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Modelling the influence of hot air on the drying kinetics of turmeric slices

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ABSTRACT

The influence of different drying temperatures and slice thicknesses on the drying kinetics of turmeric slices was studied to show how moisture is removed. The best model for predicting the drying kinetics was also determined. Turmeric slices (3 mm, 5 mm, and 7 mm) were dried at 40, 50, and 60 °C in a laboratory oven dryer. Four thin layer drying models (Newton, Henderson and Pabis, Logarithmic, and Page) were fitted to the experimental data and the selection was done based on the model with the highest correlation coefficient (R^2), and lowest reduced chi-square (χ^2), the sum of square error (SSE), and root mean square error (RMSE). Drying time varied between 420 min and 1140 min as the air temperature increased from 40 °C to 60 °C. The effective moisture diffusivity coefficient increased with increasing drying temperature and was found to be between 1.35×10^{-10} m^2/s, and 5.00×10^{-10} m^2/s, 3.00×10^{-10} m^2/s and 10.91×10^{-10} m^2/s, and 4.56×10^{-10} m^2/s and 13.00×10^{-10} m^2/s at 40 °C, 50 °C, and 60 °C, respectively. The values obtained for the activation energy for moisture diffusion were found to be 56.809, 56.060, and 45.561 kJ/mol for 3, 5, and 7 mm, respectively. The page model was found to best describe the oven drying of turmeric slices.

Introduction

Turmeric (*Curcuma longa* Linn.) belongs to the genus *Curcuma* and the family *Zingiberaceae,* and it consists of many species (Jilani et al., 2012; Olajide et al., 2012). According to Nwaekpe et al. (2015), turmeric is a shallow-rooted and herbaceous plant with a thick and fleshy rhizome. According to some researchers, this rhizome is valued for containing a yellow-coloured phenolic pigment also known as curcumin, which is a natural colouring agent in food, cosmetics, dye, and an active ingredient in the pharmaceutical industries (Singletary, 2010; Karim et al, 2010; Amadi et al, 2015). Amadi et al. (2017) also reported that oleoresin, which is the active ingredient in turmeric, and turmeric oil are used for culinary, confectionary, and pharmaceutical purposes. Turmeric is an important spice which is acceptable both locally and globally as fresh, preserved, dried, and powdered, and in processed forms such as turmeric oil, turmeric oleoresin, turmeric candy, turmeric soft drinks, turmeric shreds, turmeric prickles, ginger chutney etc. (Nwaekpe et al., 2015). Nigeria is the fourth largest producer of turmeric with about 3% of global annual production. This is due to the favourable soil and climatic conditions in the country (Nwaekpe et al., 2015). Turmeric is cultivated mostly on subsistent bases in about 19 of the 36 states in Nigeria. Turmeric, like ginger, has shown a great potential in supporting livelihoods and improving the health and economic level of many turmeric farmers and users in the main producing areas (Amadi et al., 2018).
However, turmeric is highly perishable due to its high moisture content, which must be kept below 14% db to prolong shelf life without further spoilage and reduced quality deterioration. There are other

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preservation technologies on the industrial scale for preserving food products such as canning, freezing, and dehydration. Among these, drying (dehydration) is especially suited for developing countries with poorly established low-temperature and storage facilities. Drying represents effective and practical means of preservation for reducing postharvest losses and off-setting the shortages in supply.

Moreover, in order to overcome the current global energy crisis, an efficient drying process in terms of energy utilization is desirable. According to Afolabi et al. (2015), this can be achieved through understanding and appropriate modelling of the drying characteristics of food crops. Two major factors that affect moisture removal from any food products are the drying air conditions and material dimensions (Afolabi et al., 2015). During drying, heat and mass transfer phenomena occur concurrently, which leads to the development of many models used in describing the drying kinetics of food materials. The determination of drying kinetics of various types of food is very important due to varied responses of different food and biological materials. Several researchers have reported a model that best fits experimental values of various food materials during the drying process. Newton and Page equations are among the most commonly used models for thin-layer drying (Kingsly et al., 2007; Tunde-Akintunde and Afolabi, 2010; Afolabi et al*.,* 2015). Due to the potential of turmeric in solving challenges related to food and pharmaceutical industries, there is a need to study the drying characteristics of turmeric slices in order to understand the food material and also to establish the appropriate modelling of the drying process. Therefore, this study was carried out to (i) determine the drying characteristics of turmeric slices (3 mm, 5 mm, and 7 mm) in a convective hot air oven at temperatures of 40 °C, 50 °C, and 60 °C, and (ii) to fit the obtained experimental data to some of the generally accepted thin-layer drying models, so as to select the model that best describes the drying process.

Materials and methods

Materials

Freshly harvested turmeric rhizomes were procured from the medicinal plant unit of the Bioresources Development Centre, National Biotechnology Development Agency, Ogbomoso, Oyo State. The selection was based on the visual assessment of uniform colour and geometry. The turmeric was cut into slices of 3 mm, 5 mm, and 7 mm thickness using a knife and a Vernier calliper, so as to have a thin layer surface, after which the turmeric slices were dried at 40 °C, 50 °C, and 60 °C in other to maintain the quality of the turmeric using an oven (Gallenkamp BS oven, UK). These thicknesses and temperatures were considered to achieve faster drying, as well as retaining the quality of the turmeric sample. Readings were taken at an interval of 60 min at each varied temperature, until a constant weight was obtained.

Drying kinetics

Moisture content

The initial moisture content of turmeric slices (3 mm, 5 mm, and 7 mm) before drying was determined using a Radway Mac50/NH moisture analyser at 120 °C (Oriola et al*.,* 2020).

Moisture ratio

The moisture ratio (*MR*) for turmeric at different temperatures and slices was obtained by using Equation 1 (Afolabi et al*.,* 2015):

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

where, M is the moisture content at any time t (% db), M_e is the equilibrium moisture content (% db), and M_i is the initial moisture content (% db).

Drying rate

The drying rate (DR) of mushroom slices was calculated using the following equation

$$DR = \frac{M_t - M_{t+\Delta t}}{\Delta t} \quad (2)$$

where $M_{t+\Delta t}$ is the moisture content at $t + \Delta t$ (kg water/kg dry matter) and *t* is time (min).

Effective moisture diffusivity, activation energy

The method reported by Aremu et al. (2013), with Fick's second equation of diffusion, was used to calculate the effective moisture diffusivity (D_{eff}), putting into consideration the constant moisture diffusivity, infinite slab geometry, and a uniform initial moisture distribution.

$$MR = \frac{8}{\pi^2} \exp\left(-\frac{\pi^2 D_{eff}}{4L^2} t\right) \quad (3)$$

where, MR is the moisture ratio, D_{eff} (m^2/s) is the effective moisture diffusivity, L (m) is the sample thickness, and t is the drying time (s).
Equation 2 can be further solved to get Equation (3)

$$\ln MR = \frac{-\pi^2 D_{eff}}{4L^2} t + \frac{\ln 8}{\pi^2} \quad (4)$$

The effective diffusivity (D_{eff}) at each temperature was obtained from the slope of the plot of ln(MR) against time for corresponding temperature data. The Arrhenius equation was used to calculate the activation energy.

$$D_{eff} = D_o e^{\frac{E_a}{R_g(T+273.15)}} \quad (5)$$

where, D_o is the maximum diffusion co-efficient, E_a is the activation energy (kJ/mol), T is temperature (°C), and R_g is the gas constant.

$$\ln D_{eff} = \left[-\frac{1}{R_g(T+273.15)}\right] E_a + \ln D_o \quad (6)$$

The slope of the ln D_{eff} against $-\frac{1}{(T+273.15)}$ was used to obtain the activation energy.

Mathematical modelling

In order to get a suitable model which describes the drying process of turmeric slices, four thin-layer equations were used to fit the drying curves. The moisture ratio models for the turmeric slices are presented in Table 1.

Table 1. Thin layer mathematical models used to describe the drying of turmeric slices

Model name	Model	References
Newton	MR=exp (-kt)	Tiris et al. (1994) and El-Beltagy et al. (2007)
Henderson and Pabis	MR=A exp (-kt)	Henderson and Pabis (1961) and Shittu and Raji (2011)
Logarithmic	MR=a exp (-kt)+c	Wang et al. (2007)
Page	MR=exp (-kt^n)	Doymaz (2007) and Singh et al. (2008)

Statistical analysis

IBM SPSS Statistics version 20 was used to implement the non-linear regression analysis. The coefficient of determination (R^2), reduced mean square of the deviation or the reduced chi-square (χ2), sum square error (SSE), and root mean square error (RMSE) were the parameters that were used to describe the variation in the MR of the dried turmeric slices. The model that had the highest value of R^2 and the lowest values of reduced chi-square, SSE, and RMSE indicates that the model had the best goodness of fit (Tunde-Akintunde and Afon, 2010; Afolabi et al., 2015).
The parameters can be calculated as follows:

$$\chi^2 = \frac{\sum_{i+1}^{N} \left(MR_{(exp,i)} - MR_{(Pred,i)}\right)^2}{N-z} \quad (7)$$

$$SSE = \frac{1}{N} \sum_{i=1}^{N} \left(MR_{(exp,i)} - MR_{(Pred,i)}\right)^2 \quad (8)$$

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^{N} \left(MR_{(pred,i)} - MR_{(exp,i)}\right)^2\right]^{\frac{1}{2}} \quad (9)$$

Results

Determination of the Drying Curve, Moisture Ratio, and Drying Rate Curve

The plots of moisture content against time, as shown in Figure 1, provided the drying curves for the turmeric slices at the observed temperatures (40, 50, and 60 °C). The graphs followed the characteristic curve reported for different food materials (Pal et al., 2008; Afolabi et al., 2015; Olajire et al., 2018). Initially, moisture evaporated rapidly in an exponential way, and it later decreased as drying time increased, until an equilibrium moisture content was reached. The equilibrium moisture content for the turmeric slices was achieved between 420 -1020 min (3 mm), 540 - 1080 min (5 mm), and 660 - 1140 min (7 mm), at drying temperatures of 40 °C, 50 °C, and 60 °C, respectively. There was a reduction in the moisture content as drying time increased. This may be due to the reduction in the available free water that was evaporated during the process of drying. The drying time also increases with turmeric slice thickness at a different temperature. This could be attributed to the fact that the distance the water molecules will travel from the core of a slice with lower thickness to the outer layer where evaporation takes place is shorter compared to high slice thicknesses. This suggests that drying at lower slice thickness helps in reducing drying time, which may reduce the cost of drying (Olajire et al., 2018). Reduction in the total drying time as temperature increased was also observed. This reduction, according to Vega-Galvez et al. (2011), may be due to the increase in vapour pressure available within the product as temperature increases, which in turn results in the rapid migration of moisture to the product surface. Reports on food materials such as kurut (Karabulut et al., 2007), spinach leaves (Doymaz 2009), stone apple (Rayaguru and Routray, 2012), cocoyam (Afolabi et al., 2015), and okro slices (Olajire et al., 2018) are similar to the results of this experiment. The variation curves of the experimental data of the moisture ratio with respect to drying time is shown in Figure 2. The drying of the turmeric slices exhibited a moisture desorption characteristic in which moisture is removed initially at a constant and higher rate, followed by a falling rate that is slower in the latter stages. This characteristic behaviour according to Tunde-Akintunde and Afon (2010) is due to the numerous forms in which water is present in food products. As drying continues, the moisture ratio decreases non-linearly as drying time increases, for all the thicknesses. This trend is supported by the reports on tomatoes (Doymaz, 2007), pre-treated cassava chips (Tunde-Akintunde and Afon, 2010), and pre-treated cocoyam slices (Afolabi et al., 2015), respectively. The drying rate versus drying time curve of the turmeric slices is shown in Figure 3. Higher drying rates were observed at higher drying temperature for each thickness. This, as reported by Lee and Kim (2009), Doymaz (2010), and Rayaguru and Routray (2012), resulted in a more rapid moisture evaporation and subsequently led to a reduction in moisture content, thus reducing the total drying time.

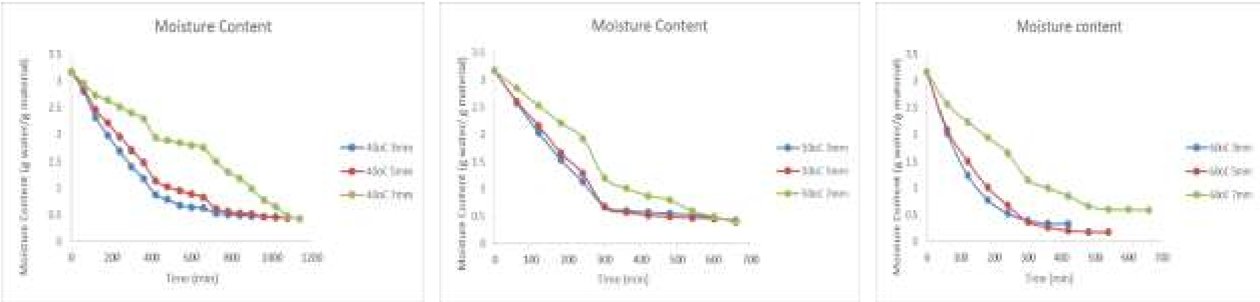

Fig. 1. Graphs of moisture content against drying time for turmeric slices

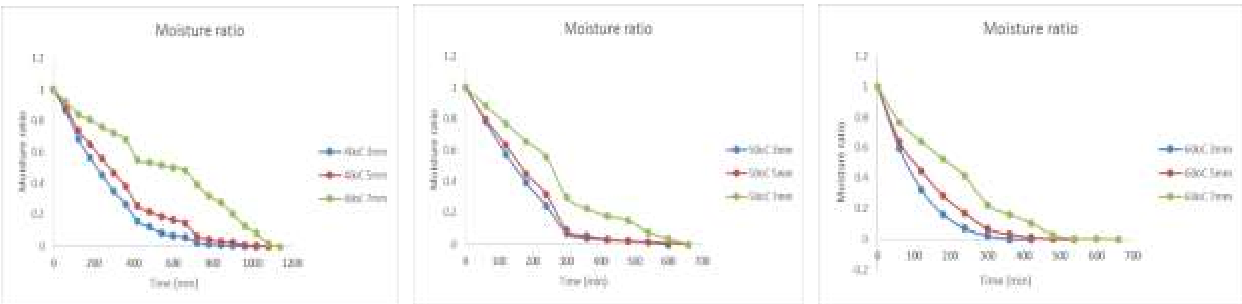

Fig. 2. Graphs of moisture ratio against drying time for turmeric slices

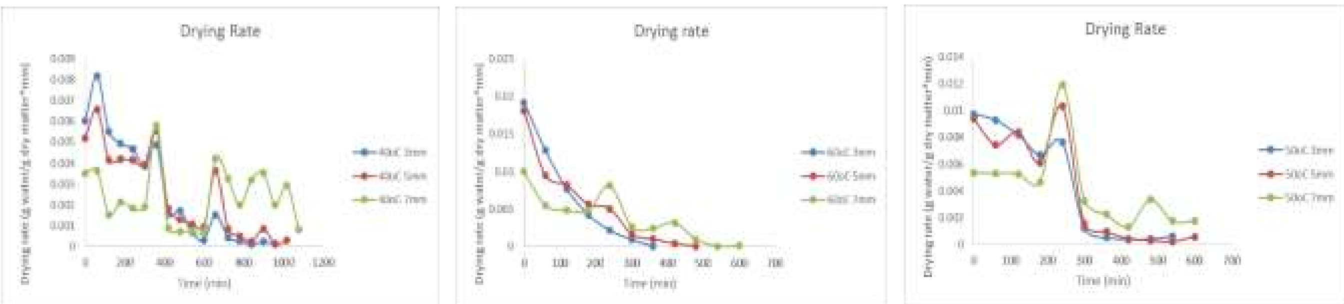

Fig. 3. Graphs of drying rate against drying time for turmeric slices

Effective moisture diffusivity (D_{eff}) and activation energy

Table (2) shows that the D_{eff} for the turmeric slices increases with temperature and decreases as slice thickness increases. This was in line with the report on the drying kinetics of mango slices (Aremu et al., 2013). The trend was a result of water diffusion which increasingly moved from the first phase of drying as drying temperature increased (Ojediran and Raji, 2011). Olajire et al. (2018) reported that moisture diffusion is a major factor responsible for moisture movement in the falling rate drying period, where most of the drying took place. The slopes of the linear plots of $\ln D_{eff}$ versus temperature, as shown in Figure 4, provided the activation energy, 56.809, 56.060, and 45.561 kJ/mol at 3 mm, 5 mm, and 7 mm, respectively. Activation energy, which is a function of temperature sensitivity, is needed to initiate the moisture diffusion within the slice. The obtained result shows that as turmeric slice thickness increased, the activation energy that is needed to drive the moisture out of the turmeric slices decreased.

Mathematical modelling of drying curves

The moisture ratio versus the obtained drying time for the different slice samples was fitted by Newton, Handerson and Pabis, Logarithmic and Page models. The four models were evaluated based on the coefficient of determination (R^2), Chi-square (χ^2), sum of square error (SSE), and root mean square error (RMSE). The best model to describe the drying behavior of the turmeric slices was selected based on the highest R^2 and lowest χ^2, SSE, and RMSE values (Afolabi et al., 2015). The values of the drying constants k and c, and coefficients a and n for the thin-layer drying models are shown in Table 3, while the statistical analysis results for the four models are shown in Table 4. R^2 values were found to be greater than 0.92 for all the models except for the one obtained at 7 mm, when the temperature was 40 °C. The page model was found to have the highest R^2 value compared to the other models. The implication is that the Page model provided a better correlation between the moisture ratio and the drying time. The χ^2 values ranged between 0.000665 – 0.003735 (3 mm), 0.000722 – 0.004881 (5 mm), 0.003628 – 0.008072 (7 mm); 0.000612 – 0.003039 (3 mm), 0.000733 – 0.004278 (5 mm), 0.003351 – 0.007282 (7 mm); 0.000199 – 0.00194 (3 mm), 0.000287 – 0.00271 (5 mm), 0.000836 – 0.003351 (7 mm), and 0.000071 – 0.000563 (3 mm), 0.000416 – 0.001049 (5 mm), 0.001229 – 0.004132 (7 mm) for Newton, Henderson and Pabis, Logarithmic, and Page models, respectively.

Table 2. Effective moisture diffusivity of the turmeric slices

	Effective Moisture Diffusivity (m^2/s)		
	Temperature (°C)		
Slice thickness (mm)	40	50	60
3	1.35×10^{-10}	3.00×10^{-10}	4.56×10^{-10}
5	2.72×10^{-10}	6.28×10^{-10}	9.00×10^{-10}
7	5.00×10^{-10}	10.91×10^{-10}	13.00×10^{-10}

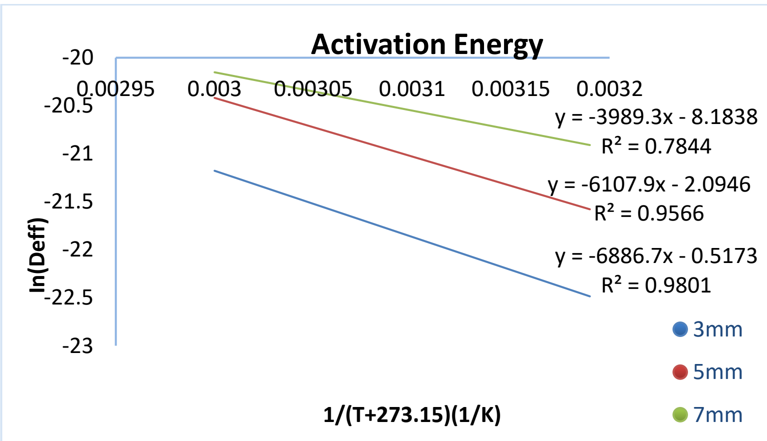

Fig. 4. Graphs of In(D_{eff}) against $\frac{1}{(T+273.15)}$ for turmeric slices

Table 3. The values of drying constants k and c and coefficients a and n for the thin-layer drying models

Model	Temperature (°C)	Slices (mm)	*n*	*A*	*k*	*c*	R^2
Newton1	40	*3*			*0.004*		*0.984*
		5			*0.003*		*0.981*
		7			*0.001*		*0.914*
	50	*3*			*0.006*		*0.971*
		5			*0.005*		*0.961*
		7			*0.004*		*0.941*
	60	*3*			*0.010*		*0.995*
		5			*0.008*		*0.993*
		7			*0.005*		*0.968*
Henderson and Pabis	40	*3*		*1.064*	*0.004*		*0.988*
		5		*1.062*	*0.003*		*0.986*
		7		*1.071*	*0.002*		*0.923*
	50	*3*		*1.061*	*0.006*		*0.975*
		5		*1.070*	*0.006*		*0.966*
		7		*1.098*	*0.004*		*0.953*
	60	*3*		*1.017*	*0.010*		*0.995*
		5		*1.011*	*0.008*		*0.993*
		7		*1.044*	*0.005*		*0.971*
Logarithmic	40	*3*		*1.100*	*0.003*	*- 0.007*	*0.994*
		5		*1.133*	*0.002*	*- 0.104*	*0.995*
		7		*1.629*	*0.009*	*- 0.089*	*0.990*
	50	*3*		*1.130*	*0.05*	*- 0.90*	*0.985*
		5		*1.144*	*0.05*	*- 0.98*	*0.978*
		7		*1.442*	*0.02*	*- 0.397*	*0.982*
	60	*3*		*1.052*	*0.09*	*- 0.44*	*0.999*
		5		*1.047*	*0.07*	*- 0.48*	*0.988*
		7		*1.188*	*0.03*	*- 0.182*	*0.990*
Page	40	*3*	*1.286*		*0.001*		*0.998*
		5	*1.286*		*0.001*		*0.996*
		7	*1.495*		*0.006*		*0.958*
	50	*3*	*1.451*		*0.001*		*0.996*
		5	*1.523*		*0.000*		*0.991*
		7	*1.595*		*0.000*		*0.990*
	60	*3*	*1.190*		*0.004*		*0.999*
		5	*1.121*		*0.004*		*0.996*
		7	*1.332*		*0.001*		*0.987*

Table 4. Statistical analysis for the four models at different thicknesses

3 mm

Temperature	Model Name	Reduced Chi-Square (χ^2)	Sum square error (SSE)	RMSE
40 °C	Newton	0.001576	0.001488	0.03858
	Henderson and Pabis	0.001203	0.001136	0.03370
	Logarithmic	0.000577	0.000545	0.02334
	Page	0.000162	0.000153	0.01238
50 °C	Newton	0.003735	0.003395	0.05827
	Henderson and Pabis	0.003090	0.002809	0.05300
	Logarithmic	0.001940	0.001764	0.04199
	Page	0.000563	0.000512	0.02263
60 °C	Newton	0.000665	0.000582	0.02413
	Henderson and Pabis	0.000612	0.000733	0.03351
	Logarithmic	0.000199	0.000174	0.01321
	Page	0.000071	0.000062	0.00788

5 mm

Temperature	Model Name	Reduced Chi-Square (χ^2)	Sum square error (SSE)	RMSE
40 °C	Newton	0.001886	0.001786	0.04227
	Henderson and Pabis	0.001447	0.001371	0.03703
	Logarithmic	0.000491	0.000465	0.02157
	Page	0.000416	0.000394	0.01986
50 °C	Newton	0.004881	0.004474	0.06689
	Henderson and Pabis	0.004278	0.003922	0.06263
	Logarithmic	0.002709	0.002484	0.04984
	Page	0.001049	0.000961	0.03101
60 °C	Newton	0.000722	0.000649	0.02548
	Henderson and Pabis	0.000733	0.000659	0.02568
	Logarithmic	0.000287	0.000258	0.01606
	Page	0.000468	0.000421	0.02053

7 mm

Temperature	Model Name	Reduced Chi-Square (χ^2)	Sum square error (SSE)	RMSE
40 °C	Newton	0.008072	0.007669	0.08757
	Henderson and Pabis	0.007282	0.006917	0.08317
	Logarithmic	0.000836	0.000794	0.02819
	Page	0.004132	0.003926	0.06266
50 °C	Newton	0.007302	0.006693	0.08180
	Henderson and Pabis	0.005912	0.005422	0.07364
	Logarithmic	0.002374	0.002176	0.04665
	Page	0.001229	0.001126	0.03356
60 °C	Newton	0.003628	0.003325	0.05767
	Henderson and Pabis	0.003351	0.003072	0.05543
	Logarithmic	0.001111	0.001018	0.03191
	Page	0.001711	0.001568	0.03960

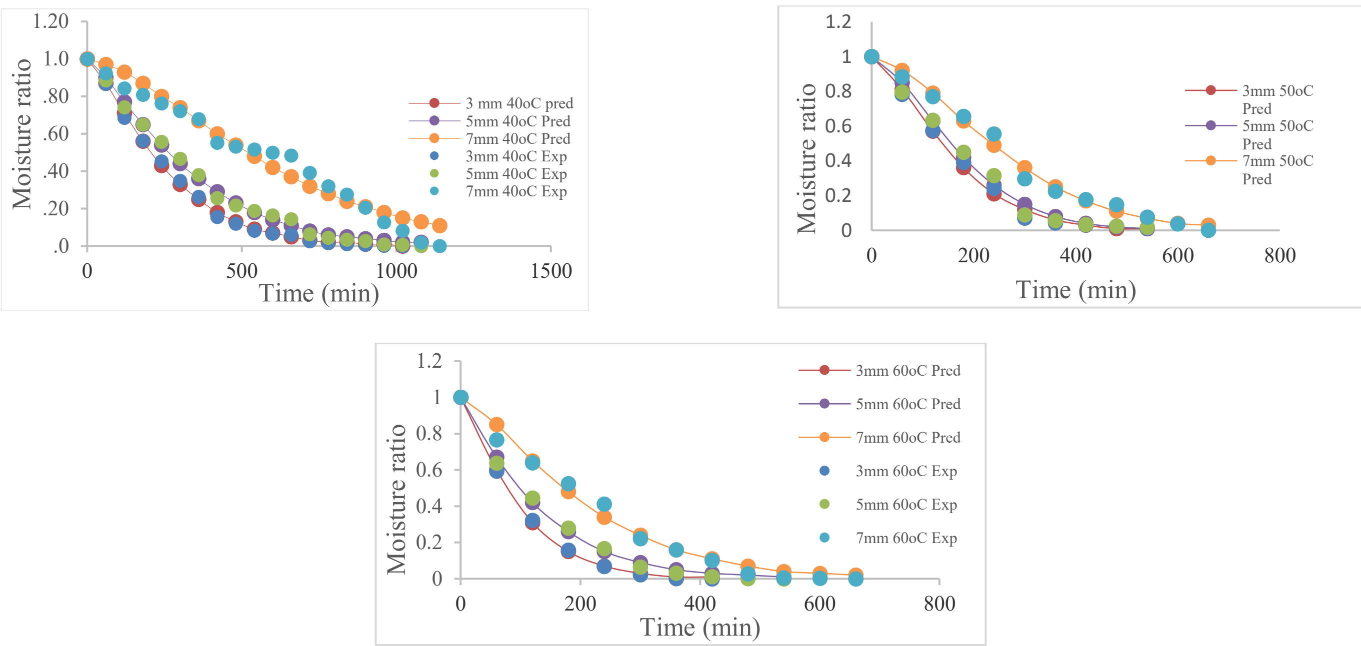

Fig. 5. Graph of experimental and predicted values of dimensionless moisture ratio for each thickness at 40 °C, 50 °C, and 60 °C

As shown in Table 4, the Page model was chosen to represent the thin layer hot-air drying of the turmeric slices, as it gave the lowest values for chi-square.

The Page model was suitable in describing the drying characteristics of turmeric slices, as it agrees with the experimental results based on the highest R^2 values and lowest χ^2 and RMSE. Similar results were reported in the literature for various food products (Kashaninejad and Tabil, 2004; Doymaz, 2007; Dissa et al., 2008; Tunde-Akintunde and Afon, 2010, Afolabi et al., 2015). Experimental and predicted values of the moisture ratio were compared with drying time, as shown in Figure 5.

The validation of the established model was made by comparing the experimental moisture ratio values with the predicted ones. There was good agreement between the experimental and predicted variables, which indicates that the Page model could be used satisfactorily to predict the thin layer hot-air drying of turmeric slices. Practically, the prediction of the Page model could serve as a reference tool for small and medium scale food processors who are interested in producing dried turmeric of good quality with a relatively low investment in equipment.

Conclusions

The drying time decreased with the increase in drying temperature in all the slices considered in this experiment. Drying was observed to take place in the falling-rate pattern throughout the drying period, thus allowing diffusion to take place as moisture migrated to the surface of the turmeric slices. The model that best described the thin-layer drying characteristics of the turmeric slices was the Page model. Predicted data obtained from the equations shows a good comparison with the experimental data.

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

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