Modeling microwave drying kinetics and moisture diffusivity of Mabonde banana variety

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Abstract: This study investigates the microwave drying kinetics of thin layer Mabonde banana variety (MBV) at power levels between 100 and 300 W. Six mathematical drying models: Wang and Singh, Verma, Two-term, Page, Two term exponential, and Logarithmic models were fitted to experimental drying data obtained from the study. The statistical consistency of the models was determined using statistical parameters including coefficient of determination, mean bias error, root mean square error, and reduced Chi square. Moisture migration from banana slices was described using the Fick's diffusion model. The effective diffusivity was calculated. The results indicated that drying took place largely in the falling rate period. The time required to reduce the moisture of banana to a certain level was dependent on the microwave output, being the longest at 100 W and shortest at 300 W. The effective moisture diffusivity increased with increasing microwave power with values at 4.89×10^{-10}, 1.09×10^{-9} and 1.69×10^{-9} m^2/s at 100, 200, and 300 W, respectively. The Wang and Singh model gave the best results for the description of thin layer drying of MBV.

Keywords: Mabonde banana variety, microwave, drying models, drying kinetics, effective moisture diffusivity

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1 Introduction

Drying refers to the removal of moisture from a material with the primary aim of reducing microbial activity and product deterioration[1]. Most foods contain enough moisture to permit the activity of native enzymes and microorganisms during storage, and drying is necessary to reduce their water activity and prevent microbial spoilage, in order to reduce weight and decrease costs of packaging, handling and transportation[2,3]. Studies on drying characteristics of agricultural products available in literature covered banana[4-6], water chestnut[7], date palm fruit[8], prickly pear fruit[9], apricots, grapes, peaches, figs and plums[10]. The study of drying kinetics of agricultural commodities is useful in the design, construction and optimization of drying systems.

Effective moisture diffusivity is 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 material structure[11]. The theory of moisture transport processes is essential for the production of quality dried banana and energy conservation of the drying process. According to Zogzas et al.[12], diffusivity values fall between 10^{-13} and 10^{-6} m^2/s while most values (92%) fall

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within 10^{-12} and 10^{-8} m^2/s. The influence of drying temperatures on moisture diffusivity and quality attributes of dried banana slices in terms of volatile compounds, shrinkage, color, texture and microstructure was investigated by Thuwapanichayanan et al. [13] Previous researchers reported that the drying rate of banana slices occurred in two sub-drying periods, the first and the second falling rate periods. Effective diffusivity was found to decrease sharply with moisture content in the first falling rate period and change slightly in the second falling rate period. Air drying of Dwarf Cavendish and Gross Michel banana slices investigated by Demirel and Turhan[14] revealed that effective moisture diffusivity increased with increasing temperature between 40°C and 70°C in the untreated samples while it increased between 40°C and 60°C, and decreased at 70°C in the pretreated samples probably due to case hardening and starch gelatinization above 60°C.

Drying with the aid of microwaves is faster, more uniform and more energy-efficient than the hot air drying process. Moisture output is faster due to the ability of microwave to generate internal heat by molecular friction. Some of agricultural commodities which have been successfully dried using microwave include banana [15-18], carrot[19,20], grape[21], and apple[22]. Compared to agricultural products that experience hot air drying, those processed by microwaves are superior in terms of quality, aroma and colour. However, it should be noted that improper and careless application of microwave drying could result in low quality products[15, 23, 24].

Mabonde banana variety (MBV) is one of the non-commercial varieties in Limpopo Province of South Africa. There are no studies on microwave drying characteristics of non-commercial banana varieties in South Africa. Furthermore there is a need to ascertain the suitability of this variety for industrial use and entrepreneurial opportunities. Therefore, the aim of this study was to investigate the microwave drying characteristics of MBV.

2 Materials and methods

2.1 Source and preparation of sample

Bananas of the variety "Mabonde" (Musa species) procured from a farm in Limpopo Province of South Africa were used in the study. The fruits had a peel colour index of 7, which is associated with the maximum sucrose content and completely yellow skin with small brownish speckles[15]. 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[25] and was found to be 81.23% (wet basis).

2.2 Drying experiment

The drying experiment was carried out in a domestic microwave oven (model P70B17L-T8) with technical features of 220-240 V, 50 Hz and 700 W at the frequency of 2 450 MHz. The dimensions of the microwave cavity were 262×452×335 mm equipped with a glass turn table of 320 mm diameter and a control facility to monitor the microwave output and processing during drying operation. Drying was conducted in triplicate at three different microwave output powers: 100, 200 and 300 W[16]. During the drying experiment, banana slices were evenly spread on the glass turn table inside the microwave and moisture loss was monitored at regular intervals by removing the glass turn table and weighed using a digital weighing balance (METTLER PJ 12 - SNR J18751) with a precision of 0.01 g.

2.3 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 Mabonde 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)[26], with M being the moisture content of the product at each moment and M_o the initial moisture content of the product before commencement of drying operation.

$$\mathrm{MR} = \frac{M}{M_o} \tag{1}$$

Table 1 Mathematical models applied to the drying curves

Model	Equation	References
Wang & Singh	$MR=1+at+bt^2$	Miranda et al [26]
Verma	$MR=a\exp(-kt)+(1-a)\exp(-gt)$	Ganesapillai et al [16]
Two- term	$MR=a\exp(-kt)+b\exp(-gt)$	Lahsasni et al [9]
Two-term exponential	$MR=a\exp(-kt)+(1-a)\exp(-kat)$	Doymaz [27]
Page	$MR=\exp(-kt^n)$	Lahsasni et al [9]
Logarithmic	$MR=a\exp(-kt)+c$	Ganesapillai et al [16]

Note: MR is moisture ratio, a, b, c, k, g, and n are model constants, and t is time in minutes.

2.3.1 Statistical evaluation of drying models

Relevant statistical parameters were used to select the best drying model expressing the drying curves of Mabonde banana 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 MBE were used as a basis for determining the best fit[16,28,29]. The statistical parameters were calculated using Equations (2), (3), and (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.

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

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

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

2.4 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[30] and Doymaz[31]. Equations (5), (6), and (7) summarize the solution of Fick's second law of diffusion, where, MR is moisture ratio; D_{eff} is the effective moisture diffusivity, m^2/s; L is the half-thickness of the banana slices, m.

$$MR=\frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-\frac{\pi^2(2n+1)^2}{4L^2}D_{eff}t\right) \qquad (5)$$

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[32]. Equation (5) could be simplified to a straight line equation; the plot of experimental drying data in terms of ln(MR) against time gives a straight line with a negative slope (φ)

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

$$\varphi=\frac{\pi^2D_{eff}}{L^2} \qquad (7)$$

3 Results and discussion

3.1 Effect of microwave power on drying kinetics

The drying curves for MBV obtained by plotting the moisture ratio versus drying time as influenced by microwave heating power is shown on Figure 1.

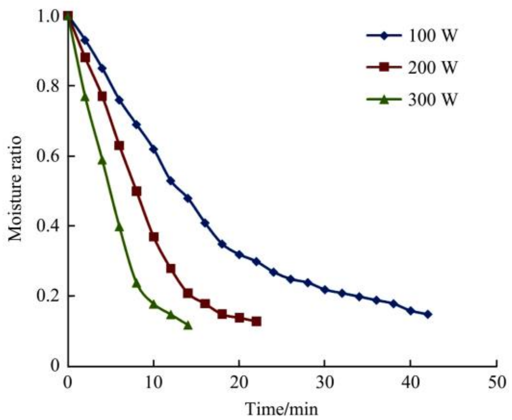

Figure 1 Drying curves of Mabonde banana at different microwave heating power levels

It is conspicuous from the curve that an increase in the microwave power ultimately resulted in a decrease in the drying time. This is in line with findings reported by Drouzas and Schubert[23], Sousa and Marsaioli[15], and Ganesapillai et al[16]. The time required to reduce the moisture to a certain level was dependent on the microwave output, being the longest at 100 W and shortest at 300 W. The moisture content of samples reduced from the initial 81.23% (w.b) to a final moisture content of 12.07%, 11.03%, and 10.03% (w.b) at a drying time of 42, 22 and 14 minutes, respectively. It is also obvious from the curves that drying of MBV at 100, 200 and 300 W took place mainly in the falling rate period which is an indication that moisture removal from the banana was through diffusion mechanism. Similar observations were reported for banana by Silva et al[6], Abano and Sam-Amoah[11], Sousa and Marsaioli[15], Ganesapillai et al[16], Dandamrongrak et al[33] and Queiroz and Nebra[34].

3.2 Application of drying models to drying curves

The drying curves were fitted with six drying models. Estimated parameters for the models as well as various statistical parameters, i.e. MBE, RMSE, R^2 and X^2, are presented on Table 2. The average values of the statistical parameters were considered in selecting the model that best describes the drying behavior of banana. Wang and Singh model was selected as the most suitable model representing the thin layer drying of MBV, based on the criteria of the highest R^2 and the lowest X^2, RMSE and MBE. For Wang and Singh model, it can be seen that the average value of the coefficient of determination R^2 was found to be the highest and X^2, RMSE and MBE values lowest when compared to other models tested. The R^2, X^2, RMSE, and MBE of the Wang and Singh model varies between 0.9921 and 0.9970, 3.99×10^{-6} and 2.13×10^{-5}, 0.0214 and 0.0392, 1.96×10^{-4} and 5.75×10^{-4}, respectively. Validation of the predicted moisture ratio values obtained from the Wang and Singh model was done by comparing the experimental moisture ratio data with those predicted with the Wang and Singh model at 100, 200, and 300 W as shown in Figures 2, 3, and 4. The values of the coefficient of correlation for the straight line obtained were 0.996, 0.995, and 0.997 for 100, 200, and 300 W, respectively. These relatively high values of coefficient of determination (R^2) are an indication of good correlation between the predicted and experimental moisture ratio values.

Table 2 Results of statistical computations and values of constants obtained from models applied to drying curves of Mabonde banana variety

Model	Power/W	Constants				R^2	RMSE	X^2	MBE
Wang & Singh	100	a = -0.04508	b = 6.13E-03			0.9945	0.0204	1.15E-05	1.87E-04
	200	a = -0.0782	b = 1.72E-03			0.9921	0.0295	7.22E-06	3.52E-04
	300	a = -0.1283	b = 4.68E-03			0.9970	0.0193	2.49E-07	1.39E-04
					Average	0.9945	0.0229	6.32E-06	2.26E-04
Verma	100	a = 3.53E-03	k = -0.1202	g = 0.0529		0.9934	0.0230	5.33E-06	2.26E-04
	200	a = 1.313	k = 0.1215	g = 0.4438		0.9953	0.0236	2.83E-06	2.09E-04
	300	a = 24.63	k = 0.1017	g = 0.9821		0.9919	0.0345	7.11E-06	3.72E-04
					Average	0.9935	0.0270	2.69E-04	5.09E-06
Two-Term	100	a = 1.036	k = 0.05647	b = 0.001952	g = - 0.0843	0.9954	0.0196	2.68E-06	1.56E-04
	200	a = 51.06	k = 0.1345	b = - 49.58	g = 0.1342	0.7164	0.0195	0.0116	0.0126
	300	a = -2.111	k = 0.1279	b = 3.14	g = 0.1376	0.9916	0.0394	0.0116	3.88E-04
					Average	0.9011	0.0848	3.87E-03	4.38E-03
Page	100	k = 0.05152	n = 0.9968			0.9900	0.0276	1.16E-05	3.44E-04
	200	k = 0.05193	n = 1.254			0.9936	0.0263	4.78E-06	2.87E-04
	300	k = 0.116	n = 1.151			0.9949	0.0251	2.40E-06	2.37E-04
					Average	0.9928	0.0263	6.26E-06	2.89E-04
Logarithmic	100	a = 0.9651	k = 0.06346	c = 0.0777		0.9943	0.0214	3.99E-06	1.96E-04
	200	a = 1.131	k = 0.08502	c = - 0.08795		0.9871	0.0392	2.13E-05	5.75E-04
	300	a = 1.069	k = 0.1436	c = - 0.05031		0.9920	0.0344	7.00E-06	3.69E-04
					Average	0.9911	0.0316	1.07E-05	3.80E-04
Two-term exponential	100	a = 5.98E-04	k = 85.36			0.9899	0.0276	1.17E-05	3.45E-04
	200	a = 1.007	k = 0.09503			0.9788	0.0478	5.22E-05	1.43E-03
	300	a = 1.692	k = 0.2078			0.9950	0.0248	2.28E-06	1.53E-04
					Average	0.9879	0.0334	2.21E-05	6.42E-04

3.3 Moisture migration during drying

The variations in ln(MR) with drying time for MBV with predicted regression equations at different microwave power levels are shown in Figure 5. It was found that ln(MR) versus time resulted to straight line equations with negative slopes, which were used in the determination of effective moisture diffusivities. The effective moisture diffusivities of MBV were 4.89×10^{-10},

1.09×10^{-9} and 1.69×10^{-9} m^2/s at 100, 200, and 300 W (Figure 6). The values are in line with the general range of 10^{-12} m^2/s to 10^{-8} m^2/s for food materials[12].

It is obvious from Figure 6 that the values of moisture diffusivity increased with the increase in microwave power. Similar observation was made by Aghbashlo et al[35], Caglar et al[36], Zielinska and Markowski[37], Omolola et al[38]. The moisture diffusivity values determined in this study were relatively higher than values reported for banana by Marinos-Kouris and Maroulis[39] and Thuwapanichayanan et al[13]. This may be attributed to the effect of variety, composition and tissue characteristics of bananas.

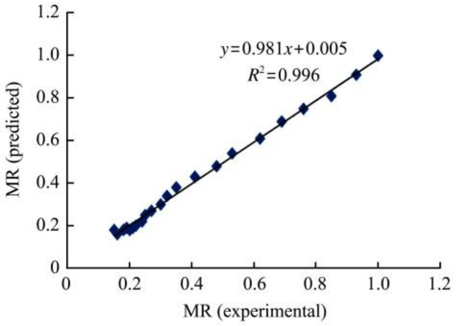

Figure 2 Comparison of experimental and predicted moisture ratios from the Wang and Singh model at microwave power of 100 W for Mabonde banana variety

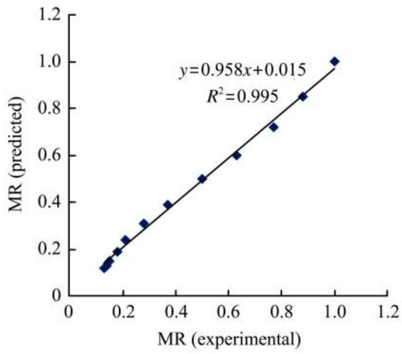

Figure 3 Comparison of experimental and predicted moisture ratio from Wang and Singh model at microwave power of 200 W for Mabonde banana variety

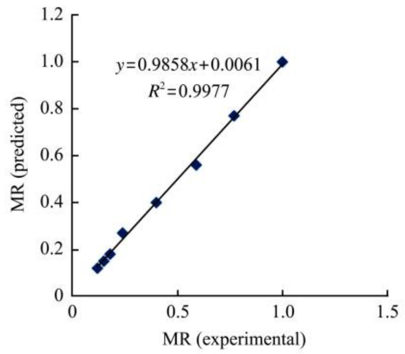

Figure 4 Comparison of experimental and predicted moisture ratios from the Wang and Singh model at microwave power of 300 W for Mabonde banana variety

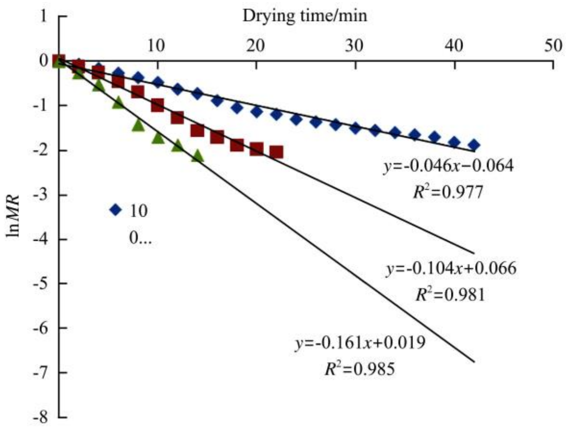

Figure 5 Variation in ln (MR) with drying time at different microwave power levels for Mabonde banana variety

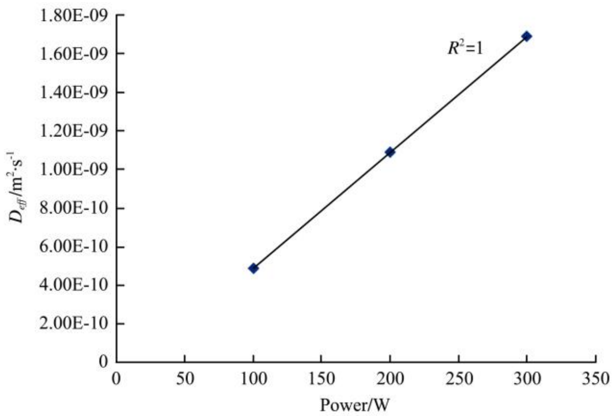

Figure 6 Effects of microwave heating power on the effective moisture diffusivity of Mabonde banana variety

4 Conclusions

Results obtained for microwave drying kinetics of MBV show that (i) the increase in microwave power from 100 W to 300 W decreased the drying time from 42 min to 14 min; (ii) the entire drying operation took place mainly in the falling rate period; (iii) among the models tested, the Wang and Singh model was found suitable for the description of microwave drying kinetics of MBV, and (iv) the moisture diffusivity increased with increasing microwave power with values at 4.89×10^{-10}, 1.09×10^{-9} and 1.69×10^{-9} m^2/s at 100, 200, and 300 W, respectively. The results obtained in this study could be used for the design of effective drying equipment and description of heat penetration during drying of MBV.

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Nomenclature

t Drying time, min

M_o	Initial moisture content, kg water/kg dry matter
M	Moisture content of the product, kg water/kg dry matter
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}	Effective moisture diffusivity, m^2/s
L	Half-thickness, m
k, n, a, b, g, c	Model constants
P	Microwave heating power, W
Greek symbol	
φ	Slope

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