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Effect of Tomato Juice and Different Drying Methods on Selected Properties of Courgette

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Abstract: The purpose of this study was to determine the impact of vacuum impregnation on selected physical properties of courgettes, the drying process, and kinetics of the drying process. Vacuum impregnation was used as a pretreatment in the conducted research. The drying process was carried out using three techniques (convection drying, freeze drying, and vacuum drying). In the presented work, selected properties of courgettes, i.e., water activity, dry weight, density, VGI, shrinkage, and color were investigated, and the best model describing the kinetics of the drying process was selected. As a result of the study, it was found that the pretreated courgette was characterized by increased dry matter (0.44% to 4.08%) and density content (15.52% to 33.78%) and reduced or increasing water activity (−5.08 to 38.62%) depending on the drying method. The process also resulted in reduced drying shrinkage (−2.13% to −6.97%). Tomato juice was used as an impregnating solution, resulting in an increase in red intensity (8.44) and a decrease in the L* color index (80.16 to 58.00 for the fresh courgette). Dries with the most favorable properties were obtained using the freeze-drying method. The best model of the drying process kinetics was the logistic model.

Keywords: drying; vacuum impregnation; courgette; kinetics; color; VGI; density

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1. Introduction

Courgettes are a vegetable with a very high water content, oscillating between 93.5% and 95%, and a low energy value of about 21 kilocalories per 100 g [1]. It is a source of many valuable nutrients. It contains folic acid at 24 µg per 100 g, which contributes to the proper functioning of the human body, especially in the context of cell development and nervous system health. In addition, courgettes provide 261 mg of potassium per 100 g, which is important for maintaining normal blood pressure and muscle function. The provitamin A, or beta-carotene, present in courgettes is converted into vitamin A in the body, providing 200 IU per 100 g. This vitamin is important for eye health, skin health, and the immune system. Courgettes are also a source of carbohydrates, fiber, and protein, which are essential for proper digestion and maintaining muscle mass. Courgettes also contain vitamin C, which is known for its antioxidant properties and support for the immune system, as well as potassium and manganese, which are important for bone health and energy production in the body. Courgettes also contain vitamin E, thiamin, niacin, and pantothenic acid, which are important for many metabolic functions in the body [2].

Drying is the process of removing water from raw materials and reducing water activity; this allows the food to last for a prolonged shelf life. During this process, there is a reduction in the volume of dried material, which has a beneficial impact on reducing packaging costs and improving transportation and storage. Reducing the water content of fruits and vegetables reduces its activity, which inhibits the growth of microorganisms. In addition, the drying process slows down enzymatic and non-enzymatic reactions in food products [3,4]. Convection drying, as one of the methods of removing moisture from raw materials of agricultural origin, is described as a highly destructive process that significantly reduces the final quality of the product compared to unprocessed raw material. Nevertheless, it is widely used in the food industry due to its advantages, such as low cost, manufacturing, and a well-studied theoretical basis [5]. The process of freeze drying is viewed as the most concentrated drying method, characterized by the higher quality of the resulting dried product as opposed to other techniques. The mechanism of this process is involved in the evaporation of water from the material through freeze drying, a phase transformation that allows a direct transition from solid to gas, bypassing the liquid phase. This process makes it possible to obtain a dried product of exceptional quality, which makes this method particularly valued [6,7]. In addition, due to the formation of ice crystals and its further sublimation, the structure and shape of the product can be preserved [4]. Vacuum drying (VI), on the other hand, allows water to evaporate at lower temperatures than at normal atmospheric pressure, which is particularly beneficial for heat and heat-sensitive compounds. As a result, thermal degradation is minimized and the products retain most of their nutritional value and organoleptic characteristics such as color, flavor, and aroma [8]. Conducting tests based on a number of drying methods makes it possible to determine their effects on the properties of dried materials. In addition, it enables the selection of the optimal drying method for a specific agricultural raw material. Although drying effectively prolongs the shelf life of agricultural products, it is generally accepted that the traditional drying process inevitably results in the loss of sensory and nutritional qualities due to unfavorable textural and biochemical alterations [9]. Pretreatment is used to reduce the adverse effects of the drying process [10]. VI is a process that uses a pressure difference to fill the spaces and capillary channels in the material with an impregnating solution. The process consists of two phases: a reduced pressure phase and an atmospheric pressure phase. In the first phase, the pressure is lowered, causing the capillaries to deform and expand, allowing them to be partially filled with the solution. Then, when the pressure returns to atmospheric pressure, the capillaries are further constricted, resulting in an intense flow of fluid into them. The efficiency of impregnation depends on a lot of factors, including the properties of the tissue, the concentration and composition of the impregnating solution, the level of vacuum pressure applied, as well as the temperature and duration of the process [11]. The authors who studied the vacuum impregnation process observed a significant mass exchange betwixt the apples and the impregnating solution [12]. In addition, by changing the parameters of the pretreatment process, the efficiency of the process can be favorably affected, and manipulation of the impregnating solutions makes it possible to obtain an attractive product for potential consumers [13,14].

Courgettes are a popular vegetable with a low glycemic index. In addition, it contains many valuable nutrients, so it can be successfully used as a dried snack [1,2]. The vacuum impregnation process, in which tomato juice was used, is an innovative feature of this test. Therefore, the purpose of the work was to study the effect of different drying techniques and parameters of courgettes and VI courgettes on selected physical properties and the kinetics of the drying process.

2. Materials and Methods

2.1. Samples Preparation

The raw material used for the study was a courgette (C) purchased from a nearby vegetable market. The vegetable was thoroughly cleaned and washed to remove any dirt on the surface. After thorough cleaning, the courgette was dried and subjected to slicing with an electric vegetable slicer (GRAEF SKS 110 Universal Slicer, Gebr. Graef GmbH & Co. KG, Arnsberg, Germany) into even slices, each 4 mm thick.

2.2. Pretreatment

In the conducted research, a pretreatment under the drying process, which was vacuum impregnation (VI), was used. VI was carried out in a prototype plant designed and constructed in the Wrocław University of Life Sciences. The courgette was placed in a cylinder. The entire process took 21 min and consisted of 3 stages. First, the material was placed in the machine to perform VI at a pressure of 6 kPa for 2 min. Then, 1000 mL of tomato juice was added to the machine and the courgette slices remained in the impregnation machine for 4 min. Then, the atmospheric pressure was brought back, and the samples were left in the impregnation machine for another 15 min. After this time, the courgette was removed and filtered [15]. After the vacuum impregnation (CT) process, the courgette was subjected to the planned tests and drying process.

Pressed tomato juice was used in the study. The juice was produced by MBF sp. z o.o., Góra Kalwaria. The nutritional value of the tomato juice in 100 mL was as follows: energy value: 81 kJ/19 kcal; fat: <0.5 g, including saturated fatty acids: <0.1 g; carbohydrates: 3.2 g, including sugars: 3 g; protein: 0.8 g; and salt: 1.0 g.

2.3. Drying Methods

2.3.1. Convective Drying

Drying was carried out using a convection dryer designed and built at the Institute of Agricultural Engineering (Wrocław, Poland) [16]. The convection dryer consisted of six chimneys. Drying was performed at a temperature of 50 °C, 60 °C, and 70 °C; the air flow rate was 1 m·s^{-1}. Drying was carried out according to the methodology described by Kręcisz et al. [15] to obtain equilibrium moisture content. Drying time ranges from 130 to 240 min depending on the drying temperature and pretreatment process. The process was performed in three technological repetitions. The courgette was dried to equilibrium moisture content. The process parameters were determined based on our previous studies.

2.3.2. Vacuum Drying

Vacuum drying was performed in a laboratory dryer (Memmert, VO101, Schwabach, Germany) at 60 °C at a vacuum pressure of 10 kPa for 24 h. The process parameters were determined based on our previous studies [15].

2.3.3. Freeze Drying

Freeze drying was carried out in a 4.5 L FreeZone unit (Labconco, Fort Scott, KS, USA). Samples were frozen at −20 °C. Drying was carried out according to the methodology described by Kręcisz et al. [15].

2.3.4. Methodology

Fresh and dried vegetables, without pretreatment and vacuum-impregnated, were subjected to the following tests.

2.3.5. Water Activity (AW)

Determination of water activity in fresh material and after the drying process was performed using an AquaLab 4TE ± 0.003 apparatus (AquaLab, Warsaw, Poland) maintaining a constant temperature (25 °C). The result was the average of three repetitions [13].

2.3.6. Dry Matter (*DM*)

Dry mass was determined using the vacuum method. The measurement was performed for 24 h at a pressure of 10 kPa and a temperature of 70 °C. Precisely weighed courgette samples of 0.5 g were subjected to the drying process. Drying was carried out using a pressure of 10 kPa at 70 °C for 24 h. The result was the average of three repetitions [17].

Dry matter content was calculated according to the following equation:

$$DM = 1 - \left(\frac{m_t - m_d}{m_t}\right) \cdot 100 \quad (1)$$

where:

DM is the dry matter [%].

m_t is the wet sample weight [g].
m_d is the dry sample weight [g].

2.3.7. Bulk Density (p_b)

Density was determined using a measuring cylinder and an electronic balance (AS160/C/2, Radwag, Radom, Poland; accuracy of measurement: ±0.01 g) from which the volume was read. Each measurement was taken three times, and the values were calculated according to the following formula [18]:

$$p_b = \frac{\omega_s}{V} \quad (2)$$

where:

p_b is the density [kg·m^{-3}].
ω_s is the mass of samples [kg].
V is the volume [m^3].

2.3.8. VGI

The volumetric gelation index (VGI) was determined according to the method developed by Kim et al. with some modifications [19]. Twenty milliliters of distilled water at 20 °C was added to two milliliters of ground courgette. It was left for 15 min in a measuring cylinder, and then the result was read [14].

2.3.9. Drying Shrinkage (S_v)

In this study, a method was used to measure the volume (V) of the material before and after the drying process. This procedure makes it possible to determine the degree of shrinkage of the material, which is crucial for assessing the quality of the final product. The shrinkage value for the samples was calculated using the following formula [20]:

$$S_V = \left(1 - \frac{V_f}{V_i}\right) \cdot 100 \quad (3)$$

where:

S_V is the volume shrinkage [%].
V_i is the initial volume [cm^3].
V_f is the final volume [cm^3].

2.3.10. Color

Color analysis of both fresh and dried samples was carried out using a Minolta CR-400 colorimeter (Osaka, Japan). Measurements included the surface color of the analyzed samples, and the results were presented in L*, a*, b* color space. All determinations were carried out using a D65 standard light source. The results were based on ten replicates. The total color change (ΔE) was calculated according to Wójtowicz et al. [21].

2.3.11. Kinetics of the Drying Process

To describe the kinetics of the convection drying process of courgettes, the relative water content was determined using the following equation [22]:

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

where:

M_t is the water content after time (g water/g dry weight).
M_e is the equilibrium water content (g water/g dry weight).
M_0 is the initial water content (g water/g dry weight).

In order to select the best mathematical model, the following models available in the literature were analyzed:

Page Model [23]:

$$MR = exp(-k \cdot \tau^{a}) \tag{5}$$

Henderson and Pabis Model [24]:

$$MR = a \cdot exp(-k\tau) \tag{6}$$

Newton Model [25]:

$$MR = exp(-k\tau) \tag{7}$$

Logarithmic Model [26]:

$$MR = a \cdot exp(-k\tau) + b \cdot exp(-k_i \cdot \tau) \tag{8}$$

Logistics Model [27]:

$$MR = \frac{b}{(1 + a \cdot \exp(k \cdot \tau))} \tag{9}$$

2.3.12. Statistical Analysis

All statistical analyses were conducted using STATISTICA 13.3 software (StatSoft, Krakow, Poland). The results obtained from analyses were presented as mean values ± standard deviation. Tukey's test was used to evaluate the significance of differences ($p \leq 0.05$) between the mean values.

3. Results and Discussion

3.1. Water Activity

Figure 1 shows the results of the tests conducted, which provided important information on the variation in the samples tested. In the dried materials, the water activity ranged from 0.203 for the freeze-dried courgette without pretreatment to 0.545 for the convection-dried courgette at 50 °C.

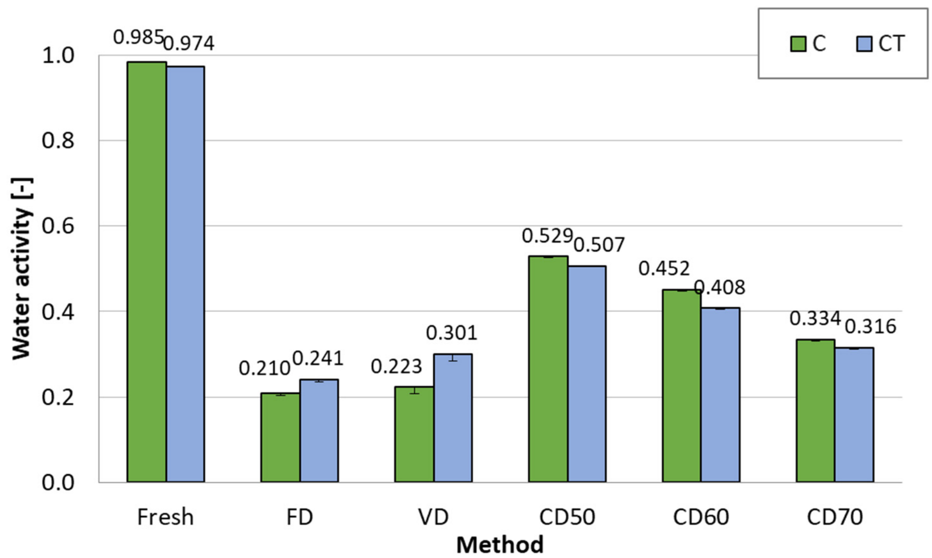

Figure 1. Water activity of courgette (C) and courgette after vacuum impregnation (CT), fresh (Fresh), freezedried (FD), vacuum-dried (VD), and convection-dried at 50 °C (CD50), 60 °C (CD60), and 70 °C (CD70).

An analysis of the effect of the drying method on the water activity of the courgette showed that the application of the drying process significantly affected the studied parameter, with the greatest differences noted in the case of vacuum and freeze drying, which is as expected. VD and FD are considered highly effective techniques for removing water from plant material, which is crucial for extending shelf life and preserving food quality [28]. Convection drying, carried out at different temperatures, also showed the ability to reduce water activity, but it was not as effective as the vacuum- or freeze-drying methods. Higher water activity in the case obtained by convection than by other drying techniques was also observed by other authors studying red cabbage [6]. The application of the VI process using tomato juice resulted in a reduction in water activity in the fresh courgette not subjected to the drying process. This supports the theory that VI reduces AW. The vacuum occurring during impregnation improves mass transfer and capillary flow. As a result of VI, the intracellular spaces will be filled with the impregnating solution. Moreover, the higher viscosity makes it difficult for the impregnating solution to get into the courgette tissue, which is why greater water loss is observed [11]. This pretreatment also affected the water activity level of the dried products. In the case of convection drying, lower water activity was observed in the samples after the VI process, indicating that desorption is improved and may increase the shelf life of the products [10]. For vacuum and freeze drying, the vacuum impregnation process paradoxically raised the values of the parameter under study, indicating that dehydration in the samples after the VI process was hindered. A study of the effect of temperature during drying on water activity showed that a higher convection drying temperature resulted in a steady reduction in water content. This observation is consistent with the drying theory that higher temperatures accelerate the evaporation of water, resulting in increased dehydration of the product [29].

3.2. Dry Matter (DM)

Dry matter weight is an important indicator of the efficiency of the drying process, reflecting both the degree of water evaporation and the change in volume of the material. The results in Figure 2 show that the dry matter content was lowest in the samples of fresh courgette without pretreatment (5.3%), which is as expected, since the absence of a drying process results in a higher water content in the product. The highest dry matter content was observed in courgette samples after freeze drying (98.8%), which indicates a significant removal of water and results in increased product stability by reducing the availability of water to microorganisms. The data presented show that the lowest dry matter value for dried materials was recorded for the courgette dried convectively at 50 °C (84.4%).

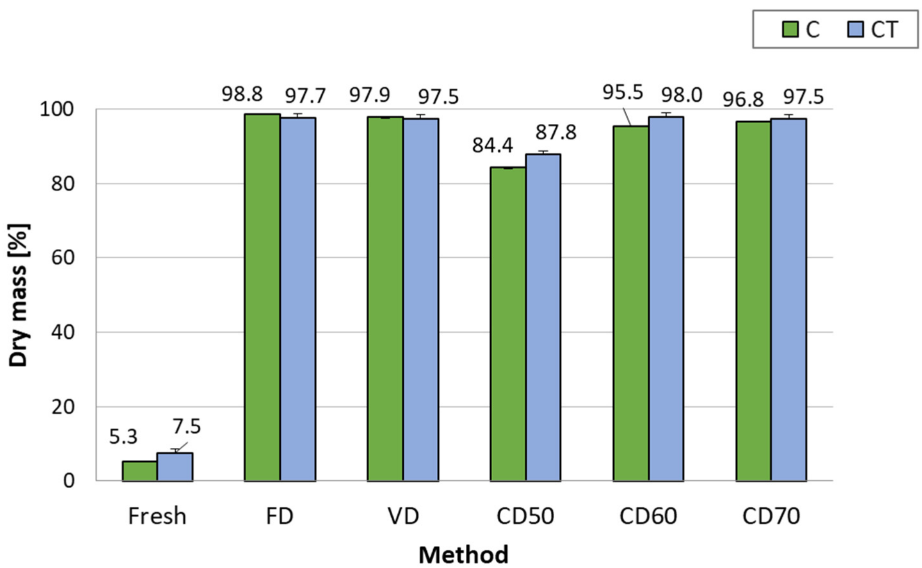

Figure 2. Dry weight of courgette (C) and courgette after vacuum impregnation (CT), fresh (Fresh), freeze-dried (FD), vacuum-dried (VD), and convection-dried at 50 °C (CD50), 60 °C (CD60), and 70 °C (CD70).

Despite the various drying methods, the results obtained, shown in Figure 2, show minimal differences in dry matter content. It is interesting to note that vacuum impregnation contributed to an increase in dry matter in fresh samples and those subjected to convection drying, while a slight decrease in dry matter after impregnation was observed for the freeze drying and vacuum methods. These results are consistent with those of other researchers who studied courgettes [14]. Other authors also observed an increase in dry matter in convection-dried beets after preliminary treatments (blanching and ultrasound) [30]. Nevertheless, the effect of temperature during convection drying was clear—higher temperatures in the drying process led to higher dry matter content in the dries. This trend underscores the crucial importance of temperature in optimizing the drying process to maintain the desired properties of the product.

3.3. Bulk Density (p_b)

The analysis of the density of the dried courgette obtained using different drying methods revealed significant differences in density values expressed in kg/m^3. The highest density was recorded for the fresh courgette after impregnation (351.78 kg/m^3) and the fresh courgette not subjected to pretreatment (262.95 kg/m^3). The density of dried samples ranged from 15.42 kg/m^3 for courgettes without pretreatment after freeze drying to 51.27 kg/m^3 for vacuum-dried courgettes after impregnation. By analyzing the bulk density, it is possible to determine the effect of the drying process on the parameter under study. In particular, vacuum-dried samples showed a higher density, which may be due to the characteristics of this process (Figure 3). In this method, water is removed more intensively, which can lead to greater shrinkage of the material and, as a result, to a higher density, despite the formation of a porous structure [14].

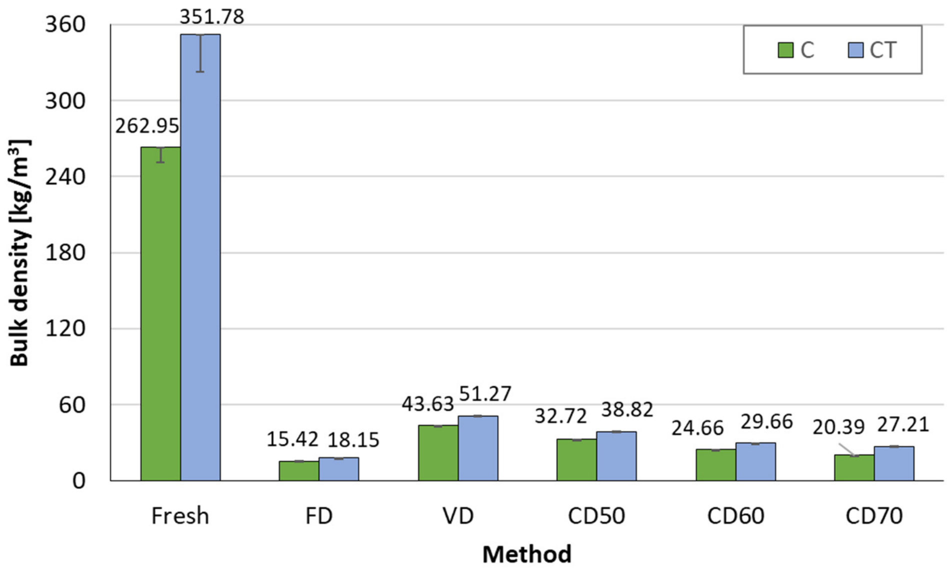

Figure 3. Bulk density of courgette (C) and courgette after vacuum impregnation (CT), fresh (Fresh), freeze-dried (FD), vacuum-dried (VD), and convection-dried at 50 °C (CD50), 60 °C (CD60), and 70 °C (CD70).

Tomato juice impregnation increased the density of the courgette in all tested materials, both fresh and after drying, as a result of the absorption of the impregnating liquid. Fresh samples that were impregnated showed an increase in density of 33% on average compared to non-impregnated samples. For the courgette dried using various methods after vacuum impregnation, the average increase in density was about 15% compared to the corresponding samples dried without pretreatment. In addition, it was observed that higher convection drying temperatures resulted in a lower density of the courgette, indicating that temperature is crucial to the drying process, significantly affecting shrinkage and dehydration of the material [31].

3.4. Gelation Index (VGI)

Understanding the impact of different technological processes on the gelation index in courgettes is crucial for the food industry, which strives to provide products that combine nutritional value with high sensory quality [19]. Analysis of the results (Figure 4) indicated that the highest value of the gelation index (VGI) was recorded for the courgette samples not subjected to the impregnation process before freeze drying, where it reached 308.33%, and the lowest value was for the courgette after the vacuum impregnation process before convection drying at 50 °C (108.33%).

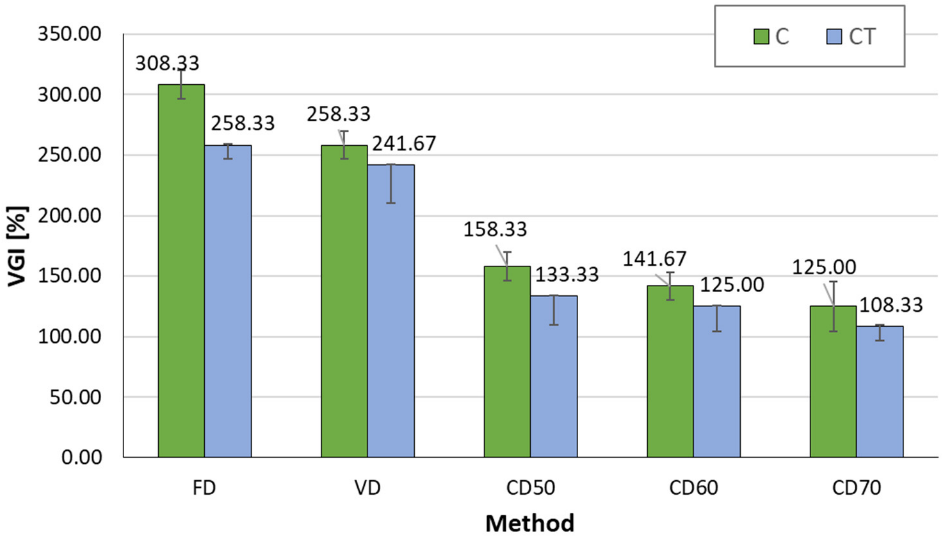

Figure 4. Gelation index of courgette (C) and courgette after vacuum impregnation (CT), freeze-dried (FD), vacuum-dried (VD), and convection-dried at 50 °C (CD50), 60 °C (CD60), and 70 °C (CD70).

The drying method appeared to have a significant effect on the gelation index (Figure 4). Samples subjected to FD and VD showed the highest VGI values compared to convection-dried samples. FD and VD are more delicate in removing water, so they yielded a product with the best gelling properties. In addition, the lower values of vacuum and convection drying compared to freeze drying prove that the vacuum and convection method destroys the chambers in the material, so it is more difficult to absorb water in the dried product [14].

The process of impregnation with tomato juice contributed to lower values of the gelation index (VGI) of the courgette in all the drying methods tested (Figure 5), suggesting that impregnation may also negatively affect the courgette's ability to gel after rehydration. The greatest decrease in VGI values after impregnation was observed in freeze-dried samples, indicating that in this method, impregnation significantly reduced the courgette's ability to gel.

Increasing the temperature of convection drying results in obtaining dried material with lower VGI values. These results make it possible to infer relationships between thermal conditions and the gel structure of courgettes, which is important for rehydration processes in the context of industrial applications.

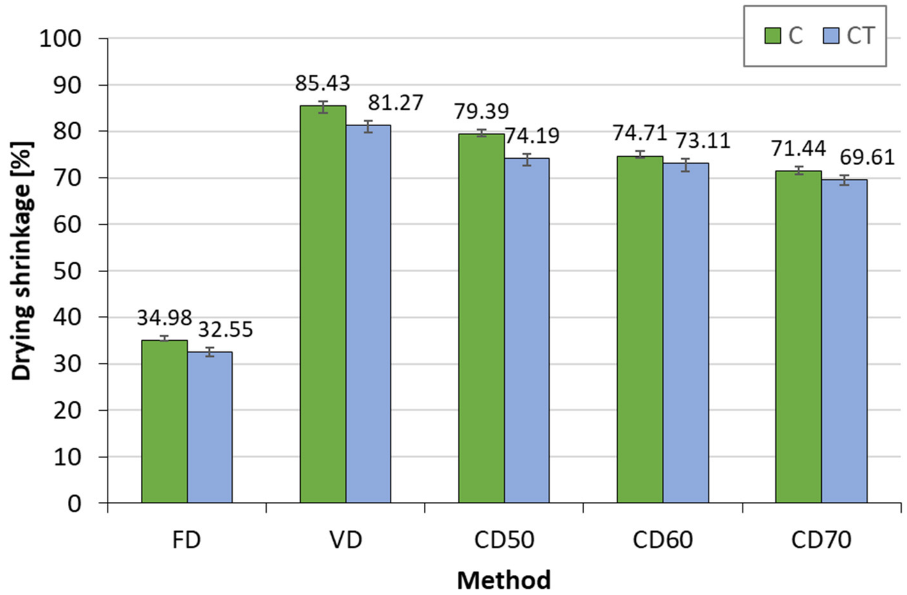

Figure 5. Drying shrinkage of courgette (C) and courgette after vacuum impregnation (CT), freeze-dried (FD), vacuum-dried (VD), and convection-dried at 50 °C (CD50), 60 °C (CD60), and 70 °C (CD70).

3.5. Drying Shrinkage (S)

The analysis of drying shrinkage of the courgette samples subjected to different drying methods and the impregnation process included a detailed recognition of the influence of the mentioned factors on the change in the volume of the material, which is important for the final quality of the food product. The shrinkage values oscillated in the range from 32.55% for the courgette impregnated with tomato juice before freeze drying to 85.43% for the vacuum-dried samples without pretreatment impregnation.

The analysis of the effect of the drying method on shrinkage showed significant differences (Figure 5). Significant differences in shrinkage values were observed for FD and the other types of drying, with dried material obtained using the freeze-drying method not having such a drastic reduction in material volume as those obtained using the other methods. These differences may result from the characteristics of the processes: during FD, water sublimates directly from the solid to the gaseous phase, which can have a less drastic effect on the structure of the material unlike other types of drying, which can cause more intense dehydration [32].

The VI process had a clear effect on the parameter studied, reducing the shrinkage value by an average of 5% in each drying method used. Similar results were obtained during the impregnation of courgettes with beet juice [14] and beetroot subjected to blanching and ultrasound treatment [30].

With regard to drying temperature, especially in the context of convection drying, it was observed that dries obtained at higher temperatures had less shrinkage. Samples dried at 70 °C showed less shrinkage compared to those dried at 50 °C and 60 °C.

3.6. Color

The detailed appearance is shown in Figure 6. The highest brightness value (L*) was observed for courgettes after freeze drying (83.4). This indicates an increase in the value of the studied parameter compared to the raw material (Table 1). An increase in brightness in the freeze-dried courgette was also observed by other authors studying pear pomace [33] and Gastrodia elata [34]. Freeze drying is the only one to show an increase in brightness in both the courgette without pretreatment and the courgette after the vacuum impregnation process. In addition, it was observed that courgettes after convection drying at 50 °C showed significant darkening, which was noted as the lowest values of the L* parameter and the largest color differences ΔE. Typically, the greatest change in color is associated with drying under the influence of warm air [35], which is confirmed by studies performed by other authors [10,33]. In all the samples studied, it was observed that the addition of tomato juice reduced the value of the color parameter L*; this is due to the darker color of the impregnating solution used. These results are in accordance with previously performed studies [14,33].

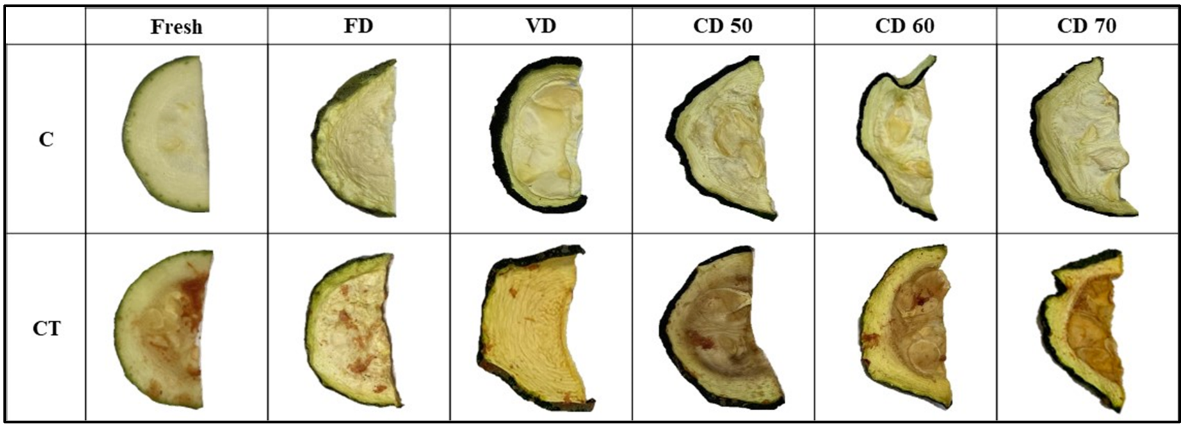

Figure 6. Appearance of courgette (C) and courgette after vacuum impregnation (CT), fresh (Fresh), freeze-dried (FD), vacuum-dried (VD), and convection-dried at 50 °C (CD50), 60 °C (CD60), and 70 °C (CD70).

Table 1. Color of courgettes without pretreatment (C) and after pretreatment (CT), freeze-dried (FD), vacuum-dried (VD), and convection-dried (CD).

Method	L*	a*	b*	ΔE
C	80.16 ± 1.10 d	−5.67 ± 0.36 a	17.90 ± 0.40 a	-
C FD	83.40 ± 1.02 d	−2.63 ± 0.45 b	19.43 ± 0.23 b	4.70
C VD	80.59 ± 0.57 d	−5.29 ± 0.33 a	19.13 ± 0.51 b	1.35
C CD50	73.37 ± 0.29 c	−3.36 ± 0.45 b	21.25 ± 1.01 c	7.92
C CD60	80.76 ± 1.94 d	−4.44 ± 0.38 a	19.76 ± 0.97 b	2.31
C CD70	78.25 ± 0.96 c	−4.67 ± 0.44 a	20.15 ± 1.06 c	3.11
CT	58.00 ± 1.91 b	0.45 ± 0.18 b	19.12 ± 0.50 b	23.02
CT FD	77.62 ± 1.74 c	1.59 ± 0.45 c	23.40 ± 0.32 e	9.45
CT VD	59.50 ± 0.57 b	2.65 ± 0.24 c	21.82 ± 0.46 c	22.62
CT CD50	45.01 ± 1.68 a	8.44 ± 0.99 f	17.48 ± 0.69 a	37.88
CT CD60	57.27 ± 0.57 b	4.31 ± 0.31 d	22.63 ± 0.22 d	25.42
CT CD70	56.32 ± 0.72 b	6.59 ± 0.38 e	22.20 ± 0.44 d	27.15

Values (mean of three replications) ± standard deviation followed by different letters (a–f) are different ($p \leq 0.05$) according to Tukey's test.

Referring to the effect of the impregnation process using tomato juice on the color of the courgette, attention was drawn to the increased values of the parameter (a*), particularly evident in the courgette samples after convection drying at 50 °C. Positive values indicate an increase in the intensity of red in the color of the product, which is directly related to the use of tomato juice as an impregnating solution. Such an increase can have a significant impact on the sensory perception of courgettes by potential consumers, underscoring the importance of selecting appropriate juices in the impregnation process to achieve the desired color characteristics.

In addition, when considering the effect of the temperature of the drying medium during convection drying on the color parameters studied, it was observed that a higher drying temperature did not unequivocally reduce the brightness of the courgette, suggesting that other factors, such as drying time or the characteristics of the courgette itself, may play an equally important role. In dries obtained using the convection method, the greatest change in color expressed as ΔE is observed, indicating the greatest loss of color in the dried materials.

3.7. Drying Kinetics

Based on the data presented in Table 2, it was concluded that the best model for the kinetics process is the logistic model. The results indicated that this model, characterized by particularly high values of the coefficient of determination R^2 (between 0.9991 and 0.9999), low root mean square error (RMSE in the range of 0.0032–0.0102), minimum chi-square test values (x^2 0.0000 to 0.0001), and relatively low residual variability (Ve in the range of 0.9–3.4%), effectively describes the drying dynamics of the courgette slices. These observations confirm the suitability of the logistic model for analyzing drying kinetics, suggesting that it can be a useful tool in optimizing drying processes for this type of vegetable. The results for the logistic model showed that increasing the temperature to 60 °C results in a decrease in the values of the a and b coefficients for the courgette, while the value of the k coefficient, which is an indicator of the drying rate, increases. With a further increase in temperature to 70 °C, an increase in the values of all three parameters was observed, especially for courgettes after the VI process.

Table 2. The values of the parameters a, b, k, R2, RMSE, χ^2, and Ve functions describe the drying kinetics of courgette samples before (C) and after (CT), convection-dried at different temperatures.

Method	Material	Model Parameters			Statistical Parameters				Drying Time [min]
		k	a	b	RMSE	Ve [%]	R2	χ^2	
Pagea Model									
CD50	C	0.0128	1.1625	0	0.0098	0.0269	0.9992	0.0001	240
	CT	0.014	1.1391	0	0.0061	0.0168	0.9997	0.0000	210
CD60	C	0.0166	1.1483	0	0.0073	0.0214	0.9996	0.0001	180
	CT	0.0154	1.1847	0	0.0117	0.0331	0.9989	0.0002	150
CD70	C	0.0198	1.1491	0	0.0115	0.035	0.9989	0.0002	150
	CT	0.0245	1.1532	0	0.0129	0.0422	0.9986	0.0002	130
Henderson and Pabis Model									
CD50	C	0.0235	0	0	0.027	0.0743	0.9972	0.0009	240
	CT	0.0236	0	0	0.0226	0.062	0.9981	0.0006	210
CD60	C	0.0282	0	0	0.0239	0.0694	0.9978	0.0007	180
	CT	0.0296	0	0	0.0306	0.0869	0.9964	0.0012	150
CD70	C	0.0331	0	0	0.0251	0.0766	0.9971	0.0008	150
	CT	0.0404	0	0	0.0255	0.0837	0.9969	0.0008	130
Newton Model									
CD50	C	0.0246	1.0369	0	0.0232	0.0637	0.9961	0.0007	240
	CT	0.0246	1.0329	0	0.0188	0.0518	0.9973	0.0004	210
CD60	C	0.0293	1.0333	0	0.0205	0.0596	0.997	0.0005	180
	CT	0.031	1.0393	0	0.0269	0.0762	0.9949	0.0009	150
CD70	C	0.0342	1.029	0	0.0228	0.0696	0.9962	0.0007	150
	CT	0.0416	1.0274	0	0.0237	0.0775	0.996	0.0007	130
Logarithmic Model									
CD50	C	0.0223	1.1407	0	0.0236	0.0649	0.9956	0.0006	240
	CT	0.0223	1.1364	0	0.0193	0.053	0.9969	0.0004	210
CD60	C	0.0268	1.1625	0	0.0202	0.0588	0.9967	0.0004	180
	CT	0.0284	1.1788	0	0.0714	0.9948	0	0.0007	150
CD70	C	0.0315	1.1857	0	0.0221	0.0674	0.9961	0.0005	150
	CT	0.0388	1.2294	0	0.0216	0.0708	0.9963	0.0005	130
Logistics Model									
CD50	C	0.0325	1.1517	2.1406	0.0042	0.0125	0.9999	0.0000	240
	CT	0.0329	1.2118	2.2008	0.0026	0.0075	0.9999	0.0000	210
CD60	C	0.0377	1.1834	2.1735	0.0064	0.0196	0.9997	0.0000	180
	CT	0.0414	0.9542	1.9294	0.0102	0.0281	0.9992	0.0001	150
CD70	C	0.0474	0.9975	1.9768	0.0058	0.0186	0.9997	0.0000	150
	CT	0.0583	1.1934	2.1615	0.0095	0.0342	0.9992	0.0001	130

In the analyzed process of convection drying of courgettes, it was noted that increasing the temperature from 50 °C to 70 °C led to a gradual decrease in drying time. This trend was evident for all variants of the samples, with a clear acceleration in the drying process at higher temperatures, a phenomenon typical of thermal processes. Similar observations were noted by the authors of this publication in earlier studies of courgettes [14] and celery [15]. Vacuum impregnation with tomato juice reduced drying time for samples dried at 50, 60, and 70 °C, indicating the positive effect of pretreatment on the drying process. Other authors examining the effect of blanching on the drying time of beets observed an increase in drying time of 13% in samples subjected to the blanching process, and ultrasounds had no effect on the drying time [30].

In Figure 7a,b showing equilibrium moisture content, it was observed that a higher drying temperature led to a faster decrease in equilibrium moisture content, and thus the faster drying of the courgette. This is consistent with other studies by the authors [10].

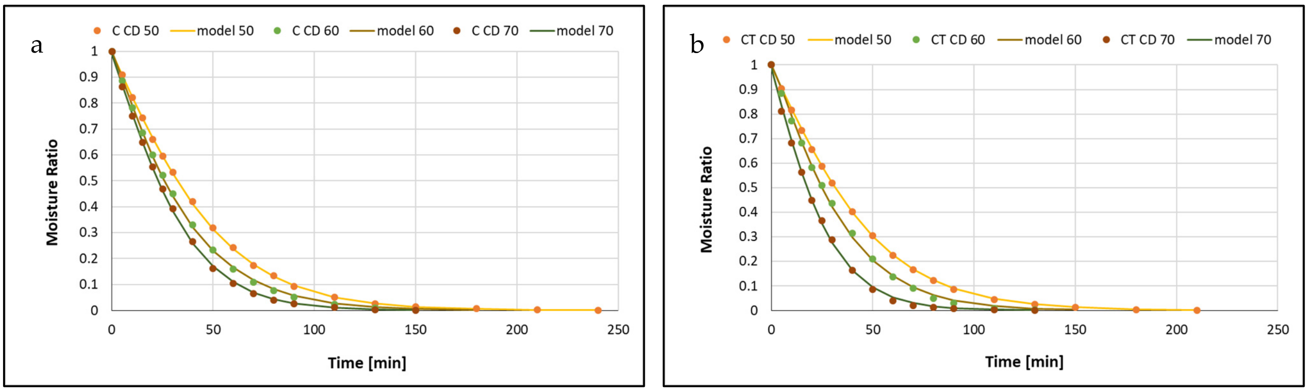

Figure 7. Moisture Ratio of (**a**) courgette (C) and (**b**) courgette after vacuum impregnation (CT) process, convection-dried at 50 °C (CD50), 60 °C (CD60), and 70 °C (CD70).

The curves corresponding to the drying of the courgette impregnated with tomato juice reach a lower moisture content in a shorter time than non-impregnated samples. This means that impregnation contributes to drying efficiency, allowing lower moisture content to be achieved in a given time, which is desirable in food processing. Increasing the drying temperature caused the water content of the courgette to drop faster (Figure 8a,b). This is an expected result since higher temperatures should increase the evaporation rate of water. These results are consistent with those of other authors who dried figs [36], potatoes [37], and cauliflower [38].

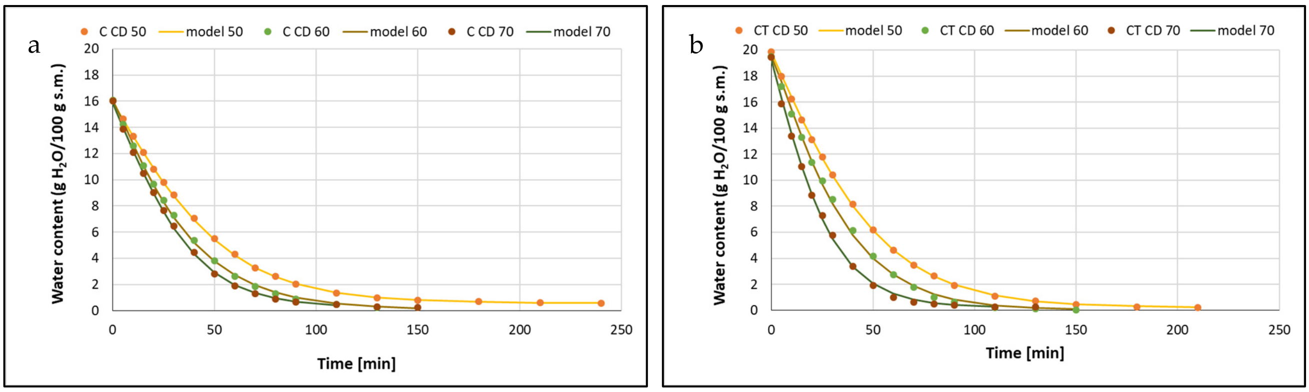

Figure 8. Water content of (**a**) courgette (C) and (**b**) courgette after vacuum impregnation (CT) process, convection-dried at 50 °C (CD50), 60 °C (CD60), and 70 °C (CD70).

4. Conclusions

In all the materials tested, the water activity was <0.6, indicating the effective removal of water from the material and ensuring microbiological safety.

Vacuum impregnation had a significant effect on the properties of the courgette, increasing dry matter content and density and decreasing AW, which promotes better shelf life and microbiological safety. The courgette after VI was characterized by lower drying shrinkage. In terms of color, impregnation with tomato juice increases the intensity of red, positively affecting the visual aspects of the courgette.

Dried material obtained using the freeze-drying method are characterized by increased brightness of the courgette, which is important for its visual appeal. In addition, the dried material is characterized by the lowest water activity, contributing to better product shelf life and microbiological stability. In addition, dried material obtained using this method are characterized by higher dry matter content and lower density. In addition, freeze drying minimizes shrinkage of the material, helping to preserve the original structure and shape of the courgette. Its effect on the high gelling index is also significant, indicating better gelling properties of the courgette after rehydration, which is important in the context of its various industrial applications.

The logistic model best describes the kinetics of courgette drying, with high R2 values, low RMSE and χ^2, suggesting its usefulness in optimizing drying processes.

Increasing the temperature in the convection drying process accelerates the evaporation of water, shortens the drying time, increases the dry weight, and reduces the water activity, density, VGI, and shrinkage of the courgette.

5. Patents

Patent Poland, no. 421913. Vacuum impregnating machine and method for initial processing of material. Wrocław University of Environmental and Life Sciences, Wrocław, PL. Authors: Bogdan Stępień, Radosław Maślankowski, Leszek Rydzak, Marta Pasławska.

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