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Thin Layer Drying of Orange Skin Paste for Biofuel Production: Drying Characteristics and Mathematical Modelling

[1]Agbede, O.O., [1]Adebiyi, A.O., [2]Oke, E.O., [1]Arinkoola, A.O., [1]Ogunleye, O.O., [1]Agarry, S.E., [1]Babatunde, K.A. and *[1]Osuolale, F.N.
[1]Department of Chemical Engineering, Ladoke Akintola University of Technology, Ogbomoso, Nigeria.
[2]Department of Chemical Engineering, Michael Okpara University of Agriculture, Umudike, Nigeria.
*fnosuolale@lautech.edu.ng

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ABSTRACT

Huge amount of orange waste is generated during juice extraction and this could be converted to bioenergy through pyrolysis, gasification or combustion. However, improved efficiency of these processes requires drying, hence, the drying characteristics of orange skin paste was investigated in this study. Orange skin wastes were crushed and then dried to constant mass in a hot air oven dryer (at 80, 120 and 140 °C), solar dryer and direct sunlight. Twelve thin layer models were fitted to the drying data. Hot air oven drying of orange skin paste took place in the falling rate period with effective moisture diffusivity (D_{eff}) which varied from 7.0 x 10^{-9} to 1.8 x 10^{-8} m^2 s^{-1}. The temperature dependence of D_{eff} was suitably described by an Arrhenius-type equation and an activation energy of 16.1 kJ mol^{-1} was required for drying the orange skin paste. The specific energy required for hot air drying was 846 – 1475 kJ/g. Open sun and solar drying of orange skin paste also occurred in the falling rate period with D_{eff} values of 2.0 x 10^{-9} and 2.16 x 10^{-9} m^2 s^{-1}, respectively. The Midilli-Kucuk, Logarithmic and Midilli-Kucuk models best fitted the hot air oven, open sun and solar drying, respectively.

1. INTRODUCTION

Bioenergy, a renewable energy derived from biological sources or biomass, is deemed a potential alternative or supplement to fossil fuels which are fast depleting, high polluting and non-renewable (Dincer, 2000; Panwar et al., 2011; Ho et al., 2014; Demirbas et al., 2017). Biomass are materials derived from microorganisms, animals and plants and they include algae, energy crops, animal wastes, food wastes, wood and wood wastes, agricultural residues, municipal solid wastes and industrial residues (Saxena et al., 2009; Demirbas et al., 2017). Biomass may be used directly or first converted into biofuel before it is utilised for transportation or electricity generation. (Saxena et al., 2009; Ellabban et al., 2014). They can be converted into biofuels or bioenergy through thermochemical, biochemical and physicochemical processes. The thermochemical conversion processes are pyrolysis, gasification, hydrothermal liquefaction and direct combustion. The biochemical processes include fermentation, anaerobic digestion and biophotolysis while the physicochemical process involves oil extraction e.g. from seed biomass followed by transesterification (Kumar et al., 2009; Kumar et al., 2015).

The moisture content of biomass may be high, and this can limit the efficiency of thermochemical conversion processes (Hughes and Larson, 1998; McKendry, 2002; Demirbas, 2004; Samuelsson et al., 2006). Hence, biomass usually requires drying prior to pyrolysis, gasification and direct combustion (Bennion et al., 2015; Azizi et al., 2018). Drying is a preservation method used to reduce the moisture content of agricultural products thereby decreasing microbial and enzyme activities, increasing the shelf-life of the products and reducing packing and transportation cost (Mujumdar and Law 2010; Guine et al., 2012). Sun drying is the traditional method of drying agricultural products, but it is extremely weather dependent, takes a long time and materials are prone to contamination with dust, insect, etc. Solar drying employs a solar dryer which shades the material from direct exposure to rainfall, dust, insects, etc., but still uses energy from sun radiation to dry the material in a chamber heated up directly or indirectly by the sun radiation. In contrast, hot air drying uses a mechanical equipment which requires electricity to generate heat for raising the temperature of drying air; it is also more hygienic and provides better uniformity in drying (Diamante and Munro 1993).

The orange juice manufacturing industry generates a huge quantity of waste which is about 50 – 60% by weight (wet basis) of the processed fruit (Wilkins et al., 2007; Koppar and Pullammanappallil, 2013; Mamma and Christakopoulos, 2014). About 60-65% of this waste is composed of peels (Crawshaw, 2003). This waste can be converted via thermochemical processes into biofuels (Aguiar et al., 2008; Miranda et al., 2009; Lopez-Velasquez et al., 2013; Volpe et al., 2015; Siles et al, 2016). Orange waste has a very high water content (Siles et al., 2016) and requires a drying pre-treatment prior to biofuel production via thermochemical conversion processes (Miranda et al., 2009; Volpe et al., 2015).

When materials are dried as one layer of sample particles or slices, so that the material has a thin structure, it is usually known as thin layer drying (Akpinar, 2006; Erbay and Icier, 2010). The drying characteristics of several agricultural products including fruits, vegetables and staple foods have been reported in the literature (Rajkumar et al., 2007; Doymaz, 2010; Erbay and Icier, 2010; Ojediran and Raji, 2010; Davishi, 2017) but little has been reported on the thin layer drying of biomass. Hence, this study investigated the thin layer sun, solar and hot air oven drying characteristics of orange skin paste for biofuel production. Drying involves simultaneous coupled heat and mass transfer (Diamante et al., 2010), so mass and heat transfer properties of biomass such as effective moisture diffusivity, activation energy and energy consumption, essential for dryer design were measured.

Drying is a complex process which require effective mathematical models for process design, optimization and control as well as energy integration. Thin layer drying mathematical models have been applied in the study of the drying of foods, fruits and vegetables (Toğrul and Pehlivan, 2004; Akpinar and Bicer, 2008; Doymaz, 2010; Ojediran and Raji, 2010; Doymaz and Ismail, 2011; Tunde-Akintunde, 2011). However, mathematical modelling of the drying of biomass has not been adequately investigated, so, this study also considered the thin layer mathematical modelling of the drying of orange skin paste.

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2. MATERIALS AND METHODS

2.1. Sample Preparation

Fresh oranges, (*Citrus sinensis*) were obtained from a local market in Ogbomoso, Nigeria. The oranges were washed and wiped dry using a clean cloth to remove residual moisture on the surface of the oranges. The outer layer (peel) of the orange skin was removed using a razor blade. The oranges were then cut using a clean knife, juiced and the pulp removed leaving the whitish skin. The whitish skin was afterwards crushed to obtain a paste, using an electric blender, in order to increase the surface area of the orange skin before drying. The orange skin paste was then held in aluminium pans of dimension 7.5 by 7.5 cm, fabricated by local artisans, for the drying operations. The orange skin paste was evenly spread in the aluminium drying pans to a depth of 20 mm (amounting to an initial mass of about 50 g) for all experiments.

2.2. Drying Methods

Aluminium drying pans containing orange skin paste to a depth of 20 mm were separately placed in sunlight (open sun drying method), direct type solar dryer (solar drying method) and preheated hot air oven dryer to dry. A natural convection direct solar dryer which has a triangular prism shaped drying chamber as shown in Figure 1 was utilized in this study. The drying chamber has a height of 0.67 m while its rectangular base on which the aluminium drying pans were placed has a dimension of 1.2 by 0.7 m. The sun and solar drying experiments were carried out in the month of October, 2018, and samples were dried between 9 am and 6 pm. They were removed from the dryer/sunlight at sunset and kept overnight in the laboratory till the next day when drying was resumed until a constant mass was achieved. During the sun and solar drying operations, the mass of the material was measured initially at an interval of 30 min then at an interval of 60 min towards the end of the drying process. A Uniscope SM9053A laboratory hot air oven dryer (Surgifriend Medicals, England) operating with an air velocity of 1.5 m s^{-1} was also utilised in this study. The hot air oven drying experiments were carried out at temperatures of 80, 120 and 140 ^{o}C. The samples were weighed at 15- or 20-min interval until the weight remained constant. A Citizen digital weighing balance which has an accuracy of 0.001 g was used for measuring the mass of the material. The drying process was stopped when the mass of the orange skin paste became constant. All experiments were performed in triplicates.

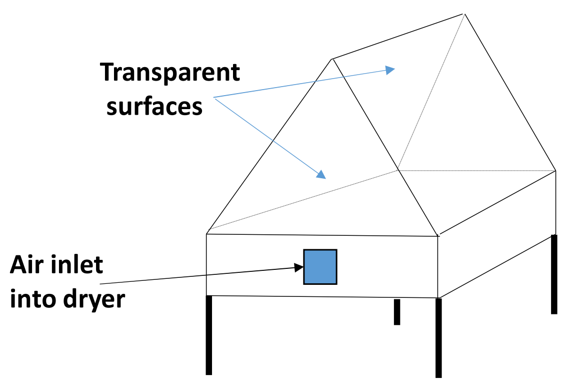

Figure 1: Schematic of a direct solar dryer

2.3. Analysis of Experimental Data

The moisture content of orange skin paste at time t, X_t (g water. g dry matter^{-1}) was defined as:

$$X_t = \frac{m_t - m_d}{m_d} \tag{1}$$

where m_t (g) and m_d (g) are mass of sample at any time t and absolute dried mass of sample, respectively. The drying rate of the paste was computed from Equation (2):

$$D_R = \frac{X_{t+dt} - X_t}{dt} \tag{2}$$

where D_R (g water/g dry matter. min) is drying rate, X_{t+dt} (g water. g dry matter^{-1}) is moisture content at time $t+dt$ and dt (min) is time increment. The moisture content can be expressed as dimensionless moisture ratio (M_R):

$$M_R = \frac{X_t - X_e}{X_i - X_e} \tag{3}$$

where X_i and X_e (g water/g dry matter) are initial and equilibrium moisture contents, respectively. The values of X_e are small compared with X_t and X_i for a long drying time, so the moisture ratio may be simplified as (Dissa et al., 2011; Perea-Flores et al., 2012):

$$M_R = \frac{X_t}{X_i} \tag{4}$$

The diffusion of moisture from the internal part of the orange skin paste to the surface during the falling rate drying period, when internal mass transfer is the controlling mechanism, may be described by Fick's second law of diffusion (Doymaz, 2008; Ruiz Celma et al., 2008). The Fick's law in terms of M_R is expressed as (Vega-Galvez et al, 2010):

$$\frac{dM_R}{dt} = D_{eff}\frac{d^2M_R}{dx^2} \tag{5}$$

where D_{eff} (m^2 s^{-1}) is the effective moisture diffusivity and x (m) is spatial dimension. The orange skin paste in the drying pan had a slab geometry. Assuming a one-dimensional transport of moisture in an infinite slab, negligible shrinkage, uniform initial moisture distribution, negligible external resistant and constant diffusivity, the mathematical solution of Equation (5) according to Crank (1975) is:

$$M_R = \frac{8}{\pi^2}\sum_{i=0}^{\infty}\frac{1}{(2i+1)^2}\exp\left[\frac{-(2i+1)^2 D_{eff}\pi^2 t}{4L^2}\right] \tag{6}$$

The first term in the series expansion of Equation (6) gives a good estimate of the solution for sufficiently long drying time (Di Scala and Crapiste, 2008):

$$M_R = \frac{8}{\pi^2}\exp\left[\frac{-D_{eff}\pi^2 t}{4L^2}\right] \tag{7}$$

where L (m) is half of the thickness of the slab and t (s) the time of drying. Equation (7) can be written in a linear form as:

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

A plot of $In(M_R)$ versus t yields a straight line with slope (S_1) from which D_{eff} is calculated:

$$S_1 = \frac{D_{eff}\pi^2}{4L^2} \quad (9)$$

An Arrhenius relationship may be used to describe the hot air temperature dependence of the effective moisture diffusivity (Tunde-Akintunde and Ogunlakin, 2011):

$$D_{eff} = D_o \exp\left(-E_a / RT\right) \quad (10)$$

where D_o ($m^2\ s^{-1}$) is the Arrhenius factor, E_a ($kJ\ mol^{-1}$) the activation energy, R the universal gas constant ($8.314\ J\ mol^{-1}\ K^{-1}$) and T (K) the absolute temperature. A linear equation is obtained on taking the natural logarithm of both sides of Equation (10):

$$In\ D_{eff} = In\ D_o - \frac{E_a}{RT} \quad (11)$$

The activation energy E_a ($kJ\ mol^{-1}$) can be determined from the slope (S_2) of the straight line obtained from the plot of lnD_{eff} versus $1/T$:

$$S_2 = \frac{E_a}{R} \quad (12)$$

The specific energy E_{sp} (kWh/kg) required for drying the orange skin paste was computed from Equation (13):

$$E_{sp} = \frac{A\upsilon\rho_a c_a \Delta T D_t}{W_o} \quad (13)$$

where A (m^2) is tray area, ΔT (°C) is temperature difference, υ ($m\ s^{-1}$) is air velocity, ρ_a (kg/m^3) is air density, c_a (kJ/kg °C) is specific heat of air, D_t (s) is total drying time and W_o (kg) is initial weight of orange skin paste.

2.4. Thin Layer Drying Models

Twelve thin layer drying models which have been severally reported to suitably fit agricultural products were fitted to the experimental drying data. These models are presented on Table 1. The coefficient of determination (R^2), sum of square error (SSE), root mean square error (RMSE) and Chi-square (χ^2) were the statistical parameter used as criteria to determine the model that best fit the moisture ratio – time data. The model that best fit the data is one that has the highest value of R^2 and lowest values of SSE, RMSE and χ^2 (Erbay and Icier, 2010; Kucuk *et al*, 2014). These criteria are given in Equations 14 to 17.

Table 1: Thin layer drying models fitted to drying data

S/No	Model Name	Model	References
1	Midilli-Kucuk	$M_R = a\exp\left(-kt^n\right)+bt$	Midilli et al., 2002
2	Page	$M_R = \exp\left(-kt^n\right)$	Page, 1949
3	Logarithmic	$M_R = a\exp\left(-kt\right)+c$	Chandra and Singh, 1995; Yagcioglu *et al.*, 1999
4	Two-term	$M_R = a\exp\left(-k_0 t\right)+b\exp\left(-k_1 t\right)$	Henderson, 1974; Glenn, 1978
5	Wang and Singh	$M_R = 1+at+bt^2$	Wang and Singh, 1978
6	Approximation of diffusion	$M_R = a\exp\left(-kt\right)+\left(1-a\right)\exp\left(-kbt\right)$	Kaseem, 1998
7	Modified Henderson and Pabis	$M_R = a\exp\left(-kt\right)+b\exp\left(-gt\right)+c\exp\left(-ht\right)$	Karathanos, 1999
8	Modified Page	$M_R = \exp\left(-(kt)^n\right)$	White *et al.*, 1978
9	Henderson and Pabis	$M_R = a\exp\left(-kt\right)$	Henderson and Pabis, 1961
10	Two-term exponential	$M_R = a\exp\left(-kt\right)+\left(1-a\right)\exp\left(-kat\right)$	Sharaf-Eldeen *et al.*, 1980
11	Verma et al.	$M_R = a\exp\left(-kt\right)+\left(1-a\right)\exp\left(-gt\right)$	Verma *et al.*, 1985
12	Weibull	$M_R = a-b\exp\left(-kt^n\right)$	Weibull, 1951; Yi et al., 2012

$$R^2 = 1-\left[\frac{\sum_{i=1}^{N}\left(M_{R_{\exp,i}}-M_{R_{pred,i}}\right)^2}{\sum_{i=1}^{N}\left(M_{R_{\exp,i}}-\bar{M}_R\right)^2}\right] \tag{14}$$

where $\bar{M}_R = \frac{1}{N}\sum_{i=1}^{N} M_{R_{\exp,i}}$

$$SSE = \frac{1}{N}\sum_{i=1}^{N}\left(M_{R_{\exp,i}}-M_{R_{pred,i}}\right)^2 \tag{15}$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(M_{R_{pred,i}}-M_{R_{\exp,i}}\right)^2\right]^{\frac{1}{2}} \tag{16}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(M_{R_{\exp,i}}-M_{R_{pred,i}}\right)^2}{N-z} \tag{17}$$

where $M_{R_{\exp,i}}$, $M_{R_{pred,i}}$, N and z are experimental moisture ratio, predicted moisture ratio, number of observations and number of constants, respectively.

The moisture ratio-drying time data derived from the experimental data for open sun, solar and hot air oven drying of orange skin paste were fitted to the twelve thin layer drying mathematical models described in Table 1 and the criteria of Equations (14-17) were used to determine the model which best fit the experimental drying data. Non-linear regression analysis was employed to fit experimental data of moisture ratio (MR) versus drying time (t) to the thin layer drying models. Statistical Package for the Social Sciences (SPSS) version 20 (SPSS Inc., Chicago, Illinois), was the software used for the regression analysis. The R^2 values were computed by SPSS while SSE, RMSE and χ^2 were calculated from Equations (15), (16) and (17), respectively, using Microsoft Excel.

3. RESULTS AND DISCUSSION

3.1. Open Sun Drying

The orange skin paste samples were dried in the sun over a period of three days. The moisture ratio decreased progressive during the drying operation as shown in the plot of moisture ratio versus drying time of Figure 2. This implies that moisture was successfully removed from the material by air heated through the sun radiation. Figure 3 shows the plot of drying rate versus drying time for sun drying of orange skin paste. The peaks at drying times 210 and 510 min correspond to the beginning of the drying process on the second and third days, respectively. The drying is generally in the falling rate period on each of the three drying days, which implies that diffusion of moisture from the inner part of the orange skin paste to its surface controlled the drying rate (Doymaz, 2008; Ruiz Celma et al., 2008). Falling rate drying period has been reported for the drying of mint, parsley and basil leaves (Akpinar, 2006). The effective moisture diffusivity for open sun drying of orange skin paste of 20 mm depth was measured as 2.00 x 10^{-9} m^2 s^{-1}, and this value is close to the value of 3.09 x 10^{-9} m^2 s^{-1} reported for the sun drying of 8 mm thick tomato (Rajkumar et al., 2007).

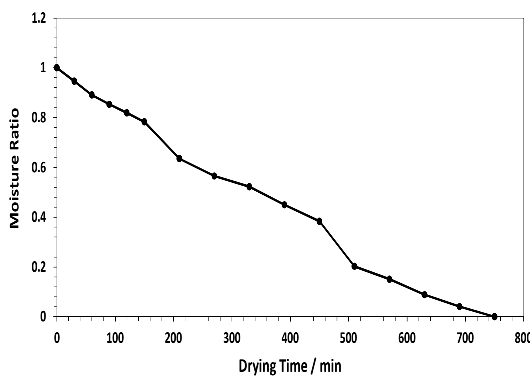

Figure 2: Plot of moisture ratio versus drying time for sun drying of orange skin paste

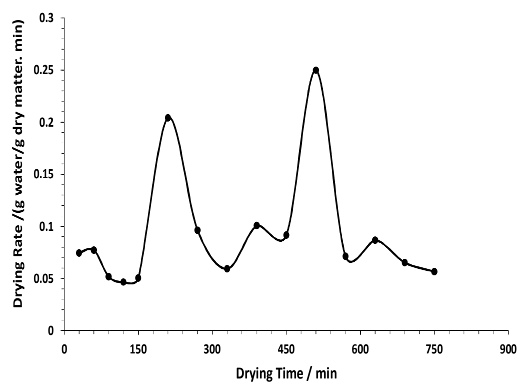

Figure 3: Plot of drying rate versus drying time for sun drying of orange skin paste

The statistical parameters obtained after the twelve thin layer models were fitted to the open sun drying data are shown in Table 2. The Midilli-Kucuk, Logarithmic and Weibull models had the same value of R^2 (0.993), which was the highest value compared to those of the other nine models. However, the Logarithmic model had the lowest SSE (0.02158308), RMSE (0.146911812) and χ^2 (0.026563791) compared to those of the other eleven models. Hence, the Logarithmic model best describe the open sun drying of orange skin paste. The Logarithmic model has been reported to best fit the open sun drying of *Gundelia tournefortii* L. (Evin, 2012).

Table 2: Statistical parameters for thin layer drying models for open sun drying of orange skin paste

Model	R^2	SSE	RMSE	χ^2
Midilli-Kucuk	0.993	0.056635713	0.237982590	0.075514284
Page	0.890	0.040354069	0.200883223	0.046118936
Logarithmic	0.993	0.021583080	0.146911812	0.026563791
Two-term	0.949	0.060427905	0.245820880	0.080570540
Wang and Singh	0.862	0.026766736	0.163605429	0.030590556
Approximation of diffusion	0.704	0.021757263	0.147503435	0.026778170
Modified Henderson and Pabis	0.949	0.060427905	0.245820880	0.096684648
Modified Page	0.898	0.023713732	0.153992635	0.027101408
Henderson and Pabis	0.949	0.060161800	0.245279024	0.068756342
Two-term exponential	0.704	0.021757260	0.147503430	0.024865440
Verma et al	0.929	0.045619363	0.213586898	0.056146908
Weibull	0.993	0.056314998	0.237307812	0.075086664

3.2. Solar Drying

The orange skin paste samples were dried in the solar dryer over a period of two days. The moisture ratio decreased progressive during the drying process as shown in the plot of moisture ratio versus drying time of Figure 4, signifying that moisture was successfully removed from the material by hot air within the solar dryer chamber. Figure 5 shows the plot of drying rate versus drying time for solar drying of orange skin paste. The drying rate initially increased with time then decreased during drying on the first day between 10 am and 3 pm represented by the first 240 min of the drying period. The initial increase was possibly due to the heating up of the air as the sun radiation increased from morning to mid-afternoon. However, the drying rate decreased with time and completely depicted a falling rate period during the second day as shown in Figure 5 from drying time 300 to 500 min representing the period 12 noon to 6 pm on the second day.

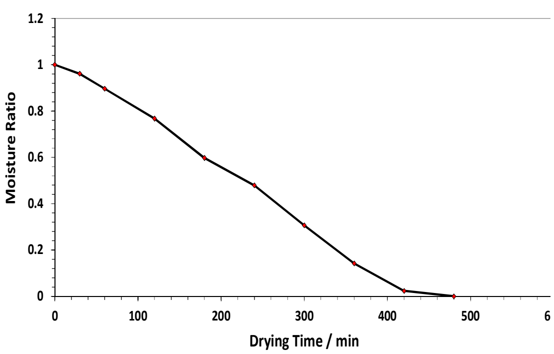

Figure 4: Plot of moisture ratio versus drying time for solar drying of orange skin past

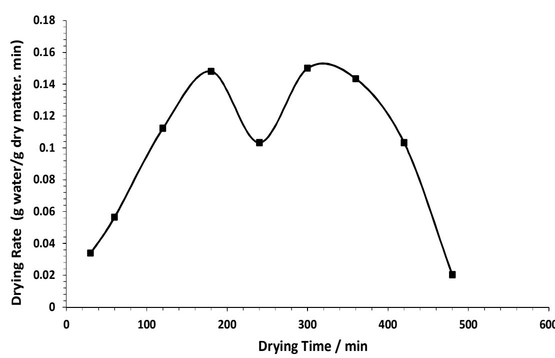

Figure 5: Plot of drying rate versus drying time for solar drying of orange skin paste

Hence, for a solar dryer whose drying chamber is already heated up, the drying operation is generally in the falling rate period and the drying rate is controlled by diffusion of moisture from the internal part of the orange skin paste to its surface (Doymaz, 2008; Ruiz Celma et al., 2008). A falling rate drying period has been reported for the solar drying of mint leaves (Akpinar, 2010) and long green pepper (Akpinar and Bicer, 2008). The effective moisture diffusivity for solar drying of orange skin paste of 20 mm depth was measured as 2.16 x 10^{-9} m^2 s^{-1}. The moisture in orange skin paste was completely removed at a shorter period in the solar dryer compared to open sun.

The Midilli-Kucuk and Weibull models had the same value of R^2 (0.997) when fitted to the moisture ratio-drying time data for solar drying of orange skin paste. This value was the highest compared to the values obtained for the other thin layer drying models, as shown in Table 3. The SSE, RMSE and χ^2 for the Midilli-Kucuk model were 0.000414566, 0.020360899 and 0.000690944, respectively, while those of the Weibull models were 0.00041953, 0.020482437 and 0.000699217, respectively. These values are lower than those of the other ten thin layer drying models investigated. The values of SSE, RMSE and χ^2 obtained for the Midilli-Kucuk model were lower than those of the Weibull model; hence, the Midilli-Kucuk model is deemed to best describe the solar drying of orange skin paste. The Midilli-Kucuk model has been reported to best fit the solar drying of Moroccan rosemary leaves (Mghazli et al., 2017).

Table 3: Statistical parameters for thin layer drying models for solar drying of orange skin paste

Model	R^2	SSE	RMSE	χ^2
Midilli-Kucuk	0.997	0.000414566	0.020360899	0.000690944
Page	0.990	0.001317096	0.036291814	0.001646370
Logarithmic	0.992	0.001061150	0.032575299	0.001515929
Two-term	0.931	0.009277102	0.096317712	0.015461836
Wang and Singh	0.990	0.001412075	0.037577590	0.001765094
Approximation of diffusion	0.910	0.011756494	0.108427365	0.016794991
Modified Henderson and Pabis	0.931	0.009277362	0.096319062	0.023193404
Modified Page	0.990	0.001316312	0.036281013	0.00164539
Henderson and Pabis	0.931	0.071404774	0.267216718	0.089255968
Two-term exponential	0.912	0.011756494	0.108427365	0.014695617
Verma et al	0.978	0.261955871	0.511816248	0.374222673
Weibull	0.997	0.000419530	0.020482437	0.000699217

3.3. Hot air Oven Drying

The plot of moisture ratio versus drying time for orange skin paste dried at 80, 120 and 140 ^oC is shown in Figure 6. The moisture ratio decreased with increasing drying time and temperature, while the drying time required decreased with increasing temperature. This observation implies that drying air temperature enhanced the drying rate of orange skin paste and considerably shorter drying time can be achieved at higher drying temperatures. Reduction in drying time of agricultural products with increasing temperature has been reported in the literature (Doymaz and Özdemir, 2014; Zhu and Shen, 2014).

The drying rate of orange skin paste decreased with time at each of the temperatures considered as shown in Figure 7. This implies that the drying process occurred entirely in the falling rate period and the drying of orange skin paste was controlled by diffusion of moisture from the internal part of the paste to the surface (Doymaz, 2008; Ruiz Celma et al., 2008). There was no constant drying period. Several authors have reported a falling rate drying period for the hot air oven drying of many agricultural products (Tunde-Akintunde and Ogunlakin 2011; Chen et al., 2012; Doymaz and Özdemir, 2014; Tunde-Akintunde, 2014; Olanipekun et al, 2015).

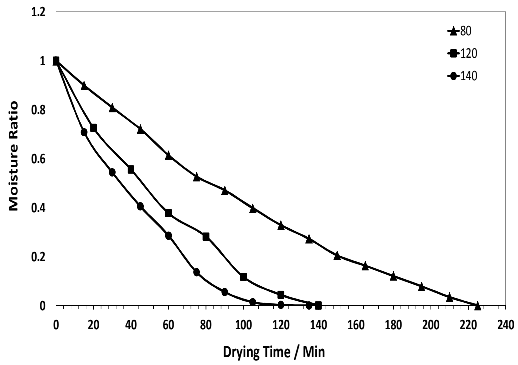

Figure 6: Plot of moisture ratio versus drying time for hot air oven drying of orange skin paste

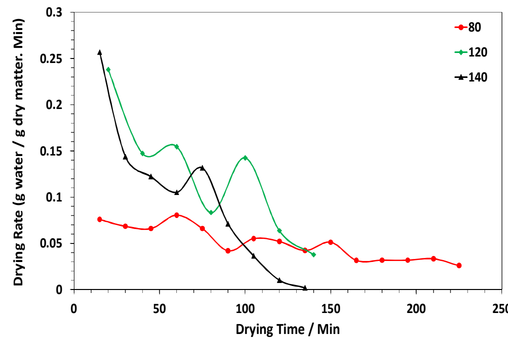

Figure 7: Plot of drying rate versus drying time for hot air oven drying of orange skin paste

The effective moisture diffusivity (D_{eff}) for the hot air oven drying of orange skin paste obtained from the slope of the plot of In (M_R) versus drying time are presented in Table 4. The effective moisture diffusivity of 7.00, 7.63 and 18 x 10^{-9} m^2 s^{-1} were measured at 80, 120 and 140 °C, respectively. The moisture diffusivity increased with increasing temperature because the rise in temperature elevated the activity of water molecules, due to increase in thermal energy, which led to higher moisture diffusivity (Xiao et al., 2010). The effective moisture diffusivity reported for the hot air oven drying of orange skin paste lie within the range of 10^{-10} – 10^{-8} m^2 s^{-1} reported for drying of agricultural products (Erbay and Icier, 2010).

Table 4: Effective moisture diffusivity for hot air oven drying of orange skin

Temperature (°C)	D_{eff} (m^2 s^{-1})
80	7.00 x 10^{-9}
120	7.63 x 10^{-9}
140	1.80 x 10^{-8}

Table 5: Specific energy requirement for hot air oven drying of orange skin

Drying temperature (°C)	Specific energy requirement (kJ g^{-1})
80	846
120	1013
140	1475

The temperature dependence of the effective moisture diffusivity for the drying of orange skin paste was suitably described by an Arrhenius-type Equation (10) and an activation energy of 16.1 kJ mol^{-1} was required for drying the orange skin paste. This activation energy for drying orange skin paste is the energy barrier that must be overcome for moisture to diffuse from the inner part of the material to its surface. The activation energy measured in this study is close to the range 18 to 49.5 kJ mol^{-1} reported for the drying of most agricultural products (Erbay and Icier, 2010). The specific energy required for hot air oven drying of the orange skin paste at 80, 120 and 140 °C were 846, 1013 and 1475 kJ g^{-1}, respectively, as presented on Table 5. An increase in drying air temperature resulted in observed increase in drying rate and consequently a decrease in drying time. However, the increase in drying temperature required an additional energy to raise the temperature.

The statistical parameters obtained after the twelve thin layer models were fitted to the hot air drying data are shown in Tables 6 – 8. The Midilli-Kucuk model best fitted the drying moisture ratio – time data for all the drying operations. This model had the highest R^2 and lowest SSE, RMSE and χ^2 compared to those of the other eleven models. The Midilli-Kucuk model has been reported to best fit the hot air drying of sawdust (Chen et al., 2012), dill leaves (Doymaz et al., 2006), red chili pepper and leech lime leaves (Waewsak et al., 2006).

Table 6: Statistical parameters for thin layer drying models for hot air oven drying of orange skin paste at 80 °C

Model	R^2	SSE	RMSE	χ^2
Midilli-Kucuk	1.000	0.000176039	0.013267973	0.000293399
Page	0.994	0.004064484	0.063753304	0.005080605
Logarithmic	0.998	0.000281278	0.016771333	0.000401825
Two-term	0.954	0.004956514	0.070402511	0.008260856
Wang and Singh	0.998	0.000855074	0.029241644	0.001068842
Approximation of diffusion	0.943	0.006279205	0.079241435	0.008970293
Modified Henderson and Pabis	0.954	0.004956514	0.070402511	0.012391284
Modified Page	0.994	0.000764188	0.027643949	0.000955235
Henderson and Pabis	0.945	0.004956514	0.070402511	0.006195642
Two-term exponential	0.987	0.214365403	0.462996116	0.267956754
Verma et al	0.973	0.214322353	0.462949622	0.306174789
Weibull	0.404	0.064709347	0.254380319	0.107848911

Table 7: Statistical parameters for thin layer drying models for hot air oven drying of orange skin paste at 120 °C

Model	R^2	SSE	RMSE	χ^2
Midilli-Kucuk	0.998	0.000467959	0.021632361	0.000935918
Page	0.657	0.043420561	0.208376008	0.057894081
Logarithmic	0.530	0.059493298	0.243912479	0.095189276
Two-term	0.204	0.100684785	0.317308660	0.201369571
Wang and Singh	0.996	0.001380896	0.037160407	0.001841194
Approximation of diffusion	0.204	0.100684785	0.31730866	0.161095657
Modified Henderson and Pabis	0.204	0.100684910	0.317308856	0.402739642
Modified Page	0.372	0.079420245	0.281815978	0.105893660
Henderson and Pabis	0.204	0.100684785	0.317308660	0.134246381
Two-term exponential	0.204	0.100684785	0.317308660	0.134246381
Verma et al	0.204	0.100684785	0.317308660	0.161095657
Weibull	0.530	0.059493298	0.243912479	0.118986595

Table 8: Statistical parameters for thin layer drying models for hot air oven drying of orange skin paste at 140 °C

Model	R^2	SSE	RMSE	χ^2
Midilli-Kucuk	0.999	0.000163945	0.012804117	0.000295102
Page	0.998	0.000184085	0.013567781	0.000236680
Logarithmic	0.997	0.000313824	0.017715090	0.000470737
Two-term	0.994	0.000611034	0.024719101	0.001099861
Wang and Singh	0.972	0.909023626	0.953427305	1.168744662
Approximation of diffusion	0.994	0.000645545	0.025407579	0.000968318
Modified Henderson and Pabis	0.994	0.000611034	0.024719101	0.001833102
Modified Page	0.777	0.023925912	0.154680031	0.030761887
Henderson and Pabis	0.994	0.000611034	0.024719101	0.000785615
Two-term exponential	0.994	0.000645545	0.025407579	0.000829987
Verma et al	0.997	0.000322743	0.017965060	0.000484115
Weibull	0.675	0.034884401	0.186773663	0.062791922

4. CONCLUSION

Orange skin paste biomass were successfully dried in open sun, direct solar dryer and hot air oven dryer. Drying of orange skin paste took place in the falling rate period. The effective moisture diffusivities of open sun and solar drying of orange skin paste were 2.00 and 2.16 x 10^{-9} m^2 s^{-1}, respectively, while those of hot air oven drying were 7.00 x 10^{-9}, 7.63 x 10^{-9} and 18 x 10^{-9} m^2 s^{-1} at 80, 120 and 140 °C, respectively. The drying rate of orange skin paste dried in the hot air oven dryer increased while the drying time decreased with increasing drying temperature. An Arrhenius-type relationship described the temperature dependence of the diffusivity coefficients and an activation energy of 16.1 kJ mol^{-1} was required for hot air oven drying of orange skin paste. The specific energies required for hot air oven drying of the orange skin paste at 80, 120 and 140 °C were 846, 1013 and 1475 kJ g^{-1}, respectively. The drying rate of orange skin paste increased in the order: hot air oven drying > solar drying > open sun drying. The thin layer drying models which best described the hot air oven, open sun and solar drying of orange skin paste biomass were the Midilli-Kucuk, Logarithmic and Midilli-Kucuk models, respectively.

5. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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