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Drying Kinetics, Physicochemical and Thermal Analysis of Onion Puree Dried Using a Refractance Window Dryer

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Abstract: Onions have a high moisture content, which makes them more susceptible to microbial growth. Drying is one of the postharvest preservation methods applied to decrease onion moisture content, thereby increasing its storage life. In this study, onions were peeled, washed, cut into quarters, hot water blanched, and pureed. The puree was further dried using two different drying methods: refractance window drying (RWD) (water temperature: 70 °C) and convective drying (CD) (50 °C). The puree was spread on prefabricated trays at varying thicknesses of 2 mm, 4 mm, and 6 mm. It was observed that, irrespective of the drying method, moisture ratio (MR) decreased and drying time and effective moisture diffusivity increased with respect to the thickness of the puree. In addition, the Lewis model and the Wang and Singh model showed the highest R^2 and lowest SEE value for RWD and CD, respectively. Moreover, the MR of onion puree during RWD and CD was predicted using a multi-layer feed-forward (MLF) artificial neural network (ANN) with a back-propagation algorithm. The result showed that the ANN model with 12 and 18 neurons in the hidden layer could predict the MR, with a high R^2 value for RWD and CD, respectively. The results also showed that the thickness of the puree and drying method significantly affected the physicochemical quality (color characteristics, pyruvic acid content, total phenolic content, total flavonoid content, antioxidant capacity, and hygroscopicity) of onion powder. It was concluded that RWD proved to be a better drying method than CD in terms of the quality of dried powder and reduced drying time. Irrespective of the drying method, 2 mm-thick puree dried yielded the best-dried onion powder in terms of physicochemical quality, as well yielding the lowest drying time. These samples were further analyzed for calculating the glass transition temperature.

Keywords: refractance window drying; convective drying; onion puree; artificial neural network; modelling; quality

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Citation: Zalpouri, R.; Singh, M.; Kaur, P.; Kaur, A.; Gaikwad, K.K.; Singh, A. Drying Kinetics, Physicochemical and Thermal Analysis of Onion Puree Dried Using a Refractance Window Dryer. *Processes* **2023**, *11*, 700. https://doi.org/10.3390/pr11030700

Academic Editor: Dariusz Dziki

Received: 2 February 2023
Revised: 24 February 2023
Accepted: 24 February 2023
Published: 26 February 2023

1. Introduction

One of the world's most widely grown and consumed vegetables, the onion (*Allium cepa* L.), is known to contain considerable amounts of bioactives with anti-degenerative disease characteristics [1]. It is largely used as a flavor component in different nations and contains a variety of useful fibers, vitamins, organic acids, phenolic compounds, and other antioxidants [2]. One of the postharvest treatments for onions is drying; in this process, the moisture content is reduced by applying heat [3,4]. Harvested onions have a high moisture content of more than 80%, which can be decreased to 10% or less by drying, thereby increasing their storage life. Dried onion products are used as a culinary component in a wide range of food compositions, including soups, sauces, salad dressings, sausage, and other ready-to-eat meals [5].

Onions are often dried using the convective drying (CD) process, which causes color and quality degradation [6,7]. CD reduces the porosity and moisture absorption capacity of the food substance being dried. This might be produced by the solute moving from the inner core to the surface at high temperatures [8]. It has been discovered that CD of food materials with low thermal conductivity decreases heat transmission to the interior of the product during the falling rate period [9,10].

An alternate drying procedure is necessary to prevent deterioration and ensure successful thermal processing. Refractance window drying (RWD) is one such approach, which is both innovative and effective for drying thin materials [11,12]. This sort of drying is theoretically based on three heat transmission methods: conduction, convection, and radiation, with water serving as the heating medium [13]. It normally employs hot water (below boiling point temperature) and atmospheric pressure. A uniformly thin layer of food material is spread over a polyester film that is kept above the water bath. This polyester film is extremely thin and quickly reaches the temperature of the hot water flowing beneath it. When a wet material is applied to the top of the film, it reduces refraction at the plastic–puree interface, allowing radiant thermal energy to pass through the plastic and into the product [11,14,15]. As a result, faster drying of products like tomato [16], potato [17], carrots [18], strawberry [19], banana [20], passion fruit [21], jackfruit [22], cherry [23], blueberry [24], orange [25], kiwi [26], and mango [27,28] are achieved.

Mathematical models of drying processes are useful for describing process behavior and extrapolating it to different operating conditions [29]. Some effective models for drying onion slices are the Logarithmic model for single-layer infrared radiative and convective drying [30]; the Logarithmic and modified Page for convective drying [31]; the Page model for microwave and convective drying [32]; and reaction engineering approach for convective drying [33,34]. Despite the fact that these models can provide good regression for experimental data under very specific conditions, there is no way to obtain general equations that describe every product's drying process [35]. ANN models provide several advantages over conventional modelling techniques, due to their learning abilities and ability to fit nonlinear processes. As a result, ANNs have been found to be more advantageous in predicting drying kinetics accurately and can easily be applied to non-linear processes [35,36]. Despite this, insufficient information is available about the thin-layer modelling of onion puree to understand the drying process. In the available literature, there are no published reports on the RWD of onion purees with variable thicknesses and ANN modelling. Therefore, this study aimed to estimate the effective moisture diffusivity of onion puree and select the best thin layer kinetic model for RWD and CD and compare it with ANN modelling. Further, this study also evaluates the physicochemical parameters of dehydrated samples and determines the glass transition temperature of the best quality sample.

2. Materials and Methods

2.1. Sample Preparation

Fresh onions (cv. Punjab Naroya) were procured from local farms near Ludhiana, Punjab, having an initial moisture content of 88.79 ± 0.09% wb. The onions were peeled, washed, and cut into quarters. The quarters were further blanched in hot water (temperature: 98 ± 2 °C) for 3 min and immediately submerged in ice-cold water to halt further cooking [9]. The blanched quarters were then pureed using a pulper.

2.2. Drying of Onion Puree

Two different drying methods were used to dry freshly-made onion puree: refractance window drying (RWD) and convective drying (CD). At 50 °C, the CD was performed in a Kilburn tray dryer (Macheill and Magor Ltd., Kolkata, India). At a water temperature of 70 °C, the RWD experiment was conducted in a batch-type pilot-scale dryer of size

1.8 m × 1.2 m × 0.15 m, developed at the Department of Processing and Food Engineering, Punjab Agricultural University, Ludhiana, India (Figure 1). For experimental purposes, the onion puree was equally spread in 2 mm-, 4 mm-, and 6 mm-thick layers in the prefabricated trays of the convective dryer and sample tray of the RW dryer. The bottom part of the trays used for RWD had metalized polyester film for the transmittance of heat from the water to the onion puree. The RW dryer consists of an insulated water bath attached with two electrical heaters (1 kW and 2 kW) for heating water, and a thermostat for regulating water temperature. The drying of onion puree was maintained until weight loss became consistent. The initial and final weights of the products were determined. The dried flakes were further ground to form a powder using a grinder (Dynamix DX, Sujata, New Delhi, India), which was passed through a 212 μm sieve for uniformity of size.

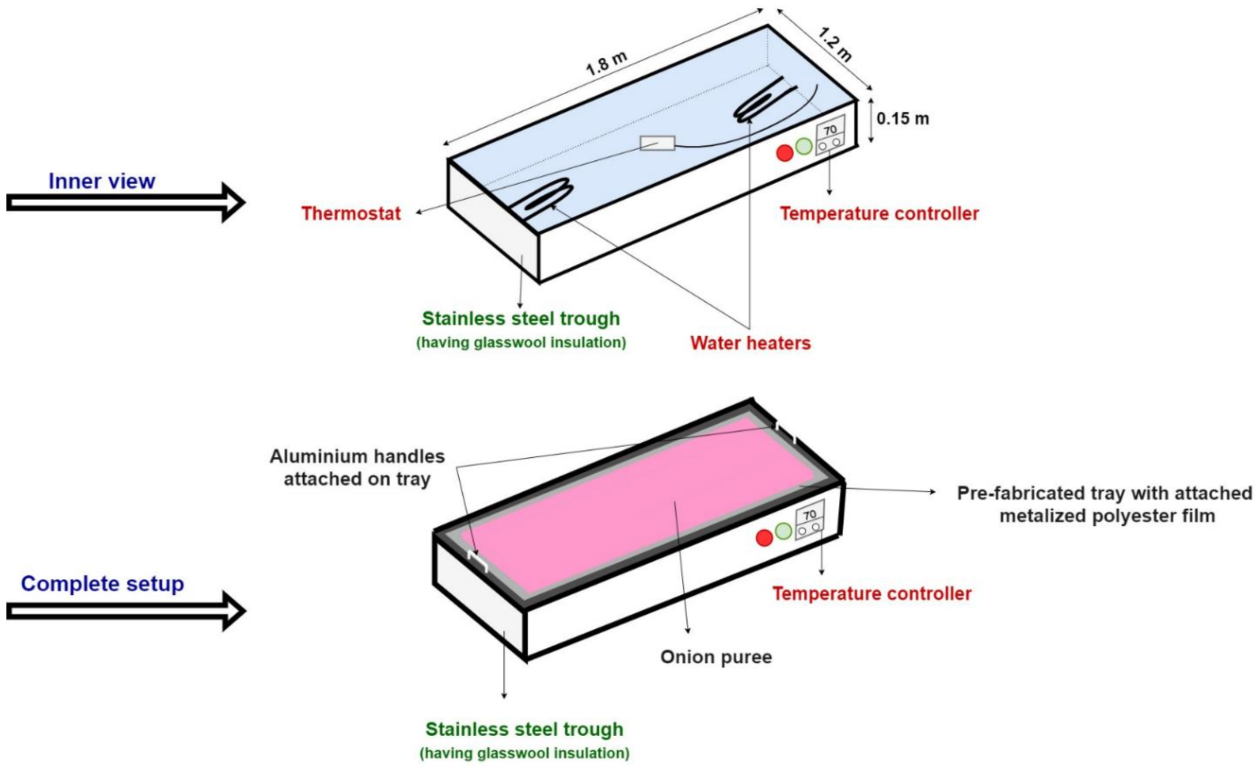

Figure 1. Schematic diagram of the refractance window dryer.

2.3. Drying Kinetics and Drying Models

The MR was calculated, as given by [37]:

$$\text{MR} = \frac{M - M_e}{M_o - M_e} \quad (1)$$

where, M = Moisture content at any instance (%), M_e = Equilibrium moisture content (%), and M_o = Initial moisture content (%).

Understanding the behavior of the drying process requires modelling of the drying characteristics of the sample. The concept of model fitting is used to determine how well the available thin layer drying model equations fit the drying kinetic data. It would be beneficial to study the drying characteristics of the product by using the best-fitting model equation. The experimental data obtained in this study were plotted as a dimensionless MR against drying time in minutes. The coefficient of determination (R^2) and root mean square error (RMSE) values were used as major criteria in selecting the best equation to describe the experimental data [38,39].

2.4. Effective Moisture Diffusivity

During the falling rate period, food materials are generally dried. Mathematical models based on Fick's second law have been proposed to predict moisture transfer during this period. According to Fick's second law, the effective moisture diffusivity of an infinite slab can be calculated by considering the following assumptions: (a) moisture is uniformly distributed throughout a mass at the beginning; (b) mass transfer is symmetrical around the center; (c) the moisture content of the sample surface immediately reaches equilibrium with that of the surrounding air; (d) in contrast to the internal resistance of the sample, the resistance at the surface to mass transfer is negligible; (e) mass transfer is by diffusion only; and (f) the diffusion coefficient is constant and shrinkage is negligible.

Fick's second law of diffusion (Equation (2)) can approximate mass transfer in a sample, regardless of the mechanism involved during long drying times [40,41]. The logarithmic form of Equation (2) was given in Equation (3). Experimental drying data are typically plotted in terms of ln(MR) versus drying time (t), which leads to a straight line with a slope of ln(MR) versus drying time (t).

$$\mathrm{MR} = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{eff}}{4L^2}\right)\cdot t \tag{2}$$

$$\ln(\mathrm{MR}) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 \times t \times D_{eff}}{4L^2}\right) \tag{3}$$

$$\mathrm{Slope} = \frac{\pi^2 D_{eff}}{4\,L^2} \tag{4}$$

where, 'D_{eff}' represents the effective moisture diffusivity (m^2/s), 'L' represents the half thickness of the sample, and 't' represents the drying time (s).

2.5. Artificial Neural Network (ANN) Modelling

MATLAB software (R2018a, MathWorks, USA) was used to develop and test different ANN models to predict MR during RWD and CD of onion puree. A multi-layer feed-forward (MLF) algorithm with back-propagation learning was selected. This algorithm uses a supervised training method that initializes the biases and weights at random. Typically, multilayer feed-forward nodes have three layers (input/hidden/output). The ANN was fed two input variables (thickness of puree and time of drying) and one output variable (MR) (Figure 2). The experimental statistics were shuffled before being divided into subgroups for training, validation, and testing. In addition to gradient estimation, training network weights and biases were estimated using 70% of the data, while 15% of the data were used to evaluate the network and 15% of the data were used to test the network. In this study, Tansig was used as the network transfer function, and Levenberg–Marquardt was used as the training function [42]. To build the best ANN model, the number of neurons in the hidden layer was calculated by trial and error. As a final step, three statistical criteria were used to evaluate the performance of the ANN model: mean square error (MSE), RMSE, and correlation coefficient (R).

$$\mathrm{MSE} = \frac{1}{n}\sum\nolimits_{i=1}^{n}(V_{p,\,i} - V_{e,\,i})^2 \tag{5}$$

$$\mathrm{RSME} = \left\{\frac{1}{n}\sum\nolimits_{i=1}^{n}(V_{p,\,i} - V_{e,\,i})^2\right\}^{1/2} \tag{6}$$

$$\mathrm{R}^2 = \frac{\sum_{i=1}^{n}(V_{p,\,i} - V_{e,\,i})2}{\sum_{i=1}^{n}\left(V_{p,i}^2\right) - \sum_{i=1}^{n}\left(V_{e,i}^2\right)} \tag{7}$$

where, n is the number of observations, $V_{p,i}$ is the predicted MR for the ith observation, and $V_{e,i}$ is the experimental MR for the ith observation.

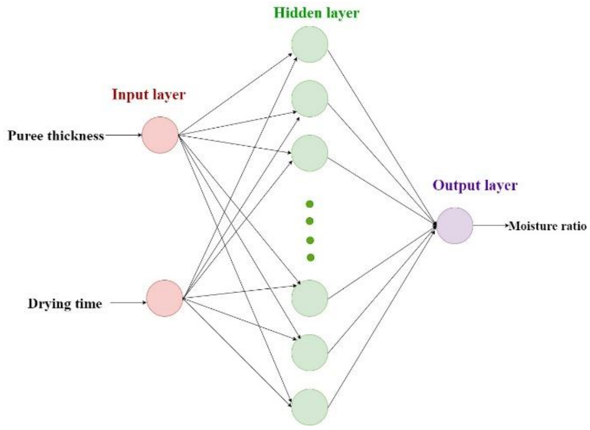

Figure 2. Diagrammatic representation of the ANN model.

2.6. Physicochemical Quality Analysis

2.6.1. Color Characteristics

The color in terms of L*, a* and b* values of the sample was measured by using a colorimeter (Konica Minolta Sensing Inc., Japan). The total color difference [43], chroma [43], and hue angle [44] were calculated using Equations (8)–(10), respectively.

$$\text{Total color difference } (\Delta E) = ((L_o - L^*)^2 + (a_o - a^*)^2 + (b_o - b^*)^2)^{1/2} \quad (8)$$

$$\text{Chroma} = (a^{*2} + b^{*2})^{1/2} \quad (9)$$

$$\text{Hue angle} = \tan^{-1} (b^*/a^*) \text{ when } 0^\circ < a^* < 90^\circ \text{ and } 0^\circ < b^* < 90^\circ \quad (10)$$

where L_o, a_o and b_o value represents a color parameter for the fresh sample.

2.6.2. Hygroscopicity (Absorbed Moisture per 100 g Dry Solids)

Hygroscopicity is described as a powder's capacity to absorb moisture from a high relative humidity environment. It was measured using the method adopted by Shirkole and Sutar [45]. Onion powder (approximately 2 g) was incubated in a desiccator with a saturated solution of sodium sulphate (Molychem, India) for 7 days at 25 °C, and the final weight of powder was recorded.

2.6.3. Pyruvic Acid Content (µmol/g dw) (PAC)

The enzyme alliinase, found in the cytoplasm of onion cells, comes into contact with the flavor precursors, S-alk(en)yl-L-cysteine sulphoxides, when they are ruptured mechanically. Furthermore, stoichiometric quantities of ammonia and pyruvic acid are released during the enzymatic degradation of the S-alk(en)yl-L-cysteine sulphoxides [46,47]. As a result, PAC was determined to indicate onion flavor intensity using a spectrophotometric technique [48].

2.6.4. Total Phenolic Content (mg Gallic Acid Equivalent (GAE)/100 g dw) (TPC)

The amount of TPC in the methanolic extract was determined with Folin–Ciocalteu reagent, according to the method of McDonald et al. [49]. Using a spectrophotometer (Spectroscan 80DV, Biotech Engineering Management Company Limited, Nicosia, Cyprus), the absorbance of each sample was measured at 760 nm against a reference blank, prepared similarly with no sample or standard. TPC was calculated from a standard curve of gallic acid. The concentration of gallic acid solution was taken in a range of 5–25 µg/mL for preparing the standard curve.

2.6.5. Total Flavonoid Content (mg Quercetin Equivalent (QE)/100 g dw) (TFC)

Using the Carvalho and Clemente [50] method, the TFC value was evaluated. In spectrophotometer measurements at 415 nm, the absorbance of sample was compared to a methanol reference blank. The TFC was estimated using the quercetin standard curve. The concentration of quercetin solution was taken in a range of 5–25 μg/mL for preparing the standard curve.

2.6.6. Antioxidant Capacity (%) (AC)

As described by de Ancos et al. [51], a free radical-scavenging test was conducted. Aliquots of 0.1 mL samples were collected in a test tube for estimation. It was placed in the dark for 45 min after the addition of a 3.9 mL 2,2-diphenyl-1-picrylhydrazyl (DPPH) (HiMedia Laboratories, India) solution. Discoloration in the solution was measured at 515 nm using a spectrophotometer. AC was calculated using Equation (11).

$$\mathrm{AC} = \frac{A_o - A_s}{A_o} \times 100 \quad (11)$$

where A_o is the absorbance value of control sample and A_s is the absorbance value of dried sample.

2.7. Thermal Analysis

Thermal characteristics were determined using a differential scanning calorimeter (DSC) (Mettler Toledo DSC 821, Mettler Toledo, Switzerland). Powder samples (4 mg) were analyzed in hermetically sealed Tzero aluminum pans with nitrogen gas (25 mL/min) at a heating rate of 10 °C/min. The on-set temperature (T_1), peak temperature (T_p), end-set temperature (T_2), enthalpy (ΔH), and specific heat capacity (C_p) were all measured [52,53].

2.8. Statistical Analysis

The non-linear regression analysis was carried out using the Origin Pro 8.5 program. The drying curve fits were evaluated using the reduced chi-square (χ^2), RMSE, and R^2. Using R (4.0.5) software; analysis of variance (ANOVA) was employed to test the influence of parameters such as puree thickness and drying technique. The analysis findings were utilized to assess the significant difference between the various parameters at $p < 0.05$.

3. Results and Discussion

3.1. Drying Kinetics and Drying Models

Both the RWD and CD techniques revealed a considerable variance in the MR of onion purees of varying thicknesses. Figure 3 shows that, as the thickness of the onion puree increased from 2 to 6 mm, the drying time of the sample rose from 135 to 240 min for RWD and from 510 to 660 min for CD, respectively. Drying times for RWD samples were 135 min, 195 min, and 240 min, whereas drying times for CD samples were 510 min, 600 min, and 660 min for puree thicknesses of 2 mm, 4 mm, and 6 mm, respectively, to reach a final moisture content of <7% wb. Irrespective of the drying method, with an increase in the thickness of the puree, drying time increased. A rise in puree thickness may result in an increase in the distance water molecules have to travel to escape from the sample surface, causing an increase in drying time [54,55]. Similar outcomes were observed by Castoldi et al. [56] and Rajoriya et al. [54] for tomato and banana puree dried using an RW dryer, respectively.

There was a considerable degree of fit between all models. For RWD, all models except the Logarithmic and Two-term models had R^2 values higher than 0.9282 (Table 1). Statistical analysis revealed that the Lewis model had the lowest SEE, RMSE, and χ^2 value and the highest R^2 value. However, for CD, all models studied had an R^2 value higher than 0.9450 for all thicknesses of puree (Table 2). Statistical analysis showed that the Wang and Singh model had the highest R^2 and lowest RMSE, SEE, and χ^2 values. Figure 3 depicts a fitted plot for MR against time for both experimental and predicted data, using the Lewis model for RWD and the Wang and Singh model for CD, respectively. The lowest χ^2 values of these models suggested goodness of fit among the experimental and predicted data, suggesting that all the residuals are close to zero or randomly distributed [57]. Table 1 showed that, with a decrease in the thickness of puree, the k value of the Lewis model increased. As the k value increases, the drying curve becomes steeper, indicating faster drying [58].

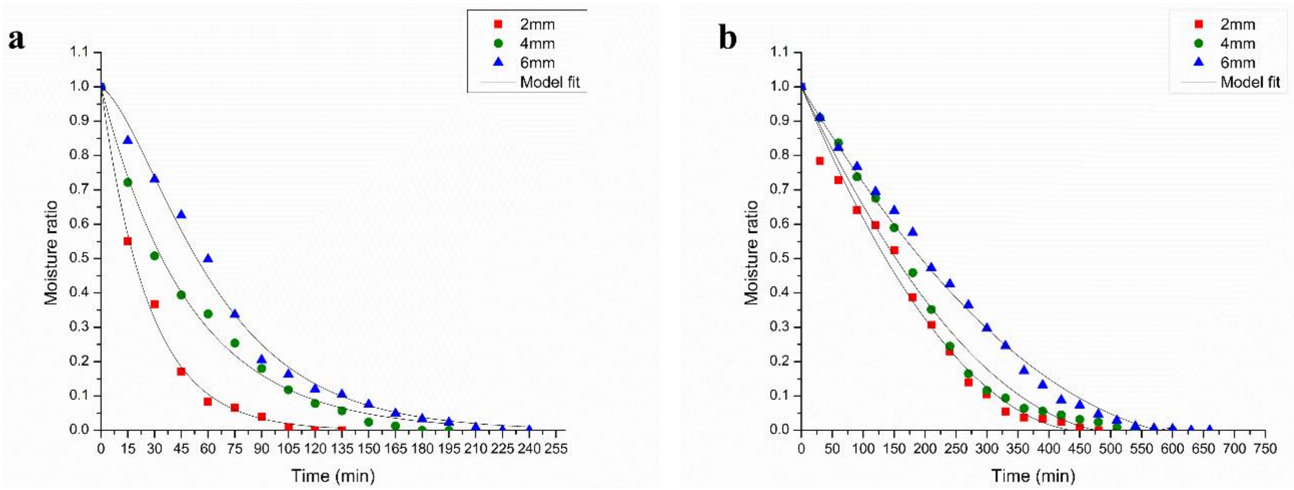

Figure 3. Moisture ratio vs time with best-fit model line: (**a**) RW dryer and (**b**) convective dryer.

Table 1. Mathematical models used to predict the moisture ratio values and regression coefficients with statistical parameters of RW-dried samples.

Model and Equation	Thickness of Puree (mm)	Coefficients						R^2	RMSE	SEE	χ^2
		k	n	A	b	k_0	k_1				
Lewis MR = exp(−kt)	2	0.0375	-	-	-	-	-	0.9966	0.0019	0.0011	0.0001
	4	0.0203	-	-	-	-	-	0.9939	0.0024	0.0005	0.0010
	6	0.0147	-	-	-	-	-	0.9945	0.0055	0.0008	0.0030
Page MR = exp(−kt^n)	2	0.0359	1.0122	-	-	-	-	0.9962	0.0201	0.0032	0.0001
	4	0.0220	0.9804	-	-	-	-	0.9935	0.0245	0.0072	0.0010
	6	0.0027	1.3881	-	-	-	-	0.9946	0.0242	0.0088	0.0010
Henderson & Pabis MR = a × exp(−kt)	2	0.0375	-	0.9986	-	-	-	0.9962	0.0201	0.0032	0.0001
	4	0.0200	-	0.9888	-	-	-	0.9936	0.0244	0.0071	0.0010
	6	0.0157	-	1.0727	-	-	-	0.9765	0.0505	0.0383	0.0030
Exponential two term MR = a × exp(−kt) + (1−a) × exp(−kat)	2	0.0407	-	1.3261	-	-	-	0.9963	0.0199	0.0032	0.0001
	4	0.5373	-	0.0364	-	-	-	0.9938	0.0237	0.0067	0.0010
	6	0.0217	-	1.9195	-	-	-	0.9935	0.0266	0.0106	0.0010
Wang and Singh (MR = 1 + at + bt^2)	2	-	-	−0.0217	0.0001	-	-	0.9282	0.0875	0.0612	0.0077
	4	-	-	−0.0133	0.0000	-	-	0.9563	0.0635	0.0484	0.0040
	6	-	-	−0.0103	0.0000	-	-	0.9883	0.0357	0.0191	0.0013
Modified Page MR = exp(−$(kt)^n$)	2	0.0374	1.0127	-	-	-	-	0.9962	0.0032	0.0032	0.0004
	4	0.0204	0.9813	-	-	-	-	0.9935	0.0072	0.0072	0.0006
	6	0.0140	1.3892	-	-	-	-	0.9946	0.0088	0.0088	0.0006
Logarithmic MR = a × exp(−kt) + b	2	-1.0345×10^5	-	0.9069	0.0931	-	-	0.3545	0.9621	0.4809	0.0687
	4	-1.2592×10^5	-	0.8353	0.1647	-	-	0.1532	1.3262	1.1704	0.1064
	6	-1.4552×10^5	-	0.8010	0.1990	-	-	0.3820	2.3875	2.1020	0.1501
Two-term MR = a × exp(−k_0t) + b × exp(−k_1t)	2	-	-	0.5000	0.5000	-6.2388×10^4	-6.2288×10^4	0.2469	0.9831	0.4809	0.0802
	4	-	-	0.5000	0.5000	-8.2619×10^4	-8.1619×10^4	0.2686	1.9421	1.1704	0.1170
	6	-	-	0.5000	-9.5298×10^4	0.5000	-9.6298×10^4	0.4884	2.9021	2.1020	0.1617

Table 2. Mathematical models used to predict the moisture ratio values and regression coefficients with statistical parameters of convective-dried samples.

Model and Equation	Thickness of Puree (mm)	Coefficients						R^2	RMSE	SEE	χ^2
		k	n	a	b	k_0	k_1				
Lewis MR = exp(−kt)	2	0.0060	-	-	-	-	-	0.9590	0.0629	0.0647	0.0042
	4	0.0050	-	-	-	-	-	0.9450	0.0789	0.0809	0.0065
	6	0.0040	-	-	-	-	-	0.9530	0.0710	0.0726	0.0053
Page MR = exp(−kt^n)	2	0.0010	1.3390	-	-	-	-	0.9790	0.0456	0.0469	0.0022
	4	0.0002	1.6666	-	-	-	-	0.9900	0.0231	0.0237	0.0006
	6	0.0001	1.4970	-	-	-	-	0.9921	0.4543	0.4655	0.2167
Henderson & Pabis MR = a × exp(−kt)	2	0.0060	-	1.0400	-	-	-	0.9610	0.0612	0.0630	0.0040
	4	0.0060	-	1.1210	-	-	-	0.9590	0.0680	0.0697	0.0049
	6	0.0050	-	1.0960	-	-	-	0.9620	0.0633	0.0648	0.0042
Exponential two-term MR = a × exp(−kt) +(1−a) × exp(−kat)	2	8.2940	-	0.0010	-	-	-	0.9590	0.0629	0.0648	0.0042
	4	0.0080	-	2.0650	-	-	-	0.9890	0.0356	0.0365	0.0013
	6	0.0060	-	1.9520	-	-	-	0.9860	0.0377	0.0385	0.0015
Wang and Singh (MR = 1 + at + bt^2)	2	-	-	−0.0043	0.0000	-	-	0.9886	0.0345	0.0191	0.0012
	4	-	-	−0.0038	0.0000	-	-	0.9944	0.0430	0.0351	0.0019
	6	-	-	−0.0030	0.0000	-	-	0.9953	0.0229	0.0110	0.0005
Modified Page MR = exp(−$(kt)^n$)	2	0.0060	1.3390	-	-	-	-	0.9790	0.0456	0.0469	0.0022
	4	0.0050	1.6660	-	-	-	-	0.9920	0.0231	0.0237	0.0006
	6	0.0040	1.4970	-	-	-	-	0.9910	0.0291	0.0298	0.0009
Logarithmic MR = a × exp(−kt) + b	2	0.0040	-	1.1850	−0.1921	-	-	0.9830	0.0419	0.0431	0.0019
	4	0.0040	-	1.2250	−0.1451	-	-	0.9777	0.0502	0.0514	0.0026
	6	0.0030	-	1.3030	−0.2680	-	-	0.9900	0.0333	0.0341	0.0012
Two-term MR = a × exp(−k_0t) + b × exp(−k_1t)	2	-	-	0.3610	0.6790	0.0060	0.0070	0.9610	0.0613	0.0631	0.0040
	4	-	-	0.6560	0.4650	0.0060	0.0060	0.9590	0.0680	0.0697	0.0049
	6	-	-	0.5850	0.5110	0.0050	0.0060	0.9620	0.0633	0.0648	0.0042

3.2. Effective Moisture Diffusivity

To assess moisture diffusivity, the slopes approach was utilized, which entails plotting ln(MR) vs drying time (t) with respect to data obtained at various thicknesses of onion puree dried using RWD and CD methods. Table 3 displays the D_{eff} values and accompanying coefficients of determination (R^2) at various thicknesses of puree. This investigation showed that D_{eff} values of onion puree ranged from 2.509×10^{-7} to 9.446×10^{-7} m^2/s for RWD and 1.234×10^{-7} to 9.379×10^{-7} m^2/s for CD, respectively. It was noted that D_{eff} values increased with the increasing thickness of the puree, which was in accordance with Akinola and Ezeorah [59]. Furthermore, the D_{eff} values obtained in the current study were within the general range of 10^{-7}–10^{-14} m^2/s for various food products [60,61].

Table 3. Effective moisture diffusivity values for different samples.

	Thickness of Puree (mm)	Effective Moisture Diffusivity		
		Slope	D_{eff} (m^2/s)	R^2
RWD	2	0.619	2.509×10^{-7}	0.970
	4	0.368	5.976×10^{-7}	0.963
	6	0.259	9.446×10^{-7}	0.968
CD	2	0.304	1.234×10^{-7}	0.934
	4	0.285	4.628×10^{-7}	0.948
	6	0.256	9.376×10^{-7}	0.913

3.3. ANN Modelling

An artificial neural network (ANN) was developed using a multi-layer feed-forward topology, and these topologies were evaluated in order to determine the number of hidden neurons. According to Figure 4, the MSE is plotted against the number of hidden neurons to illustrate how the number of hidden neurons affects the performance of the artificial neural network. An optimal model has a lower MSE value, along with the highest R value. In both RWD and CD, a three-layered topology with hidden neurons was the most effective (2-12-1 for RWD and 2-18-1 for CD). ANN predicted R values for training, validation, and testing of 0.999, 0.998, and 0.975, and 0.999, 0.999, and 0.996 for RWD and CD, respectively (Figure 5). This figure illustrates the best ANN model prediction for the MR of sample variation during the RWD and CD processes. For all puree thicknesses, Figure 6 displays both the experimental and projected MR. Based on the results obtained in this study, it appears that the MLF- ANN with a back-propagation algorithm can be used for predicting the drying kinetics of RWD and CD of onion puree.

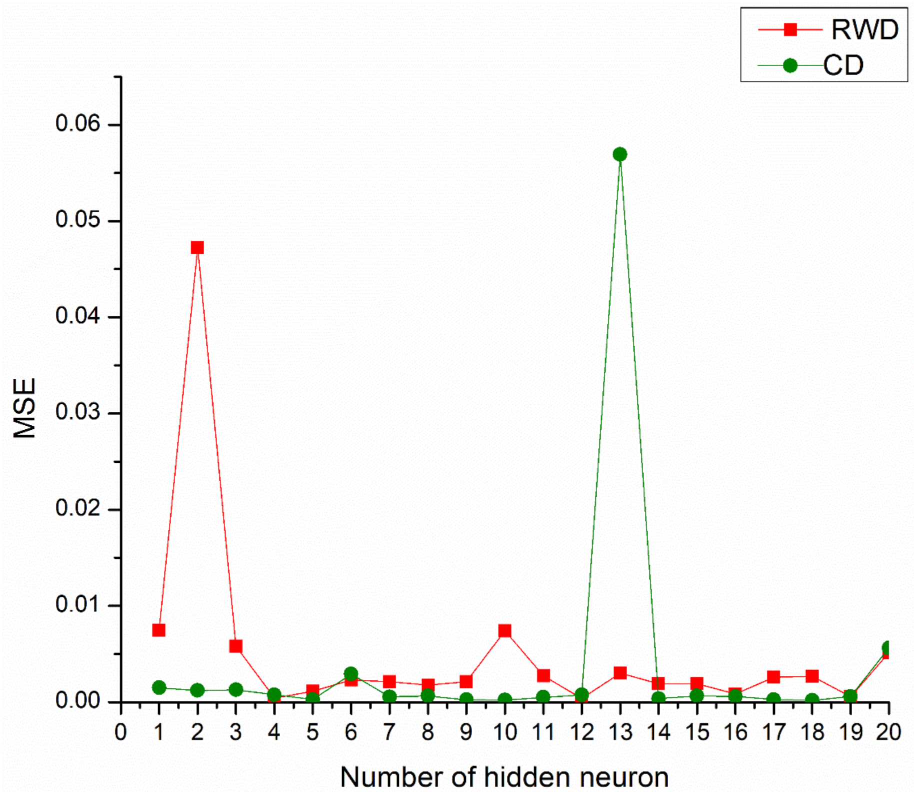

Figure 4. Performance evaluation of the ANN model.

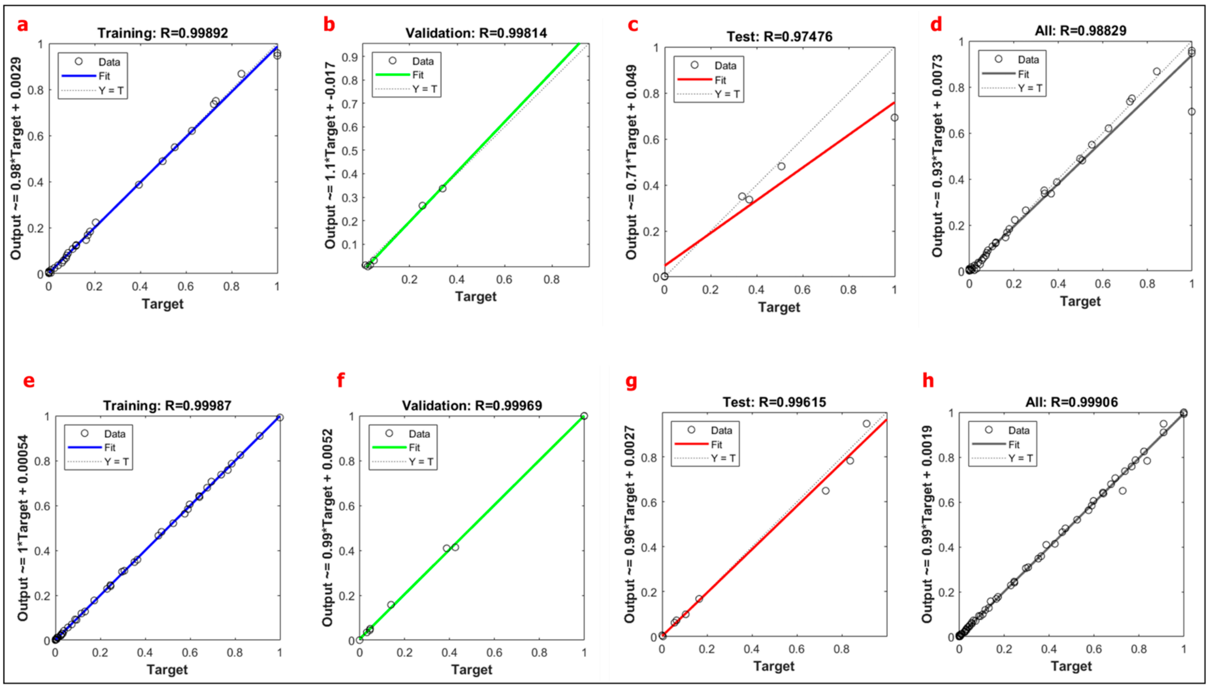

Figure 5. Regression plot obtained using ANN: (**a**–**d**) RW dryer and (**e**–**h**) convective dryer.

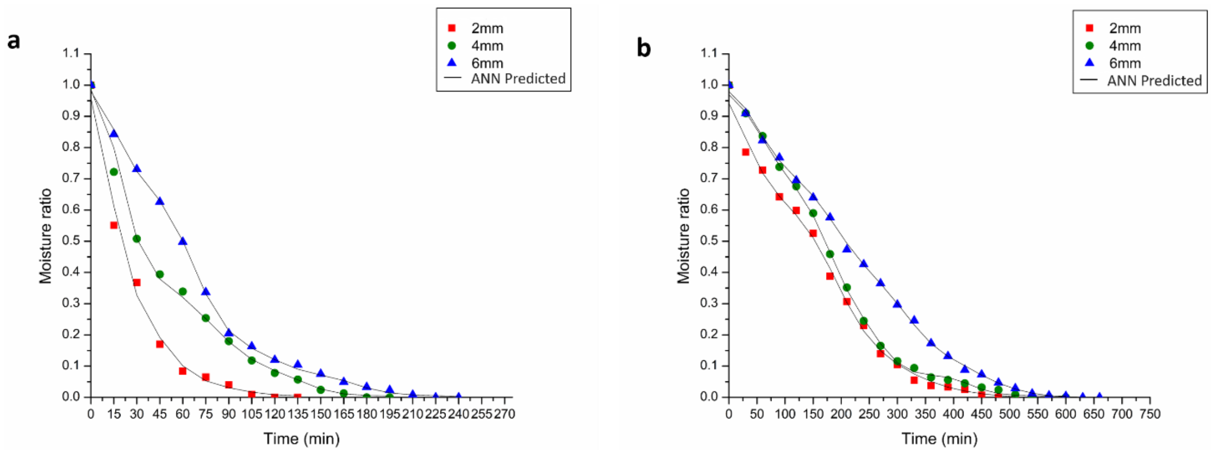

Figure 6. Model prediction through ANN and experimental data of moisture ratio of (**a**) RW dryer and (**b**) convective dryer.

3.4. Comparison between the Best Drying Model and ANN Model

Table 4 shows the R^2 and RMSE values of the best drying model and ANN model. It was observed that the ANN model showed a higher R^2 value and lower RMSE value when compared to the best drying model for both drying methods. The ANN model was able to predict the MR for both drying methods with a reasonable level of accuracy. Independent of the parameters used, the prediction capability of the trained ANN model was better than that of the drying models. Similar results were reported by Jafari et al. [62] for heat pump-assisted fluidized bed-dried green bell pepper and by Tarafdar et al. [63] for freeze-dried button mushrooms.

Table 4. R^2 and RMSE values of the best drying model and ANN model.

Models		**RWD**			**CD**		
		2 mm	**4 mm**	**6 mm**	**2 mm**	**4 mm**	**6 mm**
Best drying model	R^2	0.9966	0.9939	0.9945	0.9886	0.9944	0.9953
	RMSE	0.0019	0.0024	0.0055	0.0345	0.0430	0.0229
ANN model	R^2	0.9971	0.9943	0.9992	0.9958	0.9986	0.9983
	RMSE	0.0008	0.0005	0.0001	0.0004	0.0001	0.0001

Note: Best drying models for RWD and CD are the Lewis model and the Wang and Singh model, respectively.

3.5. Physicochemical Quality Analysis

3.5.1. Color Characteristics

Color is a key factor that determines the organoleptic qualities of a dried sample [64,65]. The intensity of heat treatment also has an effect on color; harsher treatment reduces quality [66]. The value of color parameters viz. L*, a*, b*, ΔE, hue angle, and chroma of onion powder are shown in Table 5. It was observed that, irrespective of the puree thickness, there was a significant decrease in luminosity (L* value) of convective-dried samples when compared to RW-dried samples. This is due to the high temperature and prolonged exposure durations during the drying process [67]. Since red predominated in onion puree, parameter a* on the Hunter scale was the best choice to differentiate color changes brought on by drying. Similarly, there was a significant decrease in the a* and b* values of convective-dried samples when compared to RW-dried samples. The positive b* value suggested yellow color in the powder that was due to the presence of flavonols (color pigment present in onion). The hue angle also suggested that the color of the sample remained in the first quadrant of the Hunter scale, and RW-dried samples had better retention of a red color than convective-dried samples. Table 5 also showed that, irrespective of the thickness of the puree, ΔE was significantly affected by the drying method. As a result, RW-dried samples had significantly lower color degradation than convective-dried samples (Figure 7). A similar trend was observed by Zalpouri et al. [9] for potato flakes and Tontul et al. [68] for cherry powder dried using a RW dryer and convective dryer.

Table 5. Physicochemical qualities of RW- and convective-dried samples.

Physicochemical Qualities	RWD			CD		
	2 mm	4 mm	6 mm	2 mm	4 mm	6 mm
Moisture content (%wb)	5.115 ± 0.007^{f}	5.735 ± 0.035^{e}	5.914 ± 0.005^{d}	6.025 ± 0.021^{c}	6.100 ± 0.014^{b}	6.725 ± 0.021^{a}
L*	78.600 ± 0.001^{a}	78.400 ± 0.141^{a}	78.850 ± 0.070^{a}	63.500 ± 3.818^{b}	67.250 ± 0.637^{b}	65.500 ± 0.141^{b}
a*	3.550 ± 0.495^{ab}	3.750 ± 0.071^{a}	3.400 ± 0.141^{ab}	0.250 ± 0.212^{c}	2.250 ± 0.071^{b}	0.750 ± 0.778^{c}
b*	24.000 ± 0.036^{a}	23.250 ± 0.141^{ab}	21.500 ± 0.141^{b}	17.450 ± 1.485^{c}	21.550 ± 0.212^{b}	18.350 ± 0.495^{c}
ΔE	3.965 ± 0.037^{b}	3.463 ± 0.016^{b}	3.791 ± 0.117^{b}	13.066 ± 3.991^{a}	8.072 ± 0.651^{ab}	10.825 ± 0.176^{a}
Hue angle	81.586 ± 1.156^{c}	80.835 ± 0.307^{c}	81.015 ± 0.310^{c}	89.206 ± 0.629^{a}	84.040 ± 0.128^{bc}	87.628 ± 0.385^{ab}
Chromaticity	11.778 ± 0.054^{a}	11.005 ± 0.359^{ab}	9.314 ± 0.117^{b}	6.954 ± 0.959^{c}	9.609 ± 0.185^{b}	7.313 ± 0.845^{b}
Hygroscopicity (absorbed moisture per 100 g dry solids)	3.711 ± 0.115^{b}	3.815 ± 0.095^{b}	3.985 ± 0.0297^{b}	4.136 ± 0.007^{a}	4.166 ± 0.166^{a}	4.193 ± 0.023^{a}
Pyruvic content (μmol/g dw)	0.566 ± 0.042^{a}	0.546 ± 0.061^{b}	0.495 ± 0.078^{c}	0.437 ± 0.037^{d}	0.381 ± 0.024^{e}	0.338 ± 0.035^{f}
Total phenolic content (mg GAE/100 g dw)	30.038 ± 0.094^{a}	29.865 ± 0.019^{a}	29.793 ± 0.047^{a}	25.207 ± 0.085^{b}	24.932 ± 0.104^{b}	24.478 ± 0.132^{c}
Total flavonoids content (mg QE/100 g dw)	12.819 ± 0.049^{a}	12.728 ± 0.113^{a}	12.266 ± 0.109^{b}	10.802 ± 0.227^{c}	10.684 ± 0.019^{c}	10.675 ± 0.007^{c}
Antioxidant capacity (%)	89.934 ± 0.700^{a}	88.394 ± 0.701^{ab}	88.064 ± 0.388^{b}	88.284 ± 0.389^{ab}	87.844 ± 0.233^{b}	87.403 ± 0.078^{b}

Note: Mean ± standard deviation; similar letters in row have no significant difference ($p < 0.05$).

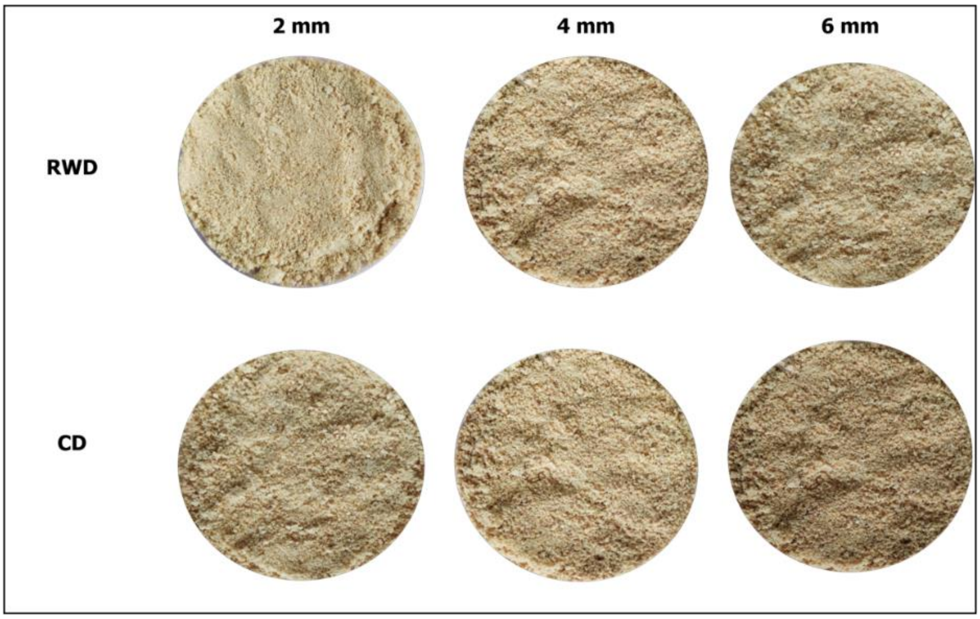

Figure 7. Onion powder samples obtained at varying thicknesses of puree.

3.5.2. Hygroscopicity

Food powders are particularly hygroscopic, due to their low moisture and water activity [69]. The hygroscopicity of powders may differ depending on their nature, porosity, the presence of glassy amorphous forms of sugar, and how much water they hold from the surrounding atmosphere [70,71]. Therefore, it is crucial to determine the hygroscopicity of powder. Table 5 shows that, irrespective of the drying method hygroscopicity increased with an increase in the thickness of the puree, but this increase was found to be non-significant. While comparing drying methods, RW-dried samples had a lower hygroscopicity value than convective-dried samples. It was observed that the drying method had a significant effect ($p < 0.05$) on the hygroscopicity value of onion powders. The higher value of hygroscopicity was found for a convective-dried sample with a puree thickness of 6 mm, whereas a lower value was found for an RW-dried sample with a puree thickness of 2 mm. The higher value of hygroscopicity was attributed to a high moisture content of powder, the high porosity of the product or the presence of a glassy amorphous state in the sugars [70,72]. Table 5 also showed that a higher value of hygroscopicity was observed for samples with higher moisture content values. The moisture–hygroscopicity correlation, however, cannot be generalized to all powder samples. A similar pattern was discovered by Tontul et al. [73] for Kefir powder dried in a RW dryer; as the thickness of the kefir sample increased, the hygroscopicity of the dried powder increased.

3.5.3. Pyruvic Acid Content (PAC)

The PAC has been utilized as a pungency indicator in onions. Pungency is typically lost with dehydration, which might be caused by heat and other degradative changes in pyruvic acid. Therefore, it is important to measure the PAC of onion products. The PAC of fresh onion was found to be 1.153 ± 0.021 µmol/g dw. The interaction effect of the thickness of the puree and drying method was significant ($p < 0.05$) on PAC. Table 5 illustrates that, irrespective of the drying method, pyruvic acid decreased with an increase in the thickness of the puree. The highest PAC was observed for 2 mm-thick puree dried using the RWD method, whereas the lowest was found in 6 mm-thick puree dried using the CD method. While comparing drying methods, RW-dried samples had higher PAC than convective-dried samples. The reduction in pyruvic acid concentration was linked to alliinase losses at high temperatures and prolonged drying [74]. Furthermore, increased onion puree thickness resulted in a longer drying period, causing a drop in pyruvic acid concentration [75].

3.5.4. Total Phenolic Content (TPC)

The production of total phenols in fruits and vegetables increases multiple defense genes, which help fight inflammation, oxidative stress, and platelet activation [76]. Hence, it is critical to analyze the retention of total phenols in dried products. The interaction effect of the thickness of the puree and drying method was non-significant ($p > 0.05$) on TPC, whereas the drying method had a significant ($p < 0.05$) effect on TPC. TPC is sensitive to heat treatment; therefore, it is significantly affected by the drying method [77]. Table 5 illustrates, that irrespective of the drying method, TPC decreased with an increase in the thickness of the puree, but there was no significant difference observed among them. The highest TPC was observed for 2 mm-thick puree dried using the RWD method, whereas the lowest was found in 6 mm-thick puree dried using the CD method. It was observed that the TPC of RW-dried samples was significantly higher than convective-dried samples. This was due to the binding of phenolic compounds to proteins or changes in their chemical structures caused by the effects of heat on tannin compounds, as well as cell destruction and vacuole destruction. High temperatures and prolonged drying processes decompose tannins, which are hydrolysable compounds [78]. Due to the longer processing time of CD compared to RWD, the phenolic content in the samples decreases during CD. Padhi and Dwivedi [20] and Seyfi et al. [79] found that RW-dried unripe banana powder and aloe vera powder, respectively, had higher total phenol retention than a convective-dried sample.

3.5.5. Total Flavonoid Content (TFC)

As antioxidants, antibacterial, antiviral, and anti-inflammatory compounds, flavonoids have been found to be beneficial for human health, as well as potential-reducing agents that protect from oxidative damage due to hydroxyl groups [80,81]. The retention of flavonoids in dried products is important, since they also function as free radical scavengers [82]. The interaction effect of the thickness of puree and drying method was non-significant ($p > 0.05$) on TFC, whereas the drying method had a significant ($p < 0.05$) effect on TFC. Table 5 illustrates, that irrespective of the drying method, TFC decreased with an increase in the thickness of the puree, but the decrease was not significant. The highest TFC was observed for 2 mm-thick puree dried using the RWD method, whereas the lowest was found in 6 mm-thick puree dried using the CD method. The TFC of convective-dried samples was found to be significantly lower than that of RW-dried samples. This is explained by the possibility that prolonged heating time degraded flavonoids [83,84]. Padhi and Dwivedi [20] found that RW-dried unripe banana powder had higher total flavonoid retention than a convective-dried sample.

3.5.6. Antioxidant Capacity (%) (AC) by DPPH Assay

In foods and biological systems, AC is determined by redox molecules' ability to scavenge free radicals. The powder with a higher level of antioxidants scavenges free radicals more readily. In this regard, the AC of onion powder should be measured [85]. The interaction effect of the thickness of the puree and drying method was significant ($p < 0.05$) on AC, whereas the thickness of the puree had a non-significant ($p > 0.05$) effect on AC. Table 5 illustrates the AC of samples at the variable thicknesses and different drying methods. The highest AC was observed for 2 mm-thick puree dried using the RWD method, whereas the lowest was found in 6 mm-thick puree dried using the CD method. It was observed that the RWD method resulted in maximum AC in dried samples when compared to the CD method. The decrease of AC in convective-dried onion powder can be caused by prolonged exposure of puree to heated air, causing an oxidation reaction in the product. When compared to CD, RWD requires less drying time. Due to this, phenolic compounds bound in the cell matrix are released more readily because of the high local vapor pressure produced by moisture evaporation [86,87]. Consequently, this condition prevented the oxidation of antioxidants in onion puree. A similar pattern was seen by Nindo et al. [87] for asparagus puree; Asiimwe et al. [21] for passionfruit puree; and Padhi and Dwivedi [20] for unripe green banana puree.

3.6. Thermal Analysis

Dry onion powder obtained using RWD and CD can be tested for shelf stability by measuring its glass transition temperature (T_g), as this influences physical properties such as stickiness, caking, and agglomeration [88,89]. The best sample obtained in both the drying techniques in terms of low drying time and higher physicochemical quality was used for determining T_g. Figure 8 represents the thermograms of 2 mm-thick puree dried using both methods. Table 6 shows a substantial ($p < 0.05$) rise in T_1, T_p, and T_2 values in RW- than convective-dried onion powder. The gelatinization temperature was the same as the T_p. The ΔH value of the RW-dried sample was low when compared to the convective-dried sample because of variation in crystal stability [20]. The C_p value of the RW-dried sample was lower when compared to the convective-dried sample. The lower T_g can cause an increase in caking, stickiness, and agglomeration of the sample during transportation and storage. The low T_g of the convective-dried sample might be ascribed to the high total sugar content or high value of water activity (a_w) [52,90]. Water plasticized the amorphous content of the food matrix, resulting in this inverse relationship between T_g and a_w [90]. A similar observation was quoted by Padhi & Dwivedi [20] for unripe green banana flour, where T_g of the RW-dried sample was higher when compared to convective-dried samples.

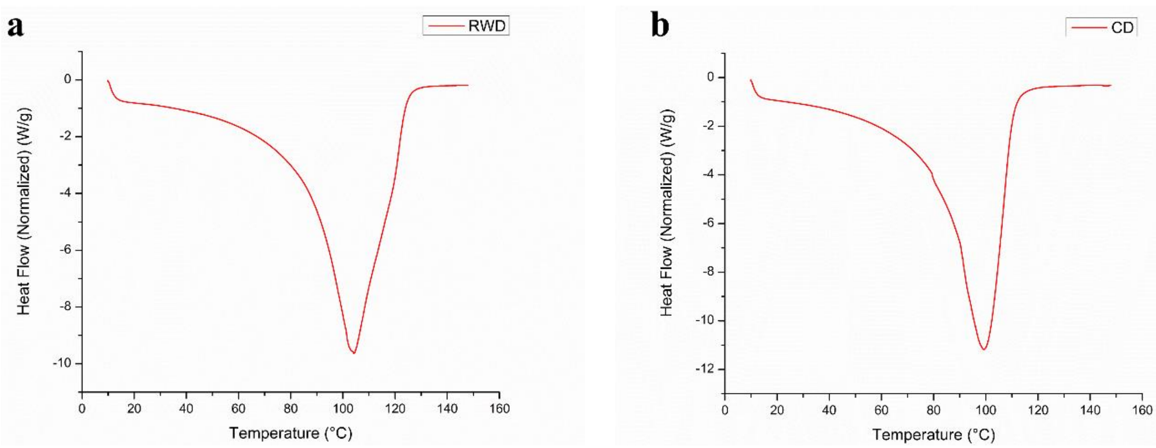

Figure 8. Thermal analysis of (**a**) RW-dried and (**b**) convective-dried onion powder.

Table 6. Thermal properties of RW- and convective-dried onion powder.

Thermal Properties	RWD	CD
On-set temperature (T_1) (°C)	69.061 [a]	53.056 [b]
Peak temperature (T_p) (°C)	103.838 [a]	99.561 [b]
End-set temperature (T_2) (°C)	127.682 [a]	113.334 [b]
Specific heat capacity (C_p) (J/g °C)	105.087 [b]	2337.515 [a]
Enthalpy (ΔH) (J/g)	28.912 [b]	32.377 [a]

Note: Similar letters in a row have no significant difference ($p < 0.05$).

4. Conclusions

In this study, onion puree of varying thicknesses were dried using RWD and CD methods to evaluate drying kinetics, physicochemical qualities, and thermal analysis of the dried powder. It was observed that, with an increase in thickness of the puree from 2 to 6 mm, drying time increased from 135 to 240 min for RWD and 510 to 660 min for CD. The Lewis model and the Wang and Singh model for RWD and CD, respectively, were found to be the best-fit models among eight selected models. The effective moisture diffusivity also increased with respect to thickness (2.509×10^{-7} to 9.446×10^{-7} m^2/s for RWD and 1.234×10^{-7} to 9.376×10^{-7} m^2/s for CD). To predict accurate MR of onion puree using RWD and CD, MLF- ANN with a back-propagation algorithm was used. ANN was found to be an effective method to predict MR for both drying methods. Further, physicochemical quality showed that RW-dried onion powder had higher L*, a*, b* values, chroma, PAC, TPC, TFC and AC, as well as the lowest ΔE, hue angle and hygroscopicity values compared to convective-dried samples. Among all the samples, 2 mm-thick puree produced better-quality dried powder, which was further used to analyze the thermal properties of the powder. It was also concluded that RW-dried powder had a higher T_g value than a convective-dried sample. Thus, the onion powder produced using RWD can be further incorporated in ready-to-serve meals, soup, and for seasoning various cuisines, etc. Since this study compares the effect of variable thicknesses of puree and one drying temperature, further research can be conducted to analyze the combined effect of varying thicknesses and drying temperatures. Additionally, based on the research conducted, it can be inferred that the RW dryer can be upscaled and used by small/medium industries for batch production of onion powder with better nutritive quality.

Author Contributions: Conceptualization, R.Z., M.S. and P.K.; Methodology, R.Z. and K.K.G.; Software, R.Z. and A.K.; Validation, M.S. and A.S.; Formal analysis, R.Z. and A.K.; Investigation, M.S.; Resources, M.S., P.K., K.K.G. and A.S.; Writing—original draft, R.Z.; Writing—review & editing, R.Z., M.S., P.K. and A.S.; Visualization, A.K.; Supervision, M.S., P.K. and A.K.; Project administration, M.S. and P.K. All authors have read and agreed to the published version of the manuscript.

Funding: No funding was received to perform this research.

Data Availability Statement: The authors have chosen not to specify which data has been used.

Conflicts of Interest: No conflict of interest among authors.

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