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Single-layer drying modeling of pumpkin (Cucurbita Maxima)

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ABSTRACT

The main objective of this paper is to evaluate and assess the chosen appropriate form of drying curves available in the open literature for thin layer drying of pumpkin (Cucurbita maxima) pulp pieces. This goal was achieved by applying non-linear regression analysis included in the Statistica software to the experimental data and determining the best model among the semi-theoretical and/or empirical 23 alternative mathematical models utilizing seven evaluation criteria. For this purpose, thin-layer drying tests were carried out by using a laboratory-scale dryer. The experiments were performed at 50, 60, 70, and 80 ºC drying temperatures, 62-75 percent of relative humidity and 1.4 m/s of drying air velocity for 50 g of pulp piece of pumpkin with 3 mm and 5 mm thickness. Upon analyzing the experimental results, it was found that Alibas (modified Midilli-Kucuk) model was selected as the most effective model for drying Cucurbita maxima in a single layer among the adopted drying conditions.

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1. INTRODUCTION

Drying is one of the conservation methods of agricultural products which is commonly used and among the most energy-intensive process in the industry [1]. This process can be conducted as a thin layer or deep layer. The former has also been widely used in drying agricultural products. Drying materials that are completely exposed to the air flowing through them is known as thin-layer drying [2, 3]. In this work, the pulp pieces of mammoth pumpkin (Cucurbita maxima) were dried an as thin layer. The term "pumpkin" refers to certain varieties of Cucurbita pepo, Cucurbita moschata, and Cucurbita maxima, etc. Pumpkins belong to the family Cucurbitaceous. Cucurbita maxima are closely related to other winter squashes [4].

Pumpkin fruit is an excellent candidate for use as a functional ingredient in the food industry due to its high nutritional value and low cultivation costs. Mammoth pumpkins are cultivated in the East Black Sea Region of Türkiye. They are brined for pickling after being harvested. However, the producers also store the pulp pieces of mammoth pumpkins for commercial purposes in winter season in East Black Sea Region villages. Also, they make various foods from it, such as stuffed courgettes, fried marrow, and pumpkin with syrup and walnuts, which are the traditional tastes of Turkish cuisine. It was particularly observed that the pumpkin producers in the villages aimed to freshly conserve the pulp pieces of mammoth pumpkins from one season to the next and also to export them to places where pumpkins are not abundantly grown. As a result of this, not only will this process require more expenditure depending on the weight of the products, but the products may also be decomposed and subject to internal or external damages during the exporting process. Thus, it is necessary to reduce both volume and weight to effectively conserve the pulp pieces of the mammoth pumpkin so that they can be moved and/or stored without difficulty. Therefore, these negative effects should be minimized. The best way to accomplish this is to dry mammoth pumpkin with hot air.

Theoretical, semi-theoretical, and empirical thin-layer drying models have been employed by researchers as available in the literature. Only the external resistance to moisture transfer between the product and air is taken into account by the semi-theoretical and empirical models [5]. Theoretical models for the thin-layer drying of food products frequently use the solution of Fick's second law [6]. The developed models in the literature are used for establishing novel drying systems, deciding the appropriate drying conditions, and estimating simultaneous mass and heat transmission phenomena [6]. Furthermore, heat-sensitive bio-origin materials' drying kinetics can be anticipated by employing mathematical models [7]. The basis of modeling is the presence of a series of mathematical equations that are sufficiently detailed and simple to appropriately describe the entire system [8]. Nevertheless, a set of two nonlinear, coupled partial differential equations is used in comprehensive models to represent simultaneous heat and mass transfer equations with

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varying food characteristics and shrinkage [8]. Drying models are essential to determine and evaluate the ideal drying method for a certain product [6]. Using these techniques, the producer can determine whether the thin-layer drying process results in the production of high-quality products, and it is efficient or not [6]. A crucial step in characterizing the behavior of the thin-layer drying process is choosing the optimal model. However, the researchers should carry out experimental studies precisely and accurately, measure the parameters accurately using tools with high accuracy, and gather the experimental data in a trustworthy manner before choosing the optimal model [6].

The thin-layer drying method has been covered extensively in the literature. However, the studies on thin layer drying of pulp pieces of mammoth pumpkin or other types are limited. For example, microwave, air, and combined microwave-air drying parameters of pumpkin slices were experimentally studied [9]. In the study, the Page model was determined as the best model depending on R^2 and SEE as evaluation criteria. Also, optimum drying period, color, and energy consumption were obtained.

The kinetics of forced convective air drying of pumpkin slices was also studied by Doymaz [10]. In a hot-air experiments conducted and the air-drying properties of pumpkin slices were examined. Fick's diffusion model was used to characterize moisture transfer from the pumpkin slices. Ten semi-theoretical and empirical thin layer drying models were chosen to fit the experimental data on moisture loss, and the mathematical models were compared based on three assessment criteria (R^2, χ^2, and RMSE). In the experiments drying temperatures were chosen as 50, 55, and 65 °C. In conclusion, the drying characteristics of pumpkin slices were satisfactorily represented by the logarithmic and Verma et al. models.

Another experimental study was performed to determine the drying characteristics of hull-less seed pumpkins using hot air, solar tunnel, and open sun drying methods by Sacilik [11]. In that study, an Arrhenius-type relationship was used to describe the temperature dependence of effective diffusivity. The Page, Henderson, and Pabis logarithmic and two-term models were fitted to the experimental drying data of hull-less seed pumpkin, and non-linear regression analysis was used to obtain the drying rate constants and coefficients of the tested models. Depending on the evaluation criteria (R^2, χ^2, RMS, and EMD), the logarithmic model was chosen from among the numerous models examined to understand the drying behavior of hull-less seed pumpkins.

Zenoozian et al. examined the impact of osmotic dehydration as a pretreatment on the hot-air drying kinetics of pumpkin [12]. It was aimed to assess the optimum model for this purpose, and to use a computer vision system to analyze how the color changed while drying. In the study, pumpkin cubes were treated in 50% w/w sorbitol or sucrose solutions at 50 °C for up to 6 h, followed by hot air drying at 60 °C and air velocity of 1 m/s. Eleven drying kinetic models were fitted to drying data. The evaluation criteria R^2, χ^2, RMSE, E (%) were used to evaluate the performance of the curve-fitting. The two-term equation was found to be the best fit for sucrose preosmosed samples, whereas the modified Henderson and Pabis model best described drying kinetics of the samples treated by the sorbitol solution.

Guine et al. conducted an investigation on the mass transfer characteristics of pumpkin (Cucurbita moschata) exposed to air drying in which drying temperatures ranged from 30 to 70 °C [13]. Proteins, lipids, crude fiber, moisture content, acidity, and other properties of the samples were examined in the study, both in their raw form and after drying. Drying resulted in some reductions in acidity, lipids, fibers, and proteins, according to chemical analyses. Based on the results of fitting the experimental data to the mathematical models, Henderson-Pabis was found to be the best model for the current situation, while Vega-Lemus was shown to be the least accurate. Thin layer drying equations contribute to the understanding of the drying characteristics of agricultural materials and the empirical equations are easily applied to drying simulation as they depend on experimental data [14]. There are numerous thin-layer drying-curve models and criteria in the literature. In a review study [6], sixty-seven equations and twenty-eight evaluation criteria were given. The authors of this study make it possible for researchers to choose the finest drying equations and evaluations for their products and also provide to determine which of them are preferred most in the open literature.

Akpinar et al. experimentally investigated the drying behavior and conditions of pumpkin slices via a convective cyclone-type dryer at air inlet temperatures of 60, 70, and 80 ºC and air velocities of 1 and 1.5 m s^{-1} [15]. Also, Tunde-Akintunde and Ogunlakin experimentally studied the thin-layer drying characteristics of the pretreated and untreated pumpkin samples by using a hot-air dryer [16]. Moreover, Teferi et al. investigated the drying kinetics of pumpkin (Cucurbita Spp.) fruit slices subjected to pre-drying treatments by using uncontrolled sun and oven drying [17]. Mokhtarian et al. performed a feasibility investigation by using an artificial neural network and thin layer drying models of pumpkin air drying by a laboratory-scale convective hot air dryer at four different temperatures (65, 75, 85, and 95 ºC) by considering R^2 as evaluation criteria [18]. Jittanit studied the kinetics and temperature-dependent moisture diffusivities of pretreated pumpkin seeds with both a tray dryer and a fluidized bed dryer at drying temperatures of 60, 70, and 80 °C different air velocities of 1.8 m/s for fluidized bed dryer and in the range 0.23-0.28 m/s for tray dryer by using four thin-layer drying models namely the Page, Lewis, Wang and Singh, and two-compartment models considering R^2 and RMSE as evaluation criteria [19].

Akpinar determined a suitable thin layer drying curve for pumpkin slices by using thirteen different models by considering r and χ^2 as evaluation criteria for convective cyclone dryer at 60, 70, and 80 °C of drying air temperature and 1 and 1.5 m/s of drying air velocity [20].

Perez and Schmalko mathematically modeled pretreated pumpkin slices dried in a pilot plant convective dryer by considering ten thin layer drying models depending on evaluation criteria such as R^2, χ^2, RMSE, and MPE for 50, 60, and 70 ºC of drying air temperature and 2.5 m/s of drying air velocity [21].

Tunde-Akintunde and Ogunlakin studied the mathematical modeling of drying of pretreated and untreated pumpkin by using a hot air dryer by considering six drying models depending on R^2,

χ^2, and RMSE as evaluation criteria for temperature ranges between 0-80 ºC, and 1.5 m/s of air velocity [22].

Guine et al. carried out a study on the convective drying of pumpkin (Cucurbita maxima) for an air flux of 300 m^3/h and temperatures of 30, 40, 50, 60, and 70 ºC [23]. Six different drying curve equations were used for mathematical modeling and Page, and modified Page models were found the best models to describe the dehydration kinetics of pumpkin. Also, drying periods were determined as 8 h and 2 h for 30 and 70 ºC, respectively.

In the literature, some studies were performed relating to modeling of thin layer drying of pumpkin by using limited thin layer drying curve equations and evaluation criteria. In this paper, a comprehensive study was performed for thin layer drying of pulp pieces of pumpkin (Cucurbita Maxima) by using the 23 most preferred mathematical models, which are semi-theoretical and/or empirical, and those were applied to the experimental data performing non-linear regression analysis using the Statistica software and the results were compared according to their calculated evaluation criteria (r, R^2, χ^2, $\bar{\mathbf{R}}^2$, RMSE, RSSE, MBE). This paper also presents an experimental investigation and determination of thin layer drying of pulp pieces of pumpkin (Cucurbita Maxima). The experiments were performed at 50, 60, 70, and 80 ºC of drying temperatures, 62-75 percent of relative humidity, and 1.4 m/s of drying air velocity for 50 g of pulp piece of pumpkin with 3 mm and 5 mm thickness. This study may contribute to the optimization of drying procedure of Cucurbita Maxima for producers to reduce the expenses related with the storage, preservation, and exporting.

2. MATHEMATICAL MODELING

23 different mathematical models as seen in Table 1, which are either semi-theoretical and/or empirical, were applied to the experimental data performing non-linear regression analysis by using the Statistica software, and compared according to evaluation criteria such as the correlation coefficient (r), the coefficient of determination (R^2), adjusted R^2 ($\bar{R}^2$), reduced chi-square (χ^2), root mean square error (RMSE), reduced sum square error (RSSE) and mean bias error (MBE) as seen in Table 2. The highest values of the r, R^2, and $\bar{R}^2$, and the lowest values of the χ^2, RMSE, RSSE, and MBE give the best model. The values of the r, R^2, and $\bar{R}^2$ should be close to "1" and the values of the χ^2, RMSE, RSSE and MBE should be close to "0".

Table 1. Thin-layer drying-curve equations.

Model name	*Model equation*	*Eq. No*	*Reference*
Newton (Lewis, Exponential, Single exponential)	$MR = exp(-kt)$	(1)	[6, 27- 29]
Page	$MR = exp(-kt^n)$	(2)	[6, 27, 28, 30]
Modified Page	$MR = exp(-(kt)^n)$	(3)	[6, 27, 28, 31]
Modified Page-I	$MR = exp((-kt)^n)$	(4)	[6, 28, 32]
Modified Page-II	$MR = exp\left(-c\left(\frac{t}{L^2}\right)^n\right)$	(5)	[6, 28, 33]
Henderson and Pabis (Single term)	$MR = a\,exp(-kt)$	(6)	[6, 27-29]
Logarithmic (Asymptotic), Yagcioglu et al.	$MR = a\,exp(-kt) + c$	(7)	[6, 27-29]
Midilli-Kucuk (Midilli, Midilli et al.)	$MR = a\,exp(-kt^n) + bt$	(8)	[6, 27-29]
Demir et al.	$MR = a\,exp(-kt)^n + b$	(9)	[6, 27, 28, 34]
Two-Term	$MR = a\,exp(-k_1t) + b\,exp(-k_2t)$	(10)	[6, 27-29]
Two-Term Exponential	$MR = a\,exp(-kt) + (1-a)\,exp(-kat)$	(11)	[6, 27, 28, 35]
Verma et al. (Modified Two-Term Exponential)	$MR = a\,exp(-kt) + (1-a)\,exp(-gt)$	(12)	[6, 28, 36]
Approximation of Diffusion (Diffusion approach)	$MR = a\,exp(-kt) + (1-a)\,exp(-kbt)$	(13)	[6, 28, 34]
Modified Henderson and Pabis (Three Term Exponential)	$MR = a\,exp(-kt) + b\,exp(-gt) + c\,exp(-ht)$	(14)	[6, 28, 29]
Thompson	$t = a\,ln(MR) + b(ln(MR))^2$	(15)	[6, 28, 37]
Wang and Singh	$MR = 1 + at + bt^2$	(16)	[6, 27-29]
Hii et al.	$MR = a\,exp(-kt^n) + c\,exp(-gt^n)$	(17)	[6, 28, 33]
Simplified Fick's diffusion (SFFD)	$MR = a\,exp\left(-c\left(\frac{t}{L^2}\right)\right)$	(18)	[6, 28, 33, 38]
Weibull	$MR = exp\left(-\left(\frac{t}{a}\right)^b\right)$	(19)	[6, 28, 39]
Aghbashlo et al.	$MR = exp\left(-\frac{k_1t}{1+k_2t}\right)$	(20)	[6, 28, 39]
Parabolic	$MR = a + bt + ct^2$	(21)	[6, 28, 40]
Balbay and Şahin	$MR = (1-a)\,exp(-kt^n) + b$	(22)	[6, 28, 41]
Alibas (Modified Midilli-Kucuk)	$MR = a\,exp(-kt^n) + bt + g$	(23)	[6, 28, 42]

Dimensionless mass loss of pulp pieces of pumpkin (Cucurbita Maxima) was calculated by applying Equation (24) [24].

$$MR = \frac{M_t - M_e}{M_i - M_e} \tag{24}$$

Where M_t, M_e, and M_i are mass of product at t, mass of product in an equilibrium state, and stand for mass of product at t=0, respectively.

The variation of moisture content on a wet basis for pulp pieces of pumpkin was calculated as in Equation (25) [24].

$$MC_{wb} = \frac{M_t - M_e}{M_i} \times 100 \tag{25}$$

Some physical and/or chemical changes take place on the dried pulp pieces because of mass loss. The most important physical change that appeared on the pieces is the mass shrinkage. Mass shrinkage ratios of pulp pieces were calculated using Equation (26) [24, 25, 26].

$$S_{mr} = \frac{M_t(t)}{M_i(t=0)} \tag{26}$$

Table 2. Evaluation criteria of thin-layer drying curve-equations.

Evaluation par.	*Equation*	*Eq. No*	*References*
Correlation coefficient	$r = \frac{N\sum_{i=1}^{N}(MR_{pre,i})(MR_{exp,i}) - (\sum_{i=1}^{N} MR_{pre,i})(\sum_{i=1}^{N} MR_{exp,i})}{\sqrt{\left(N\sum_{i=1}^{N} MR_{pre,i}^2 - (\sum_{i=1}^{N} MR_{pre,i})^2\right)\left(N\sum_{i=1}^{N} MR_{exp,i}^2 - (\sum_{i=1}^{N} MR_{exp,i})^2\right)}}$	(27)	[6, 28, 43]
Coefficient of determination	$R^2 = 1 - \frac{SSE}{SST} = 1 - \frac{\sum_{i=1}^{N}(MR_{exp,i} - MR_{pre,i})^2}{\sum_1^n (MR_{exp,i} - MR_{avg})^2}$	(28)	[6, 28]
Adjusted R^2	$\bar{R}^2 = 1 - (1 - R^2)\frac{N-1}{N-k-1}$	(29)	[6, 28, 44]
Reduced chi-square	$\chi^2 = \frac{\sum_{i=1}^{N}(MR_{exp,i} - MR_{pre,i})^2}{N-n}$	(30)	[6, 28, 45]
Root mean square error	$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,i})^2}{N}}$	(31)	[6, 28, 45]
Reduced sum square error	$RSSE = \frac{\sum_{i=1}^{N}(MR_{exp,i} - MR_{cal,i})^2}{N}$	(32)	[6, 28, 46]
Mean bias error	$MBE = \frac{\sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,i})}{N}$	(33)	[6, 28]

3. MATERIAL AND METHOD

3.1. Material

As a material pumpkin (Cucurbita Maxima) grown in Yeşilyurt, Araklı, Trabzon, Türkiye was used. Outside and inside views of this pumpkin is given in Figure 1. In drying experiments, a laboratory scale drier model number of KTUN MC19 AOA OV 1081 was used. The arrangement of the experimental setup for the drying process is schematically shown in Figure 2. During the experiments, the two-digit electronic balance was used to weigh the mass changes of samples. The inlet and outlet velocities of the drying air were determined by means of TA2 type anemometer. All temperatures were measured by sensitive thermometers with 50 scale and strengthened 76 mm immersion nitrogen-filled.

Fig. 1. Outside and inside views of pumpkin (Cucurbita Maxima).

3.2. Method

Before drying experiments, the initial moisture content of the samples was firstly determined as follows: 50 g of fresh pulp pieces of pumpkin (Cucurbita Maxima) was put in the high-temperature oven and kept there at 120 ºC for almost 3.5 hours. It was determined that the fresh samples had 80% of moisture. After this process, the samples were prepared for the thin-layer drying experiments. The pulp pieces of pumpkin (Cucurbita Maxima) were cut in sizes of 3x19x19 mm and 5x19x19 mm and then 50 g of the samples were placed on the mesh-wire containers. The inside temperature of the electrically assisted drying cupboard was adjusted to 50, 60, 70, and 80 ºC with an uncertainty of ±1 ºC for each experiment, respectively. Each container was separately settled in a drier as shown in Figure 2 so that the drying air could homogeneously pass through the samples. During drying experiments, temperatures (wet and dry bulb temperatures of inlet and outlet drying air, laboratory temperature, inside temperature of drier), mass losses of the samples, and also drying air velocity were measured every 20 minutes. The drying process flow diagram of pulp pieces of pumpkin (Cucurbita Maxima) was presented in Figure 3.

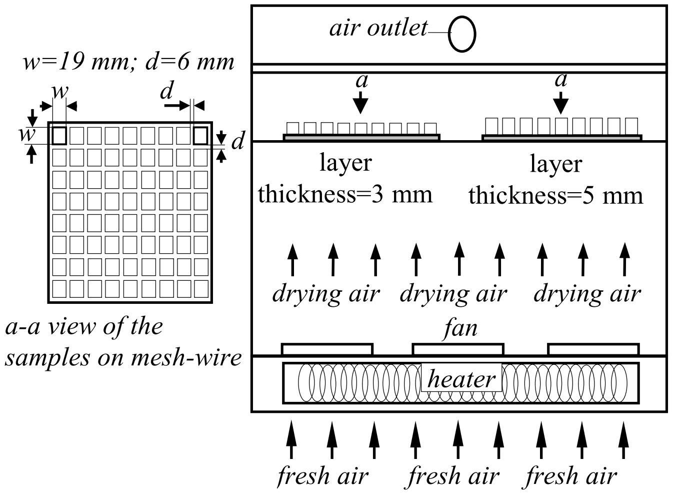


Fig. 2. Schematic diagram of dryer and placement of pulp pieces on the mesh-wire container.

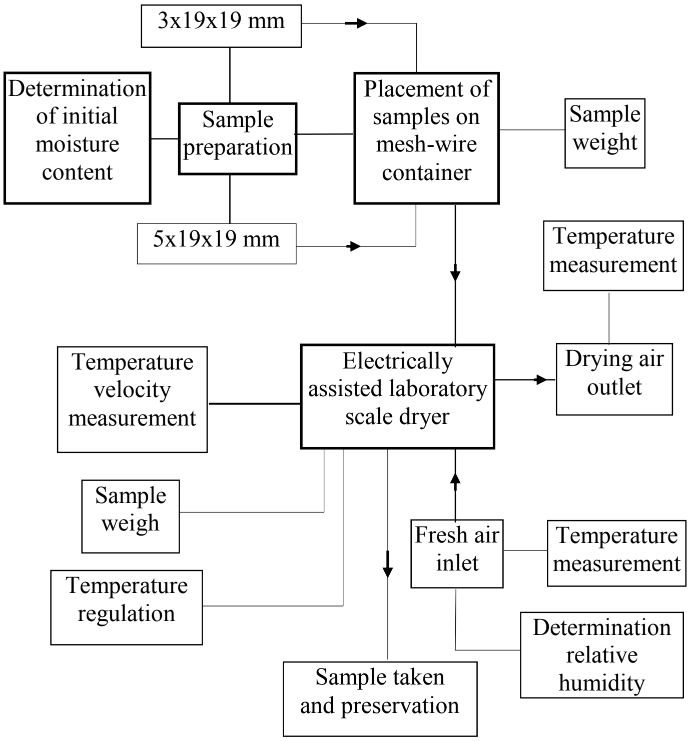


Fig. 3. Flow chart of thin layer drying process of pulp pieces of pumpkin.

4. RESULTS AND DISCUSSION

The thin layer drying experiments of pulp pieces of pumpkin with the thickness of 3 and 5 mm were conducted at four different temperatures of 50, 60, 70, and 80 °C of drying air by a laboratory scale dryer. However, moisture content and mass shrinkage were presented as a function of drying time in Figure 4 and Figure 5. Also, the experimental uncertainty of each parameter affecting the drying process of pulp pieces of pumpkin was determined as seen in Table 3.

Table 3. Uncertainties of the measured parameters.

Parameter	*Uncertainty*
Mass loss of samples	± 0.02 g
Laboratory temperature	± 0.20 °C
Inside temperature of the dryer	± 1.0 °C
Inlet temperature of drying air	± 0.20 °C
Dry bulb temperature	± 0.20 °C
Wet bulb temperature	± 0.20 °C
Outlet temperature of drying air	± 0.10 °C

The variations of moisture content wet basis of pulp pieces with drying time are given in Figure 4. It is noted that, at a constant drying temperature, as pumpkin thickness rises, drying time also increases. In addition, as the temperature increases, the moisture content of the samples decreases faster, and the drying time is considerably reduced. Using Equation (25), the final moisture contents on a wet basis were calculated as 1.6, 3.6, 1.2, and 3.8% at 50, 60, 70, and 80 °C, respectively for pumpkin with 3 mm-thickness; and 3.6, 0.8, 3, and 2.6% at 50, 60, 70, and 80 °C, respectively, for pumpkin with 5 mm-thickness. The above given values showed that the pulp pieces were perfectly dried. When the properties of pulp pieces during the experiments were taken into consideration, it can be understood that the samples are sufficiently dried at 70 °C without decomposition of their physical structures.

Figure 5 presents variation of mass shrinkage ratio calculated by using Equation (26) as a function of drying time. It was important to determine the mass shrinking to describe the mass changes taking place on pulp pieces of pumpkin through drying. Also, as seen in Figure 5, as the drying temperature increases, the mass shrinkage ratio decreases for a constant sample thickness. Moreover, for a constant temperature, when the sample thickness increases, the mass shrinkage ratio also rises. The mass shrinkage ratio exponentially decreases with the increased drying time, and while the sample thickness increases, the required mass shrinkage ratio is reached over a long time.

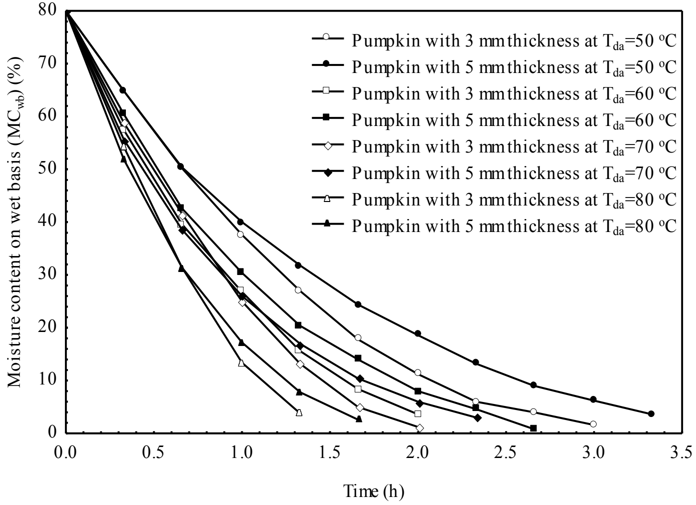


Fig. 4. Variation of moisture content on the wet basis as a function of drying time.

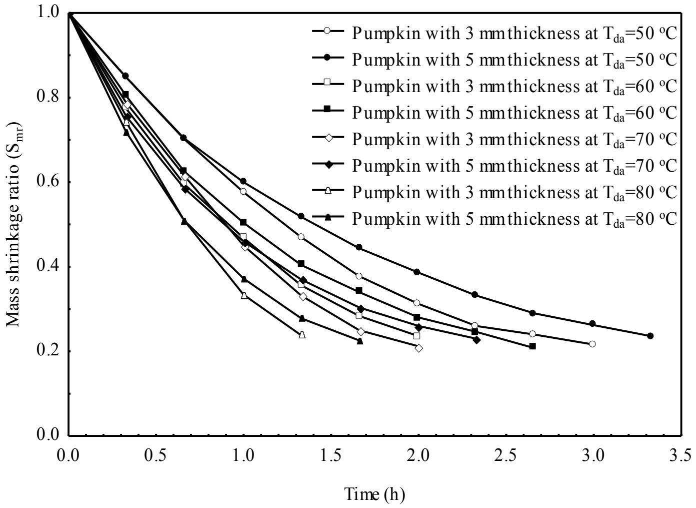


Fig. 5. Variation of mass shrinkage ratio as a function of drying time.

Evaluation criteria used to choose the best seven thin-layer drying curve equation for thin-layer drying of pulp pieces of pumpkin are given in Tables 4 for 50, 60, 70, and 80 ºC of drying air temperatures for 3 mm sample thickness, respectively. Moreover, for 5 mm of sample thickness, the evaluation criteria for the best seven thin layer drying equation are presented in Tables 5 for 50, 60, 70, and 80 ºC of drying air temperatures, respectively. The highest values of the correlation coefficient (r), the coefficient of determination (R^2), and adjusted R^2 ($\bar{R}^2$) and the lowest values of the root mean square error (RMSE), the reduced chi-square (χ^2), the reduced sum square error (RSSE) and the mean bias error (MBE) give the most suitable model describing thin layer drying behavior and conditions for Cucurbita Maxima. As seen in Table 4, Midilli-Kucuk (Eq. (8)), Demir et al. (Eq. (9)), Wang and Singh (Eq. (16)), Aghbashlo et al. (Eq. (20)), Parabolic (Eq. (21)), Balbay and Şahin (Eq. (22)) and Alibas (Eq. (23)) models give the best results depending on the evaluation criteria presented in Table 3 for thin layer drying of pulp pieces of pumpkin for 50 ºC drying air temperature and 3 mm sample thickness.

As it can be noted from Table 4, Midilli-Kucuk, Demir et al., Wang and Singh, Aghbashlo et al., Parabolic, Balbay and Şahin, and Alibas models were determined as the more accurate single layer drying curve equations depending on evaluation criteria (Table 3) for thin layer drying of pulp pieces of pumpkin at 70 oC drying air temperature and 3 mm sample thickness (Table 4). However, Alibas (modified Midilli-Kucuk) model was determined as the best model (Table 4).

For 60 ºC drying air temperature and 3 mm sample thickness of pumpkin (Cucurbita Maxima), logarithmic (Eq. (7)), Midilli-Kucuk, Demir, et al., Verma et al., modified Henderson and Pabis (Eq. (14)), Balbay and Şahin and Alibas models were found more suitable as thin layer drying curve equations by taking into the consideration the evaluation criteria (Table 3) for thin layer drying of pulp pieces of pumpkin (Table 4).

Table 4. Evaluation criteria for single layer drying of pumpkin for 3 mm of sample thickness.

Model Name	*r*	*R^2*	*χ^2*	*$\bar{R}^2$*	*RMSE*	*RSSE*	*MBE*
50 °C							
Midilli-Kucuk	0.99973	0.99970	0.00010	0.99945	0.00772	0.00006	0.00007
Demir et al.	0.99977	0.99974	0.00008	0.99954	0.00706	0.00005	0.00000
Wang and Singh	0.99994	0.99992	0.00002	0.99989	0.00400	0.00002	0.00079
Aghbashlo et al.	0.99996	0.99995	0.00001	0.99994	0.00314	0.00001	0.00064
Parabolic	0.99994	0.99994	0.00002	0.99991	0.00349	0.00001	0.00000
Balbay and Şahin	0.99977	0.99974	0.00008	0.99954	0.00706	0.00005	0.00000
Alibas (Modified Midilli-Kucuk)	*0.99997*	*0.99997*	*0.00001*	*0.99994*	*0.00236*	*0.00001*	*0.00001*
60 °C							
Logarithmic	0.99984	0.99981	0.00006	0.99962	0.00605	0.00004	0.00000
Midilli-Kucuk	0.99985	0.99982	0.00008	0.99947	0.00586	0.00003	0.00002
Demir et al.	0.99987	0.99985	0.00007	0.99955	0.00540	0.00003	0.00000
Verma et al.	0.99988	0.99986	0.00005	0.99972	0.00518	0.00003	0.00014
Modified Henderson and Pabis	0.99992	0.99991	0.00012	-	0.00416	0.00002	0.00000
Balbay and Şahin	0.99987	0.99985	0.00007	0.99955	0.00540	0.00003	0.00000
Alibas (Modified Midilli-Kucuk)	*0.99992*	*0.99991*	*0.00006*	*0.99945*	*0.00420*	*0.00002*	*0.00001*
70 °C							
Midilli-Kucuk	0.99954	0.99946	0.00025	0.99837	0.01045	0.00011	0.00006
Demir et al.	0.99960	0.99952	0.00022	0.99856	0.00982	0.00010	0.00000
Wang and Singh	0.99978	0.99972	0.00008	0.99959	0.00744	0.00006	0.00090
Aghbashlo et al.	0.99985	0.99981	0.00005	0.99971	0.00618	0.00004	0.00185
Parabolic	0.99979	0.99975	0.00009	0.99949	0.00715	0.00005	0.00000
Balbay and Şahin	0.99960	0.99952	0.00022	0.99856	0.00982	0.00010	0.00000
Alibas (Modified Midilli-Kucuk)	*0.99988*	*0.99985*	*0.00010*	*0.99912*	*0.00542*	*0.00003*	*0.00003*
80 °C							
Midilli-Kucuk	0.99994	0.99993	0.00007	-	0.00384	0.00001	0.00001
Demir et al.	0.99996	0.99994	0.00006	-	0.00340	0.00001	0.00000
Wang and Singh	0.99968	0.99954	0.00015	0.99909	0.00961	0.00009	0.00152
Aghbashlo et al.	0.99986	0.99979	0.00007	0.99958	0.00655	0.00004	0.00191
Parabolic	0.99969	0.99959	0.00021	0.99838	0.00906	0.00008	0.00000
Balbay and Şahin	0.99996	0.99994	0.00006	-	0.00340	0.00001	0.00000
Alibas (Modified Midilli-Kucuk)	*1.00000*	*1.00000*	*-*	*-*	*0.00091*	*0.00000*	*0.00001*

As it can also be seen in Table 4, Midilli-Kucuk, Demir et al., Wang and Singh, Aghbashlo et al., Parabolic, Balbay and Şahin, and Alibas models were determined more suitable for thin layer drying of pumpkin slices for 80 ºC drying air temperature and 3 mm sample thickness of pumpkin slices.

The best thin layer drying model was determined as Alibas (modified Midilli-Kucuk) (Table 4) for 50, 60, 70, and 80 ºC of drying air temperatures and a 3 mm sample thickness of pumpkin slices. The comparison of the dimensionless mass loss ratio (MR) obtained from this model and experimental data was given in Figure 6(a) to 6(d) and very close agreement was obtained between experimental and model data.

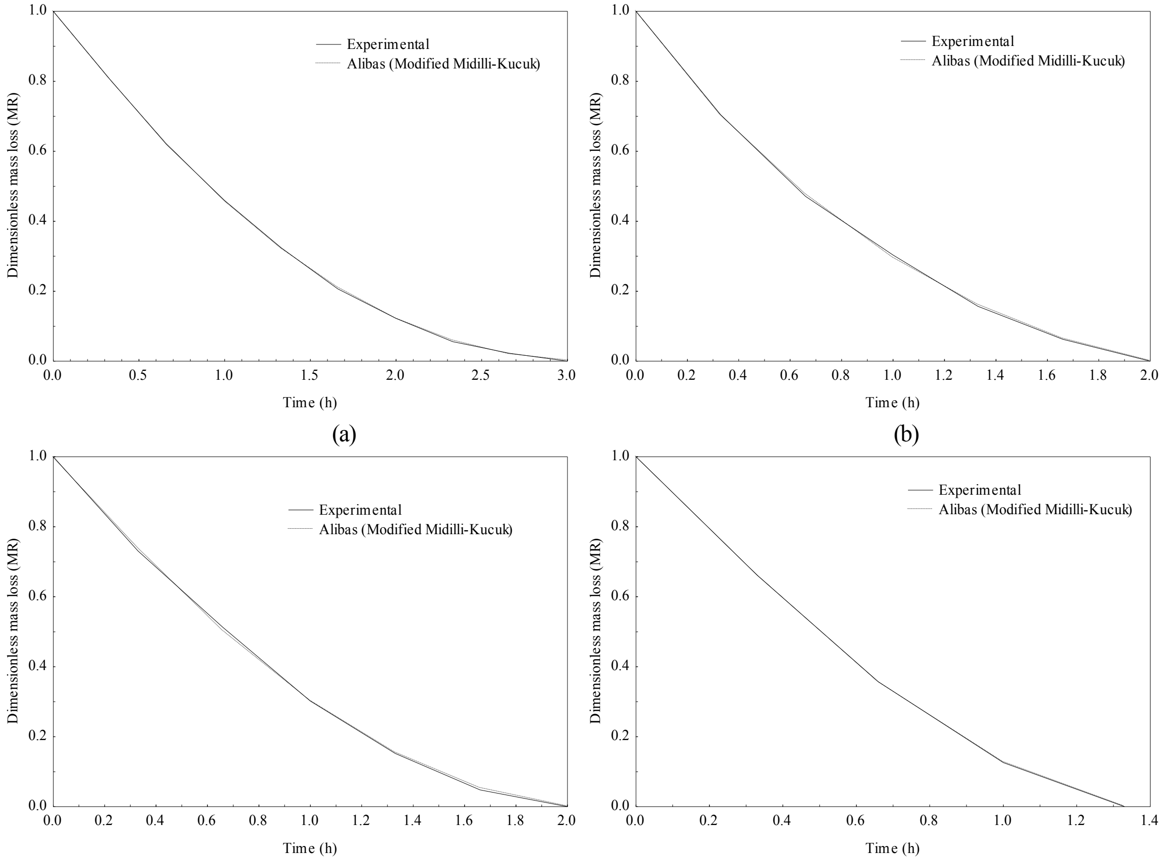
For 3 mm sample thickness, drying curve equations of the best model at 50, 60, 70, and 80 ºC of drying air temperature in Equations (34) to (37), respectively.

$$MR = 0.846413 \times exp(-0.747278 \times t^{1.206736}) - 0.022804 \times t + 0.15292 \qquad (34)$$

$$MR = 0.860135 \times exp(-0.974212 \times t^{1.021923}) - 0.049336 \times t + 0.14042 \qquad (35)$$

$$MR = 0.899399 \times exp(-0.988853 \times t^{1.185232}) - 0.031644 \times t + 0.098999 \qquad (36)$$

$$MR = 0.759095 \times exp(-1.599668 \times t^{1.285905}) - 0.111577 \times t + 0.240486 \qquad (37)$$



(a) (b)

(c) (d)

Fig. 6. Variation of dimensionless mass loss ratio with respect to time for 3 mm sample thickness of pumpkin; a) 50, b) 60, c) 70, d) 80 ºC.

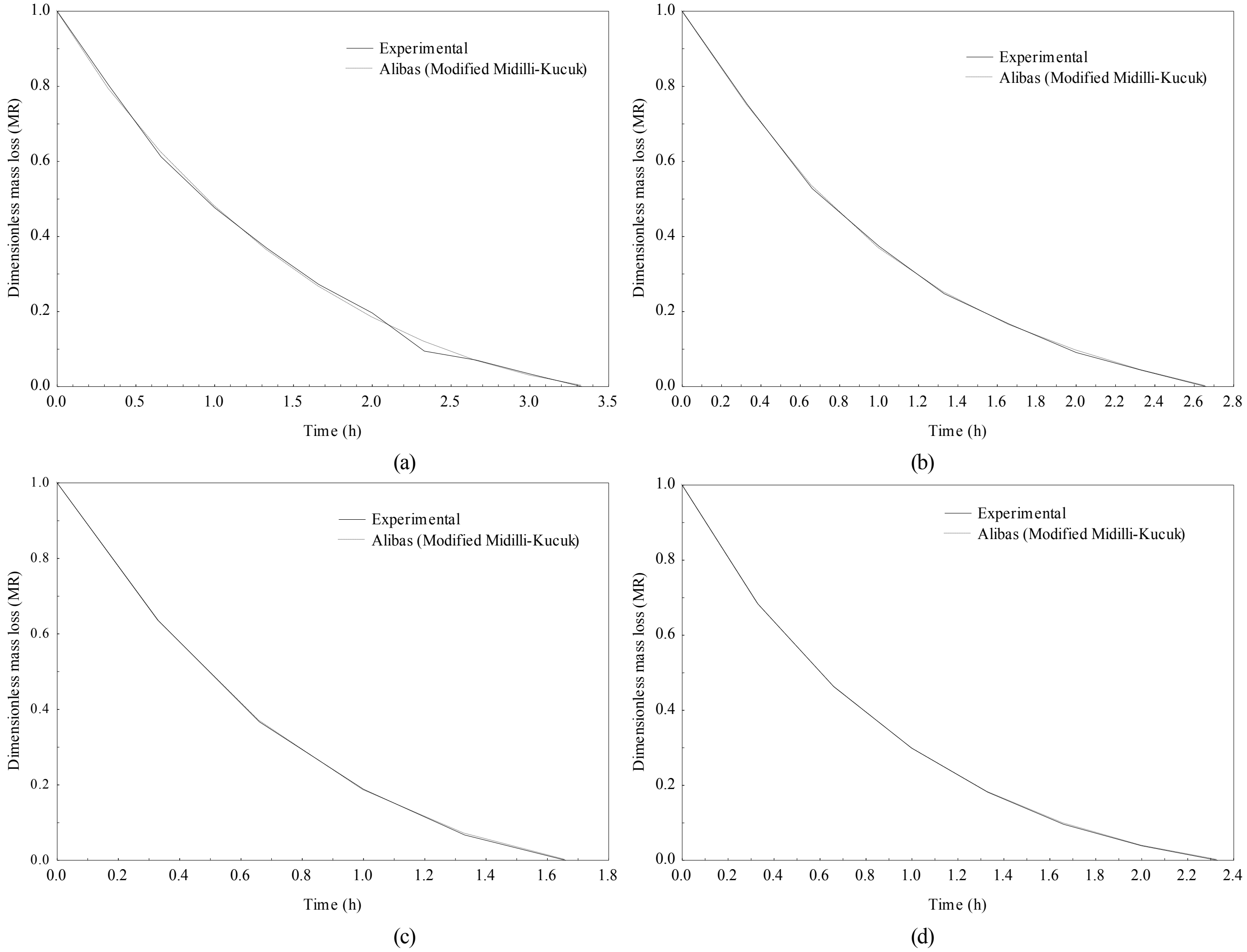
Table 5 presents the evaluation criteria for single-layer drying of Cucurbita Maxima at 50 °C and 5 mm of sample thickness. As seen in Table 5, logarithmic, Midilli-Kucuk, Demir et al., Verma et al. (Eq. 12), Thompson (Eq. 15), Balbay and Şahin and Alibas models give the best results depending on the evaluation criteria as seen in Table 3. However, Alibas (modified Midilli-Kucuk) model was determined as the best thin layer drying curve equation for thin layer drying of pulp pieces of pumpkin for 50 ºC drying air temperature and 5 mm sample thickness.

For 60 ºC drying air temperature and 5 mm sample thickness of pumpkin, logarithmic, Midilli-Kucuk, Demir, et al., Thompson, Aghbashlo, et al., Balbay and Şahin and Alibas models were obtained as more suitable models (Table 5).

For 70 ºC drying air temperature and 5 mm sample thickness logarithmic, Midilli-Kucuk, Demir, et al., Verma, et al., Thompson, Balbay and Şahin and Alibas models were found as more suitable thin layer drying curve equations.

Table 5. Evaluation criteria for single-layer drying of pumpkin for 5 mm of sample thickness.

Model Name	*r*	*R^2*	*χ^2*	*$\bar{R}^2$*	*RMSE*	*RSSE*	*MBE*
			50 °C				
Logarithmic	0.99944	0.99940	0.00016	0.99914	0.01063	0.00011	0.00000
Midilli-Kucuk	0.99943	0.99939	0.00018	0.99898	0.01073	0.00012	0.00003
Demir et al.	0.99946	0.99942	0.00017	0.99903	0.01046	0.00011	0.00000
Verma et al.	0.99948	0.99944	0.00014	0.99920	0.01026	0.00011	0.00009
Thompson	0.99915	0.99893	0.00025	0.99867	0.01417	0.00020	0.00338
Balbay and Şahin	0.99946	0.99942	0.00017	0.99903	0.01046	0.00011	0.00000
Alibas (Modified Midilli-Kucuk)	*0.99950*	*0.99947*	*0.00018*	*0.99894*	*0.00998*	*0.00010*	*0.00000*
			60 °C				
Logarithmic	0.99981	0.99979	0.00006	0.99966	0.00624	0.00004	0.00000
Midilli-Kucuk	0.99990	0.99989	0.00004	0.99978	0.00448	0.00002	0.00002
Demir et al.	0.99989	0.99987	0.00004	0.99974	0.00490	0.00002	0.00000
Thompson	0.99980	0.99970	0.00007	0.99960	0.00736	0.00005	0.00243
Aghbashlo et al.	0.99955	0.99947	0.00013	0.99929	0.00987	0.00010	0.00147
Balbay and Şahin	0.99989	0.99987	0.00004	0.99974	0.00490	0.00002	0.00000
Alibas (Modified Midilli-Kucuk)	*0.99994*	*0.99993*	*0.00003*	*0.99980*	*0.00366*	*0.00001*	*0.00000*
			70 °C				
Logarithmic	0.99998	0.99997	0.00001	0.99996	0.00209	0.00000	0.00000
Midilli-Kucuk	0.99996	0.99996	0.00002	0.99990	0.00277	0.00001	0.00002
Demir et al.	0.99998	0.99998	0.00001	0.99994	0.00206	0.00000	0.00000
Verma et al.	0.99998	0.99998	0.00001	0.99996	0.00208	0.00000	0.00015
Thompson	0.99991	0.99960	0.00009	0.99943	0.00837	0.00007	0.00718
Balbay and Şahin	0.99998	0.99998	0.00001	0.99994	0.00206	0.00000	0.00000
Alibas (Modified Midilli-Kucuk)	*1.00000*	*1.00000*	*0.00000*	*0.99999*	*0.00077*	*0.00000*	*0.00000*
			80 °C				
Logarithmic	0.99987	0.99983	0.00006	0.99956	0.00565	0.00003	0.00000
Midilli-Kucuk	0.99997	0.99996	0.00002	0.99982	0.00253	0.00001	0.00001
Demir et al.	0.99998	0.99997	0.00002	0.99986	0.00226	0.00001	0.00000
Henderson and Pabis	0.99994	0.99992	-	1.00041	0.00386	0.00001	0.00002
Aghbashlo et al.	0.99968	0.99954	0.00013	0.99924	0.00914	0.00008	0.00226
Balbay and Şahin	0.99998	0.99997	0.00002	0.99986	0.00226	0.00001	0.00000
Alibas (Modified Midilli-Kucuk)	*0.99998*	*0.99998*	*0.00003*	-	*0.00211*	*0.00000*	*0.00000*



(a) (b) (c) (d)

Fig. 7. Variation of dimensionless mass loss ratio with time for 5 mm sample thickness of pumpkin; a) 50 ºC, b) 60 ºC, c) 70 ºC, d) 80 ºC.

For 80 ºC drying air temperature and a 5 mm sample thickness, logarithmic, Midilli-Kucuk, Demir et al., modified Henderson and Pabis, Aghbashlo et al., Balbay and Şahin and Alibas thin layer drying curve equations were determined as more suitable models.

The best thin layer drying model was determined as Alibas (modified Midilli-Kucuk) for 50, 60, 70, and 80 ºC of drying air temperatures, and a 5 mm sample thickness of pumpkin slices. The comparison of the dimensionless mass loss ratio (MR) obtained from this model and experimental data was given in Figure 7(a) to 7(d) and very close agreement was obtained between experimental data and model data.

For 3 mm sample thickness, drying curve equations of the best model at 50, 60, 70, and 80 ºC of drying air temperatures are given in Equations (38) to (41), respectively.

$$MR = 0.489211 \times exp(-1.132089 \times t^{1.186057}) - 0.106512 \times t + 0.509579 \quad (38)$$

$$MR = 0.94808 \times exp(-0.838782 \times t^{1.029332}) - 0.004117 \times t + 0.054769 \quad (39)$$

$$MR = 1.07871 \times exp(-0.852022 \times t^{0.941968}) + 0.03071 \times t - 0.077071 \quad (40)$$

$$MR = 0.962197 \times exp(-1.231867 \times t^{1.044083}) - 0.001887 \times t + 0.038286 \quad (41)$$

4. CONCLUSION

In this study, a comprehensive analysis was performed for single-layer drying modeling of pulp pieces of Cucurbita Maxima by using the twenty-three most preferred mathematical models, which are semi-theoretical and/or empirical, were applied to the experimental data performing non-linear regression analysis using the Statistica software and compared to their calculated evaluation criteria for single-layer with 3 mm and 5 mm at different drying air temperatures of 50, 60, 70, and 80 °C at drying air velocity of 1.4 m/s. The following conclusions are obtained from this study.

Alibas (modified Midilli-Kucuk) model was determined as the most accurate model for single-layer drying of Cucurbita Maxima for all drying conditions by considering evaluation criteria.

To evaluate the performance of the thin layer drying models the number of experiments should be at least two more than the maximum number of the constants of the thin layer drying curve equations used in the drying modeling.

Nomenclature

a, b, c, g	Empirical constants in models
a, b, c, g, h, k, k_1, k_2	Drying constants (min^{-1})
E	Percent mean relative deviation modulus (%)
EMD	Mean relative percentage deviation
MC	Moisture content
MR	Dimensionless mass loss ratio
M_i	Mass of product at t=0 (g)
M_e	Mass of product in an equilibrium state (g)
M_t	Mass of product at t (g)
MBE	Mean bias error
n	Number of drying constants
N	Number of observation
r	Correlation coefficient
R^2	Coefficient of determination
$\bar{R}^2$	Adjusted R^2
RMSE	Root mean square error
RSSE	Reduced sum square error
SEE	Standard error of estimate
t	Time (h)
T	Temperature (°C)

Greek Symbols

$\chi2$	Reduced chi-square

Subscripts

avg	Average
da	Drying air
exp	Experimental
pre	Predicted
wb	Wet basis

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