Thin layer drying models for sweet potato in tray dryer

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Abstract: Sweet potato is increasingly becoming important and popular as food stuff all over the world. Therefore investigation of thin layer drying of sweet potato slices in three different dimensions was carried out between 50℃ and 80℃ in tray dryer using hot air at a flow rate of 2.5 m s^{-1} and 10% relative humidity. Eight thin-layer drying kinetic models were assessed on blanched and unblanched sweet potato slices presented in three different dimensions. The drying rate was observed to decrease with thickness and mass at a constant drying temperature. Also, the drying rate was found to increase with temperature and the blanched slices dried faster than unblanched slices. The eight models investigated fitted the experimental data of the six sweet potato samples between 50℃ and 80℃ adequately. However, Page model was found to be the best for all the samples. The results obtained are comparable to some of the reported works.

Keywords: sweet potato, thin-layer drying models, page model, tray dryer, diffusion mechanism

Citation: Olawale, A. S., and S. O. Omole. 2012. Thin layer drying models for sweet potato in tray dryer. Agric Eng Int: CIGR Journal, 14 (2): 131−137.

1 Introduction

Thin layer drying is an important dehydration technique in food industry. The resulting dried products usually record minimal loss of their native nutritional, chemical and physical qualities while the shelf life and onset of microbial spoilage of the products is extended (Akpinar and Bicer, 2008; Orikasa et al., 2010; Sablani, 2006). Sweet potato (*Ipomoea batatas*) is an important stable food in Africa, Asia and South America (Singh and Pandey, 2010; Fawole, 2007; Woolfe, 1992; Engone, Mugisha and Bashaasha, 2005). An FAO data for 2009 showed China as the leading producer with 80.15×10^6 tonnes followed by Nigeria with 3.3×10^6 tonnes per annum (FAO, 2011). The uses of the crop have been on the increase even in developed countries such as United States of America, Japan, Australia and New Zealand. The utilization of the crop in virtually every part of the world is indicative of its commercial importance. It is thus necessary to pay attention to means of preserving this food crop over a long period of time with little or no quality change. One way of achieving this goal is to subject the food crop to thin layer drying.

Thin layer drying kinetics is needed for design, operation and optimization of food crops dryers. The falling rate drying period is important in thin layer drying but the exact theoretical basis for moisture diffusion within the materials during the drying process is not fully understood (Akpinar and Bicer, 2008; Akpinar, 2006; Menges and Ertekin, 2006). So thin layer drying kinetics are commonly given as empirical and semi-empirical correlations. Of the fifteen thin layer drying kinetic models available in the literature (Akpinar, 2006; Menges and Ertekin, 2006; Alkal, Kahveci and Cihan, 2007; Tunde-Akintunde and Ayala, 2010; Singh and Pandey, 2010) only Wang and Singh and, geometric models do not contain exponential term(s). The presence of these exponential terms in majority of the models is indicative of contribution of diffusion mechanism in thin layer drying. Factors such as type and conditions of the crop (morphology, pretreatment, initial moisture content and dimension), drying conditions

Received date: 2012-02-23 **Accepted date:** 2012-04-12

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(temperature, pressure, air-flow rate and humidity) type of dryer (tray, tunnel, fluidized bed, etc) and thermal energy type (hot air, infrared, microwave, etc) employed are known to affect the drying kinetics and qualities of the dried material (Mitra, Shrivastava and Rao, 2011; Akpinar and Bicer, 2008; Menges and Ertekin, 2006; Alkal, Kahveci and Cihan, 2007; Bakal et al, 2011; Tunde-Akintunde and Ayala, 2010; Orikasa et al, 2010; Sablani, 2006;Velic et al, 2007a; Velic et al, 2007b; Gazer and Mohsenimanesh, 2010). Singh and Pandey (2010) studied the kinetics of thin layer drying of sweet potato cubes between 50℃ and 90℃ with and without pretreatment and established the appropriateness of Page model. Falade and Solademi (2010) found Page and a modified Page model appropriate for thin layer drying of 5-15 mm thick slices of sweet potato between 50℃ and 80℃. Modified Page model was the best kinetic model when slices, shredded chips and grates of sweet potato were dried (Diamante and Munro, 1981; Tan et al., 2001). In contrast, Doymaz (2010) reported logarithmic model is the most appropriate for drying slices of sweet potato. The same model was found appropriate for drying sweet potato slices with infrared light (Doymaz, 2011).

Single rack tray dryer is simple in construction and operation and can be easily adapted for thin-layer drying in farm settlements, most especially, in developing countries. None of the reported works on thin layer drying of sweet potato has been carried out in tray dryer. Therefore, this paper is on the assessment of empirical and semi-empirical kinetic models for thin layer drying of sweet potato slices in single rack tray hot air dryer. The study was carried out between 50°C and 80°C on slices of varying dimensions at constant air flow rate and relative humidity.

2 Materials and methods

2.1 Preparation of samples

Fresh sweet potatoes (*Ipomoea batatas*) tubers were obtained from a market in Zaria, Kaduna State, Nigeria. They were peeled, washed in clean water and sliced uniformly into three dimensions (i.e.10×10×5 mm, 20×20×10 mm and 20×20×5 mm) and labelled A, B and C respectively. For each determination, the required weight of the sliced sample was blanched by holding in distilled water at 45℃ for 30 min. The prepared blanched and unblanched samples were allowed to drain under standard conditions. The initial moisture content was determined according to official method (AOAC, 1995).

2.2 Drying procedure

About 10 g of the prepared samples was weighed, dried in a single rack tray dryer (*Heraeus* Model T503D) at 50℃ for 15 min after which it was reweighed. The weighing balance used had an accuracy of 0.001 g. This determination was replicated three times and the average value obtained was used to generate moisture contents and moisture ratio (MR) data. All moisture contents were obtained on dry basis (d.b.). This procedure was repeated at 15 min interval till equilibrium mass was obtained. The steps described above were repeated for each slice dimensions at 60℃, 70℃ and 80℃. These derived data were subsequently used to evaluate the drying characteristics of the sweet potato slices. Hot air flow rate was kept at 2.5 m s^{-1} and relative humidity maintained at 10%. This follows the procedure described by Kallemulla and Kailappan (2006). The re-hydration ratio for each sample was determined as described by Sacilik (2007).

2.3 Evaluation of thin-layer drying of sweet potato

Moisture ratio of samples during drying was expressed by the following equations

$$MR = \frac{M_t - M_e}{M_o - M_e} \tag{1}$$

where, MR is the dimensionless moisture ratio; M_t = moisture content at time t; M_O = initial moisture content; M_e = equilibrium moisture content

Moisture ratio data obtained with Equations 1 for each sample were fitted to eight thin layer drying equations (Table 1) to assess their suitability as models for thin layer drying kinetics of sweet potato slices in tray dryer. MATLAB 7.4 was used to fit the experimental data to the eight thin-layer models. Coefficient of determination (R^2) was used to determine the appropriateness of the model while the accuracy of fits was assessed using sum square of error (SSE) and root mean square error ($RMSE$). For quality fit, R^2 value should be closed to one while SSE and RMSE values should be closed to zero.

Table 1 Some thin-layer drying models

No	Model Name	Equation
1	Newton	$MR = \exp(-kt)$
2	Logarithmic	$MR = a\exp(-kt) + c$
3	Henderson and Pabis	$MR = a\exp(-kt)$
4	Page	$MR = \exp(-kt^n)$
5	Modified page 1	$MR = a\exp[-(kt)^n]$
6	Two-term exponential	$MR = a\exp(-kt) + (1-a)\exp(-kat)$
7	Two-term	$MR = a\exp(-kt) + c\exp(-k_1t)$
8	Wang and Singh	$MR = 1 + at + bt^2$

The fit parameters (a, b, n, k, etc) and fit statistics (R^2, SSE and $RMSE$) associated with the best three of the eight models for the different sweet potato slices investigated are presented in Tables 3 and 4. Figures 1a and 1b give the variation of moisture ratio with time at 50℃ while Figures 2a and 2b show the validity of Page model for the samples investigated.

3 Results and discussion

3.1 Drying rate

The charts presented in Figures 1a-b shows how moisture ratio changes with time in the course of drying of slices of sweet potato of different dimensions and conditioning. The dimension of the sweet potato slices and their pretreatments were observed to influence the drying characteristics of the crop. The thinnest of the blanched slices having the least mass (A50) recorded the fastest drying rate while the thickest and heaviest slices (B50) recorded the slowest rate. Water vapour or liquid diffuses to the surface of the material quicker the thinner the slice since less distance is covered. Lower viscosity resulting at higher temperature is also expected to lead to faster drying rate (McCabe, Smith and Harriot, 1985; Treybal, 1981).

Also the blanched slices were observed to dry faster than the unblanched slices of similar dimension. Here the water solubles such as simple sugars will be depleted in blanched slices. Less sugar would cause less surface hardening in sweet potato (Orikasa et al, 2010). This, in addition to improved porosity due to blanching, would improve diffusion of water to the surface of the slices and thus faster drying. Blanching causes change in inner structures of some materials such as tubers, grains, fruits, etc.

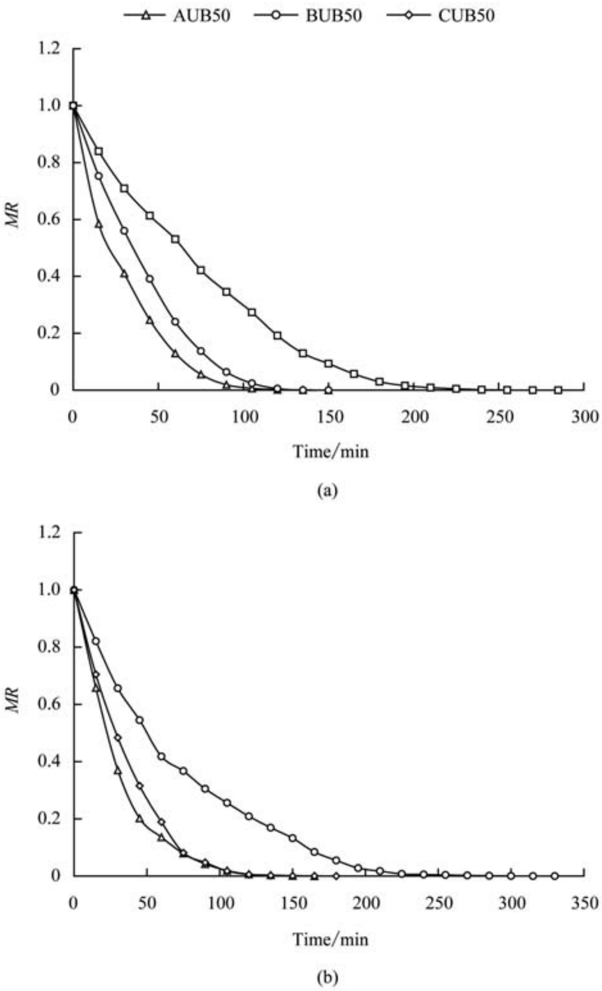

Figure 1 *MR* Variation with time of (a) blanched (b) unblanched potato slices at 50℃

Since moisture desorption in slices is largely a diffusion process, the increased porosity arising from blanching would enhance diffusion, reduced thickness implies less desorption time. The thinner and more porous the slice the less time is required to move the moisture to the surface of the slice where ultimate evaporation into the hot air occurs. The results are comparable to those obtained by other workers (Bakal et al, 2011; Akpinar and Bicer, 2008; Tunde-Akintunde and Ayala, 2010; Singh and Pandey, 2010; Falade and Solademi, 2010). The results presented in Figures 1a and 1b for drying at 50℃ are similar to those at 60℃, 70℃ and 80℃. The drying rate was observed to increase with drying temperature for slices of sweet potato with similar dimensions and pretreatment.

The rehydration ratio was observed to reduce with temperature and thickness of the slices. This might be due to greater destruction of sweet potato structure occurring as more heat is consumed by the material.

3.2 Drying models

Tables 2 presents the maximum and minimum coefficient of determination (R^2) for the eight models fitted to moisture ratio data of the 24 sweet potato samples. We can see that all the eight models assessed were appropriate, to varying degree, for the sweet potato samples investigated. However, Page, two-term and logarithmic models were found to be the best three models for correlating the drying kinetic data of the potato pellets when closeness of the maximum and minimum R^2 values for the 8 models are considered.

Table 2 Coefficient of determination range for some thin-layer drying models applied to sweet potato pellets

No	Model Name	Coefficient of Determination (R^2) Range	
		Unblanched Potato Pellets	Blanched Potato Pellets
1	Newton	0.9969 – 0.9782	0.9947 – 0.9490
2	Page	0.9991 – 0.9930	0.9993 – 0.9952
3	Modified Page	0.9951 – 0.9329	0.9909 – 0.8544
4	Henderson	0.9972 – 0.9817	0.9947 – 0.9537
5	Logarithmic	0.9989 – 0.9862	0.9978 – 0.9817
6	Wang	0.9958 – 0.8943	0..9974 – 0.9544
7	Two-term	0.9986 – 0.9916	0.9958 – 0.9623
8	Two-term Exponential	0.9979 – 0.9781	0.9976 – 0.9490

From Tables 3a-b, the Page model was the most appropriate when coefficient of deterrmination (R^2), sum square of error (*SSE*) and root mean square of error (*RMSE*) were used as the criteria for assessment. It is known that the nearer R^2 is to 1.00, *SSE* and *RMSE* are to zero, the better the predictive ability of the model. Other works on thin layer drying of sweet potato indicated the appropriateness of Page, modified Page and logarithmic models, with the Page model being the best in many instances (Singh and Pandey, 2010; Diamante and Munro, 1993; Diamante and Munro, 1981; Falade and Solademi, 2010; Tan et al, 2001; Doymaz, 2010).

Tables 4a-b give the model (fit) parameters of Page, logarithmic and two-term models for blanched and unblanched sweet potato pellets which were dried between 50 and 80℃.

The two parameters of Page model for unblanched samples appear to follow a consistent trend for samples A and B as the values were observed to increase with temperature. However, for sample C no trend was observable; the parameter values appear to be fairly constant. The trend displayed by the parameters' values for samples A (10 × 10 × 5 mm) and B (20 × 20 × 10 mm) were expected (since drying rate is expected to increase with temperature), but the result for C (20 × 20 × 10 mm) cannot be explained. The parameters of blanched samples recorded increase values with temperature as expected. However, values for parameter 'a' were generally lower than those for unblanched while reverse is the case for parameter 'b'. Parameters 'b' and 'c' for two-term and logarithmic models respectively recorded negative values consistently for blanched and unblanched sample.

Table 3a Fit statistics of thin-layer drying models for unblanched potato pellets

No.	ID	Thin-layer drying models and fit statistics								
		Page			Logarithmic			Two-term		
		R^2	*RMSE*	*SSE*	R^2	*RMSE*	*SSE*	R^2	*RMSE*	*SSE*
1	A50	0.9991	0.0101	0.0010	0.9978	0.0165	0.0024	0.9976	0.0183	0.0026
2	A60	0.9974	0.0189	0.0028	0.9922	0.0350	0.0086	0.9964	0.0256	0.0039
3	A70	0.9988	0.0129	0.0013	0.9916	0.0364	0.0092	0.9983	0.0177	0.0018
4	A80	0.9990	0.0115	0.0013	0.9862	0.0442	0.0176	0.9986	0.0583	0.0272
5	B50	0.9955	0.0199	0.0083	0.9974	0.0155	0.0048	0.9964	0.0221	0.0102
6	B60	0.9964	0.0365	0.0267	0.9951	0.0225	0.0096	0.9917	0.0303	0.0165
7	B70	0.9965	0.0462	0.0363	0.9953	0.0236	0.0089	0.9916	0.0324	0.0157
8	B80	0.9960	0.0409	0.0058	0.9989	0.0107	0.0018	0.9950	0.0231	0.0080
9	C50	0.9930	0.0319	0.0112	0.9872	0.0397	0.0189	0.9912	0.0344	0.0130
10	C60	0.9975	0.0496	0.0320	0.9965	0.0196	0.0038	0.9965	0.0205	0.0038
11	C70	0.9959	0.0201	0.00445	0.9935	0.0288	0.0075	0.9963	0.0232	0.0043
12	C80	0.9986	0.0129	0.00167	0.9956	0.0235	0.0055	0.9958	0.0242	0.0052

Table 3b Fit statistics of thin-layer drying models for blanched potato pellets

No.	ID	Page			Logarithmic			Two-term		
		R^2	*RMSE*	*SSE*	R^2	*RMSE*	*SSE*	R^2	*RMSE*	*SSE*
1	A50	0.9952	0.0236	0.0050	0.9884	0.0363	0.0224	0.9781	0.0515	0.0424
2	A60	0.9975	0.0189	0.0032	0.9845	0.0441	0.0331	0.9809	0.0505	0.0409
3	A70	0.9993	0.0094	0.0007	0.9817	0.0521	0.0217	0.9958	0.0267	0.0049
4	A80	0.9975	0.0189	0.0032	0.9887	0.0428	0.0146	0.9872	0.0487	0.0166
5	B50	0.9983	0.0155	0.0026	0.9884	0.0363	0.0224	0.9781	0.0515	0.0424
6	B60	0.9965	0.0205	0.0075	0.9887	0.0428	0.0146	0.9872	0.0487	0.0166
7	B70	0.998	0.0147	0.0032	0.9978	0.0160	0.0036	0.9938	0.0279	0.0101
8	B80	0.9973	0.017	0.0046	0.9975	0.0171	0.0044	0.9922	0.0311	0.0136
9	C50	0.9978	0.0198	0.0035	0.9947	0.0280	0.0062	0.9909	0.0394	0.0108
10	C60	0.9986	0.0145	0.0031	0.9229	0.0162	0.2633	0.9623	0.0788	0.0560
11	C70	0.9977	0.0162	0.0031	0.9951	0.0245	0.0066	0.9941	0.0283	0.0080
12	C80	0.9984	0.0145	0.0018	0.9914	0.0355	0.0101	0.9948	0.0296	0.0061

Thin-layer drying models and fit statistics

Table 4a Fit parameters of thin-layer drying models for unblanched potato pellets

No.	ID	Page		Logarithmic			Two-term			
		k	*n*	*k*	*a*	*c*	*k*	*a*	*b*	k_1
1	A50	0.0207	1.128	0.0323	1.027	-0.0122	0.0278	1.060	-0.08 9	0.0268
2	A60	0.0088	1.343	0.0276	1.087	-0.0621	0.0542	1.351	-0.133	0.0585
3	A70	0.0090	1.364	0.0305	1.076	-0.0490	0.0611	1.402	-0.199	0.0656
4	A80	0.0053	1.457	0.0276	1.088	-0.0409	0.0226	1.224	-0.139	0.0228
5	B50	0.0104	1.063	0.0127	1.027	-0.0317	0.5422	1.250	-0.193	0.0585
6	B60	0.0132	1.004	0.0119	1.081	-0.0538	0.0146	1.311	-0.211	1.66
7	B70	0.0131	1.009	0.0113	1.127	-0.0868	0.0152	1.164	-0.101	2.079
8	B80	0.0106	1.351	0.0134	1.036	-0.0447	0.0156	1.202	-0.102	2.227
9	C50	0.0114	1.227	0.0250	1.055	-0.0345	0.0310	1.216	-0.216	1.811
10	C60	0.0139	1.008	0.0226	1.089	-0.0414	0.0293	1.123	-0.096	2.17
11	C70	0.0371	0.974	0.0322	0.9974	-0.0110	0.0317	0.993	-0.106	1.825
12	C80	0.0124	1.283	0.0327	1.050	-0.0272	0.0313	1.223	0.202	1.041

Thin layer drying models and fit parameters

Table 4b Fit parameters of thin-layer drying models for blanched potato pellets

No.	ID	Page		Logarithmic			Two-term			
		k	*n*	*k*	*a*	*c*	*c*	*a*	*b*	k_1
1	A50	0.0271	1.055	0.0308	0.019	-0.025	0.0335	1.008	-0.080	1.385
2	A60	0.0028	1.503	0.0170	0.188	-0.143	0.0274	1.297	-0.296	1.326
3	A70	0.0046	1.575	0.0332	0.082	-0.037	0.0494	1.518	-0.517	2.333
4	A80	0.0028	1.503	0.0170	0.088	-0.043	0.0274	1.297	-0.296	1.326
5	B50	0.0032	1.296	0.0104	0.118	-0.101	0.0141	1.110	-0.109	2.403
6	B60	0.0012	1.514	0.0108	0.168	-0.101	0.0151	1.220	-0.220	2.275
7	B70	0.0053	1.227	0.0126	0.100	-0.078	0.0164	1.122	-0.123	2.19
8	B80	0.0045	1.250	0.0117	0.112	-0.086	0.0156	1.130	-0.130	2.196
9	C50	0.0066	1.32	0.0194	0.119	-0.097	0.0276	1.195	-0.195	1.484
10	C60	0.0023	1.487	0.0112	0.109	-0.082	0.0213	1.200	-0.200	1.247
11	C70	0.0090	1.240	0.0215	0.065	-0.043	0.0266	1.150	-0.150	2.367
12	C80	0.0079	1.358	0.0273	0.082	-0.051	0.0374	1.285	-0.285	2.167

Thin layer drying models and fit parameters

The two parameters of Page model for unblanched samples appear to follow a consistent trend for samples A and B as the values were observed to increase with temperature. However, for sample C no trend was observable; the parameter values appear to be fairly constant. The trend displayed by the parameters' values for samples A (10 × 10 × 5 mm) and B (20 × 20 × 10 mm) were expected (since drying rate is expected to increase with temperature), but the result for C (20 × 20 × 10 mm) cannot be explained. The parameters of blanched samples recorded increase values with temperature as expected. However, values for parameter 'a' were generally lower than those for unblanched while reverse is the case for parameter 'b'. Parameters 'b' and 'c' for two-term and logarithmic models respectively recorded negative values consistently for blanched and unblanched sample.

3.3 Model validation

Figures 2a-b show the comparison between the actual (experimental) and predicted moisture ratio for Page model. The predictive accuracy of Page model for thin layer drying data obtained is obvious from the values of correlation coefficients (R^2>0.99) for the two charts. The drying of blanched sliced sweet potatoes appears to be better predicted by the equation than the unblanched samples.

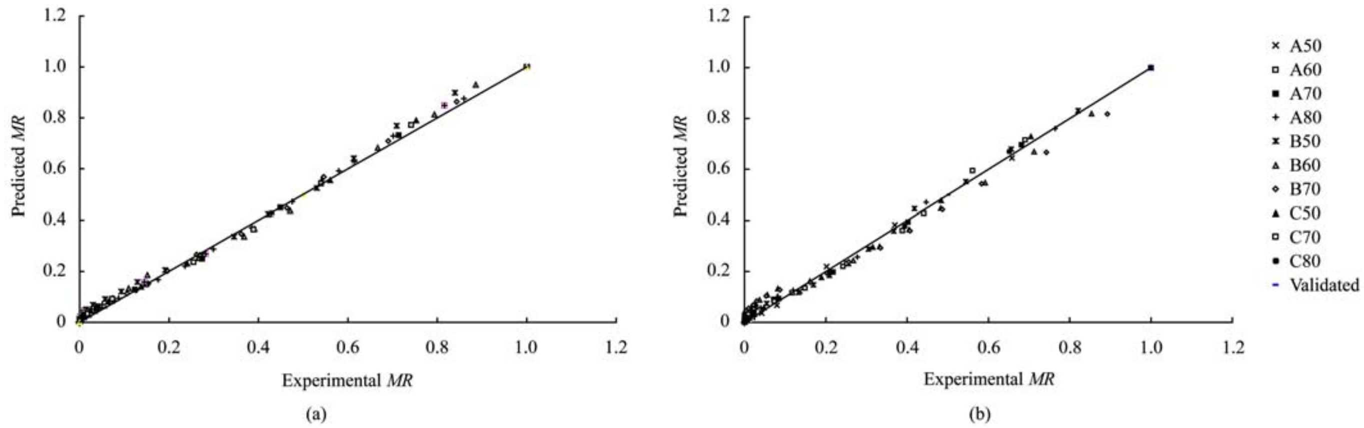

Figure 2 Validation of Page model for (a) blanched and (b) unblanched slices between 50℃ and 80℃

4 Conclusions

Page model has been found to describe the kinetics of thin-layer drying of sweet potato slices between 50°C and 80℃ in a tray dryer. The two-term and logarithmic models displayed superior correlation to rest five models. The time for achieving equilibrium moisture content was observed to increase with thickness and mass of the slices and decrease with drying temperature. Blanching of the sweet potato slices enhanced the drying rate. The quality of dried sweet potato as reflected by re-hydration ratios indicated that structure destruction increased with temperature. However, the qualities of the dried slices were found to be good.

Nomenclature

A	10×10×5 mm potato slices
B	10×10×10 mm potato slices
C	20×20×5 mm potato slices
M_e	equilibrium moisture content, fractional
M_o	initial moisture content, fractional
M_t	moisture content at time t, fractional
MR	moisture ratio
R^2	coefficient of determination
RMSE	root mean square of error
SSE	sum square of error

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