mats gained shown via XRCT scanning was from 57.7 to 65.6% (Figure 5). Kiwiberry foam-mat dried at 10 °C was characterized by the highest total porosity and visibly compacted structure. As expected, the decrease in porosity was noted with an increase of shelf temperature. The higher porosity may be identified along with less structural damage which occurred during drying at low temperatures [64].

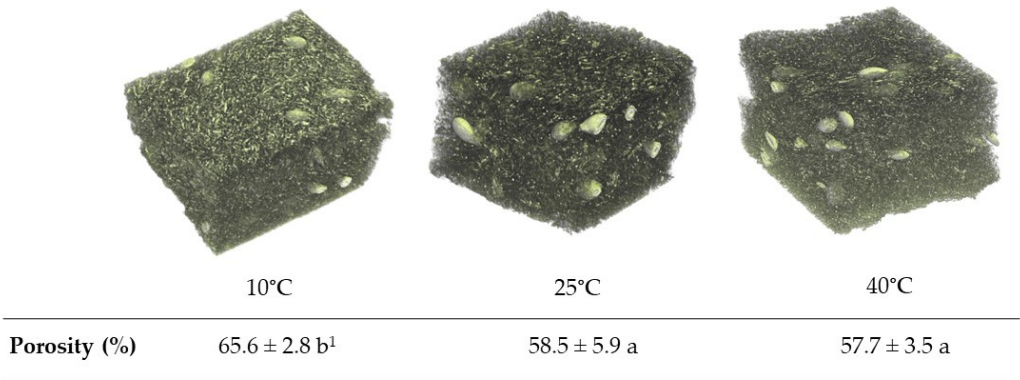


Figure 5. XRCT microstructure of foam-mat dried kiwiberry pulp. ¹ Different letters within row for porosity indicate the statistical difference (Tukey’s HSD, *p* < 0.05).

XRCT scanning allowed us also to identify the walls as well as pore size distribution. The foam mat dried at 10 °C was characterized by the lowest volume (97.0%) of pores smaller than 0.4 mm (Figure 6), while foam mats dried at 25 °C and 40 °C presented about 98.7 and 99.4% of the volume pores. Hence for the foam mat (10 °C), 3% of pores (larger than 0.4 and up to 1.4 mm) had a crucial impact on the higher porosity. The distribution of pores inside the foam mats was more homogeneous for the samples dried at 10 °C and 25 °C. For these samples, about 83.9 and 81.8% of the pore population, respectively, had dimensions between 0.1 and 0.2 mm. In turn, for the foam mat dried at 40 °C, about 80.2% of the pore population demonstrated the same dimensions. Furthermore, for all the tested foam mats, pores with a thickness of 0.1 mm had the highest volume of total pore population.

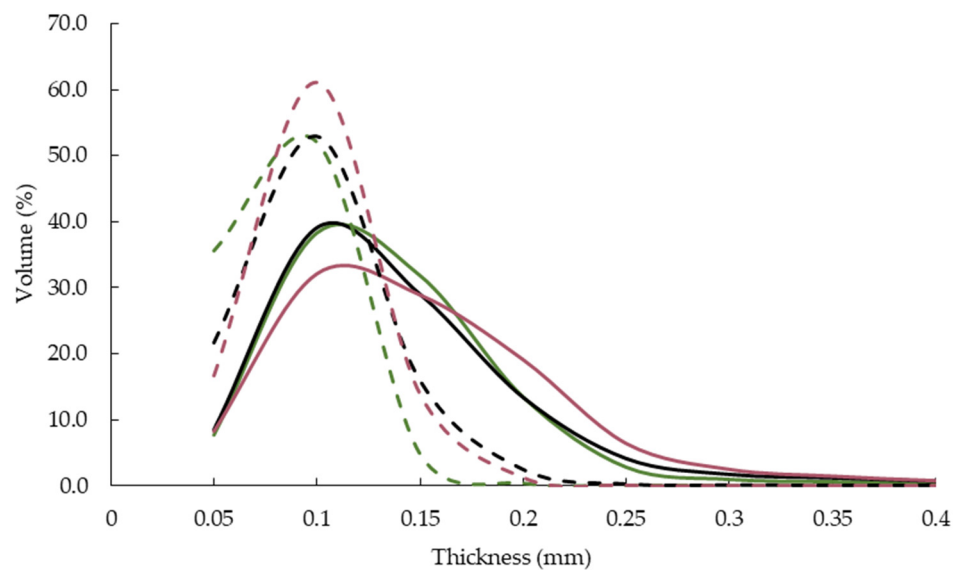


Figure 6. Percentage distribution of walls (dashed lines) and pores (solid lines) of thickness of freeze-dried foam-mat kiwiberry pulp: green lines (10 °C), black lines (25 °C), red lines (40 °C).

The biggest differences in wall size between the tested foam mats were noted for walls with a thickness of 0.05 mm and 0.15 mm. Kiwiberry foam-mat dried at 10 °C demonstrated the highest number of walls (35.7%) with a thickness of 0.05 mm and the lowest number of walls (4.9%) with a thickness of 0.15 mm. The differences may be related to the water diffusion during freeze drying (Figure 1). At higher temperatures, water diffusion is accelerated, which may have resulted in the initial rapid evaporation of water and affected the ordered internal structure and wall size distribution.

4. Conclusions

The aim of the study was to assess the effects of shelf temperature (10, 25 and 40 °C) during freeze drying on the foam-mat drying process of kiwiberry pulp and the quality of the obtained product evaluated on the basis of moisture content, water activity, hygroscopicity, solubility, microstructure and spectral properties using the FTIR method. The results demonstrated that the shelf temperature influenced the kiwiberry foam-mat properties. With an increasing shelf temperature, drying time, water activity and hygroscopicity, the total porosity decreased, while the dry matter content and solubility increased.

The higher shelf temperatures (25 and 40 °C) during the freeze drying of foam-mat kiwiberry pulp reduced the drying by 37.3 and 40.7%, respectively, compared to the foam mat dried at the lowest temperature (10 °C). This is a positive phenomenon due to the lower energy consumption.

Kiwiberry foam-mat dried at the highest temperature (40 °C) was characterized by the lowest water activity (0.159). Also, due to the low total porosity (57.7%), the hygroscopic properties for that foam mat were the lowest (1.41 g water/100 g d.m.). This is

positive from a technological point of view, as it ensures the greater stability of the material during storage.

As the shelf temperature increased, the solubility of the analyzed kiwiberry foam mats increased. This is a positive advancement, suggesting that it can be used as an ingredient in the production of food in a powder form such as baby food, cake premixes and dietary supplements.

Nevertheless, further research is necessary to investigate the impact of such an additive on the properties of the food product in question and to determine the bioactive properties of freeze-dried foam-mat kiwiberry pulp.

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

Funding: The research for this publication was carried out with the use of research equipment purchased as part of the “Food and Nutrition Centre—modernisation of the WULS campus to create a Food and Nutrition Research and Development Centre (CŻiŻ)” co-financed by the European Union from the European Regional Development Fund under the Regional Operational Programme of the Mazowieckie Voivodeship for 2014–2020 (project no. RPMA.01.01.00-14-8276/17).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author.

Acknowledgments: The authors would like to thank Nikodem Dominiak for his help.

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

References

1. Kostyra, E.; Król, K.; Knysak, D.; Piotrowska, A.; Żakowska-Biemans, S.; Latocha, P. Characteristics of Volatile Compounds and Sensory Properties of Mixed Organic Juices Based on Kiwiberry Fruits. *Appl. Sci.* **2021**, *11*, 529. [\[CrossRef\]](#)
2. Bialik, M.; Wiktor, A.; Latocha, P.; Gondek, E. Mass Transfer in Osmotic Dehydration of Kiwiberry: Experimental and Mathematical Modelling Studies. *Molecules* **2018**, *23*, 1236. [\[CrossRef\]](#) [\[PubMed\]](#)
3. Latocha, P. The Nutritional and Health Benefits of Kiwiberry (*Actinidia arguta*)—A Review. *Plant Foods Hum. Nutr.* **2017**, *72*, 325–334. [\[CrossRef\]](#) [\[PubMed\]](#)
4. Szpadzik, E.; Zaráś-Januszkiewicz, E.; Krupa, T. Storage Quality Characteristic of Two Minikiwi Fruit (*Actinidia arguta* (Siebold & Zucc.) Planch. Ex Miq.) Cultivars: ‘Ananasnaya’ and ‘Bingo’—A New One Selected in Poland. *Agronomy* **2021**, *11*, 134. [\[CrossRef\]](#)
5. Latocha, P.; Debersaques, F.; Hale, I. *Actinidia Arguta* (Kiwiberry): Botany, Production, Genetics, Nutritional Value, and Postharvest Handling. In *Horticultural Reviews*; Ian Warrington, Ed.; John Wiley & Sons, Ltd.: Hoboken, NJ, USA, 2021; Volume 48, pp. 37–152. ISBN 9781119750802.
6. Kaveh, M.; Abbaspour-Gilandeh, Y.; Nowacka, M. Optimisation of Microwave-Rotary Drying Process and Quality Parameters of Terebinth. *Biosyst. Eng.* **2021**, *208*, 113–130. [\[CrossRef\]](#)
7. Bialik, M.; Gondek, E.; Wiktor, A.; Latocha, P.; Witrowa-Rajchert, D. Mathematical Modeling of *Actinidia Arguta* (Kiwiberry) Drying Kinetics. *Agric. Eng.* **2017**, *21*, 5–13. [\[CrossRef\]](#)
8. Dadan, M.; Nowacka, M. The Assessment of the Possibility of Using Ethanol and Ultrasound to Design the Properties of Dried Carrot Tissue. *Appl. Sci.* **2021**, *11*, 689. [\[CrossRef\]](#)
9. Xie, L.; Mujumdar, A.S.; Fang, X.M.; Wang, J.; Dai, J.W.; Du, Z.L.; Xiao, H.W.; Liu, Y.; Gao, Z.J. Far-Infrared Radiation Heating Assisted Pulsed Vacuum Drying (FIR-PVD) of Wolfberry (*Lycium barbarum* L.): Effects on Drying Kinetics and Quality Attributes. *Food Bioprod. Process.* **2017**, *102*, 320–331. [\[CrossRef\]](#)
10. Piotrowski, D.; Kostyra, E.; Grzegory, P.; Janiszewska-Turak, E. Influence of Drying Methods on the Structure, Mechanical and Sensory Properties of Strawberries. *Eur. Food Res. Technol.* **2021**, *247*, 1859–1867. [\[CrossRef\]](#)
11. Buljat, A.M.; Jurina, T.; Jurinjak Tušek, A.; Valinger, D.; Gajdoš Kljusurić, J.; Benković, M. Applicability of Foam Mat Drying Process for Production of Instant Cocoa Powder Enriched with Lavender Extract. *Food Technol. Biotechnol.* **2019**, *57*, 159–170. [\[CrossRef\]](#)

12. Wiktor, A.; Witrowa-Rajchert, D. Drying Kinetics and Quality of Carrots Subjected to Microwave-Assisted Drying Preceded by Combined Pulsed Electric Field and Ultrasound Treatment. *Dry. Technol.* **2020**, *38*, 176–188. [\[CrossRef\]](#)
13. Darniadi, S.; Ifie, I.; Luna, P.; Ho, P.; Murray, B.S. Foam-Mat Freeze-Drying of Blueberry Juice by Using Trehalose- β -Lactoglobulin and Trehalose-Bovine Serum Albumin as Matrices. *Food Bioprocess Technol.* **2020**, *13*, 988–997. [\[CrossRef\]](#)
14. Kumar, P.S.; Keran, D.A.; Pushpavalli, S.; Shiva, K.N.; Uma, S. Effect of Cellulose and Gum Derivatives on Physicochemical, Microstructural and Prebiotic Properties of Foam-Mat Dried Red Banana Powder. *Int. J. Biol. Macromol.* **2022**, *218*, 44–56. [\[CrossRef\]](#) [\[PubMed\]](#)
15. Bogusz, R.; Wiktor, A.; Nowacka, M.; Ćwintal, J.; Gondek, E. Foam-Mat Convective Drying of Kiwiberry (*Actinidia arguta*) Pulp. *Czech. J. Food Sci.* **2022**, *40*, 187–194. [\[CrossRef\]](#)
16. Dehghannya, J.; Pourahmad, M.; Ghanbarzadeh, B.; Ghaffari, H. Heat and Mass Transfer Enhancement during Foam-Mat Drying Process of Lime Juice: Impact of Convective Hot Air Temperature. *Int. J. Therm. Sci.* **2019**, *135*, 30–43. [\[CrossRef\]](#)
17. Jakubczyk, E.; Ostrowska-Ligeza, E.; Gondek, E. Moisture Sorption Characteristics and Glass Transition Temperature of Apple Puree Powder. *Int. J. Food Sci. Technol.* **2010**, *45*, 2515–2523. [\[CrossRef\]](#)
18. Du, Y.; Zhang, M.; Mujumdar, A.S.; Liu, W.; Yang, C. Innovative Applications of Freeze-Drying to Produce Compound Formula Instant Foods: A Review. *Dry. Technol.* **2021**, *40*, 2583–2597. [\[CrossRef\]](#)
19. Fongin, S.; Alvino Granados, A.E.; Harnkarnsujarit, N.; Hagura, Y.; Kawai, K. Effects of Maltodextrin and Pulp on the Water Sorption, Glass Transition, and Caking Properties of Freeze-Dried Mango Powder. *J. Food Eng.* **2019**, *247*, 95–103. [\[CrossRef\]](#)
20. Caliskan, G.; Ergun, K.; Dirim, S.N. Freeze Drying of Kiwi (*Actinidia deliciosa*) Puree and the Powder Properties. *Ital. J. Food Sci.* **2015**, *27*, 385–396. [\[CrossRef\]](#)
21. Watharkar, R.B.; Chakraborty, S.; Srivastav, P.P.; Srivastava, B. Foaming and Foam Mat Drying Characteristics of Ripe Banana [Musa Balbisiana (BB)] Pulp. *J. Food Process. Eng.* **2021**, e13726. [\[CrossRef\]](#)
22. Silva-Espinoza, M.A.; Ayed, C.; Foster, T.; Del Mar Camacho, M.; Martínez-Navarrete, N. The Impact of Freeze-Drying Conditions on the Physico-Chemical Properties and Bioactive Compounds of a Freeze-Dried Orange Puree. *Foods* **2020**, *9*, 32. [\[CrossRef\]](#) [\[PubMed\]](#)
23. Nowak, D.; Jakubczyk, E. The Freeze-Drying of Foods—The Characteristic of the Process Course and the Effect of Its Parameters. *Foods* **2020**, *9*, 1488. [\[CrossRef\]](#) [\[PubMed\]](#)
24. Darniadi, S.; Ifie, I.; Ho, P.; Murray, B.S. Evaluation of Total Monomeric Anthocyanin, Total Phenolic Content and Individual Anthocyanins of Foam-Mat Freeze-Dried and Spray-Dried Blueberry Powder. *J. Food Meas. Charact.* **2019**, *13*, 1599–1606. [\[CrossRef\]](#)
25. Nowak, D. The Impact of an Inert Gas Atmosphere on the Kinetics of Changes in the Physical and Chemical Properties of Carrot Lyophilisate. *Int. J. Food Eng.* **2019**, *16*, 20180414. [\[CrossRef\]](#)
26. Ciurzyńska, A.; Popkowicz, P.; Galus, S.; Janowicz, M. Innovative Freeze-Dried Snacks with Sodium Alginate and Fruit Pomace (Only Apple or Only Chokeberry) Obtained within the Framework of Sustainable Production. *Molecules* **2022**, *27*, 3095. [\[CrossRef\]](#) [\[PubMed\]](#)
27. Sramek, M.; Schweiggert, R.M.; van Kampen, A.; Carle, R.; Kohlus, R. Preparation of High-Grade Powders from Tomato Paste Using a Vacuum Foam Drying Method. *J. Food Sci.* **2015**, *80*, 1755–1762. [\[CrossRef\]](#) [\[PubMed\]](#)
28. Egas-Astudillo, L.A.; Martínez-Navarrete, N.; Camacho, M.M. Impact of Biopolymers Added to a Grapefruit Puree and Freeze-Drying Shelf Temperature on Process Time Reduction and Product Quality. *Food Bioprod. Process* **2020**, *120*, 143–150. [\[CrossRef\]](#)
29. Lang, S.; Ozcelik, M.; Kulozik, U.; Steinhaus, M. Processing of Raspberries to Dried Fruit Foam: Impact on Major Odorants. *Eur. Food Res. Technol.* **2020**, *246*, 2537–2548. [\[CrossRef\]](#)
30. Seerangurayar, T.; Manickavasagan, A.; Al-Ismaili, A.M.; Al-Mulla, Y.A. Effect of Carrier Agents on Physicochemical Properties of Foam-Mat Freeze-Dried Date Powder. *Dry. Technol.* **2018**, *36*, 1292–1303. [\[CrossRef\]](#)
31. Seerangurayar, T.; Manickavasagan, A.; Al-Ismaili, A.M.; Al-Mulla, Y.A. Effect of Carrier Agents on Flowability and Microstructural Properties of Foam-Mat Freeze Dried Date Powder. *J. Food Eng.* **2017**, *215*, 33–43. [\[CrossRef\]](#)
32. Ozcelik, M.; Ambros, S.; Morais, S.I.F.; Kulozik, U. Storage Stability of Dried Raspberry Foam as a Snack Product: Effect of Foam Structure and Microwave-Assisted Freeze Drying on the Stability of Plant Bioactives and Ascorbic Acid. *J. Food Eng.* **2020**, *270*, 109779. [\[CrossRef\]](#)
33. de Carvalho Tavares, I.M.; de Castilhos, M.B.M.; Aparecida Mauro, M.; Mota Ramos, A.; Teodoro de Souza, R.; Gómez-Alonso, S.; Gomes, E.; Da-Silva, R.; Hermosín-Gutiérrez, I.; Silva Lago-Vanzela, E. BRS Violeta (BRS Rúbea $\times$ IAC 1398-21) Grape Juice Powder Produced by Foam Mat Drying. Part I: Effect of Drying Temperature on Phenolic Compounds and Antioxidant Activity. *Food Chem.* **2019**, *298*, 124971. [\[CrossRef\]](#) [\[PubMed\]](#)
34. Santacruz-Vázquez, V.; Santacruz-Vázquez, C.; Laguna Cortés, J.O. Physical Characterization of Freeze-Dried Foam Prepared from Aloe Vera Gel and Guar Gum. *Rev. Vitae* **2015**, *22*, 75–86. [\[CrossRef\]](#)
35. Jedlińska, A.; Samborska, K.; Wiktor, A.; Balik, M.; Derewiaka, D.; Matwijczuk, A.; Gondek, E. Spray Drying of Pure Kiwiberry Pulp in Dehumidified Air. *Dry. Technol.* **2021**, *40*, 1421–1435. [\[CrossRef\]](#)
36. Barańska, A.; Jedlińska, A.; Samborska, K. Is It Possible to Produce Carrier-Free Fruit and Vegetable Powders by Spray Drying? *Pol. J. Food Nutr. Sci.* **2023**, *73*, 214–223. [\[CrossRef\]](#)

37. Bogusz, R.; Pobiega, K.; Rybak, K.; Wiktor, A.; Parniak, O.; Smetana, S.; Nowacka, M. The Pulsed Electric Field Treatment Effect on Drying Kinetics and Chosen Quality Aspects of Freeze-Dried Black Soldier Fly (*Hermetia illucens*) and Yellow Mealworm (*Tenebrio Molitor*) Larvae. *Appl. Sci.* **2023**, *13*, 10251. [\[CrossRef\]](#)
38. Kandasamy, P.; Varadharaju, N.; Kalemullah, S.; Maladhi, D. Optimization of Process Parameters for Foam-Mat Drying of Papaya Pulp. *J. Food Sci. Technol.* **2014**, *51*, 2526–2534. [\[CrossRef\]](#) [\[PubMed\]](#)
39. Kandasamy, P.; Varadharaju, N.; Dhakre, D.S.; Smritikana, S. Assessment of Physicochemical and Sensory Characteristics of Foam-Mat Dried Papaya Fruit Powder. *Int. Food Res. J.* **2019**, *26*, 819–829.
40. Wilson, R.A.; Kadam, D.M.; Chadha, S.; Sharma, M. Foam Mat Drying Characteristics of Mango Pulp. *Int. J. Food Sci. Nutr. Eng.* **2012**, *2*, 63–69. [\[CrossRef\]](#)
41. Deng, L.Z.; Yang, X.H.; Mujumdar, A.S.; Zhao, J.H.; Wang, D.; Zhang, Q.; Wang, J.; Gao, Z.J.; Xiao, H.W. Red Pepper (*Capsicum annuum* L.) Drying: Effects of Different Drying Methods on Drying Kinetics, Physicochemical Properties, Antioxidant Capacity, and Microstructure. *Dry. Technol.* **2018**, *36*, 893–907. [\[CrossRef\]](#)
42. Dehghannya, J.; Pourahmad, M.; Ghanbarzadeh, B.; Ghaffari, H. Influence of Foam Thickness on Production of Lime Juice Powder during Foam-Mat Drying: Experimental and Numerical Investigation. *Powder Technol.* **2018**, *328*, 470–484. [\[CrossRef\]](#)
43. Salahi, M.R.; Mohebbi, M.; Taghizadeh, M. Development of Cantaloupe (*Cucumis melo*) Pulp Powder Using Foam-Mat Drying Method: Effects of Drying Conditions on Microstructural of Mat and Physicochemical Properties of Powder. *Dry. Technol.* **2017**, *35*, 1897–1908. [\[CrossRef\]](#)
44. de Cól, C.D.; Tischer, B.; Hickmann Flôres, S.; Rech, R. Foam-Mat Drying of Bacaba (*Oenocarpus bacaba*): Process Characterization, Physicochemical Properties, and Antioxidant Activity. *Food Bioprod. Process.* **2021**, *126*, 23–31. [\[CrossRef\]](#)
45. Qadri, T.; Naik, H.R.; Hussain, S.Z.; Naseer, B.; Bhat, T.; Vijaykumar; Wani, F.J. Spray Dried Apple Powder: Qualitative, Rheological, Structural Characterization and Its Sorption Isotherm. *LWT* **2022**, *165*, 113694. [\[CrossRef\]](#)
46. Wanderley, R.d.O.S.; de Figueirêdo, R.M.F.; Queiroz, A.J.d.M.; dos Santos, F.S.; Silva, A.P.d.F.; Paiva, Y.F.; Moura, H.V.; Silva, E.T.d.V.; Carvalho, A.J.d.B.A.; Lima, M.d.S.; et al. Effect of Drying Temperature on Antioxidant Activity, Phenolic Compound Profile and Hygroscopic Behavior of Pomegranate Peel and Seed Flours. *LWT* **2023**, *189*, 115514. [\[CrossRef\]](#)
47. Franco, T.S.; Perussello, C.A.; Ellendersen, L.N.; Masson, M.L. Effects of Foam Mat Drying on Physicochemical and Microstructural Properties of Yacon Juice Powder. *LWT—Food Sci. Technol.* **2016**, *66*, 503–513. [\[CrossRef\]](#)
48. Karwacka, M.; Rybak, K.; Smetana, S.; Galus, S.; Janowicz, M. Analysis of Selected Functional Properties, Resource Demands, and Energy Consumption of Freeze-dried Vegetable Snacks. *J. Food Process. Preserv.* **2022**, *46*, e16721. [\[CrossRef\]](#)
49. Rin-ut, S.; Rattanapitigorn, P. Effect of Foaming Agents on Process Conditions, Characteristics, and Stability of Foam-mat Freeze-dried Pandan (*Pandanus amaryllifolius*) Powder. *J. Food Process. Preserv.* **2020**, *44*, e14690. [\[CrossRef\]](#)
50. Vimercati, W.C.; Araújo, C.d.S.; Macedo, L.L.; Correa, J.L.G.; Pimenta, C.J. Encapsulation of Coffee Silverskin Extracts by Foam Mat Drying and Comparison with Powders Obtained by Spray Drying and Freeze-drying. *J. Food Sci.* **2022**, *87*, 1767–1779. [\[CrossRef\]](#)
51. Asokapandian, S.; Venkatachalam, S.; Swamy, G.J.; Kuppusamy, K. Optimization of Foaming Properties and Foam Mat Drying of Muskmelon Using Soy Protein. *J. Food Process. Eng.* **2016**, *39*, 692–701. [\[CrossRef\]](#)
52. Wilson, R.A.; Kadam, D.M.; Chadha, S.; Grewal, M.K.; Sharma, M. Evaluation of Physical and Chemical Properties of Foam-Mat Dried Mango (*Mangifera indica*) Powder during Storage. *J. Food Process. Preserv.* **2014**, *38*, 1866–1874. [\[CrossRef\]](#)
53. Baranowska-Wójcik, E.; Szwajgier, D. Characteristics and Pro-Health Properties of Mini Kiwi (*Actinidia arguta*). *Hortic. Env. Biotechnol.* **2019**, *60*, 217–225. [\[CrossRef\]](#)
54. Panato, K.; Muller, C.M.O. Drying Kinetics and Physicochemical and Technological Properties of Pumpkin Purée Flour Dried by Convective and Foam-Mat Drying. *Food Process. Preserv.* **2022**, *46*, e16264. [\[CrossRef\]](#)
55. Rybak, K.; Wiktor, A.; Kaveh, M.; Dadan, M.; Witrowa-Rajchert, D.; Nowacka, M. Effect of Thermal and Non-Thermal Technologies on Kinetics and the Main Quality Parameters of Red Bell Pepper Dried with Convective and Microwave–Convective Methods. *Molecules* **2022**, *27*, 2164. [\[CrossRef\]](#)
56. Samborska, K.; Jedlińska, A.; Wiktor, A.; Derewiaka, D.; Wołosia, R.; Matwiczuk, A.; Jamróz, W.; Skwarczyńska-Maj, K.; Kielczewski, D.; Błażowski, L.; et al. The Effect of Low-Temperature Spray Drying with Dehumidified Air on Phenolic Compounds, Antioxidant Activity, and Aroma Compounds of Rapeseed Honey Powders. *Food Bioproc Tech* **2019**, *12*, 919–932. [\[CrossRef\]](#)
57. Shanmugavel, D.; KumarYadav, P.; Khadimallah, M.A.; Ramadoss, R. Experimental Analysis on the Performance of Egg Albumen as a Sustainable Bio Admixture in Natural Hydraulic Lime Mortars. *J. Clean. Prod.* **2021**, *320*, 128736. [\[CrossRef\]](#)
58. Durazzo, A.; Kiefer, J.; Lucarini, M.; Camilli, E.; Marconi, S.; Gabrielli, P.; Aguzzi, A.; Gambelli, L.; Lisciani, S.; Marletta, L. Qualitative Analysis of Traditional Italian Dishes: FTIR Approach. *Sustainability* **2018**, *10*, 4112. [\[CrossRef\]](#)
59. Uncu, O.; Ozen, B. A Comparative Study of Mid-Infrared, UV–Visible and Fluorescence Spectroscopy in Combination with Chemometrics for the Detection of Adulteration of Fresh Olive Oils with Old Olive Oils. *Food Control.* **2019**, *105*, 209–218. [\[CrossRef\]](#)
60. Canteri, M.H.G.; Renard, C.M.G.C.; Le Bourvellec, C.; Bureau, S. ATR-FTIR Spectroscopy to Determine Cell Wall Composition: Application on a Large Diversity of Fruits and Vegetables. *Carbohydr. Polym.* **2019**, *212*, 186–196. [\[CrossRef\]](#)
61. Edelmann, A.; Diewok, J.; Schuster, K.C.; Lendl, B. Rapid Method for the Discrimination of Red Wine Cultivars Based on Mid-Infrared Spectroscopy of Phenolic Wine Extracts. *J. Agric. Food Chem.* **2001**, *49*, 1139–1145. [\[CrossRef\]](#)

62. Bureau, S.; Cozzolino, D.; Clark, C.J. Contributions of Fourier-Transform Mid Infrared (FT-MIR) Spectroscopy to the Study of Fruit and Vegetables: A Review. *Postharvest Biol. Technol.* **2019**, *148*, 1–14. [[CrossRef](#)]
63. Azizpour, M.; Mohebbi, M.; Khodaparast, M.H.H. Effects of Foam-Mat Drying Temperature on Physico-Chemical and Microstructural Properties of Shrimp Powder. *Innov. Food Sci. Emerg. Technol.* **2016**, *34*, 122–126. [[CrossRef](#)]
64. Bialik, M.; Wiktor, A.; Witrowa-Rajchert, D.; Samborska, K.; Gondek, E.; Findura, P. Osmotic Dehydration and Freezing Pretreatment for Vacuum Dried of Kiwiberry: Drying Kinetics and Microstructural Changes. *Int. Agrophysics* **2020**, *34*, 265–272. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.