Thin layer modelling of hybrid, solar and open sun drying of tomato slices

J. B. Hussein¹, K. B. Filli¹ and M. O. Oke^{2*}

¹Department of Food Science and Technology, Modibbo Adama University of Technology Yola, P. M. B. 2076, Yola, Adamawa State, Nigeria.

²Department of Food Science and Engineering, Ladoke Akintola University of Technology Ogbomosho, P. M. B. 4000, Ogbomosho, Oyo State, Nigeria.

*Corresponding author. Email: ola4ade@yahoo.com, mooke47@lautech.edu.ng

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ABSTRACT: The thin layer drying behaviour of tomato slices dried using hybrid drying method as well as solar and open sun drying was investigated. Six thin layer drying models (Page, Logarithmic, Henderson and Pabis, Newton (Lewis), Wang and Singh and Parabolic) were used to optimize the goodness of fit to the experimental data. The models were compared using coefficient of determination (R^2), chi-square (χ^2) and root mean square error (RMSE). The tomato slice dried faster when subjected to hybrid drying method compared to other methods. Tomato slices of 4, 6 and 8 mm thicknesses were dried from 94.22 to 10% (wet basis), for 300, 360, 420 minutes respectively in hybrid drying method. However, it took 420, 510, 600 and 510, 630, 840 min in solar and open sun drying respectively. The drying took place only in a falling rate drying period. The Page model was found to fit the experimental data better as compared to other models. The effective moisture diffusivity values were found to be between 2.00×10^{-10} and $5.84 \times 10^{-10} \text{ m}^2/\text{s}$ in hybrid dried slices, 1.37×10^{-10} and $4.40 \times 10^{-10} \text{ m}^2/\text{s}$ in solar dried slices and 1.33×10^{-10} and $4.01 \times 10^{-10} \text{ m}^2/\text{s}$ in open sun dried tomato slices of 4 to 8 mm thicknesses. The results of these measures have confirmed the consistency of the developed model to describe satisfactorily the thin-layer hybrid, solar and open sun drying characteristics of tomato slices.

Keywords: Drying equation, hybrid dryer, moisture content, solar dryer, tomato slice.

INTRODUCTION

Tomatoes (*Lycopersicon esculentum* L.var) are one of the most important grown vegetable crops, mostly in the tropical countries. It is highly seasonal and available in large quantities at a particular season of the year. Due to market glut during peak season large quantity of tomato gets spoiled. Processing, preservation and storage of tomatoes during peak season can prevent the huge post-harvest losses in tomato and make them available in the off season at comparatively lesser cost. Tomatoes and tomato products are rich in health valued food components such as carotenoids (Lycopene), ascorbic acid (Vitamin C), vitamin E, folate and dietary fibre

(Davies and Hobson, 1981; Rajkumar, 2007). Dehydration processes offer an alternative way of using tomato for consumption and the dehydration of tomato has been practiced for many years as a means of preservation.

Tomatoes, as other vegetables, can be dried using various methods. In any tomato drying technique the required time for drying the product depends on many parameters such as tomato variety, the soluble solids content ($^{\circ}$ brix) of the fresh product, the air humidity, the size of the tomato segments, the air temperature and velocity and the efficiency of the drying system. The rate of drying affects the end quality of the dried product

(Andritsos et al., 2003). In general, dried tomatoes undergo the following process steps: pre-drying treatments, (such as size selection, washing and tray placing), drying or dehydration, and post-dehydration treatments, such as inspection, screening and packaging (Andritsos et al., 2003).

Sun drying of agricultural products is the traditional method employed in most of the developing countries. Sun drying is used to denote the exposure of a commodity to direct solar radiation and the convective power of the natural wind. Sun drying offers a cheap method of drying but often results to inferior quality of products due to its dependence of weather conditions (Amer et al., 2010). Andritsos et al. (2003) reported that traditional sun-drying of tomatoes has the advantages of simplicity and the small capital investments, but it requires long drying times that may have adverse consequences to the product quality: the final product may be contaminated from dust and insects or suffer from enzyme and microbial activity. On the other hand, solar energy drying is an alternative which offers several advantages over the traditional method and it has been developed for various agricultural products. Solar energy for crop drying is environmentally friendly and economically viable in the developing countries. It's also form a sustainable energy that has a great potential for wide variety of applications because it is abundant and accessible, especially for countries located in the tropical region. Solar-energy drying overcomes the drawbacks of traditional open sun drying such as, contamination from dust, insects, birds and animals, lack of control over drying conditions, possibility of chemical, enzymatic, and microbial spoilage due to long drying times (Ajay et al., 2009; Gutti et al., 2012). Solar drying offers an alternative which can process the vegetables and fruits in clean, hygienic and sanitary conditions, to acceptable national and international standards. It saves energy, time, occupies less area, improves product quality, makes the process more efficient and protects the environment (Funebo and Ohlsson, 1998; Zhang et al., 2006; Aware and Thorat, 2012).

However, one significant disadvantage of solar dryer is that it can only be used during the daytime when there is adequate solar radiation. That is they are normally constructed with no any form of back-up heating systems (Geramitcioski and Mitrevski, 2011). For commercial producers, this factor limits their ability to process a crop when the weather is poor. It can also extend the drying time because drying can only occur during the day time when there is solar radiation. This not only limits production but can result in an inferior product (Werner and Josef, 2003). For commercial producers, the ability to process continuously with reliability is important to satisfy their markets. Therefore, it is necessary to provide solar-energy dryer with additional source of energy such is the case of hybrid dryer (solar dryer with energy storage

system).

In a hybrid solar dryer, drying is continued during off sunshine hours by back-up heat energy or storage heat energy. Therefore, drying is continued and the product is saved from possible deterioration by microbial infestation. Puiggali and Varichon (1982) reported that thermal storage during the day can be used as a heat source during the night for continuing drying of agricultural products and also preventing their re-hydration from the surrounding air. Continuous drying also prevents microbial growth during drying (Hossain and Gottschalk, 2006). Also, it was found that storage and auxiliary heat supply can be used to assess compatibility of solar energy to meet the drying process temperature (Vlachos et al., 2002). Some hybrid dryers were developed to control the drying air conditions throughout the drying time independent of sun-shine especially at night or poor weather when it is not possible to use the solar energy, using alternative heating sources such as sawdust burner (Bassey, 1985); kerosene stove (Babarinsa 2006) or by using a biomass stove (Prasad and Vijay, 2005; Amer et al., 2010); electric heater (Boughali et al., 2009; Reyes et al., 2014). It is reported that significant improvement was registered after the heater is added to the solar dryer during periods of low sun-shine (Bennamoun and Belhamri, 2003).

In order to successfully transfer knowledge acquired experimentally from studies on food dehydration into industrial applications, mathematical modelling of drying kinetics is required. Moreover, a mathematical model is an important tool used to optimize operating parameters and to predict performance of a drying system (Babalís and Belessiotis, 2004). Numerous mathematical models, empirical and semi-empirical, have been proposed to estimate the drying characteristics of agricultural products (Mirzaee et al., 2010). These simple models, also known as thin layer models, allow prediction of mass transfer during dehydration and are applied to simulate drying curves under similar conditions (Doymaz, 2007; Purkayastha et al., 2013).

Many researches have been conducted on the mathematical modeling and experimental studies on thin layer solar drying processes of various vegetables and fruits, such as green bean (Doymaz, 2005), pistachio (Midilli and Kucuk, 2003), red pepper (Akpınar et al., 2003), mint leaves (Akpınar, 2010), tarragon (Arabhosseini et al. 2008), potato (Aghbashlo et al. 2009), chilli pepper (Tunde-Akintunde, 2011), carrot (Berruti et al., 2009), citrus aurantium leaves (Mohamed et al., 2005) and tomato slice (Kulanthaisami et al., 2010; Bagheri et al., 2013). However, few reports have focused on the drying kinetics of hybrid dried tomato slices. Therefore, the aim of this study was to evaluate the drying kinetics of hybrid and solar drying of tomatoes slices in relation to open sun drying using thin layer drying models.

MATERIALS AND METHODS

Raw Material Preparation

The tomatoes used for this study were obtained from the Jimeta Modern Market, Yola, Adamawa State, Nigeria. Samples of tomatoes were selected from the lot based on firmness, colour and size uniformity. They were washed thoroughly with tap water, rinsed with distilled water and then wiped with an absorbent paper (Owusu et al., 2012). The hybrid dryer used in this study was a hybrid-photovoltaic dryer which used photovoltaic (PV) solar panel to power the heating element coil and charging the battery which store energy. The heating sources of the dryer was used separately as solar dryer and combined as hybrid dryer. The dryer was used to dried slice tomatoes and compared with open sun drying under the weather condition of Adamawa State, Yola which was geographically located at the North Eastern part of Nigeria and lies between latitude 7 and 11°N and between Longitude 11 and 14°E.

Drying Procedures

Drying experiments were carried out using a laboratory hybrid-photovoltaic solar dryer. Briefly, a schematic diagram of the experimental system is shown in Figure 1. The dryer consists of a DC extractor fan, drying chamber (500 × 500 × 1100 mm³), drying trays, collector (which is an absorber plate made of aluminum sheet painted black and a transparent glass of 5 mm thickness which permit in only sun radiation), air channel (air vent which is provided on the lower front side of the collector for easy passage of air into the dryer), DC blower fan and 500 W power heater located at the bottom of the drying chamber, two solar panel rated 180 W power each, solar battery rated 200 Ah and a temperature sensor which was located at the center of the chamber to sense the chamber temperature.

The initial moisture content of the tomato samples was determined in an oven at a temperature of 105°C for 24 h (AOAC, 2004). The initial moisture content was 94.22% (wet basis) for tomatoes. The cleaned tomatoes were pretreated in boiling water for 2 min, and drained. The samples were then divided into three portions. Then, each portion was sliced using slicer to a thickness of 4, 6 and 8 mm. The first portion of the slices (4 kg and 4 mm thick) were spread in a single layer on a four different wire meshes (1 kg on each wire mesh) and sun dried until equilibrium moisture content was achieved. The second portion (4 kg and 4 mm thick) was dried in the constructed hybrid dryer by using solar collector as the heating source alone and the third portion (4 kg and 4 mm thick) was dried by using both heating source together. One (1 kg) on each wire mesh tray and it was left until constant weight was achieved. This procedure

was repeated for 6 and 8 mm respectively. Before each experiment, the dryer was started for one hour to achieve desirable steady state condition and during each run inlet air, ambient air temperature, sample weight and sample temperature were recorded as initial readings. The moisture content of the tomato slices of all the portions were monitored and measured at every 30 minutes until equilibrium moisture content was obtained. The drying process was finished when the sample reached the moisture content of 10%. Then, the average weight of each try weight was taken and recorded.

Mathematical Modelling

Determination of moisture ratio (MR)

The moisture ratio of tomato slices dried under open sun drying, solar drying and hybrid drying at a given time, t was calculated using a relationship;

$$\text{Moisture Ratio (MR)} = \frac{M_t - M_e}{M_i - M_e} = e^{-kt} \quad \text{Eq.1}$$

Where: M_i and M_e are the initial and equilibrium dry basis moisture contents, %, M_t is dry basis moisture content at any time 't', k is the drying rate constant per minute and t is the drying time, min.

The values of M_e are relatively small compared to M_t and M_i , where error implied in the simplification is negligible. Drying curves were obtained for the tomatoes. The experimental moisture ratio versus drying time data were fitted in six thin layer drying models (Page, Logarithmic, Henderson and Pabis, Newton (Lewis), Wang and Singh, and Parabolic) widely used to describe the drying characteristics of most food products (Table 1). The best model was selected to describe the hybrid, solar and open sun drying processes of tomato slices (Akpınar, 2006 and Rajkumar, 2007). These models are generally derived by simplifying the general series solution of Fick's second law. The coefficient of determination (R^2) was used as primary criteria for selecting the model that best fit the experimental data. In addition to the coefficient of determination, the best fit of the experimental data was also selected based on various statistical parameters such as the reduced chi-square (χ^2) as the mean square of the deviations between the experimental and predicted values for the models and root mean square error analysis (RMSE). To get the best fit of the experimental data, the coefficient of determination should be higher and the χ^2 and RMSE should be lower (Akpınar et al., 2006; Tunde-Akintunde and Oke, 2012).

The statistical parameters were calculated by using the following relationships;

$$\chi^2 = \frac{[\sum_{i=1}^N (MR_{pre,i} - MR_{exp,i})^2]}{N-n} \quad \text{Eq. 2}$$

Figure 1: Isometric view of the Hybrid Dryer.

Table 1: Mathematical Models Fitted to Tomato Slice Drying Curves.

Model Name	Model Equation	References
Page	$MR = \exp(-kt^n)$	Doymaz, (2004); Da Silva et al., (2005); Singh et al., (2006); Alibas, (2007); Jangam et al., (2008); Hassan-Beygi et al., (2009).
Logarithmic	$MR = a \exp(-kt) + b$	Doymaz, (2004); Kingsly et al., (2007); Xanthopoulos et al., (2007); Khazaei et al., (2008); Tunde-Akintunde and Oke, (2012)
Henderson and Pabis	$MR = a \exp(-kt)$	Shittu and Raji (2011); Tunde-Akintunde and Oke, (2012)
Newton (Lewis)	$MR = \exp(-kt)$	Togrul and Pehlivan, (2002); Tunde-Akintunde, (2011); Tunde-Akintunde and Oke, (2012)
Wang and Singh	$MR = 1 + kt + ct^2$	Wang and Singh, (1978); Çelen et al., (2013)
Parabolic	$MR = a + kt + ct^2$	Sharma and Prasad, (2004); Doymaz, (2010); Tunde-Akintunde and Oke, (2012)

$$RSME = \sqrt{\frac{1}{N} \sum_{i=1}^N (MR_{pre,i} - MR_{exp,i})^2} \quad \text{Eq.} \quad 3$$

Where: χ^2 = chi-square, N = numbers of runs, MR_{pre} = predicted moisture ratio, MR_{exp} = expected moisture ratio and n = positive integer.

Determination of moisture effective diffusivities

Fick's equation is widely used for explaining drying

mechanism of solid food material involving diffusion of vapour (Sankat and Castaigne, 2004). When a material dries mainly in the falling rate period, then it could be assumed that the internal moisture diffusion occurs. Therefore, moisture diffusivity in tomato slices can be calculated from the experimental drying data using Fick's second law for a slab shaped material. The solution to this equation developed by Crank (1975) can be applied for tomato slices of different thicknesses by assuming uniform initial moisture distribution as:

Figure 2: Drying Curve for Hybrid Drying Method.

$$MR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(-\frac{(2n+1)^2 D_{eff} \pi^2}{4l^2} t\right) \quad \text{Eq. 4}$$

Where;

D_{eff} is the effective moisture diffusivity, m^2/s ;

t is the drying time, s ;

L is the half thickness of a thin layer sample, m ; and

n is a positive integer.

For long drying time, only the first term of equation 4 is significant (Tutuncu and Labuza, 1996) and then the solution becomes;

$$MR = \frac{8}{\pi^2} \exp\left(-\frac{D_{eff} \pi^2}{4l^2} t\right) \quad \text{Eq. 5}$$

This could be further simplified to a straight-line equation as;

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{D_{eff} \pi^2}{4l^2}\right) t$$

The effective moisture diffusivity values were determined by plotting experimental drying data in terms of $\ln(MR)$ versus drying time t . A plot of $\ln(MR)$ versus drying time gives a straight line with a slope;

$$\text{slope} = -\frac{D_{eff} \pi^2}{4l^2} \quad \text{Eq. 6}$$

Knowing the tomato slice thickness and the slope from the above plot, the moisture diffusivity (D_{eff}) was calculated.

RESULTS AND DISCUSSION

Drying curves

The change in moisture content of tomatoes slices with drying time in hybrid dryer, solar dryer and open sun drying was presented in Figures 2, 3 and 4. It was observed that the total drying time for 4, 6 and 8 mm thickness slices was 300, 360, 420 min, respectively in hybrid drying, 420, 510, 600 min, respectively in solar drying and 510, 630 and 840 min, respectively in open sun drying. This shows that for a given thickness, the hybrid drying method required shorter drying time when compared to solar and open sun drying. Also solar drying required shorter drying time when compared to open sun drying method. In other words, drying time was reduced to about 28.57 – 30% of the total drying time spent for 4 - 8 mm thickness tomato slices in hybrid dryer when compared to solar dryer, 41.18 – 50% in hybrid dryer when compared with open sun drying and 17.64 – 28.57% in solar dryer when compared with open sun drying. The reduction in the total drying time of the hybrid dryer compared to solar dryer and open sun drying was observed to be due to higher temperature in the drying chamber of the hybrid dryer.

This result is in agreement with Rajkumar (2007) findings in which the drying time reduced significantly as the thickness of slices decreases, because the resistance to moisture movement is relatively higher in thicker slices than in thinner ones. This resistance was observed to decrease the drying rate, which resulted in increased drying time of 8 mm thick slices. Generally, it was observed

Figure 3: Drying Curve for Solar Drying Method.

Figure 4: Drying Curve for Open Sun Drying Method.

that the time required to reduce the moisture content of tomato slices to any required moisture level depends on the drying conditions that are influenced by weather parameters. Similarly, Sacilik et al. (2006) also observed that the drying characteristics of tomato slices in solar tunnel and open sun drying methods were highly influenced by weather parameters.

Mathematical Modelling of the Drying curves

The summary of model parameters of the six thin layer drying models obtained from the non-linear regression of the models are shown in Tables 2, 3 and 4. It was observed that the Page model satisfactorily described the drying kinetics of tomato slices dried using hybrid, solar

Table 2: Estimated Parameters and Comparison Criteria of Moisture Ratio for Hybrid Drying.

Models	Models constants	Tomato thickness	R ²	χ^2	RMSE
Page	k = 0.286 n = 0.525	4	1.000	4.44334x 10 ⁻⁶	0.00191
	k = 0.161 n = 0.630	6	1.000	1.59561x 10 ⁻⁵	0.00367
	k = 0.111 n = 0.675	8	1.000	1.45805x 10 ⁻⁵	0.00356
Logarithmic	k = 0.057 a = 0.980 b = 0.019	4	0.997	0.00033	0.01548
	k = 0.044 a = 0.979 b = 0.017	6	0.997	0.00027	0.01446
	k = 0.034 a = 0.973 b = 0.019	8	0.995	0.00039	0.01769
Henderson and Pabis	k = 0.053 a = 0.997	4	0.994	0.00060	0.02222
	k = 0.041 a = 0.995	6	0.994	0.00050	0.02065
	k = 0.031 a = 0.988	8	0.991	0.00064	0.02347
Newton (Lewis)	k = 0.053	4	0.994	0.00054	0.02223
	k = 0.041	6	0.994	0.00046	0.02070
	k = 0.032	8	0.991	0.00060	0.02369
Wang and Singh	k = -0.012 c = 3.092x 10 ⁻⁵	4	0.471	0.05084	0.20396
	k = -0.010 c = 2.171x 10 ⁻⁵	6	0.414	0.04781	0.20113
	k = -0.009 c = 1.583x 10 ⁻⁵	8	0.417	0.04219	0.19123
Parabolic	k = -0.008 c = 1.978x 10 ⁻⁵ a = 0.667	4	0.692	0.03333	0.15569
	k = -0.006 c = 1.321x 10 ⁻⁵ a = 0.641	6	0.693	0.02758	0.14566
	k = -0.005 c = 9.431x 10 ⁻⁶ a = 0.636	8	0.720	0.02194	0.13247

Table 3: Estimated Parameters and Comparison Criteria of Moisture Ratio for Solar Drying.

Models	Models constant	Tomato thickness	R ²	χ^2	RMSE
Page	k = 0.219 n = 0.554	4	1.000	5.33838x 10 ⁻⁶	0.00354
	k = 0.079 n = 0.717	6	1.000	2.18559x 10 ⁻⁵	0.00441
	k = 0.059 n = 0.710	8	1.000	1.44509x 10 ⁻⁵	0.00220
Logarithmic	k = 0.046 a = 0.977 b = 0.019	4	0.996	0.00034	0.01636
	k = 0.027 a = 0.970 b = 0.018	6	0.995	0.00032	0.01625
	k = 0.017 a = 0.943 b = 0.023	8	0.989	0.00066	0.02376
Henderson and Pabis	k = 0.043 a = 0.994	4	0.991	0.00064	0.02349
	k = 0.025 a = 0.982	6	0.991	0.00055	0.02215
	k = 0.016 a = 0.953	8	0.984	0.00096	0.02943
Newton (Lewis)	k = 0.043	4	0.991	0.00059	0.02353
	k = 0.026	6	0.991	0.00053	0.02255
	k = 0.017	8	0.992	0.00103	0.03131
Wang and Singh	k = -0.009 c = 1.632x 10 ⁻⁵	4	0.223	0.05434	0.30721
	k = -0.007 c = 1.082x 10 ⁻⁵	6	0.355	0.04064	0.19007
	k = -0.006 c = 7.398x 10 ⁻⁶	8	0.495	0.02997	0.16466
Parabolic	k = -0.005 c = 8.994x 10 ⁻⁶ a = 0.583	4	0.634	0.02774	0.14898
	k = -0.004 c = 6.152x 10 ⁻⁶ a = 0.614	6	0.722	0.01868	0.12478
	k = -0.003 c = 4.314x 10 ⁻⁶ a = 0.650	8	0.800	0.01251	0.10353

Table 4: Estimated Parameters and Comparison Criteria of Moisture Ratio for Open Sun Drying.

Models	Models constant	Tomato thickness	R ²	χ^2	RMSE
Page	k = 0.037 n = 0.791	4	1.000	2.1903×10^{-5}	0.00441
	k = 0.029 n = 0.801	6	1.000	7.10241×10^{-6}	0.00254
	k = 0.003 n = 1.178	8	0.997	0.00021	0.01389
Logarithmic	k = 0.015 a = 0.951 b = 0.019	4	0.994	0.00047	0.01970
	k = 0.011 a = 0.943 b = 0.020	6	0.994	0.00038	0.01822
	k = 0.008 a = 1.049 b = 0.000	8	0.995	0.00047	0.02028
Henderson and Pabis	k = 0.014 a = 0.960	4	0.991	0.00062	0.02355
	k = 0.011 a = 0.950	6	0.992	0.00055	0.02239
	k = 0.008 a = 1.049	8	0.995	0.00045	0.02028
Newton (Lewis)	k = 0.015	4	0.990	0.00070	0.02568
	k = 0.011	6	0.989	0.00068	0.02551
	k = 0.008	8	0.993	0.00059	0.02383
Wang and Singh	k = -0.006 c = 8.865×10^{-6}	4	0.695	0.02186	0.13940
	k = -0.005 c = 4.926×10^{-6}	6	0.631	0.02437	0.14884
	k = -0.004 c = 3.534×10^{-6}	8	0.837	0.01362	0.11195
Parabolic	k = -0.004 c = 5.769×10^{-6} a = 0.724	4	0.865	0.01031	0.09267
	k = -0.003 c = 3.038×10^{-6} a = 0.697	6	0.857	0.00992	0.09257
	k = -0.003 c = 2.671×10^{-6} a = 0.813	8	0.904	0.00845	0.08624

and open sun drying methods followed by the Logarithmic model. Page model was also reported to give the best fit that describes the thin layer drying of some earlier studies. These include Akpınar et al. (2006) for aromatic plants; Doymaz, (2004) for carrots; and Hossain and Bala (2002) for green chillies; Kulanthaisami et al. (2010) for solar cabinet and open sun drying of tomato slices. Others are Bagheri et al. (2013) for solar dryer, shadow and open sun drying of tomato slices and Çelen et al. (2013) for vacuum drying kinetics of untreated tomato slices.

The experimental and the predicted data values using Page model for moisture ratios of tomato slices dried in hybrid, solar and open sun drying methods were shown in Figures 5, 6 and 7. The established model provided a very good conformity between the experimental data and the predicted moisture ratios of the tomato slices (4, 6 and 8 mm) dried under hybrid dryer, solar dryer and open sun drying methods. It was observed that the predicted data are banded around the ideal trend line indicating the suitability of the model in predicting the drying behaviour of tomato slices in hybrid dryer, solar dryer and by open sun drying. Queiroz et al. (2004) reported that drying curves could be well adjusted by the Page model and the model parameters were correlated as functions of drying conditions.

Effective Moisture Diffusivity

The mechanisms of mass transfer in food are complex in nature. The water migrates from the inside to the surface of the product under the effect of various mechanisms which can be combined. In this study, only a falling rate drying period, which resulted in shrinkage of the dried tomatoes was observed. Thus, the main mechanism of the water transport for the tomatoes slices is considered as diffusive type. The method of slopes as shown in Eq. (6) was used to calculate the effective moisture diffusivity coefficient. Slope of graphs of Ln (MR) versus time for the experimental drying were determined. The effective moisture diffusivity values were found to be $2.00 - 5.84 \times 10^{-10} \text{ m}^2/\text{s}$ in hybrid dried slices, $1.37 - 4.40 \times 10^{-10} \text{ m}^2/\text{s}$ in solar dried slices and $1.33 - 4.01 \times 10^{-10} \text{ m}^2/\text{s}$ in open sun dried tomato slices of 4 to 8 mm thicknesses.

The values of D_{eff} obtained for open sun dried tomato slices was the least while that of hybrid dried tomato slices had the highest value which indicates that moisture diffusivity in tomato is affected by the drying temperature. Diffusivity is a function of material characteristics as well as drying temperature. Higher diffusivity values obtained in hybrid dried tomato slices might be due to relatively lesser shrinkage of slices when compared to solar and sun dried slices. It can be due to better circulation of air

Figure 5: Experimental and Predicted Drying Curves for Tomato Slices under Hybrid Drying Method.

Figure 6: Experimental and Predicted Drying Curve for Tomato Slices under Solar Drying Method.

and perhaps also due to higher temperature and lower relative humidity (Rajkumar, 2007). The moisture from the inner core of the product migrates and replaces the surface and capillary moisture as they evaporated and eventually diffusion of moisture became the predominant

mechanism. The drying temperature has a significant effect on the internal mass transfer during drying since the higher the drying temperature, the higher the rate at which diffusion of moisture from the internal regions to the surface occurs. This is because surface water

Figure 7: Experimental and Predicted Drying Curve for Tomato Slices under Open Sun Drying Method.

removal is faster at higher temperature since most of the drying mechanism is vapour diffusion. This is similar to that which was observed for date palm fruits and tiger nut seeds (Falade and Abou, 2007; Tunde-Akintunde and Oke, 2012).

The D_{eff} values obtained for tomatoes slices in this study lie within the general range of 10^{-12} to 10^{-8} m^2/s for drying agricultural materials (Doymaz, 2010). They were also in comparison with the values reported by Sacilik et al. (2006) for open sun dried tomato slices (1.31×10^{-9} m^2/s); Akanbi and Adeyemi, (2006) for tomatoes dried at $45^\circ C$ to $75^\circ C$ ($3.72\text{--}12.27 \times 10^{-9}$ m^2/s) and Doymaz (2007) for tomatoes dried at $55^\circ C$ to $70^\circ C$ ($3.91 - 7.53 \times 10^{-10}$ m^2/s).

Conclusions

The study established that the time required to dry the tomato slices was comparatively lower in hybrid drying when compared to solar and open sun drying. The time required to dry 4 mm thickness tomato slice was lesser as compared to 6 and 8 mm thick slices. The drying rate and moisture diffusivity of tomato slices were higher in hybrid dryer. This study established that the drying behaviour of tomatoes slices occur in the falling rate period and Page model was found to be better in describing the drying kinetics. The study also concluded that the drying time and product temperatures were highly influenced by the weather parameters mainly temperature induced by solar insolation. The study has therefore provided information useful in drying process design for tomatoes which will assist in reducing losses often incurred during bumper harvesting and processing

of tomatoes. It also proved that the efficiency of agricultural dryers could be increased through the use of a combination of solar and heating element coil powered by photovoltaic (PV) solar panel, compared to conventional dryers with only solar or only biomass heating sources.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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NOMENCLATURE

a, b, c, n	the drying coefficients in thin-layer equations	s^{-1}
D_{eff}	effective moisture diffusivity	m^2/s
k	drying rate constant	s^{-1}
L	half thickness of a thin layer sample	m
M_e	equilibrium dry basis moisture contents	kg/kg dry tomato slice
M_i	initial dry basis moisture contents	kg/kg dry tomato slice
MR	moisture ratio	
M_t	dry basis moisture content at any time 't'	kg/kg dry tomato slice
N	drying power factor in thin-layer equations	
R^2	coefficient of determination	
$RMSE$	root mean square error analysis	
t	drying time	s
χ^2	reduced chi-square	