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MODELING OF THIN LAYER DRYING CHARACTERISTICS OF BANANA CV. *LUVHELE*

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Abstract

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Bananas (*Musa* spp.) are tropical fruits with high moisture and low acid content. Drying is necessary to reduce their water activity, prevent microbial spoilage, reduce weight, decreases packaging, handling and transportation costs. This study investigates the oven drying kinetics of thin layer *Luvhele* banana at temperature levels 40–60°C. Six mathematical drying models; Wang and Singh, Verma, Two-term, Page, Logarithmic and Two terms exponential were fitted to experimental drying data obtained from the study. The consistency of the models was determined using statistical parameters such as coefficient of determination, Mean Bias Error, Root Mean Square Error, and chi square. Moisture migration from the banana slices was described using the Fick's diffusion model and the effective diffusivity (ED) was calculated. The result indicated that drying took place major in the falling rate period with higher and shorter drying times achieved at a lower and higher oven temperature respectively. The ED increased with increasing oven temperatures with values in the range of 1.8×10^{-11}, 1.95×10^{-11}, and 2.28×10^{-11} m^2/s at 40, 50, and 60°C respectively. The Two-term model gave the best results for the description of thin layer drying of *Luvhele* banana variety.

Key words: oven; banana (*Luvhele* spp.), drying kinetics, drying models, effective moisture diffusivity

Nomenclature: M_0 (% wet basis) – initial moisture content of the product before commencement of the drying operation; M (% wet basis) – moisture content of the product at each moment; MR – moisture ratio); R^2 – coefficient of determination; X^2 – reduced chi square value; $RMSE$ – root mean square error; MBE – mean bias error; $MR_{exp,i}$ – experimental moisture ratio; $MR_{pre,i}$ – predicted moisture ratio; n – number of constants; N – number of observations; D_{eff} (m^2/s) – effective moisture diffusivity; L (m) – half-thickness of banana slices; φ – slope; k, n, a, b, g, c – model constants; T (°C) – oven temperature; t (min) – time

Introduction

Drying is the removal of moisture from a food material with a view of reducing microbial activity, product spoilage and extension of storage life. The knowledge of drying kinetics of banana is highly essential for the control and optimization of banana drying process, any subsequent or further process and quality of final product (Demirel and Turhan, 2003). Research focus and interest have been on banana in recent time possibly due to its nutritional and economic importance. Some drying characteristics of banana in different forms include whole fruit (Dandamrongrak et al., 2002; Queiroz and Nebra, 2001; Nogueira and Park, 1992; Sousa and Marsaioli, 2004; Silva et al., 2013), slices (Sankat and Castaigne, 1992; Sankat et al., 1996; Ganesapillai et al., 2011; Abano and Sam-Amoah, 2011; Demirel and Turhan, 2003; Leite et al., 2007) and chuncks (Mowlah et al., 1983; Garcia et al., 1988). The thin layer drying characteristics of most agricultural products including banana

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could be described using drying models. These drying models are of two main groups, the empirical (Turhan et al., 2002; Diamante et al., 2010; Kaleta and Gornicki, 2010; Mundada et al., 2011; Silva et al., 2012a; Silva et al., 2013) and diffusion models (Karim and Hawlader, 2005; Nguyen and Price, 2007; Silva et al., 2012a, 2012b, 2012c; Darvishi et al., 2012; Silva et al., 2013). According to Aguerre and Suarez (2004), diffusion models unlike the empirical models include the diffusion coefficient, which reflects a possible physical phenomenon that may occur during drying. Diffusion has often been described as one of the transport mechanisms for moisture transfer during drying, but the underlying basis of using the diffusion model for fitting the drying of fruits has not been fully justified, although descriptions and comparisons of various diffusion concepts and their applications are available (Chen, 2006).

The total world production of banana is estimated at over 99 996.519 metric tons (FAO, 2012) of which exports (essentially of Cavendish bananas) to developed countries represent less than a million tons. The rest over 85% of production is made up of a wide range of banana varieties grown by peasant farmers or small holders and their families for home use or traded in local market.

Luvhele banana is an underutilized variety in South Africa that requires research studies to ascertain the suitability for industrial use and entrepreneurial opportunities (Omolola et al., 2014). Like the commercial varieties, the high moisture content makes them highly perishable within few days under ambient conditions of 20–25°C, hence the present study seems to be hanging. There are no studies on the drying characteristics of non-commercial banana on this variety in the region. Therefore the aim of this study was to model the oven drying kinetics of *Luvhele* banana variety.

Materials and Methods

Source and preparation of banana sample

Bananas of the variety *Luvhele* (Musa species) procured from a farm in Limpopo province of South Africa in a state of maturity appropriate for drying (maximum sucrose content and completely yellow skin with small brownish speckles, according to Sousa and Marsaioli, 2004). The bananas fingers were cleaned, washed, peeled and sliced manually into a thickness of 5 mm. The sliced portions were treated with 4% (w/v) citric acid solution for 10 minutes and allowed to drain. The initial moisture content was determined using AOAC 925.45 method (AOAC, 2000) and was found to be 78.73% (wet basis).

Drying experiment

The cut slices of the banana varieties treated with citric acid were spread evenly on the tray inside a forced air oven (Prolab Instrument – model OTE 80) and dried using three different temperatures i.e. 40°C, 50°C, and 60°C. During the drying process, the samples were brought out from the oven at regular intervals and weighed using a digital weighing balance (METTLER PJ 12 – SNR J18751) with a precision of 0.01 g until a constant weight was achieved. Three different drying trials were conducted at each temperature and the average values obtained from these trials.

Mathematical modeling of drying kinetics

In order to effectively study the drying kinetics of agricultural commodities, the effective modeling of drying behavior is inevitable. The data obtained from experimental drying of *Luvhele* banana variety at different temperatures were fitted with six thin-layer drying mathematical expressions proposed by several authors as listed in Table 1. The curve fitting was done using MATLAB software version 7.11.0.584. The moisture ratio (MR) of the sample was determined using equation 1 as used by Miranda et al. (2009), with M being the moisture content of the product at each moment and M_0 the initial moisture content of the product before commencement of the drying operation.

$$MR = \frac{M}{M_0} \tag{1}$$

Statistical evaluation of drying models

Relevant statistical parameters were used to select the best drying equation/model expressing the drying curves of

Table 1
Mathematical models applied to the drying curves

Model	Equation	References
Wang & Singh	$MR = 1 + at + bt^2$	Miranda et al. (2009)
Verma	$MR = a \exp(-kt) + (1 - a) \exp(-gt)$	Ganesapillai et al. (2011)
Two-term	$MR = a \exp(-kt) + b \exp(-gt)$	Lahsasni et al. (2004)
Two-term exponential	$MR = a \exp(-kt) + (1 - a) \exp(-kat)$	Doymaz (2009)
Page	$MR = \exp(-kt^{\theta}n\text{-}I)$	Lahsasni et al. (2004)
Logarithmic	$MR = a \exp(-kt) + c$	Ganesapillai et al. (2011)

the samples and also to determine the consistency of the fits. The coefficient of determination (R^2) was used to select the best equation expressing the drying curves of the sample. In addition to the coefficient of determination, parameters such as the reduced chi square value (x^2), root mean square error (RMSE), and mean bias error (MBE) were used to determine the consistency of the fit. The highest values of R^2 and the lowest values of x^2, RMSE, and MBSE were used as a basis for determining the best fit (Wang et al., 2007; Ozbek and Dadali, 2007; Ganesapillai et al., 2011). The statistical parameters were calculated using equations 2 to 4; where $MR_{exp,i}$ is the experimental moisture ratio, $MR_{pre,i}$ is the predicted moisture ratio, n is the number of constants and N is the number of observations.

$$x^2 = \left(\frac{\sum_{i=1}^{N} \left(MR_{exp,i} - MR_{pre,i} \right)^2}{(N-n)} \right)^{½} \tag{2}$$

$$RMSE = \left(\frac{1}{N} \sum_{i=1}^{N} (MR_{pre,i} - MR_{exp,i})^2 \right)^{½} \tag{3}$$

$$MBE = \frac{1}{N} \sum_{i=1}^{N} (MR_{pre,i} - MR_{exp,i}) \tag{4}$$

Determination of moisture diffusivity

The solution of Fick's second law of diffusion was used to compute the effective moisture diffusivity as used by Crank (1975) and Doymaz (2005). Equations 5 to 7 summarize the solution of Fick's second law of diffusion, where *MR* is moisture ratio, D_{eff} is the effective moisture diffusivity (m²/s) and *L* is the half-thickness (m) of the banana slices.

$$MR = \frac{8}{\pi^2} \sum^{\infty} \left(\frac{1}{(2n+1)^2} \exp\left(-\frac{\pi^2 (2n+1)^2}{4L^2} \right) D_{eff} t \right) \tag{5}$$

Equation (5) is based on the assumption that the moisture diffusivity is constant, with the banana slices representing infinite slab geometry and the initial moisture distribution is uniform (Darvishi et al., 2013). Equation (5) could be simplified to a straight line equation (6); the plot of experimental drying data in terms of ln (*MR*) against time gives a straight line with a negative slope φ.

$$\ln(MR) = \ln\left(\frac{8}{\pi^2} \right) - \left(\frac{\pi^2 D_{eff}}{L^2} t \right) \tag{6}$$

$$\varphi = \frac{\pi^2 D_{eff}}{L^2} \tag{7}$$

Results and Discussion

Effect of oven temperature on drying kinetics of Luvhele *banana variety* (*LBV*)

The drying curve of LBV under oven drying process is shown in Figure 1 and it shows that there is no constant drying rate period in the drying of LBV under oven drying process hence all the drying took place in the falling rate period. This shows that diffusion is the dominant physical mechanism governing moisture movement in the variety. Similar results were obtained by Abano and Sam-Amoah (2011); Silva et al. (2013); and Ganesapillai et al. (2011) for banana fruit. The result shows that increasing drying temperature led to an increase in drying rate hence the reduction in drying time. This is due to the fact that drying at higher temperature implies a larger driving force for heat transfer. Prabhanjan et al. (1995) reported that the higher drying temperatures provided a larger water vapor pressure deficit or the difference between the saturated water vapor pressure and partial pressure of water vapor in air at a given temperature, which is one of the driving forces for drying. Similar behavior was observed by Jaya and Das (2003). The drying time required to reduce the initial moisture content to any given level was dependent on the drying condition, being the highest at 40°C and lowest at 60°C. For LBV, the time required to reduce the moisture content from an initial of 78.73% (w.b) to a final of 11.05, 13.01 and 12.05% (w.b) was 1260, 1080, and 900 minutes at 40, 50 and 60°C respectively.

Modeling of drying curves of LBV

The estimated constants for selected models as well as values of statistical parameters i.e. *MBE*, *RMSE*, R^2 and x^2 are presented in Table 2. The average values of the statistical parameters were considered in selecting the best model for the description of the drying behavior of LBV. Two-term model was selected as the most suitable model representing the thin layer drying of *Luvhele* banana variety, based on the criteria of the highest R^2 and the lowest x^2, *RMSE* and *MBE*. It can be seen that average value of (R^2) was found to be the highest and x^2, *RMSE* and *MBE* values were lowest when compared to other models. The R^2, x^2, *RMSE*, and *MBE* of Two-term model varies between 0.9939 and 0.9994, 2.10E-08 and 7.47E-05, 1.17E-03 and 7.48E-03, 3.43E-08 and 2.96E-04 respectively.

Validation of the predicted moisture ratio values obtained from Two-term model for the description of drying kinetics of LBV was done by comparing the experimental moisture ratio data with those predicted with the model at 40, 50, and 60°C as shown in Figures 2, 3 and

Table 2

Results of the statistical computations and values of constants obtained from the models applied to the drying curves of *LBV*

Model	*T*,°C	Constants					R^2	*RMSE*	X^2	*MBE*
	40	*a* = -0.0165	*b* = 7.86e-007				0,9818	0,0047	3,12E-05	6,14E-05
Wang & Singh	50	*a* = -0.0017	*b* = 9.13e-007				0,9757	0,0333	6,32E-05	5,15E-03
	60	*a* = -0.0016	*b* = 8.19e-007				0,9966	0,0021	8,86E-07	1,33E-06
						Average	0,9843	0,0134	3,17E-05	1,93E-04
	40	*a* = 0.8476	*k* = -0.7668	*g* = 0.7376			0,9831	0,0217	5,93E-08	2,99E-05
Verma	50	*a* = 0.84619	*k* = 0.7269	*g* = 0.5600			0,9826	0,0477	6,91E-05	1,03E-03
	60	*a* = 0.6439	*k* = 0.3597	*g* = 0.4413			0,9824	0,0596	1,27E-04	1,32E-05
						Average	0,9827	0,0429	6,53E-05	3,57E-04
	40	*a* =1.041	*k* = -0.002099	*b* = 0.000406	*g* = 0.00415		0,9994	1,17E-03	2,10E-08	3,43E-08
Two-Terma	50	*a* = 1.264	*k* = -0.002534	*b* = -0.2643	*g* = -0.1569		0,9992	7,47E-03	2,15E-06	5,00E-05
	60	*a* = -1.154	*k* = -0.002352	*b* = -0.1535	*g* = - 0.101		0,9939	7,48E-03	7,47E-05	2,96E-04
						Average	0,9975	5,02E-03	2,56E-05	1,15E-04
	40	k = 1.028	*n* = -0.001967				0,9707	0,0477	8,08E-05	8,55E-04
Page	50	k = 1.044	*n* = -0.00208				0,9618	0,0596	1,43E-04	1,26E-03
	60	k = 1.027	*n* = -0.002075				0,9921	0,0217	4,76E-06	1,56E-04
						Average	0,9748	0,0429	7,61E-05	7,57E-04
	40	*a* = 0.6743	*k* = 0.205	*c* = 0.3257			0,8285	0,2664	0,0252	0,0221
Logarithmic	50	*a* = 0.6483	*k* = 0.205	*c* = 0.3517			0,8128	0,2925	0,0292	0,0243
	60	*a* = 0.6483	*k* = 0.386	*c* = -0.6216			0,8361	0,2827	0,0191	0,0198
						Average	0,8361	0,2805	0,0245	0,022
	40	*a* = 0.0479	*k* = 0.8471				0,9345	0,033	1,02E-05	3,62E-04
Two-term exponential	50	*a* = 0.7179	*k* = 0.9444				0,9112	0,0732	1,26E-03	1,90E-03
	60	*a* = 0.3441	*k* = 0.3392				0,9136	0,0606	2,10E-05	1,37E-03
						Average	0,9197	0,0556	4,28E-04	1,21E-03

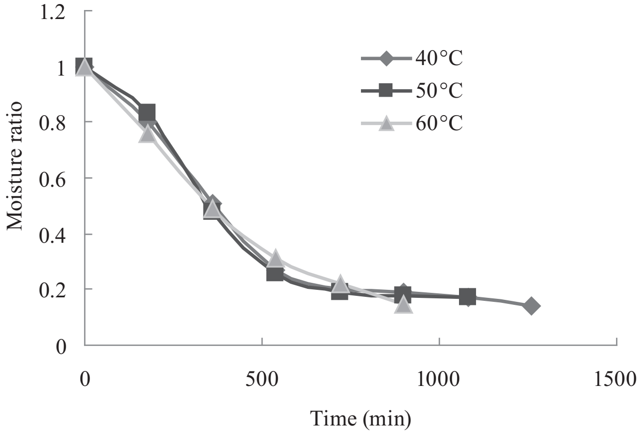

Fig. 1. Drying curves of *Luvhele* banana variety at different oven temperatures

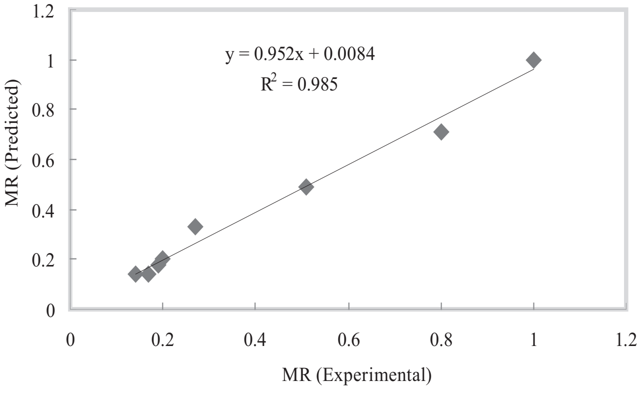

Fig. 2. Comparison of experimental and predicted moisture ratio from Two-term model at oven temperature of 40°C

4. The relatively high values of coefficient of correlation for the straight lines obtained are an indication of good fitness between the predicted and experimental moisture ratio values. Furthermore the data obtained for Two-term could be applied practically for optimization of the drying process, design of effective drying equipment, and the description of heat penetration during drying of *Luvhele* banana variety.

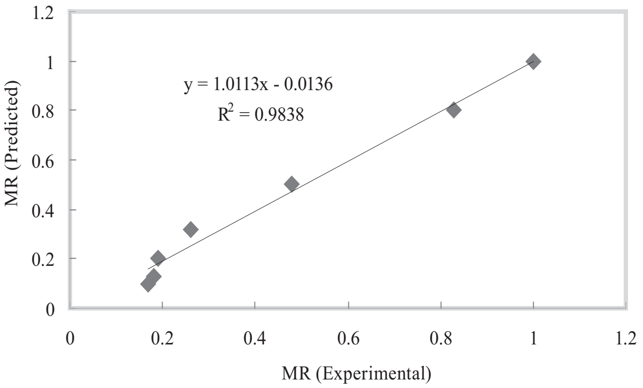

Fig. 3. Comparison of experimental and predicted moisture ratio from Two- term model at oven temperature of 50°C

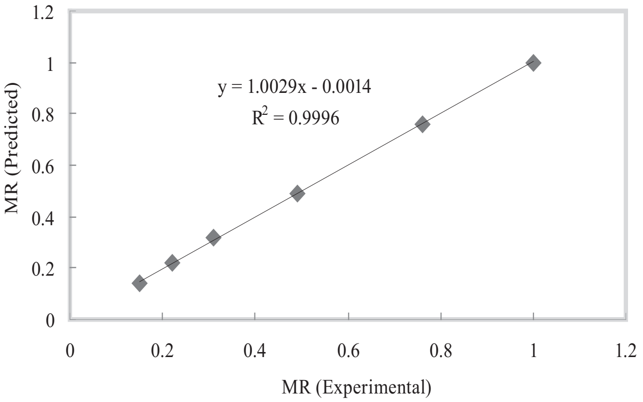

Fig. 4. Comparison of experimental and predicted moisture ratio from Two-term model at oven temperature of 60°C

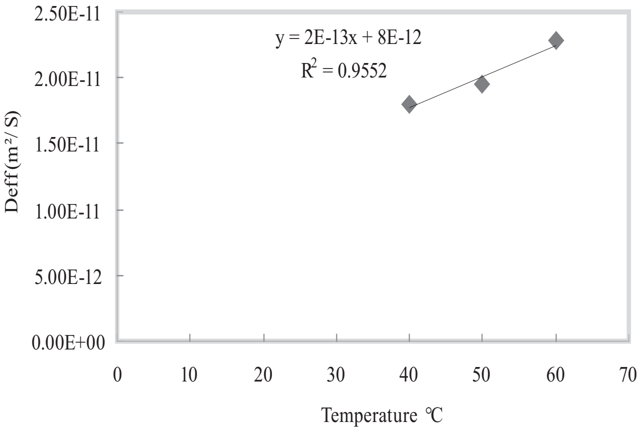

Fig. 5. Effect of oven temperature on the effective moisture diffusivity of *Luvhele* banana variety

Moisture diffusivity of LBV

The determined values of moisture diffusivity for *Luvhele* banana variety at different oven temperatures are given in Figure 5. The effective diffusivities were 1.80 × 10^{-11}, 1.95 × 10^{-11} and 2.28 × 10^{-11} m^2/s at 40, 50, and 60°C respectively. These values are in line with the general range of 10^{-12} m^2/s to 10^{-8} m^2/s for food materials (Zogzas et al., 1996). Effective moisture diffusivity is a term used to describe the migration or diffusion of moisture in agricultural products during drying operation and it is said to be a function of material moisture content and temperature, as well as of the material structure (Abano and Sam-Amoah, 2011). It is obvious from Figure 5 that the values of moisture diffusivities increased with increasing oven temperature. Similar observation was made by Aghbashlo et al. (2008); Caglar et al. (2009); Zielinska and Markowski (2010); Doymaz and Ismail (2011) for berberies fruit, seedless grape, carrots and sweet cherries respectively. The disparities in moisture diffusivity values determined in this study and the values reported for banana by Marinos-Kouris and Maroulis (1995) and Thuwapanichayanan et al. (2011) may be attributed to the effect of variety, geographical location, composition and tissue characteristics of the bananas.

Conclusion

Results obtained for oven drying kinetics of *Luvhele* banana variety shows that (i) increase in oven temperature from 40 to 60°C decreased the drying time from 1260 to 900 minutes, (ii) the entire drying operation took place in the falling rate period and no constant rate period was observed, (iii) among the models tested, Two-term model was found suitable for the description of the drying kinetics of LBV, and (iv) the moisture diffusivity increased with increasing oven temperatures with values in the range of 1.80 × 10^{-11} – 2.28 x 10^{-11} m^2/s at 40–60°C respectively. The results obtained in this study could be applied practically for the optimization of drying process; design of effective drying equipment; and the description of heat penetration during drying of *Luvhele* banana variety.

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