applied sciences

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Modeling of the Drying Process of Apple Pomace

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Abstract: Understanding biological materials is quite complicated. The material apple pomace is biologically unstable has been dried under certain conditions. Modeling the pomace drying is necessary to understand the heat and mass transport mechanism and is a prerequisite for the mathematical description of the entire process. Such a model plays an important role in the optimization or control of working conditions. Modeling of the pomace drying process is difficult as apple pomace is highly heterogeneous, as it consists of flesh, seeds, seed covers, and petioles of various sizes, shapes and proportions. A simple mathematical model (Page) was used, which describes well the entire course of the drying process. This is used to control the process. In turn, complex mathematical models describe the phenomena and scientifically explain the essence of drying. Mathematical modeling of the dewatering process is an indispensable part of the design, development and optimization of drying equipment.

Keywords: drying; modeling; apple pomace

Citation: Tulej, W.; Głowacki, S. Modeling of the Drying Process of Apple Pomace. *Appl. Sci.* **2022**, *12*, 1434. https://doi.org/10.3390/app12031434

Academic Editor: Francesca Scargiali

Received: 6 December 2021
Accepted: 27 January 2022
Published: 28 January 2022

1. Introduction

Apples are the most popular fruit grown in the European Union, with Poland being among the leaders. Due to large scale and relatively low cost of production, Poland has become the global leader in fresh apples export, and is the second largest exporter of apple juice concentrate, preceded only by China. For decades, apples have been the most important fruit in Poland, both in terms of production and consumption. In Polish society, apples constitute a significant component in the strict fruit and vegetable diet, and their consumption reaches a few kilograms per head annually [1].

Production of apples in Poland is growing. It is estimated that in 2019, apple production amounted to approx. 4.5 million tons, with 70% of the crop being used by the processing industry [2].

2. Materials and Methods

Apples are spherical in shape, with a pit at the top, out of which a pedicel (stem) sticks out. The flesh is covered by a thin yet quite hard skin. Inside, there is a core with pips. Apple trees belong to fruit trees of moderate climate, and were grown by our ancestors as early as neolith. At present, there are more than a thousand cultivars of apples, with the most popular being, i.a., Champion, Antonovka, Lobo, Cortland, Malinówka, Jonagold, Gloster or Ligol.

Apples contain approx. 2–3% of fiber, half of which constitutes soluble fiber (pectin), and the content of acids and sugars determines the attractiveness of these fruits. Other substances, responsible for biological value of apples are polyphenol compounds [3]. The compounds participate in inactivation of free radicals in the organism, as well as prevention and treatment of chronic diseases, i.e., coronary vascular disease or cancer [4]. Moreover, apples contain pectin, which reduces the level of cholesterol and removes toxic substances, e.g., heavy metals from the organism. Natural carbohydrates slowly and safely increase the level of glucose in the blood, and keep it at a stable level for a longer period of time, which also has a positive effect on human health [1]. Healthy values of apples are indicated by numerous epidemiological studies related to the decrease in LDL cholesterol levels [5], in diabetes prophylaxis, and cancer [6].

The processing of apples in the fruit-vegetable industry is connected with the generation of production waste. The amount of waste produced reaches between 10–35% of the processed apples [7]. Pomace, obtained as a result of the mechanical pressing of apples in juice production has the highest share in production waste.

Fresh apple pomace is a biologically and chemically unstable material. It contains juiced flesh, pip integuments, pips and pedicels. It is a material suitable for composting, being an ingredient of feeds, a food product and a material for use in the production of fruit fiber, bio-oils, natural dyes, food colorings or polyphenol extracts [8]. Pomace may be used to cut the cost of a wholesome animal diet. Pomace should be treated as a half-finished product, which may be further processed, as it is rich in nutrients: protein, saccharides, mineral compounds, fiber, pectin, lipids, vitamins and organic acids. Pomace obtained from apples may be a source of pectin. The value of vitamins and provitamins in the waste product, i.e., pomace, after juicing fruits, depends on the conditions during the process of pressing.

Moreover, apple pomace may be a source of energy. Energy in the form of biogas may be produced in the process of anaerobic conversion of pomace. Biofuel is produced by extracting energy from biomass, and is possible by means of fermentation of sugars into alcohol. The results of research [9] show that pomace from apples is an excellent raw material for the production of ethanol, which may be used as a biofuel or as a drink—e.g., cider.

The problem of how to efficiently use apple waste is not an easy one and existing methods are complex. The further processing necessary in the processing plant depends on technical and organizational possibilities. Extending pomace usefulness for consumption and processing requires drying [10]. It is also necessary to dry pomace in order to use it to produce solid biofuels for direct combustion [11].

Drying is one of the most important thermal processes, in which food is preserved. The aim of drying is to reduce water content to a level that prevents enzymatic reactions and the development of microorganisms, which have a negative effect on the quality of the material being dried [12,13]. High temperatures and long drying times, required to remove water from fruit material during convective drying by air, may result in considerable deterioration of taste, color, nutritional value and may decrease bulk (volumetric) density and rehydration capacity of the product being dried [14,15].

There are numerous works describing the process of convective drying of apples and evaluating the quality of dried material. However, the works do not describe the process of drying apple pomace.

Drying is one of the most energy-consuming processes in the processing industry. High consumption of energy is connected with the emission of large amounts of substances harmful to the natural environment [16]. It means that improvements contributing to the reduction in the technological process duration are both profitable to the production plant and the natural environment. Generally, shortening the time biological material is exposed to a high temperature has a positive effect on quality. As pomace is a valuable source of fiber, pectin, polyphenols and anti-oxidants as well as vitamins—a shorter drying time means higher retention of these elements in the dried material. Yet, both a too short and too long drying times may have adverse effects on the product [17,18].

Despite the essence of kinetics, modeling of drying of pomace is necessary to understand the mechanism of heat and mass transfer, and is a prerequisite for the mathematical description of the whole process. Such a model plays a significant role in the optimization and control of working conditions. Technological solutions in the industry are based on simple mathematical models, which also describe the course of the process of drying very well [19]. Therefore, they are used to control this process. On the other hand, complex mathematical models describe phenomena and scientifically explain the process of drying. Mathematical modeling of dehydration process is an inherent part of modeling, development and optimization of drying equipment [20]. It essentially involves detailed research on the kinetics of drying, which describes the impact of the process variables on moisture transfer. Correctly specified mathematical models may be used to select drying parameters, assessment of kinetics of drying and optimization of drying conditions [21]. Appropriate construction of drying equipment requires knowledge of drying characteristics of the material subjected to drying as well as drying kinetics [22]. It requires emphasizing that a higher temperature results in higher driving force of heat exchange. It also accelerates the process of drying as higher temperature increases the pressure of vapor. When choosing appropriate processing technology, optimization of the process parameters needs to be considered whenever possible so as to reduce the time needed to complete the process [23,24]. Mathematical modeling facilitates this part of modeling, and enables the course to be predicted. It allows for the application of experimental results obtained in the laboratory in industry. Modeling and simulation are also indispensable for designing industrial drying plants, drying equipment as well as choosing appropriate drying conditions.

Modeling of the process of drying pomace is more difficult due to the fact that apple pomace is highly heterogeneous as it contains flesh, pip integuments, pips, pedicles of different shapes, sizes and proportions.

Empirical process may be presented by means of one or more models. Kinetic models for drying agricultural products are models of water content and temperature changes. These models contain physical variables, knowledge of which is required for their analysis [25].

In the process of the convective drying of solid bodies, conducted in the dominant external conditions of heat and mass exchange, an important factor is the surface of the body, through which the exchange occurs. The process is determined by the conditions of transport of water molecules from the surface of the body being dried through the adjacent gas layer. The process of convective drying of such materials is almost invariably accompanied by the shrinkage phenomenon [26]. The occurrence of shrinkage in biological material subjected to drying is most frequently the result of a significant loss of water [27]. Therefore, it is important to consider its individual changes in the mathematical model of kinetics of drying of such bodies.

A mathematical model of drying kinetics of solid body molecules, with consideration to shrinkage of the particles, is described by the following system of equations:

$$u_I(\tau) = u_0\left[\frac{1}{1-b}\left(1-\frac{1-b}{Nu_0}k_0\tau\right)^N - \frac{b}{1-b}\right] \quad (1)$$

where:

$$k_0 = \frac{A_0\alpha}{m_s L}(t-t_A) = -\frac{du(\tau)}{d\tau} \quad (2)$$

The value of exponent N in Equation (1) may be determined by the trial and error method. The values of coefficient b of drying shrinkage are determined experimentally or calculated from the formula [28]:

$$b = \frac{\rho_0}{\rho_s(1+u_0)} \cong \frac{0.85}{1+u_0} \quad (3)$$

A factor that determines the further course of the process is the internal diffusion of water in a solid body being dried. It is indicated by a sudden increase in the relative error of the model of the drying process. It is visible that the process further occurs according to other laws. This change is not abrupt but continuous. At this stage, conditions of internal diffusion of water molecules to the surface of the body play a decisive role.

The process of convective drying of solid bodies in such conditions is modeled with the diffusion Equation (4).

$$u_{II}(\tau) = u_r + (u_0 - u_r)\exp^{-K\tau} \quad (4)$$

The continuity of the process requires that when $u = u_{cr}$ the drying rate during the transport of water molecules from the surface of the body being dried and during internal conditions of drying be equal. As this cannot be determined precisely, the drying rate coefficient, in the range of water content, which contains the border value, is denoted by the symbol K and determined from the following Equation (5):

$$k_0\left(1-\frac{1-b}{Nu_0}k_0\tau_{cr}\right)^{N-1} = K(u_{cr}-u_r) \tag{5}$$

Hence, the modeling equation takes the following form:

$$u_{II}(\tau) = u_r + (u_{cr}-u_r)\exp\left[-\frac{k_0(\tau-\tau_{cr})}{u_{cr}-u_r}\left(1-\frac{1-b}{Nu_0}k_0\tau_{cr}\right)^{N-1}\right] \tag{6}$$

In practice, simplified equations are used, with the equation of average water content, which takes the following form, being used more often (4). Since critical water content in a body may be reached after critical time tau, Equation (4) may take the form of Equation (7):

$$u_{II}(\tau-\tau_{cr}) = u_r + (u_{cr}-u_r)\exp[-K(\tau-\tau_{cr})] \tag{7}$$

The models presented so far, scientifically explain the essence of the drying process.

The exponential model successfully describes kinetics of the drying of certain porous materials such as clay [29,30], Al-Ni catalyzer [31] and foodstuffs [32,33]. In the literature, the Page model is a model that reflects the results of the experiment well, and is relatively simple, which makes it suitable for use in practice. Research conducted by numerous authors confirm the Page model to be a good fit for the experimental data [15,34–37]. For this reason, the Page model [38] was used to describe the process of drying apple pomace.

$$MR = \exp(-K\tau^n), \tag{8}$$

So

$$u(\tau) = u_r + (u_0-u_r)\exp(-K\tau^n), \tag{9}$$

Fresh apple pomace from Energreen company was used in the experiment. Forced convection drying was carried out in the laboratory dryer shown in the Figure 1. Drying took place at an air temperature of 40 °C and 80 °C in forced convection, with the speed of the drying agent at the level of 0.8 m/s.

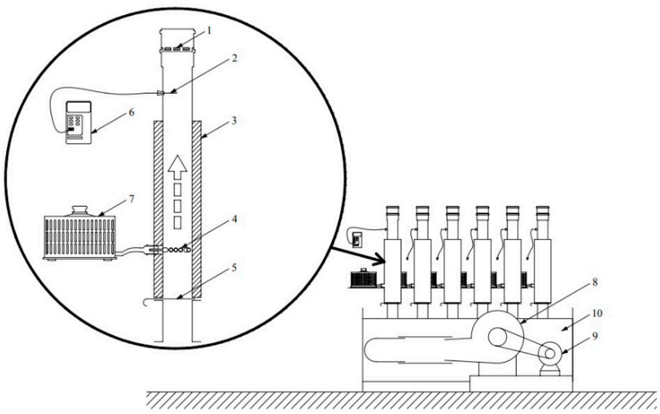

Figure 1. Convective drier scheme: 1-material basket; 2-sensor; 3-air supply duct; 4-heating element; 5-regulating valve; 6-heat recorder; 7-autotransformer; 8-fan; 9-engine; 10-expansion tank [39].

Fountain-microwave drying was performed in the MP20 dryer of the Institute of Agricultural Engineering of the University of Life Sciences in Wrocław. The construction of the device is shown in Figure 2. Fountain drying of apple pomace at 60 °C with microwave support was performed (240 W). In order to ensure the deposit's fountaining, the air flow velocity was within the range of 2.5–4 $m \cdot s^{-1}$.

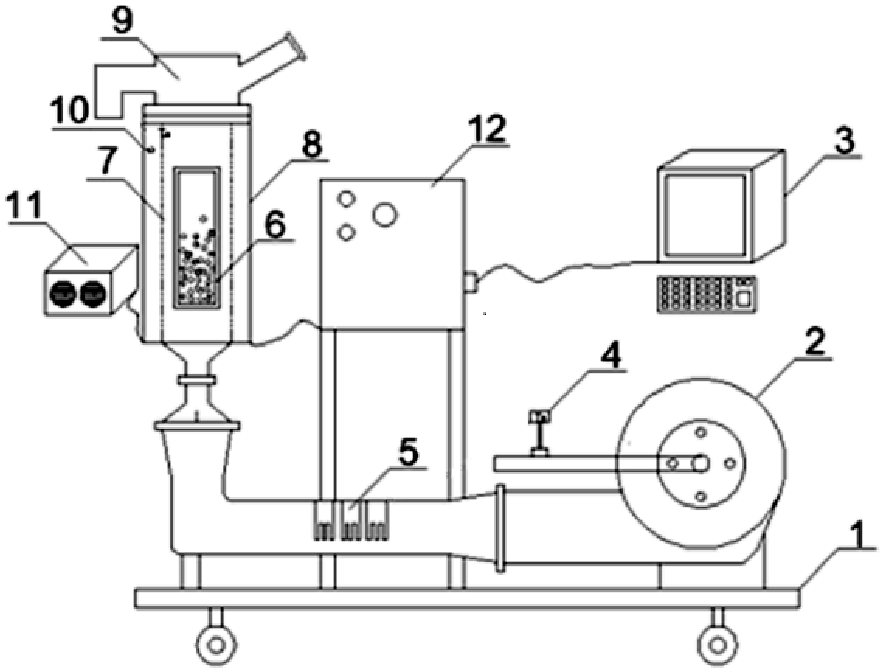

Figure 2. Laboratory stand for spouted bed-microwave drying (MP20): 1-rack; 2-fan; 3-computer; 4-temperature sensor; 5-electric heaters; 6-spouted bed; 7-drying chamber; 8-outside shield stopping microwaves; 9-cover; 10-temperature and pressure sensor; 11-magnetrons [40].

During drying, the current mass of the material was recorded each 60 s by computer software. The process was considered completed when the mass of the material did not change. It was assumed that the mass corresponded to the equilibrium water content (u_r). The process was repeated three times.

Dry mass content was determined based on the dryer-weight method according to the norm PN-77/D-04100 by drying the material at the temperature of 105 °C until dry substance was obtained.

In order to present the kinetics of the drying process, relative water content was calculated from the following formula:

$$MR = \frac{u_\tau - u_r}{u_0 - u_r} \quad (10)$$

where:

- MR—relative water content (–),
- u_r—equilibrium water content (g H_2O·g–1 d.s.),
- u_0—initial water content (g H_2O·g–1 d.s.),
- u_τ—water content after time τ (g H_2O·g–1 d.s.).

Values of the relative and the absolute errors were also calculated. The absolute error (11) is the difference between the measured value and the real value.

$$\Delta x = x - x_0, \quad (11)$$

The relative value is the quotient of the absolute error and the exact value. The relative error (12) is dimensionless and is usually expressed as a percentage.

$$\delta = \frac{\Delta x}{x_0} \times 100\% = \frac{x - x_0}{x_0} \times 100\%, \quad (12)$$

3. Results

Figure 3 presents modeling for changes of water content in the process of drying apple pomace in forced convection at 40 °C. Models used to describe the process of drying represent empirical results very well, as low values of relative and absolute errors confirm. The first 20 min of the process of apple pomace drying in forced convection at 40 °C is described by the model of external exchange with the maximum value of the error of 2% (Figure 4). The second stage, in which the external exchange of heat and mass occurs, whose intensity predominantly depends on the temperature of drying, is described by the model with the value of error below 7%.

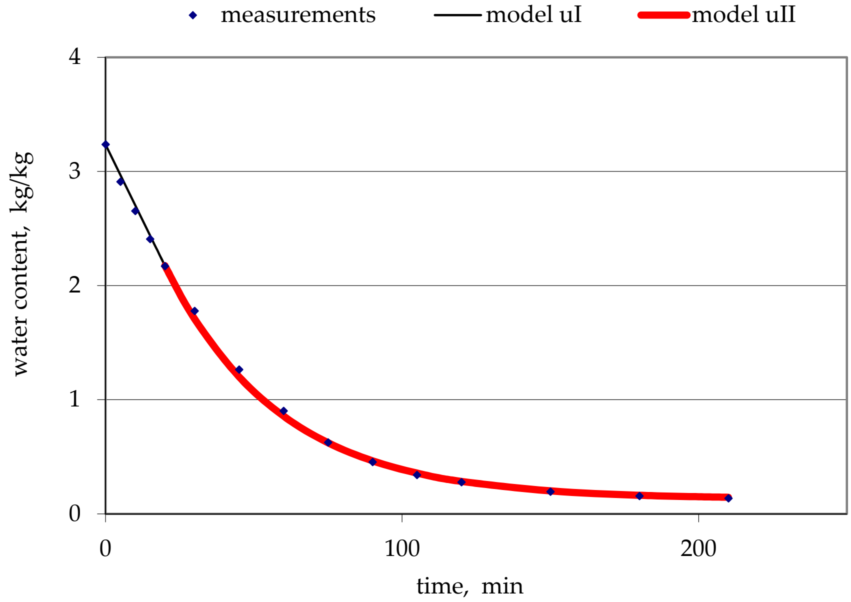

Figure 3. Modeling changes of water content in the process of drying apple pomace in forced convection at 40 °C.

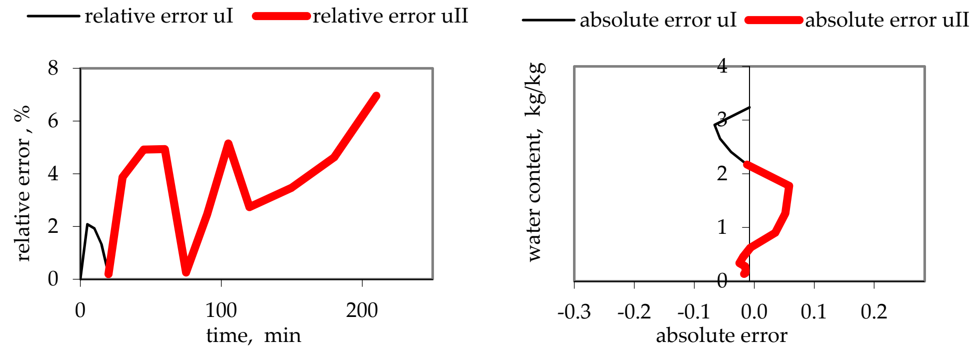

Figure 4. Relative and absolute errors for modeling of water content changes in the process of drying apple pomace in forced convection at 40 °C.

The analysis of the process of drying the sample at 80 °C (Figure 5) shows that the time of external transfer of mass is equal to approximately 10 min, and the model which describes it is burdened with an error smaller than 7%. The fitness error for the other model is below 14%.

The absolute error is very small and does not exceed 0.15 (Figure 6).

The analysis of fountain drying of apple pomace at 60 °C (Figure 7) with microwave support shows that the time of internal exchange of mass is equal to approximately 30 min, and the model which describes it is burdened with an error smaller than 6%. The fitness error for the other model is equal 14%, which is acceptable as regards its use. This is also confirmed by the absolute errors, whose values do not exceed 0.05 (Figure 8).

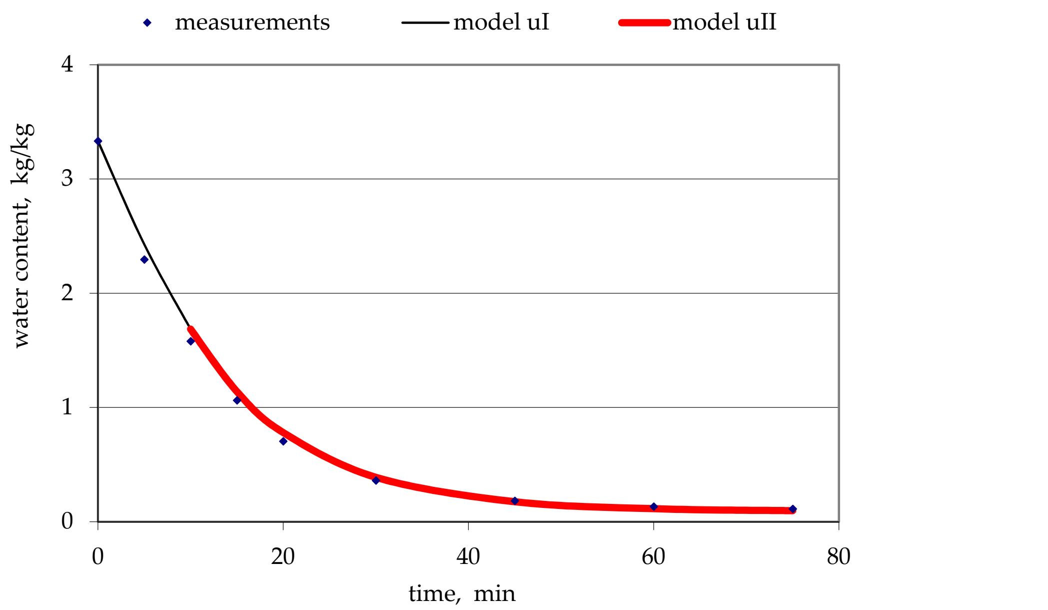

Figure 5. The graph of models for the changes in water content during the process of drying apple pomace in forced convection at 80 °C.

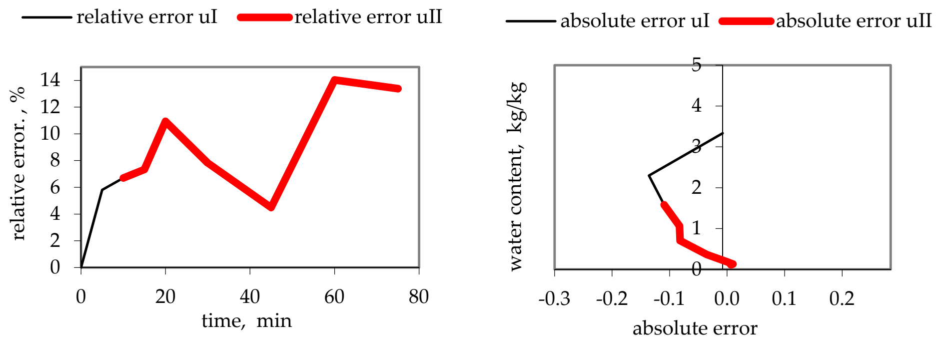

Figure 6. Relative and absolute errors for modeling of water content changes in the process of drying apple pomace in forced convection at 80 °C.

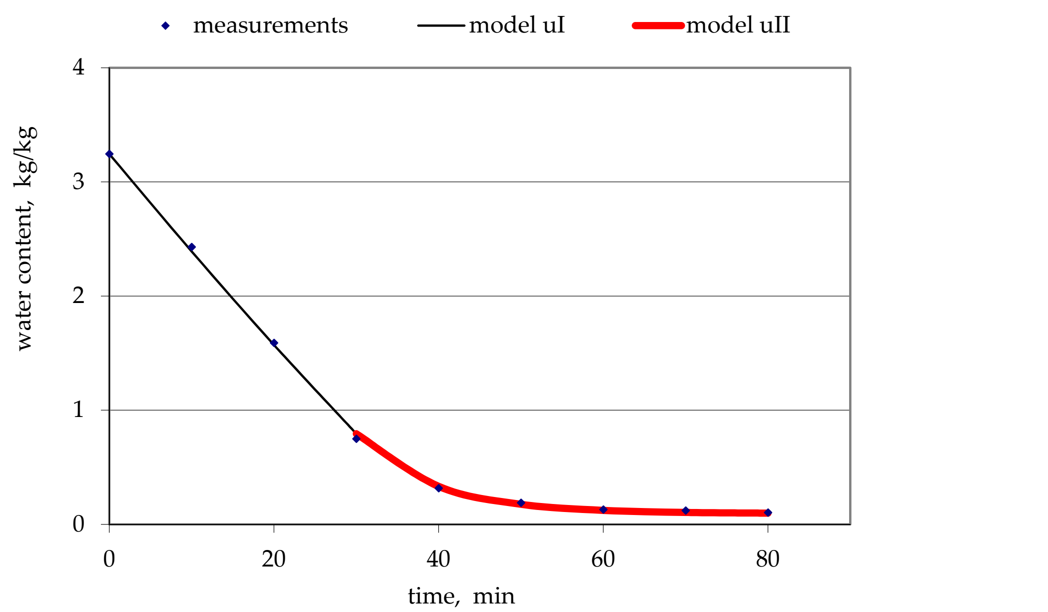

Figure 7. The graph of models of water content changes in the process of drying apple pomace in forced convection at 60 °C with microwave support (240 W).

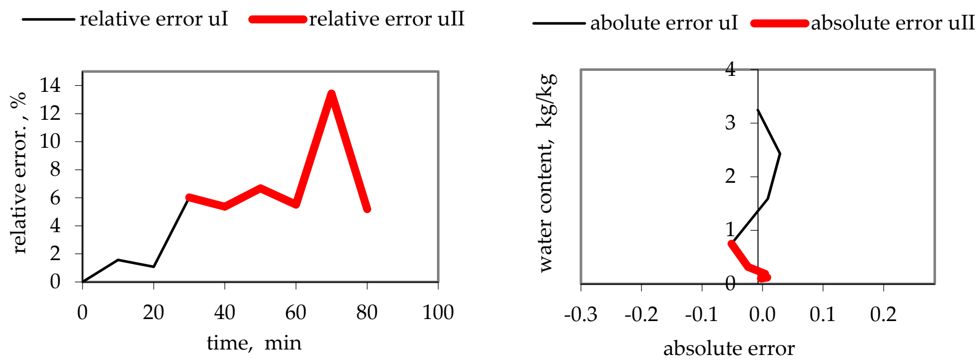

Figure 8. Relative and absolute errors for modeling of water content changes in the process of drying apple pomace in forced convection at 60 °C with microwave support (240 W).

Figure 9 presents the experimental drying curve and the drying curve determined based on the Page model. The model describes the whole process of drying. The relative and the absolute error values are smaller than or equal to 12% and 0.1, respectively (Figure 10).

The comparison of the models describing changes in water content during the process of drying apple pomace in forced convection at 40 °C shows that the values of the absolute error are 5% higher for the Page model. The values of the absolute error are comparable.

Figure 11 presents the experimental drying curve and the drying curve determined based on the Page model of apple pomace in forced convection at 80 °C.

The values of the relative and the absolute errors are smaller than 20% and 0.1, respectively (Figure 12). The relative error is large.

The comparison of the models describing changes of water content in the process of drying apple pomace in forced convection at 80 °C, shows that the values of relative error are 6% higher for the Page model.

Figures 9 and 11 present the experimental data and the data predicted based on the Page model versus air temperature introduced in the dryer. The analysis of the curves shows that the increase in the temperature has an impact on the kinetics of drying pomace. For instance, it took 270 min to reach the equilibrium water content of 0.11 for the samples dried at 40 °C, while it took only 120 min for the samples dried at 80 °C.

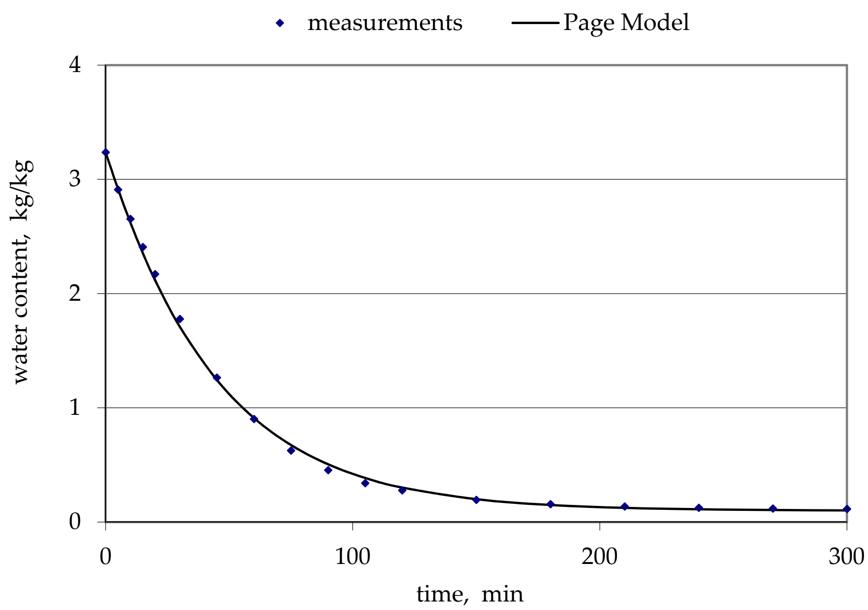

Figure 9. The Page model of water content changes in the process of drying apple pomace in forced convection at 40 °C.

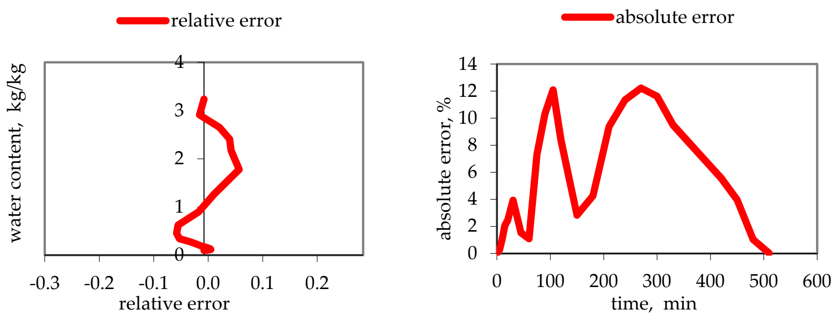

Figure 10. Relative and absolute errors for Page modeling of water content changes in the process of drying apple pomace in forced convection at 40 °C.

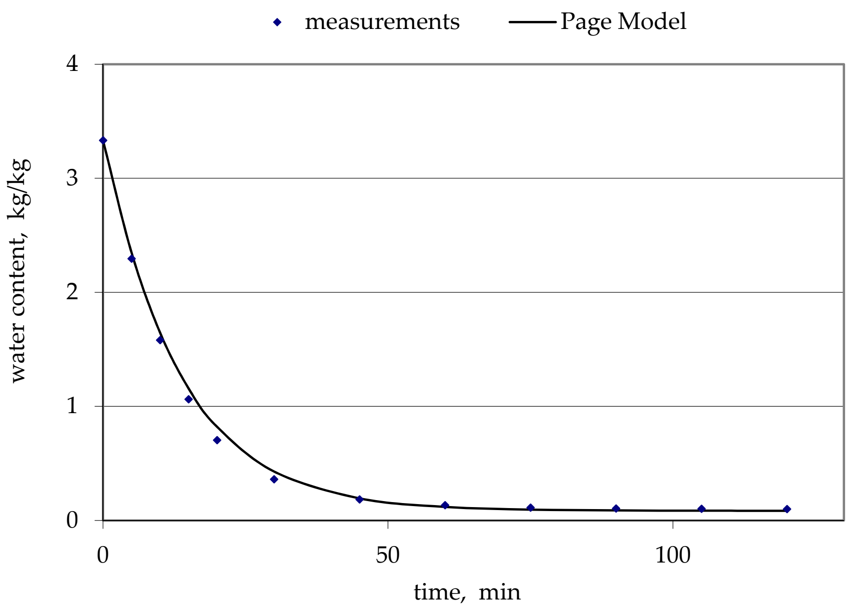

Figure 11. The Page model of water content changes in the process of drying apple pomace in forced convection at 80 °C.

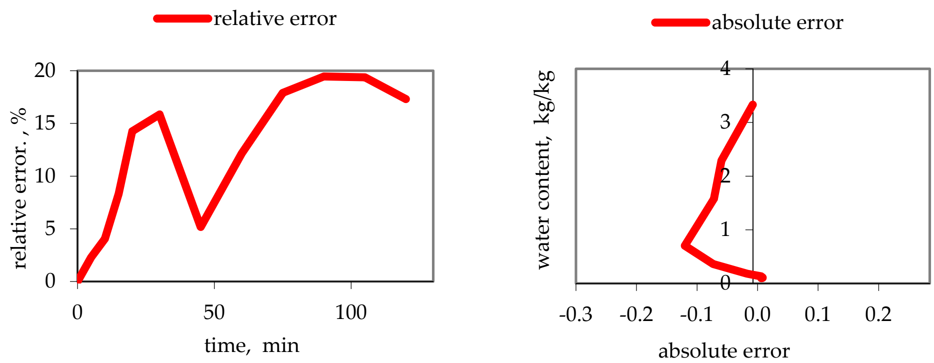

Figure 12. Relative and absolute errors for Page modeling of water content changes in the process of drying apple pomace in forced convection at 80 °C.

It may be concluded that both the distribution of measurement points and the values of coefficients in Page equation indicate the intensity of the drying process. Similar relations were observed by Jakubczyk [41], Jakubczyk and Wnorowska [42], and Seiiedlou et al. [43] regarding the process of drying foamed apple pomace.

Table 1 presents the coefficients of equations that describe the kinetics of drying depending on the method and parameters of the process.

Table 1. Coefficients of equations that describe the kinetics of drying depending on the method and parameters of the process.

Type of Drying	Equation Coefficient				
	b	**k_0**	**N**	**K**	**n**
Models of external and internal heat and mass transfer					
Forced convection 40°	0.200668	0.0533	1.03	0.0258	-
Forced convection 80°	0.196212	0.19986	4.60	0.0837	-
60-MVD	0.200260	0.0868	1.18	0.1078	-
Page model					
Forced convection 40°	-	0.021995	-	-	1.01
Forced convection 80°	-	0.069859	-	-	1.02

Following the analysis of the values of the coefficients it may be concluded that, in forced convection, the drying shrinkage coefficients vary little for different drying temperatures. Drying coefficients k_0 and K increase together with the increase in temperature, which confirms the validity of the model applied. The complete verification of the theoretical model also requires logical verification, in addition to empirical verification.

It is also worth noticing that parameter k in the Page model is interpreted as a drying coefficient, whose physical dimension is associated with the rate of drying.

Velić et al. [15] confirmed that with the increase in air flow velocity, an increase in the heat transfer coefficient and the effective diffusion coefficient is observed.

Sacilik et al. [44] found that increasing the drying air temperature and reducing the thickness of the slices shortened the drying time and increased the drying speed. It was shown that the logarithmic model showed a better fit with the experimental drying data compared to the other models. Wang came to the same conclusions. Royen et al. [45], after examining such process parameters as temperature, air humidity, air velocity and layer thickness, on the kinetics of the process and water activity in the product, decided that the thickness of the sample was the most important parameter. By increasing the slice thickness from 4 to 12 mm, the time needed to achieve the required moisture content was extended by over 500 min.

Kaleta et al. [46] in their study on the evaluation of apple drying models carried out a statistical analysis of the parameters of these models and the temperature of the drying air. The values of the constant drying rate K and the moisture diffusion coefficient increased along with the temperature of the drying air.

4. Conclusions

The process of drying apple pomace may be modeled by means of Page equation. The estimation results were consistent with the experimental results.

As expected, the results of the research also confirmed the fact that the temperature of drying air had the greatest impact on drying time. The increase in temperature resulted in a shortening of the drying time and in the increase in intensity of moisture release by the pomace.

Despite the essence of kinetics, modeling of drying of materials is indispensable for understanding the basic mechanism of transport, and is a precondition for successful simulation or for the increase in the scale of the whole process in order to optimize it or control working conditions. Simple models are effective for engineering purposes. Mathematical modeling of dehydration process is an inherent part of design, development and optimization of drying equipment.

Present expectations of consumers regarding higher quality foodstuffs result in research intensification and improvement of drying technology. The observed differences in kinetics of drying and initial processing need to be taken into account when choosing the best conditions of drying in order to improve the quality of the finished product. Consumption of energy and economic viability of the process of drying apple pomace also require consideration.

Author Contributions: Conceptualization, W.T. and S.G.; methodology, W.T. and S.G.; formal analysis, W.T.; investigation, W.T.; resources, W.T.; data curation, W.T.; writing—original draft preparation, W.T.; writing—review and editing, W.T. and S.G.; visualization, W.T.; supervision, S.G.; project administration, S.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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

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