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Influence of temperature and thickness on thin layer drying characteristics of onion (*Allium cepa* L.) varieties and rehydration capacity

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ABSTRACT

Nonlinear regression analysis was conducted for thin layer drying characteristics of two onion varieties (white and red) and some quality characteristics were also examined. The experimental data obtained at drying temperatures of 40, 50, and 60 ºC and thicknesses of 2, 4 and 6 mm, was subsequently fitted into four commonly used models (Henderson and Pabis, Lewis, Page, and logarithmic). Moisture diffusivity and activation energy ranged from 8.9×10^{-10} to 8.4×10^{-9} m^2/s and 55.98 to 65.68 KJ/mol, respectively. Significant differences ($p<0.05$) were observed in the colour profile and rehydration ratio. The optimum desirable colour was obtained at 50 ºC with 2 mm thick onion slices and the observed higher rehydration ratio indicates good quality of dried onions. Among the four selected drying models, the Page model predicted optimally ($R^2 > 0.9$) and was found to be better in describing dried onion varieties, while the Lewis model provided the least fit.

Introduction

Onion (*Allium cepa* L.) is a commonly used vegetable produce of the *Leliaceace* family (Alabi and Adebayo, 2008). There are vast amounts of different onion varieties which can be divided into four main categories; white, yellow, red, and bunching onions (with no bulb), which are used exclusively as scallion. In comparison with other fresh vegetables, it is relatively rich in protein and riboflavin (Purseglove, 1972). It is also a well-known medical plant with beneficial components that confer thrombolytic, hypocholesterolemic, as well as antibiotic, antifungal, antibacterial, and antioxidant effects (Nuutila et al., 2003; Benkeblia, 2005). In addition to these properties, onions are known for their pungency, which is related to sulfoxide levels and pyruvic acid development (Jones et al., 2004). With these vital attributes in onion, particularly in dried form, they are frequently used in the production of processed foods such as sauces, sausages, and other convenience foods (Kaymak-Ertekin and Gedik, 2005).

Recently, more technical methods have been used for preservation through the principle of drying, where water activity is maintained at a very minimal level. However, the major challenges have been retaining the colour, taste, and pungent flavour, while maintaining the desired moisture content of the onion. In order to attempt to address this, there is a need for appropriate means of preservation by drying sensitive products such as onions, on the basis of storage life and appearance. To improve its commercialization, a possibility could be employing a hot air-drying technique at a lower temperature. However, understanding the drying characteristics and the optimization of drying conditions have been aided by several developed mathematical models, which are useful for optimizing mass transfer and moisture movement during the dehydration of many bio-materials (Doymaz et al., 2006; Mwithiga and Olwal, 2005; Vega et al., 2007).

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Drying of various food products, including green bean, pistachio, carrot, apricot, eggplant, and kale have been reported in the literature (Doymaz, 2007; Ertekin and Yaldiz, 2004; Midilli and Kucuk, 2003; Toğrul and Pehlivan, 2003; Yaldýz and Ertekýn, 2001), with a dearth of information on hot air-drying of onion varieties (white and red) which are locally grown, particularly in Nigeria, with regard to primary factors such as drying temperature and slice thickness. Therefore, the present study was premised upon the hypothesis to examine the thin layer drying characteristics of two onion varieties, develop a model suitable for describing the hot air-drying process, fit the drying data into four established drying models, and determine their corresponding effective diffusivities, activation energy, colour profile, and rehydration capacity.

Material and methods

Raw material and sample preparation

The onion (*Allium cepa* L.) varieties (white and red) used for these experiments were purchased from a local market in Abeokuta (8.25ºN, 5.40ºE), Nigeria, West Africa. The onions were subsequently sorted and cleaned. 1 kg (wet weight) of each onion variety was hand peeled, aseptically washed, and sliced into varying circular slices of thickness of 2±0.1, 4±0.1, and 6±0.1 mm, respectively with the aid of a Vernier calliper (STORM Index-Temp model, Italy).

Drying procedure

Drying was carried out using the modified method of Darvishi et al. (2013). One hundred grams (100 g) of each circular sliced onion variety was dried simultaneously in a hot air drier (NYC-101 oven, FCD-3000 serials, Medical and Scientific, England) at three different temperatures of 40, 50 and 60 °C with fixed airflow speed of 0.4 m/s. The dryer was set to the desired temperature for a period of one hour before the experiment commenced to ensure a steady state condition. The weight of the onion samples was measured with the aid of an electronic weighing balance (Model number: 457, Amput electronic scale) at a 30-minute interval until a constant weight was reached. Subsequent sample weights were recorded with each experimental procedure done in triplicate.

Determination of moisture ratio

The modified method of Toğrul and Pehlivan (2002) was used for determining the moisture ratio with drying time, as presented in Equation (1):

$$MR=\frac{M - M_e}{M_o - M_e}=\exp(-kt) \qquad (1)$$

where: MR - moisture ratio, M - moisture content at time t, M_e - equilibrium moisture content (dry basis), M_o - initial moisture content (dry basis), and k - constant.

Determination of drying rate

The drying rate was determined using the method of Dandamrongrak et al. (2002) and was estimated as the weight of water removed per unit of time per kilogram of dry matter (kg min^{-1}):

$$DR = m_t + d_t - m_t/d_t \qquad (2)$$

or

$$DR = \frac{M_o - M_f}{t} \qquad (3)$$

where, DR - drying rate, $m_t + d_t$- moisture content time t + dt (kg water/ kg dry matter), M_f - final moisture content (dry basis), and t - drying time (min).

Determination of effective moisture diffusivity

The method of Sun et al. (2007) was used to estimate effective moisture diffusivity and was described using Fick's diffusion equation. For long drying periods, the effective moisture diffusivity equation is presented in Equation (4):

$$MR = \frac{(M - M_e)}{M_0 - M_e} = \frac{8}{\pi^2}\exp\left(\frac{-\pi^2 D_{eff} t}{4L_0^2}\right) \qquad (4)$$

where, D_{eff} - effective moisture diffusivity (m^2/s) and L_o - half thickness of the samples (m).
Equation (4) was linearized and presented as:

$$In(MR)=\frac{-\pi^2 D_{eff}}{4L_0^2}t + \ln\frac{8}{\pi^2} \qquad (5)$$

The experimental drying data was plotted in terms of In (MR) against time at different temperatures and the slope of the graph was calculated as follows:

$$Slope = \frac{-\pi^2 D_{eff}}{4L_0^2} \qquad (6)$$

Determination of activation energy

Activation energy of the dried onion samples was estimated using the method of Simal et al. (2004). The dependence of effective diffusivity was suitably analysed with the aid of the Arrhenius equation and was described in Equations (7) and (8):

$$D_{eff} = D_o \exp\left[-\frac{E_a}{R(T+273.15)}\right] \qquad (7)$$

where: D_{eff} - effective moisture diffusivity (m^2/s), D_o - pre-exponential factor of the Arrhenius equation or maximum diffusion coefficient (at infinite temperature) (m^2/s), E_a- activation energy (KJ/mol), R - universal gas constant (KJ/mol K) and T – temperature (°C).

Linearizing the equation thus gives the equation below (Equation 8):

$$\text{In}D_{eff} = \left[-\frac{1}{R(T+273.15)}\right] E_a + \ln D_o \qquad (8)$$

Activation energy (E_a) was obtained by plotting ln D_{eff} against$\left[-\frac{1}{R(T+273.15)}\right]$.

Colour profile determination

As described by Yam and Papadakis (2004) the colour profile of dried onions was determined with the use of Adobe Photoshop 6.0 software, normalized to, a* (+redness, -greenness), b* (+yellowness, -blueness) and L* - lightness (black - 0, white - 100) according to equations (9) – (11), as well as digitally displayed hue angles (blue - 270°, green - 180°, yellow - 90°, and red - 0°).

$$L_o = \frac{L^*}{255} \times 100 \qquad (9)$$

$$a_o = \frac{a^* 240}{255} - 120 \qquad (10)$$

$$b_o = \frac{b^* 240}{255} - 120 \qquad (11)$$

According to Sariçoban, and Yilmaz (2010), the colour difference between dried slices of onion varieties were estimated by taking the Euclidean distance between them using Equation (12):

$$\Delta E^* = \left[(L_o - L^*)^2 + (a_o - a^*)^2 + (b_o - b^*)^2\right]^{1/2} \qquad (12)$$

Determination of the rehydration ratio

The method of Marabi et al. (2004) was used to determine the rehydration ratios of the dried onion samples. This was done by immersing the sample in distilled water. 10 g of dried onion slices was placed in 50 ml of distilled water contained in a hot water bath (DK-420 Glufex Medical and Scientific, England), maintaining a temperature of 35°C for the duration of 1 h. At the end of this set time, the water remaining in the beaker was drained and the sample was removed by gently wiping off the surface with the aid of tissue paper and reweighing.

$$\text{Rehydration ratio} = \frac{\text{mass of rehydrated sample (g)}}{\text{mass of dried sample (g)}}$$

Mathematical modelling of the drying of the onion varieties

The experimental drying data of onion varieties obtained at different temperatures and thicknesses were subsequently applied into four commonly used thin-layer drying models by Aregbesola et al. (2015) as indicated in Table 1.

Statistical analysis

The experimental data was analysed using analysis of variance (ANOVA) and the nonlinear regression model (NLR) procedure of SPSS 22.0. At the 5% significance level, means were compared using Duncan's multiple range tests (DMRT). Each model was characterized by its residual sum of squares (RSS), coefficient of determination (R^2), and the sum of square error (SSE) (Gouda et al., 2014).

Results and discussion

Effect of temperature and thickness on the moisture ratio

The moisture ratio curve for white and red onions with the thickness of 2 mm dried at temperatures of 40, 50 and 60 °C is presented in Figs. 1 and 2, respectively. The relative expression of mass of water to the mass of solids in bulb scales describes the moisture ratio of onion type slices. The plots of moisture ratio versus drying time of

Table 1. Thin layer drying models

Model name	Model	Reference
Newton (Lewis)	MR = exp(-kt)	Ayensu (1997)
Logarithmic	MR = a exp(-kt)+b	Kingsly et al. (2007)
Page	MR = exp(-kt^n)	Jangam et al. (2008)
Henderson and Pabis	MR = a exp(-kt)	Figiel (2010)

white and red onion slices revealed that moisture movement decreased slowly at the start of the drying process and then exponentially with the increase in drying time, until equilibrium moisture content (EMC) was attained. Also, as drying air temperature increased, the plot became steeper, indicating higher moisture removal rates due to high energy transfer intensity. These substantial changes attributed to increased partial vapor pressure per drying temperatures and surrounding air, which resulted in higher moisture migration from the interior and evaporation through the exterior of the onion slices (Mariem and Mabrouk, 2014). These observations were similar to studies on the drying kinetics of some fruit and vegetables (Lee and Kim, 2008; Olalusi, 2014). The result showed that the moisture ratio of white onions was slightly higher than that of red onions. In both onion varieties, there were decreases in moisture ratio with an increase in thickness and EMC was reached more rapidly. Similar trends were observed in 4 and 6 mm thick onion varieties and this was due to the variation in moisture content relative to the onion variety, as thinly sliced products dried faster as a result of the increase in exposed surface area for a given product volume (Ertekin and Yaldiz, 2004; Olalusi, 2014).

Effect of temperature and thickness on the drying rate

The drying rate of white and red onion slices with increasing thickness illustrates the rate at which liquid is migrated inside-out of the bulb scales, simply through mass-transfer bound over time. Molecular diffusion principle demonstrates the transfer of moisture (in essence, from a region of higher concentration to lower concentration). In previous studies, drying air temperature and product thickness have been identified to be the major factors affecting the drying rate (Sahari and Driscoll, 2014). The drying rate shows that more heat energy was absorbed by water at the initial exterior of onion slices resulting in rapid drying and dried out exterior. Subsequently, heat transfer through the dried layer decreases due to the reduction in present water molecules which are linked at the final drying period, thus retarding the drying rates. Such observation is in agreement with the study conducted by Pathare and Sharma (2006) and Thao and Noomhorm (2011) on drying kinetics of some vegetable products. At higher temperature, the drying rate was rapid and this reflects the falling rate period characteristics and diffusion-dominant drying principle of onion slices, impacting the differences in the partial vapor pressure between onion slices and their surroundings, which is not considered to be dominant. The dehydration rates were observed to be dependent on drying air temperature and the thickness of the sliced onion samples. A similar result has been reported in earlier studies (Akpinar, 2006; Miranda et al., 2009).

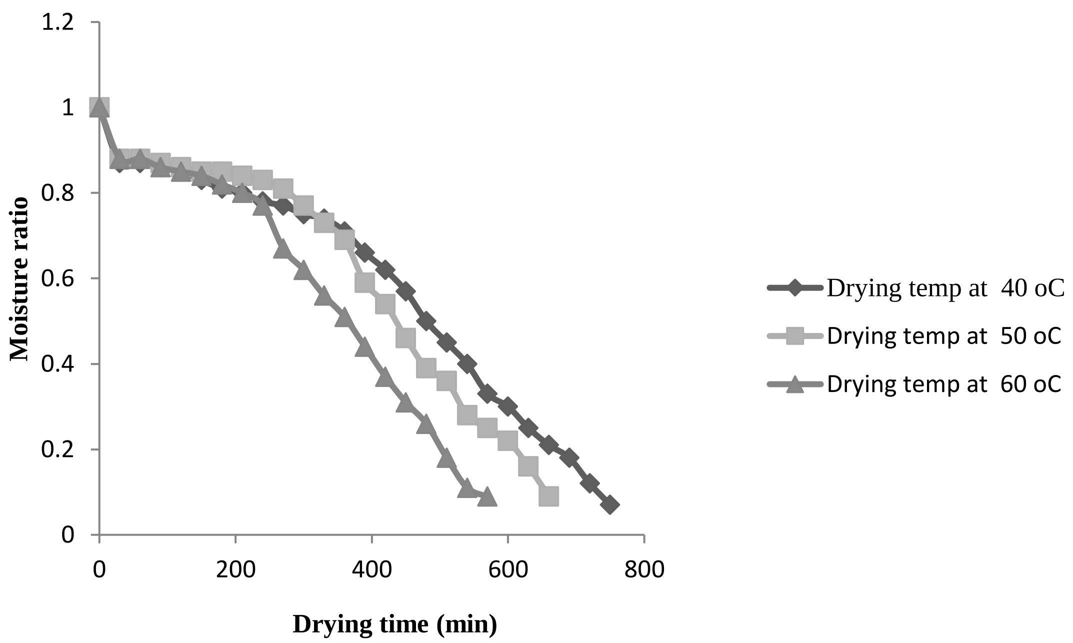

Fig. 1. Moisture ratio versus drying time (min) of white onions dried at different temperatures and 2 mm thickness

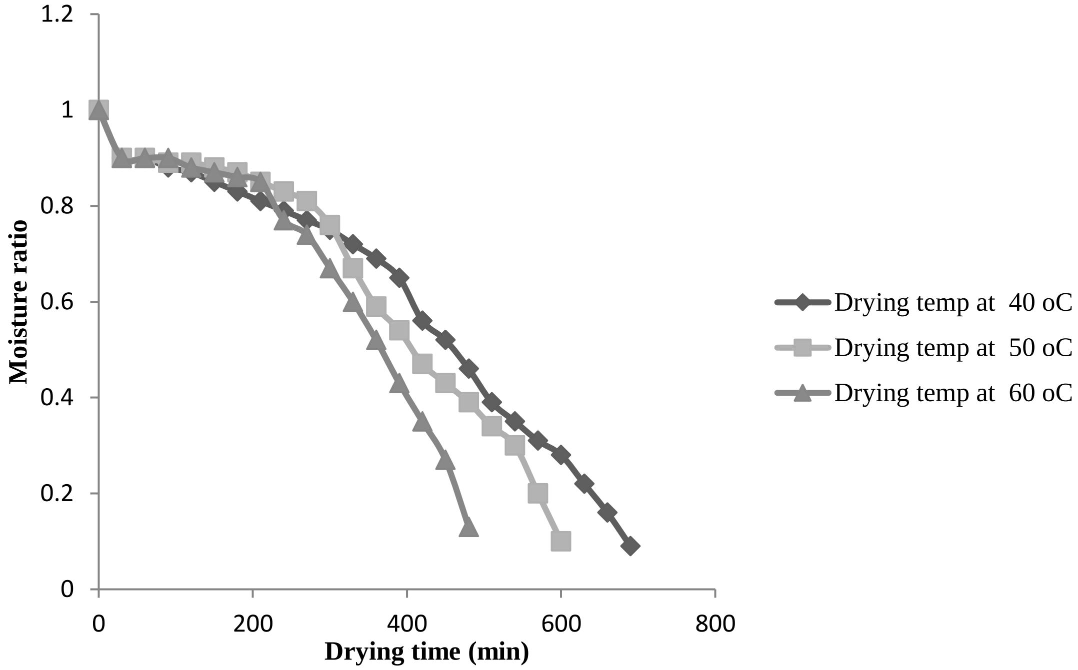

Fig. 2. Moisture ratio versus drying time (min) of red onions dried at different temperatures and 2 mm thickness

Thin layer drying models

The coefficients of thin-layer drying models and goodness of fit of the moisture ratios of white and red onions in varying thicknesses at different temperatures, examined with four established semi-theoretical thin-layer drying models (Henderson and Pabis, Lewis, Henderson and Pabis, Page, and logarithmic) are summarized in Tables 2 and 3. The tables described the drying model constants and statistical error parameters used to demonstrate coefficients of determination or goodness of fit (R^2), residual sum of squares (RSS), sum of squared errors (SSE), and mean squared error (MSE). The computed model parameters, reveal that the constants show no definite trend except for the repeated value of the constant (k) in the Lewis model for the onion slices. This depicted general series solutions of the Fick's second law of diffusion (Kemp, 2011) and the ease of quantifying the drying mechanisms of onion slices and simulating the rate of water movement, evolving the application of vastly used simple theoretical models. The Page model was observed with higher R^2 values of 0.987 and 0.979, and lowest RSS values of 0.0260 and 0.0370, for both white and red onions, respectively. This demonstrates a better consonance between the experimental and simulated data, which indicates that the model is suitable in describing the drying behaviour of onion slices. However, the least fit was observed in the Lewis model (R^2 values of 0.347 and 0.401, and RSS values of 6.706 and 6.324, for white and red onions, respectively) with all the evaluated drying conditions. A similar observation was reported by Raj et al. (2006), where the Page model predicted optimally in the dehydration of onion rings during storage, with the coefficient of determination (R^2 = 0.971 to 0.999) and RMSE (0.0024 to 0.0495). A good fit of the model has also been described by Ramachandra and Rao (2009) for the drying variables of *Aloe vera* with R^2 in the range of 0.9992 to 0.9999.

Table 2. Coefficients of thin layer drying models and goodness of fit for white onion

S/N	Model	Thickness (mm)	Temp (ºC)	Parameters	R^2	RSS	SSE	MSE
1	Lewis	2	40	k = 0.001	-0.255	5.505	4.386	4.386
			50	k = 0.001	-0.037	4.836	4.663	4.663
			60	k = 0.001	-0.111	3.982	3.585	3.585
		4	40	k = 0.001	-0.281	6.072	4.739	4.739
			50	k = 0.001	0.018	5.375	5.475	5.475
			60	k = 0.001	0.065	4.399	4.705	4.705
		6	40	k = 0.001	0.347	6.706	4.977	4.977
			50	k = 0.001	-0.064	6.018	5.654	5.654
			60	k = 0.001	0.100	4.891	5.432	5.432
2	Henderson and Pabis	2	40	k = -0.002, a = 0.251	0.830	0.344	9.547	4.773
			50	k = -0.002, a = 0.268	0.808	0.369	9.130	4.565
			60	k = -0.003, a = 0.263	0.834	0.251	7.317	3.658
		4	40	k = -0.002, a = 0.252	0.813	0.409	10.403	5.201
			50	k = -0.002, a = 0.277	0.780	0.476	10.373	5.187
			60	k = -0.002, a = 0.283	0.796	0.349	8.755	4.377
		6	40	k = -0.002, a = 0.250	0.802	0.471	11.212	5.606
			50	k = -0.002, a = 0.273	0.760	0.565	11.107	5.553
			60	k = -0.002, a = 0.290	0.767	0.442	9.880	4.940
3	Page	2	40	k = 1.135E 3, n = -1.328	0.964	0.062	9.829	4.914
			50	k = 1.410E 3, n = -1.414	0.945	0.086	9.412	4.706
			60	k = 5.080E 2, n = -1.274	0.947	0.062	7.505	3.753
		4	40	k = 9.900E 2, n = -1.279	0.813	0.409	10.403	5.201
			50	k = 1.498E 3, n = -1.400	0.961	0.071	10.779	5.389
			60	k = 4.950E 2, n = -1.248	0.961	0.053	9.051	4.526
		6	40	k = 9.970E 2, n = -1.255	0.987	0.028	11.656	5.828
			50	k = 1.531E 3, n = -1.371	0.975	0.050	11.622	5.811
			60	k = 5.190E 2, n = -1.230	0.026	0.026	10.296	5.148
4	Logarithmic	2	40	k = -2.958E-6, a = 4.070E 2, c = -4.070E 2	0.946	0.109	9.782	3.261
			50	k = -3.151E-6, a = 4.440E 2, c = -4.440E 2	0.929	0.137	9.362	3.121
			60	k = -4.260E-6, a = 3.910E 2, c = -3.910E 2	0.948	0.079	7.488	2.496
		4	40	k = -2.476E-6, a = 4.270E 2, c = -4.270E 2	0.934	0.145	10.666	3.555
			50	k = -2.318E-6, a = 5.260E 2, c = -5.260E 2	0.907	0.201	10.649	3.550
			60	k = -2.937E-6, a = 4.780E 2, c = -4.780E 2	0.918	0.140	8.964	2.988
		6	40	k = -2.122E-6, a = 4.460E 2, c = -4.460E 2	0.927	0.175	11.508	3.836
			50	k = -2.048E-6, a = 5.230E 2, c = -5.230E 2	0.892	0.254	11.417	3.806
			60	k = -2.152E-6, a = 5.590E 2, c = -5.590E 2	0.894	0.201	10.121	3.374

Table 3. Coefficients of thin layer drying models and goodness of fit for red onion

S/N	Model	Thickness (mm)	Temp (ºC)	Parameters	R^2	RSS	SSE	MSE
1	Lewis	2	40	k = 0.001	0.003	4.863	4.879	4.879
			50	k = 0.001	0.198	4.132	5.150	5.150
			60	k = 0.001	0.351	3.165	4.875	4.875
		4	40	k = 0.001	-0.089	5.597	5.141	5.141
			50	k = 0.001	-0.028	4.869	4.738	4.738
			60	k = 0.001	0.234	3.890	5.078	5.078
		6	40	k = 0.001	-0.233	6.324	5.129	5.129
			50	k = 0.001	0.401	5.466	4.867	4.867
			60	k = 0.001	0.154	4.452	5.260	5.260
2	Henderson and Pabis	2	40	k = -0.002, a = 0.268	0.840	0.298	9.444	4.722
			50	k = -0.002, a = 0.293	0.813	0.320	8.963	4.481
			60	k = -0.002, a = 0.326	0.767	0.322	7.719	3.859
		4	40	k = -0.002, a = 0.263	0.819	0.387	10.351	5.176
			50	k = -0.002, a = 0.268	0.812	0.369	9.239	4.619
			60	k = -0.002, a = 0.307	0.765	0.384	8.585	4.292
		6	40	k = -0.002, a = 0.253	0.815	0.435	11.018	5.509
			50	k = -0.002, a = 0.263	0.803	0.415	9.919	4.959
			60	k = -0.002, a = 0.294	0.787	0.373	9.339	4.670
3	Page	2	40	k = 6.450E 2, n = -1.266	0.948	0.080	9.662	4.831
			50	k = 4.300E 2, n = -1.248	0.928	0.096	9.187	4.593
			60	k = 2.510E 2, n = -1.227	0.958	0.041	8.000	4.000
		4	40	k = 1.109E 3, n = -1.327	0.968	0.057	10.681	5.340
			50	k = 1.452E 3, n = -1.422	0.944	0.090	9.517	4.759
			60	k = 5.090E 2, n = -1.300	0.969	0.039	8.929	4.465
		6	40	k = 1.353E 3, n = -1.328	0.979	0.043	11.410	5.705
			50	k = 1.397E 3, n = -1.375	0.962	0.067	10.267	5.134
			60	k = 4.260E 2, n = -1.219	0.974	0.037	9.675	4.838
4	Logarithmic	2	40	k = -3.455E-6, a = 3.780E 2, c = -3.780E 2	0.950	0.094	9.648	3.216
			50	k = -3.033E-6, a = 4.980E 2, c = -4.980E 2	0.928	0.124	9.159	3.053

		60	k = -2.842E-6, a = 6.420E 2, c = -6.420E 2	0.890	0.151	7.889	2.630
	4	40	k = -2.738E-6, a = 4.250E 2, c = -4.250E 2	0.938	0.133	10.605	3.535
		50	k = -3.221E-6, a = 4.390E 2, c = -4.390E 2	0.932	0.133	9.474	3.158
		60	k = -2.665E-6, a = 5.850E 2, c = -5.850E 2	0.893	0.175	8.793	2.931
	6	40	k = -2.446E-6, a = 4.250E 2, c = -4.250E 2	0.936	0.151	11.302	3.676
		50	k = -2.587E-6, a = 4.680E 2, c = -4.680E 2	0.925	0.157	10.177	3.392
		60	k = -2.386E-6, a = 5.540E 2, c = -5.540E 2	0.909	0.159	9.553	3.184

Effective moisture diffusivity and activation energy

The estimated effective moisture diffusivity (D_{eff}) and concurrently the pre-exponential factor of the obtained Arrhenius equation (D_o) was used to express the activation energy (E_a) with the regression coefficient (R^2) of the onion varieties of varying thickness at different temperatures (Tables 4a and 4b). Moisture diffusivity at the thickness of 2, 4, and 6 mm ranged from 9.3×10^{-10} to 8.0×10^{-9} m^2/s, 9.7×10^{-10} to 8.4×10^{-9} m^2/s and 1.1×10^{-9} to 8.4×10^{-9} m^2/s for white onion and 8.9×10^{-10} to 8.0×10^{-9} m^2/s, 9.3×10^{-10} to 8.4×10^{-9} m^2/s and 9.7×10^{-10} to 8.4×10^{-9} m^2/s for red onion, respectively. The activation energy for white onion ranged from 55.98 to 61.70 KJ/mol, 57.78 to 63.73 KJ/mol and 59.50 to 65.40 KJ/mol, while in the case of the red onion, values ranged from 55.98 to 61.88 KJ/mol, 57.78 to 63.91 KJ/mol and 59.50 to 65.68 KJ/mol, respectively. The good fit of the equation for each onion thickness within the considered consecutive drying temperatures is expressed by a straight-line relationship, where white and red onion slices had R^2 values of 0.98 and 0.97, respectively. Effective moisture diffusivity is a mechanism influencing moisture transport in the bulb scales, owing to the fact that the moisture migrates basically through diffusion phenomena. The effective moisture diffusivities increased with the rise in drying temperature and the reduced surface area of the bulb scales. This could be related to better moisture movements from thinner slices as compared to thicker slices. The moisture diffusivity estimated compared favourably with the study of Lee and Kim (2008) during the drying kinetics of onion slices using a hot air dryer at the temperature range of 50 to 70 °C, and marginally lower due to an increased air velocity used in this study. The values observed were slightly higher than the range of values (2.51 to 3.23 x 10^{-11} m^2/s) accounted by Pathare and Sharma (2006) for onion slices dried between 35 and 45 °C using the infrared convective principle. Nevertheless, the activation energy slightly differed, increased with increases in drying temperature and decreased with the reduction in the bulb surface area. This variation clarifies the fact that thinner slices of onions with large surface areas give room for more energy and moisture removal during drying compared to thicker slices (Mariem and Mabrouk, 2014; Kaymak-Ertekin, 2002). According to Senadeera et al. (2003) the activation energy for the onion slices in consecutive thicknesses fell within and slightly above the range of 12.87 to 58.15 KJ/mol. However, one major correlation between activation energy and effective moisture diffusivities was that higher activation energy resulted in lower moisture diffusivity during dehydration (Darvishi et al., 2013).

Table 4a. Effective moisture diffusivity and activation energy of white onions at varying thicknesses and drying temperatures

Thickness (mm)	M. Diff. (m^2/s) at 40 ºC	Equation of fit	R^2	A. E (KJ/mol) at 40 ºC	M. Diff. (m^2/s) at 50 ºC	Equation of fit	R^2	A. E (KJ/mol) at 50 ºC	M. Diff. (m^2/s) at 60 ºC	Equation of fit	R^2	A. E (KJ/mol) at 60 ºC
2	9.3 x10^{-10}	Y= 0.0023x -1.5604	0.9729	61.70	9.7 x10^{-10}	Y= 0.0024x -1.4282	0.9580	63.73	1.1 x10^{-9}	Y= 0.0026x -1.3245	0.9137	65.40
4	3.6 x10^{-9}	Y= 0.0022x -1.6594	0.9622	58.08	3.7 x10^{-9}	Y= 0.0023x -1.5173	0.9451	59.96	3.9 x10^{-9}	Y= 0.0024x -1.3634	0.9119	61.63
6	8.0 x10^{-9}	Y= 0.0022x -1.8210	0.9243	55.98	8.4 x10^{-9}	Y= 0.0023x -1.6803	0.9185	57.78	8.4 x10^{-9}	Y= 0.0023x -1.4668	0.9824	59.50

M. Diff = Moisture diffusivity (m^2/s), A. E = Activation energy (KJ/mol), R^2 = Coefficient of determination

Table 4b. Effective moisture diffusivity and activation energy of red onions at varying thicknesses and drying temperatures

Thickness (mm)	M. Diff. (m^2/s) at 40 ºC	Equation of fit	R^2	A. E (KJ/mol) at 40 ºC	M. Diff. (m^2/s) at 50 ºC	Equation of fit	R^2	A. E (KJ/mol) at 50 ºC	M. Diff. (m^2/s) at 60 ºC	Equation of fit	R^2	A. E (KJ/mol) at 60 ºC
2	8.9 x10^{-10}	Y= 0.0022x -1.3963	0.9634	61.88	9.3 x10^{-10}	Y= 0.0023x -1.2578	0.9233	63.91	9.7 x10^{-9}	Y= 0.0024x -1.0687	0.9507	65.68
4	3.6 x10^{-9}	Y= 0.0022x -1.5492	0.9631	57.98	4.1 x10^{-9}	Y= 0.0025x -1.4567	0.9450	59.64	4.1 x10^{-9}	Y= 0.0025x -1.2605	0.9798	61.41
6	8.0 x10^{-9}	Y= 0.0022x -1.6946	0.9618	55.98	8.4 x10^{-9}	Y= 0.0023x -1.5666	0.9450	57.78	8.4 x10^{-9}	Y= 0.0023x -1.3559	0.9798	59.50

M. Diff = Moisture diffusivity (m^2/s), A. E = Activation energy (KJ/mol), R^2 = Coefficient of determination

Colour profile

The colour profile of dried onion varieties (Fig. 3) is presented in Table 5. Values of lightness (L*), redness or greenness (a*), and yellowness or blueness (b*) at a consecutive increase in drying temperatures and thicknesses for white onion ranged from 30 to 66, 2 to 14, 12 to 26, respectively, while the red onion ranged from 40 to 57, 2 to 15, 13 to 27, respectively. The colour difference (ΔE^{*}) values with increases in degrees of drying temperatures and thicknesses for white onion varied between 172.34 and 175.07, while the red onion varied between 172.22 and 174.27, respectively. The digitally estimated hue angles (degree) for white onion ranged from 28 to 55, while red onion ranged from 27 to 40. One of the modifications of good quality food products that set in during drying processes includes their optical properties and colour attributes (Kasim and Kasim, 2015; Sobowale et al., 2017). Acceptable colour properties of some dried onions have been related to higher and lower values of L* and a*, respectively and slight total colour differences (Seiiedlou et al., 2010). The colour test on dehydrated onion slices showed that significant differences (p<0.05) existed between the uneven trend of values, with the white onion predominantly higher, in almost all the samples evaluated with increases in temperature and thickness. The L* value of onion varieties was observed to have ranged slightly above the mid-value of the grey scale, whereas faint domination of the green colour alongside more redness and lightly luminous yellow colour were observed. The optimal L* and b* values of white and red onion slices were observed at 50 °C with 2 mm thick onion slices. In spite of this, L* and b* were significantly higher in white onion slices, while a* was significantly higher in red onion slices. This observation clearly interprets that the colour of the white onion bulb scales was brighter than the dried red onion slices (Pedisic et al., 2009). The total colour difference is an index which indicates the extent of differences brought about by processing criteria on the colour of dried varieties of onion slices. The total colour difference of the onion slices established distinctly ($1.5<\Delta E<3$) differed (Adekunte et al., 2010). Hue angle represents the qualitative measure of distinct attributes of colour, natively defined as reddish, yellowish, greenish, and bluish. The hue angle of the onion slices falls within the range of 90 °, which suggests lighter red and lesser yellow character (Pedisic et al., 2009). Kortei et al. (2015) suggested the same range of angles during dehydration of mushrooms by the principle of irradiation. Over the years, studies have shown that the raw colour of sample, temperature, and slice thickness dependent was claimed to be significantly influenced the measurement of optical properties in vegetables (Kaymak-Ertekin and Gedik, 2005). These observations were highlighted in this current study. Among all colour parameters measured, only the hue angle was reported as having no significant effect (p<0.05) due to temperature and slice thickness. A similar observation was also drawn by Manolopoulou and Varzakas (2011) on the colour analysis of fresh-cut minimally processed cabbage.

Table 5. Colour profile of dried onion varieties

Temp.	Thickness (mm)	L*	a*	b*	Color difference	Hue angle (degree)	Thickness (mm)	L*	a*	b*	Color difference	Hue angle (degree)
	White						Red					
40 ºC	2	47.00^{b} (0.03)	4.00^{d} (0.01)	18.00^{b} (0.03)	173.07^{b} (0.04)	37.00^{d} (0.03)	2	40.00^{a} (0.04)	9.00^{g} (0.01)	23.00^{d} (0.04)	172.75^{c} (0.04)	31.00^{c} (0.03)
	4	50.00^{c} (0.04)	0.00^{c} (0.03)	23.00^{d} (0.04)	173.28^{d} (0.03)	46.09^{e} (0.16)	4	44.00^{b} (0.03)	3.00^{d} (0.04)	17.00^{b} (0.03)	172.63^{b} (0.03)	40.00^{e} (0.01)
	6	50.00^{c} (0.03)	12.00^{f} (0.04)	26.00^{g} (0.01)	173.90^{f} (0.01)	29.00^{b} (0.04)	6	47.00^{c} (0.04)	15.00^{h} (0.03)	27.00^{f} (0.01)	173.82^{g} (0.01)	27.00^{a} (0.03)
50 ºC	2	66.00^{g} (0.04)	2.00^{a} (0.04)	19.00^{c} (0.03)	175.07^{i} (0.04)	51.00^{h} (0.03)	2	51.00^{e} (0.03)	1.00^{b} (0.04)	25.00^{e} (0.03)	173.58^{f} (0.03)	44.00^{f} (0.04)
	4	63.00^{f} (0.03)	1.00^{b} (0.04)	25.00^{f} (0.01)	174.95^{h} (0.01)	48.00^{f} (0.04)	4	56.00^{f} (0.01)	6.00^{e} (0.03)	19.00^{c} (0.01)	174.11^{h} (0.04)	32.00^{d} (0.03)
	6	47.00^{b} (0.01)	10.00^{e} (0.03)	24.00^{e} (0.04)	173.49^{e} (0.04)	30.00^{c} (0.01)	6	57.00^{g} (0.04)	7.00^{f} (0.03)	19.00^{c} (0.04)	174.27^{i} (0.03)	31.00^{c} (0.03)
60 ºC	2	53.00^{d} (0.04)	2.00^{a} (0.04)	12.00^{a} (0.03)	173.15^{c} (0.03)	55.00^{i} (0.03)	2	47.00^{c} (0.04)	2.00^{c} (0.04)	17.00^{b} (0.03)	172.88^{d} (0.04)	40.00^{e} (0.03)
	4	56.00^{e} (0.04)	1.00^{b} (0.03)	23.00^{d} (0.04)	173.98^{g} (0.03)	49.00^{g} (0.01)	4	50.00^{d} (0.03)	2.00^{a} (0.03)	17.00^{b} (0.04)	173.02^{e} (0.04)	53.00^{g} (0.03)
	6	30.00^{a} (0.03)	14.00^{g} (0.04)	26.00^{g} (0.03)	172.34^{a} (0.04)	28.00^{a} (0.04)	6	40.00^{a} (0.03)	6.00^{e} (0.01)	13.00^{a} (0.03)	172.22^{a} (0.03)	28.00^{b} (0.03)

Means with different superscript within a column are significantly different at (P<0.05) and standard deviation. Temp. = Temperature, L* = Lightness, a* = Redness, b* = Yellowness

Temp.	Thickness (mm)	L*	a*	b*	Color difference	Hue angle (degree)	Thickness (mm)	L*	a*	b*	Color difference	Hue angle (degree)
	Red						**Red**					
40 ºC	2	40.00^{a} (0.04)	9.00^{g} (0.01)	23.00^{d} (0.04)	172.75^{c} (0.04)	31.00^{c} (0.03)	2	40.00^{a} (0.04)	9.00^{g} (0.01)	23.00^{d} (0.04)	172.75^{c} (0.04)	31.00^{c} (0.03)
	4	44.00^{b} (0.03)	3.00^{d} (0.04)	17.00^{b} (0.03)	172.63^{b} (0.03)	40.00^{e} (0.01)	4	44.00^{b} (0.03)	3.00^{d} (0.04)	17.00^{b} (0.03)	172.63^{b} (0.03)	40.00^{e} (0.01)
	6	47.00^{c} (0.04)	15.00^{h} (0.03)	27.00^{f} (0.01)	173.82^{g} (0.01)	27.00^{a} (0.03)	6	47.00^{c} (0.04)	15.00^{h} (0.03)	27.00^{f} (0.01)	173.82^{g} (0.01)	27.00^{a} (0.03)
50 ºC	2	51.00^{e} (0.03)	1.00^{b} (0.04)	25.00^{e} (0.03)	173.58^{f} (0.03)	44.00^{f} (0.04)	2	51.00^{e} (0.03)	1.00^{b} (0.04)	25.00^{e} (0.03)	173.58^{f} (0.03)	44.00^{f} (0.04)
	4	56.00^{f} (0.01)	6.00^{e} (0.03)	19.00^{c} (0.01)	174.11^{h} (0.04)	32.00^{d} (0.03)	4	56.00^{f} (0.01)	6.00^{e} (0.03)	19.00^{c} (0.01)	174.11^{h} (0.04)	32.00^{d} (0.03)
	6	57.00^{g} (0.04)	7.00^{f} (0.03)	19.00^{c} (0.04)	174.27^{i} (0.03)	31.00^{c} (0.03)	6	57.00^{g} (0.04)	7.00^{f} (0.03)	19.00^{c} (0.04)	174.27^{i} (0.03)	31.00^{c} (0.03)
60 ºC	2	47.00^{c} (0.04)	2.00^{c} (0.04)	17.00^{b} (0.03)	172.88^{d} (0.04)	40.00^{e} (0.03)	2	47.00^{c} (0.04)	2.00^{c} (0.04)	17.00^{b} (0.03)	172.88^{d} (0.04)	40.00^{e} (0.03)
	4	50.00^{d} (0.03)	2.00^{a} (0.03)	17.00^{b} (0.04)	173.02^{e} (0.04)	53.00^{g} (0.03)	4	50.00^{d} (0.03)	2.00^{a} (0.03)	17.00^{b} (0.04)	173.02^{e} (0.04)	53.00^{g} (0.03)
	6	40.00^{a} (0.03)	6.00^{e} (0.01)	13.00^{a} (0.03)	172.22^{a} (0.03)	28.00^{b} (0.03)	6	40.00^{a} (0.03)	6.00^{e} (0.01)	13.00^{a} (0.03)	172.22^{a} (0.03)	28.00^{b} (0.03)

Means with different superscript within a column are significantly different at ($P<0.05$) and standard deviation. Temp. = Temperature, L* = Lightness, a* = Redness, b* = Yellowness

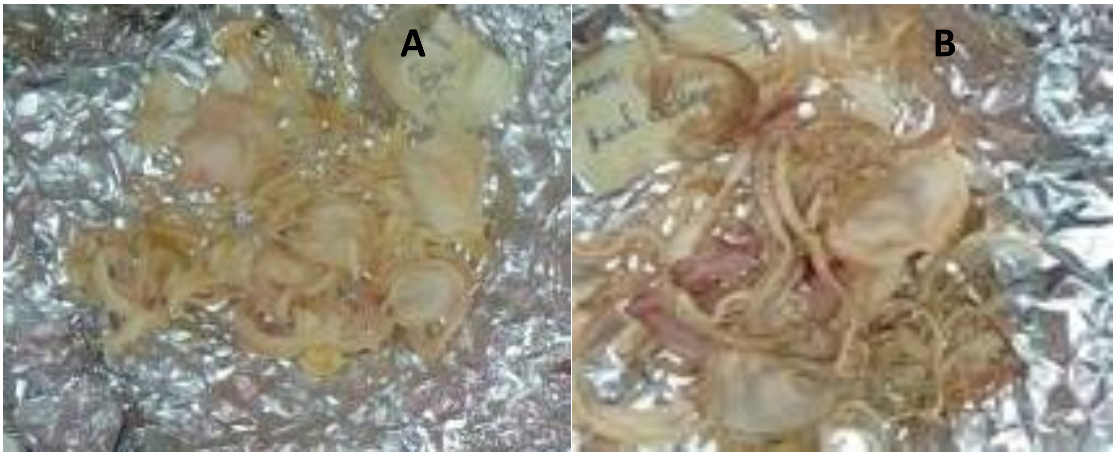

Fig. 3. Dried onion varieties (A) white (B) red

Rehydration ratio

The rehydration ratio of white and red dried onion samples of varying thicknesses at different temperatures is shown in Table 6. The values of white onion at all studied temperatures and successive thicknesses varied from 2.25 to 4.58, while red onion varied from 2.10 to 4.11. The physical properties of biological materials are altered through the process of moisture migration (Ngankham and Ram, 2011). In addition to the vast number of principal quality characteristics of dried foods, rehydration ratio is controlled by a number of conditions preceding drying (chemical composition, drying process, thickness, and temperature) (Taiwo and Adeyemi, 2009). In this study, a high rehydration ratio was observed in all the dried onion varieties, which indicates a good quality of the dried onions. Combined increases in temperature and thickness have resulted in significant increases ($p<0.05$) in the rehydration ratio of both white and red onion samples. The observed increases in the rehydration ratio are apparent due to shrinkage and internal porosity (structural disruption) of onion varieties during drying. Higher rehydration ratio was reported by several authors who conducted studies on hot air-drying of some fruit and vegetables (Prachaywarakorn et al., 2008; Jokić et al., 2009) and microwave/vacuum drying by the application of low-pressure superheated steam drying (LPSSD) (Devahastin et al., 2004; Sunjka et al., 2008).

Table 6. Rehydration ratio of onion varieties

Temperature	Thickness (mm)	Rehydration ratio	Temperature	Thickness (mm)	Rehydration ratio
	white onion			red onion	
40 °C	2	4.22^g (0.03)	40 °C	2	3.70^f (0.03)
	4	3.35^d (0.04)		4	3.06^d (0.04)
	6	2.25^a (0.03)		6	2.10^a (0.06)
50 °C	2	4.46^h (0.03)	50 °C	2	3.89^g (0.01)
	4	3.47^e (0.01)		4	3.24^e (0.04)
	6	2.54^b (0.03)		6	2.41^b (0.03)
60 °C	2	4.58^i (0.01)	60 °C	2	4.11^h (0.03)
	4	3.65^f (0.04)		4	3.66^f (0.04)
	6	2.78^c (0.01)		6	2.68^c (0.01)

Means with different superscript within a column are significantly different at (P<0.05) and standard deviation.

Conclusion

The study demonstrated that the drying rate occurred in the falling rate period and the drying process exhibited the diffusion-dominant drying principle. The effective moisture diffusivity (D_{eff}) of white and red onions ranged between 9.32×10^{-10} and 8.39×10^{-9} m^2/s, 8.91×10^{-10} and 8.39×10^{-9} m^2/s, respectively. The activation energy (E_a) for white onions ranged between 55.98 and 65.40 KJ/mol, while red onions ranged between 55.98 and 65.68 KJ/mol, respectively. Among the four drying models selected, the Page model optimally predicted $R^2 > 0.9$ and was found to be better in describing the drying of onion varieties, while the Lewis model provided the least fit. The developed model could be useful for predicting the drying process of onion varieties with the optimum conditions demonstrated essentially to facilitate the drying process towards commercial production of dried onions. Further research should be directed towards the assessment of the hot air-drying effect on the pungency characteristics of dried onions, its shelf stability, and the use of appropriate packaging materials for commercial purpose. Additionally, the comparison of energy required for economic advantage could also be investigated.

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