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Modeling of Thin Layer Drying Characteristics of Cassava Grate in a Hybrid Solar Dryer

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Abstract

Cassava grate is a source of raw material for food and other bioprocessing industries. Drying the grate offers opportunities for value addition into novel products, reduction in transportation cost and increase in availability of farming space. This study presented the mathematical models of the thin-layer drying behaviour of cassava grate using three varieties (TMS 96/1414, TMS 92/0326 and TMS 01/1368), temperature of 50ºC and 0.15m/s air velocity in a hybrid solar dryer which utilizes solar energy and an auxiliary heating system enabling drying at night or under other non-ideal irradiance conditions. A total of seventeen drying models were used for choosing the best fitness model for describing the drying process helps to improve efficiency of the dryer. The effective moisture diffusivity and activation energy were calculated using Fick's diffusion equation. The goodness of fit tests based on the criterion indicated that the Two Term exponential model was the optimum fitted to the drying data of cassava grate from TMS 96/1414, TMS 92/0326 and TMS 01/1368 respectively. The determined effective moisture diffusivity of the grate samples was 6.0984x 10^{-8} m^2 s^{-1}, 7.2116 x 10^{-8} m^2 s^{-1} and 6.7184x10^{-9} m^2 s^{-1}; the activation energy of the cassava grate samples was calculated as 36.82 kJ mol^{-1}.

Keywords: *γ-Irradiation, groundnut, chemical composition, amino acids, fatty acids*

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Introduction

Cassava (*Manihot esculenta crantz*) is the fourth most important staple food in the world after rice, wheat and maize (IFAD/FAO, 2000). There has been a substantial increase in world production of cassava since 2001 with world cassava production for the year 2018 estimated to be approximately 277.81 million tonnes. Nigeria produces over 50 million metric tonnes of cassava annually making her the world's leading producer of cassava among the top five countries (Nigeria, Thailand, Democratic Republic of Congo (DRC), Brazil and Indonesia) (FAOSTAT; Phillips *et al*., 2004; FAO, 2008; Akinpelu *et al*., 2011). Ashaye *et al*. (2005) reported that apart from serving as the primary staple food for millions of people, it can be converted into dried, stable products such as grates, chips and pellets which are useful as primary raw material in human food (such as gari, fufu etc), animal feed formulations, ethanol production and cassava beer. Due to the poor storage characteristics of the cassava tuber in its unprocessed state, it is necessary to process the product quickly into storable forms so as to minimize deterioration in quality and quantity and one of such forms in which cassava can easily be processed into is dried cassava grate.

Drying of agricultural materials majorly is to provide longer periods of storage, minimize weight and packaging requirements, reduce transportation cost and make available more farming land. Most drying of crop processes are effected using nonrenewable and expensive energy sources, such as fuel, electricity, biomass fuel and fossil; hence there is need for cheaper and renewable energy sources such as solar energy. In drying technology, one of the most important aspects is the modelling of the drying process (Khazaei and Daneshmandi, 2007). Drying models are usually used to analyze the variables involved in a process, predict drying kinetics of the agricultural product and optimize the operating parameters and circumstances and efficiency of the dryer being improved with the selection of good model which is useful in the design and optimisation of dryers. Cassava grate has high moisture content, undesirable biochemical changes and subsequent contamination and spoilage of the grate can only be prevented if the drying process is fast enough to attain the required final moisture content. Several researches on selection of drying models for thin-layer drying of some cassava by-products and other agricultural materials are reported in the literature. However, adequate and efficient drying systems for timely drying of the grate are not yet fully developed and operational. Hence the objective of the study is to determine thin-layer drying kinetics model which can predict accurately the drying behaviour of cassava grate produced from three varieties; TMS 96/1414, TMS 92/0326 and TMS 01/1368 using the hybrid solar dryer.

Materials and Methods

Description of the equipment used

The solar dryer that was used for the experiment is a hybrid solar dryer which utilizes solar energy and an auxiliary heating system enabling drying at night or under other non-ideal irradiance conditions. It consists of aluminum framed drying chamber in which perforated tray is placed horizontally. A plain glass having the same dimensions as the collector area and painted dull black was used as an absorber plate. This absorber plate overlay the thermal storage unit in which the heating elements are installed. The top of this section was covered with a plain glass. Heater and axial flow fan powered by a 250watt capacity solar panel that was connected to 12 volts, 100Amps, D.C battery for power storage used in the solar dryer was equipped with a speed regulator and control switch to prevent damage to battery. It also consists of an outlet (chimney) for discharging the used air. It is also fitted with a temperature-control device (Rueger aisi 304/1,4301) that uses a sensor and thermostatic system to maintain a set temperature in the drying chamber to within ± 1°C. When the dryer is operating, air is heated to the set temperature in the heating chamber and is then blown into the drying chamber where it picks up moisture from the product being dried and is then discharged through the air outlet. The picking-up and discharge of moisture continuously by the drying air results to a reduction in the weight and moisture content of the cassava grate in the drying chamber.

Sample preparation

Cassava tubers (three varieties) used for the experiments were harvested from FUTA research farm, Obanla. The cassava roots were peeled manually using stainless knife. The peeled roots were washed using portable water and allowed to drain. The drained roots were grated using fabricated motorized mobile grater to ensure even particle size. A 1000g of the grated cassava root was weighed using digital weighing balance (Platinum A 110C) and the moisture content was determined according to AOAC (2000) prior to drying experiment. The process was carried out for the three varieties (TMS 96/1414, TMS 92/0326 and TMS 01/1368) respectively.

Drying experiment

Prior to the commencement of drying, the hybrid solar dryer was switched on and the blower allowed to run for about 30 minutes to allow the heated air to stabilize to the desired temperature. The moisture content of the weighed wet cassava grate mash was determined and loaded into the solar dryer for tray drying process. The dryer was built in the Department of Food Science and Technology, federal University of Technology, Akure, Nigeria. The dryer was installed in an environment of Latitude of Akure, Ondo State (experiment location) was 7.25° N (Adaramola, 2002) and 50°C with average air velocity of 0.15m/s. Steady state of temperature was achieved in the dryer before the chips were loaded.

The drying response variable measured was weight loss at time intervals of 30 minutes. It involved quick withdrawal of cassava grate from the hybrid solar dryer set-up and quick weighing using a laboratory balance to evaluate moisture loss. The sample was quickly put back to continue with drying and the process was truncated when two consecutive weight remained constant for a sample. The procedure was carried out for the three varieties (TMS 96/1414, TMS 92/0326 and TMS 01/1368) of cassava respectively.

Mathematical model

Moisture ratio (MR) is one of the important criteria to determine the drying characteristics of agricultural product. MR can be determined according to external conditions. The moisture ratio (MR) of cassava grate during the drying process was obtained:

$$MR = \frac{M_t - M_e}{M_o - M_e}$$

Where Mt, Mo and Me are moisture content at each measurement time, initial moisture content, and equilibrium moisture content (kg water/kg dry matter) respectively. However, the drying varied continuously during the drying experiments, the relative moisture content of drying air is simplified as reported by Midilli *et al*. (2002) Akpinar *et al.* (2003); Kingsley and Singh (2007) and expressed as:

$$MR = \frac{M_t}{M_o}$$

To determine the drying characteristics of the three different cassava grate, the experimental data were fitted into seventeen different models as presented on Table 1. The relationship between moisture loss and drying time with various coefficients attached to each model were described by these models.

Table 1: Thin layer drying curve models considered.

S/N	Model name	Equation	Model name Reference
1	Lewis	MR = exp(-kt)	Kingly *et al.* (2007)
2	Page	MR = exp(-kt^n)	Doymaz (2004)
3	Modified Page	MR = - exp (-(kt)^n)	Overhults *et al.* (1973)
4	Henderson-Pabis	MR =a exp(-kt)	Akpinar *et al.* (2003).
5	Logarithmic	MR = a exp(-kt)+ c	Togrul and Pehlivan (2003)
6	Midilli and Kucuk.	MR = a exp(-kt^n) + bt	Midilli and Kucuk (2003)
7	Two-term	MR = a exp(-k$_o$t) + b exp(k$_1$t)	Yaldiz *et al.* (2001).
8	Two-term Exp.	MR = a exp(-kt) + (1-a) exp (-kat)	Hii *et al.* (2008)
9	Modified Henderson-Pabis	MR =a exp(-kt) +b exp(-gt)+ c exp(-ht)	Hamdami *et al.* (2006).
10	Wang and Singh	MR = 1 +at+ bt^2	Yaldiz and Ertekin (2001).
11	Diffusion Approach	MR = a exp (-kt)+(1-a) exp(-kbt)	Akpinar and Bicer (2006)
12	Verma et al.	MR = a exp(-kt) + b exp (gt) + c exp (-ht)	Verma *et al* (1985)
13	Weibull	*MR*= exp (-(t/a)^b))	Corzo *et al.* (2008)
14	Aghabashlo Model	*MR* = exp-((k$_1$t)/(1+k$_o$t))	Aghabashlo *et al.(*2008)
15	Demir *et al.*	MR = *a* exp *(-kt)^n* + *b*	Demir *et al*. (2007)
16	Simplified Fick	MR=a exp(−c(t/L^2))	Diamante and Munro, 1991
17	Modified Aghabashlo	*MR*=exp–((*k*1*t*)/(1+*k*0*t*))+*ct*	Aghabashlo *et al.*, 2009

Data Statistical Analysis

The constants of each model were estimated using a non-linear regression analysis performed using Sigma Plot 17 software and Microsoft Excel 2016 version for all drying data to test the reliability of the seventeen models. Wang *et al*. (2006), Ertekin and Yaldiz (2004), Demir *et al*. (2004) reported that a good fit is said to occur between experimented and predicted values of a mathematical model when R^2 is high while χ^2, RMSE and MBE are low; hence statistical criteria such as coefficient of determination (R^2), reduced chi-square (χ^2), mean bias error (MBE) and root mean square error (RMSE) were determined.

Coefficient of determination (R^2)

The coefficient of determination (R2) is one of the main criteria for selecting the best equation for expressing the drying curves of the sample. It evaluates how well a model fits the data and it has been used by various authors to evaluate drying models (Singh *et al.*, 2006; doymaz, 2007; Panchariya *et al.*, 2002). It can be calculated from the equation:

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

Reduced chi-square

The reduced chi-square is given as:

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

Root Mean Square Error

The RMSE gives the deviation between the predicted and experimental values and it is required to reach zero (Gohank *et al.*, 2009). It can be calculated using the equation:

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

Mean Bias Error

The mean bias error provides information on long term performance of the correlations by allowing a comparison of the actual deviation between experimented and predicted value term by term is given as:

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

Determination of effective moisture diffusivity of cassava grate

The effective moisture diffusivity of the cassava grate was calculated using second law of diffusion. Second law of diffusion postulated by Fick is a mathematical equation commonly used for describing the drying process which is based on the assumptions that moisture migration is only by diffusion; there is uniform initial moisture distribution; the effective moisture diffusivity and temperature are constant; and sample shrinkage is negligible. For infinitive slab the equation is given as:

$$LnMR = Ln\left(\frac{8}{\pi^2}\right) - \frac{\pi^2 D}{4(h)^2}\ x\ t$$

Effective moisture diffusivity was calculated by plotting the natural logarithm of experimental drying data that is (lnMR) versus time of drying yielding a straight line graph; hence the slope method was used as reported by Maskan *et al*. (2002) and Doymaz (2004) and expressed as:

$$slope = -\frac{\pi^2 D}{4(h)^2}$$

Determination of the Activation Energy of Cassava Grate

The activation energy for the cassava grate was calculated using an Arrhenius equation as reported by Akpinar *et al.* (2003) and Lopez *et al*. (2000):

$$D_{eff} = D_o \exp\left(\frac{E_a}{RT_a}\right)$$

where, *Ea* is the activation energy, kJ mol^{-1}; *R* is universal gas constant (8.3143×10^{-3} kJ mol^{-1} K^{-1}); *Ta* is absolute air temperature, *K*, and D_0 is the pre-exponential factor of the Arrhenius equation, $m^2\ s^{-1}$. The natural logarithm of each component gives:

$$InD_{eff} = InD_o \ - \frac{E_a}{RT_a}$$

A plot of ln*Deff* versus 1/*Ta* gives a straight line graph whose slope (*S*) is given as

$$S = \frac{-E_a}{R}$$

Results

Models Evaluation of drying curve using statistical criteria

The moisture ratio data for cassava grate dried with the newly developed hybrid solar dryer were fitted with thin layer drying models listed on Table 1 above. The results of statistical analyses are listed in Tables 2 and Table 3 at 1kg of drying load, respectively for TMS 96/1414, TMS 92/0326 and TMS 01/1368 at air velocity of 0.15m/s and temperature of 50ºC respectively.

Table 2: Average values of statistical parameters obtained from fitting the models to drying data.

S/N	Model	Variety	R^2	χ2	RMSE	MBE
1	Newton/Lewis	TMS 96/1414	0.9627	0.0035	0.056903	0.003113
		TMS 92/0326	0.9689	0.0028	0.051391	-0.00757
		TMS01/ 1368	0.9566	0.0049	0.045596	0.002079
2	Page	TMS 96/1414	0.9791	0.0021	0.042603	-0.00359
		TMS 92/0326	0.9745	0.0025	0.011662	-0.01815
		TMS01/ 1368	0.2682	0.1436	0.895400	0.801741
3	Modified Aghbashlo	TMS 96/1414	0.9630	0.0040	0.056676	-0.000153
		TMS 92/0326	0.9693	0.0032	0.051055	-0.004118
		TMS01/ 1368	0.9742	0.0034	0.008192	6.71154e-5
4	Weibull	TMS 96/1414	0. 9978	0.0023	0.232895	0.11034
		TMS 92/0326	0.9979	0.0031	0.246915	0.13368
		TMS01/ 1368	0. 9897	0.0024	0.8954	0.801741
5	Aghbashlo	TMS 96/1414	0.9622	0.0037	0.056902	0.003113
		TMS 92/0326	0.9689	0.0038	0.051389	-0.00757
		TMS01/ 1368	0.9566	0.0053	0.045596	0.002079
6	Modified Page	TMS 96/1414	0.9791	0.0032	0.042603	-0.00359
		TMS 92/0326	0.9979	0.0130	0.046563	0.01815
		TMS01/ 1368	0.9848	0.0018	0.040743	0.00166
7	Henderson and Pabis	TMS 96/1414	0.9642	0.0035	0.055731	0.005564
		TMS 92/0326	0.9711	0.0028	0.049528	-0.00531
		TMS01/ 1368	0.9604	0.0049	0.067424	0.004546
8	Logarithmic	TMS 96/1414	0.9965	0.0037	0.005145	1.72459e-9
		TMS 92/0326	0.9971	0.0029	7.14925e-5	511116e-7
		TMS01/ 1368	0.9883	0.0003	6.59096e-10	4.34408e-19
9	Two term	TMS 96/1414	0.9642	0.0041	0.057351	0.005645
		TMS 92/0326	0.9711	0.0033	0.049528	-0.00531
		TMS01/ 1368	0.9604	0.0056	0.067422	0.004546
10	Two term exponential	TMS 96/1414	1.0000	0.0020	0.00452	-0.00032
		TMS 92/0326	0.9988	0.0012	0.02445	-0.001972
		TMS01/ 1368	1.0000	0.0002	7.32899e-11	5.37141e-21
11	Wang and Singh	TMS 96/1414	0.8477	0.0151	0.115022	0.022114
		TMS 92/0326	0.8361	0.0159	0.118017	0.021836
		TMS01/ 1368	0. 9800	0.0012	0.052548	0.002761
12	Midill and kuccuk	TMS 96/1414	0.3869	0.0710	0.230780	-0.083658
		TMS 92/0326	0.9795	0.0023	0.041737	-0.00529
		TMS01/ 1368	0.9777	0.0016	0.001759	3.09563
13	Demir *et al*	TMS 96/1414	0.9650	0.0041	0.048652	-1.7372e-9
		TMS 92/0326	0.9719	0.0032	0.048847	-2.91454e-9
		TMS01/ 1368	0.9773	0.0032	0.052545	0.002761
14	Diffusion Approach	TMS 96/1414	0.9775	0.0024	0.044180	-0.001419
		TMS 92/0326	0.9826	0.0018	0.038458	-0.01466
		TMS01/ 1368	0.9821	0.0023	0.048177	0.002321
15	Vermal *et al*	TMS 96/1414	0.9642	0.0038	0.055731	0.005564
		TMS 92/0326	0.9711	0.0030	0.049528	-0.00531
		TMS01/ 1368	0.9604	0.0052	0.067422	0.004546
16	Modified Henderson & Pabis	TMS 96/1414	0.9642	0.0050	0.055731	0.005564
		TMS 92/0326	0.9719	0.0038	0.048836	2.46025e-5
		TMS01/ 1368	0.9604	0.0067	0.067424	0.004546
17	Simplified Fick Diffusion	TMS 96/1414	0.3756	0.0668	0.223290	-0.110338
		TMS 92/0326	0.2826	0.0750	0.246914	-0.133675
		TMS01/ 1368	0.9604	0.0052	0.067424	0.004546

Table 3: Average values of drying constants obtained from fitting drying data of the three varieties of *Manihot* grate to the different thin layer models.

Model	Variety	Model constants
Newton/Lewis	TMS 96/1414	k=0.0146
	TMS 92/0326	k=0.0314
	TMS01/ 1368	k=0.0076
Page	TMS 96/1414	n=1.4805 k=0.0017428
	TMS 92/0326	n=1.2691 k=0.0041425
	TMS01/ 1368	n=16661789.0873 k=0.0003
Modified Aghbashlo	TMS 96/1414	K_1=0.0145 k_0=-2.0540e-5 c=3.7380e-11
	TMS 92/0326	K_1=0.0136 k_0=2.4322e-5 c=1.0642e-11
	TMS01/ 1368	K_1=0.006405 k_0 =-0.0003 c=1.3199e-13
	TMS 96/1414	a=-11.1876 b=0.0699
	TMS 92/0326	a=-15.4885 b=2.4261e-12
Weibull	TMS01/ 1368	a=-5.4651 b=0.0678
	TMS 96/1414	K_1=0.0146 K_0=2.6332e-11
	TMS 92/0326	K_1=0.0134 K_0=2.4261e-12
Aghbashlo	TMS01/ 1368	K_1=0.0076266 K_0=2-2500e-11
	TMS 96/1414	n=0.6080 k=0.0213
	TMS 92/0326	n=1.2531 k=0.0119
Modified Page	TMS01/ 1368	n=1.4630 k=0.0071
	TMS 96/1414	a=1.0410 k=0.0151
	TMS 92/0326	a=1.2531 k=0.0140
Henderson and Pabis	TMS01/ 1368	a=1.0610 k=0.0080300
	TMS 96/1414	a=1.0497 c=-0.0118 k=0.0146
	TMS 92/0326	a=1.0415 c=0.0125 k=0.0146
Logarithmic	TMS01/ 1368	a=1.1553 c=-0.1287 k=0.0059732
	TMS 96/1414	a=0.5680 b=-0.4730 k_0 =0.0151 k_1= 0.0200
	TMS 92/0326	a=0.5739 b=0.4754 k_0=0.0414 k_1=0.0140
Two term	TMS01/ 1368	a=0.5644 b=0.4966 k_0=0.0080 k_1=0.0038
	TMS 96/1414	a=1.9148 k= 0.01026
	TMS 92/0326	a=2.0452 k=0.0220
Two term exponential	TMS01/ 1368	a=-1.8980 k=0.0110
	TMS 96/1414	a=-0.0073797 b=1.2264e-5
	TMS 92/0326	a=-0.006926 b=1.1249e-5
Wang and Singh	TMS01/ 1368	a=-0.0054 b=7.1638e-6
	TMS 96/1414	a=1.000 k=0.1809 b=0.0280 n=0.0698
	TMS 92/0326	a=1.0208 k=0.0028290 b=8.3149e-5 n=1.3731
Midill and kuccuk	TMS01/ 1368	a=0.9299 k=0.0024158 b=-2.2115e-5 n=1.6583
	TMS 96/1414	a=1.0497 k=0.2094 b=-0.0118 n=0.0698
	TMS 92/0326	a=1.0415 k=0.2091 b=0.0125 n=0.0697
Demir *et al*	TMS01/ 1368	a=1.1553 k=0.1339 b=-0.1287 n=0.0446
	TMS 96/1414	a=-46.5187 b=0.9819 k =0.0280
	TMS 92/0326	a=-0.3547 b=0.0354 k=0.5061
Diffusion Approach	TMS01/ 1368	a=-59.7774 b=0.9862 k=0.0144
	TMS 96/1414	a=0.5205 k=0.0151 g=0.0151
	TMS 92/0326	a=0.5246 k=0.0140 g=0.0140
Simplified Fick Diffusion	TMS01/ 1368	a=1.0610 b=5.3292 c=-8.5979

Discussion

The Chi square values for TMS 96/1414 were 0.0035, 0.0021, 0.0040, 0.0023, 0.0037, 0.0032, 0.0035. 0.0037, 0.0041, 0.0020, 0.0151, 0.0710, 0.0041, 0.0024, 0.0038, 0.0050 and 0.0668. The values for TMS 92/0326 were 0.0028, 0.0025, 0.0032, 0.0031, 0.0038, 0.0130, 0.0028, 0.0029, 0.0033, 0.0012, 0.0159, 0.0023, 0.0032, 0.0018, 0.0030, 0.0038 and 0.0750. For TMS 01/1368 the chi square results were 0.0049, 0.1436, 0.0034, 0.0024, 0.0053, 0.0018, 0.0049, 0.0003, 0.0056, 0.0002, 0.0012, 0.0016, 0.0032, 0.0023, 0.0052, 0.0067 and 0.0052. These values were recorded for Lewis /Newton, Page, Modified Aghabashlo, Weibull, Aghabashlo, Modified Page, Henderson&Pabis, Logarithmic, Two term, Two Term exponential, Wang and Singh, Midilli & Kuccuk., Demir *et al*, Diffusion Approach, Verma *et al*, Modified Henderson&Pabis and Simplified Fick respectively. For TMS 96/1414 Midilli & Kuccuk gave the highest chi square value of 0.0710 while the least value of 0.0020 was from Two Term exponential; for TMS 92/0326 0.0012 which was the least value was recorded by Two Term exponential and highest value (0.0750) was recorded by Simplified Fick. 0.0002 which was the lowest chi square value for TMS 01/1368 was recorded by Two Term exponential and highest value of 0.1436 was recorded by Page model.

The RMSE values for the seventeen models (Lewis /Newton, Page, Modified Aghabashlo, Weibull, Aghabashlo, Modified Page, Henderson&Pabis, Logarithmic, Two term, Two Term exponential, Wang and Singh, Midilli & Kuccuk., Demir *et al*, Diffusion Approach, Verma *et al*, Modified Henderson&Pabis and Simplified Fick) recorded for TMS 96/1414 were 0.056903, 0.042603, 0.056675974, 0.232895, 0.056901494, 0.042603, 0.055731, 0.005145, 0.055731, 0.00452. 0.115022, 0.230779574, 0.048652, 0.044180324, 0.055731, 0.055731 and 0.223289462 respectively. TMS 92/0326 recorded 0.051391, 0.011662, 0.051054647, 0.246915, 0.05138871, 0.04656329, 0.049528, 7.14925e-5, 0.049528, 0.02445, 0.118017, 0.041737, 0.048847, 0.038458, 0.049528, 0.048836 and 0.246914131. 0.045596, 0.8954, 0.008192399, 0.8954, 0.045596, 0.040743, 0.06724, 6,59096e-10, 0.06742243, 7.32899e-11, 0.05254822, 0.00175944, 0.052545, 0.048177, 0.067422118, 0.067424 and 0.067424 for TMS 01/1368. The result of RMSE for TMS 96/1414 revealed that Two Term exponential recorded the lowest value of 0.00452 and 0.223289462 for Simplified Fick as the highest value. In term of TMS 92/0326 the highest value of 0.246915 was recorded by Weibull model and Two Term exponential gave the least value of 0.02445. TMS 01/1368 had lowest value of 7.32899e-11 and highest value of 0.8954 for Two Term exponential and Page model respectively.

MBE values recorded for Lewis /Newton, Page, Modified Aghabashlo, Weibull, Aghabashlo, Modified Page, Henderson&Pabis, Logarithmic, Two Term, Two Term exponential, Wang and Singh, Midilli & Kuccuk., Demir *et al*, Diffusion Approach, Verma *et al*, Modified Henderson&Pabis and Simplified Fick respectively for TMS(thin), TMS(bold) and TMS (yellow) were 0.003113, -0.00359, -0.000153171, 0.11034, 0.003112828, -0. 00359, 0.005564, 1.72459e-9, 0.005564, -0.00032, 0.022114, -0.083658066, -1.7372e-9, -0.00141924, 0.005564, 0.005564 and -0.1103375. -0.00757, -0.01815, -0.00411819, 0.13368, -0.00757, 0.01815, -0.00531, 511116e-7, -0.00531, -0.001972, 0.021836, -0.00529, -0.2.91454e-9, -0.01466, -0.00531, 2.46025e-5 and -0.13367001. 0.002079, 0.801741, 6.71154e-5, 0.801741, 0.002079, 0.00166, 0.004546, 4.34408e-19, 0.004545784, 5.37141e-21, 0.002760538, 3.09563, 0.002761, 0.002321, 0.004545742, 0.004546 and 0.004546.

The R^2 values for the seventeen mathematical models were greater than 0.89, indicating a good fit (Bambang *et al.*, 2018) expect for Midilli & Kuccuk and Simplified fick's diffusion for TMS 96/1414, Simplified fick's diffusion for TMS 92/0326 and Page for TMS 01/1368 which were less than 0.89. It was evident from table 2 that the highest values of $R^2$and the lowest values of and RMSE, Chi square (χ^2) and MBE were obtained from Two Term Exponential model for the three varieties of cassava (TMS 96/1414, TMS 92/0326 and TMS 01/1368) respectively. Based on statistical analysis, these model was the best to represent the thin layer behavior of cassava chips in the newly developed hybrid solar dryer irrespective of the variety of cassava grate tested as shown in figure 1.

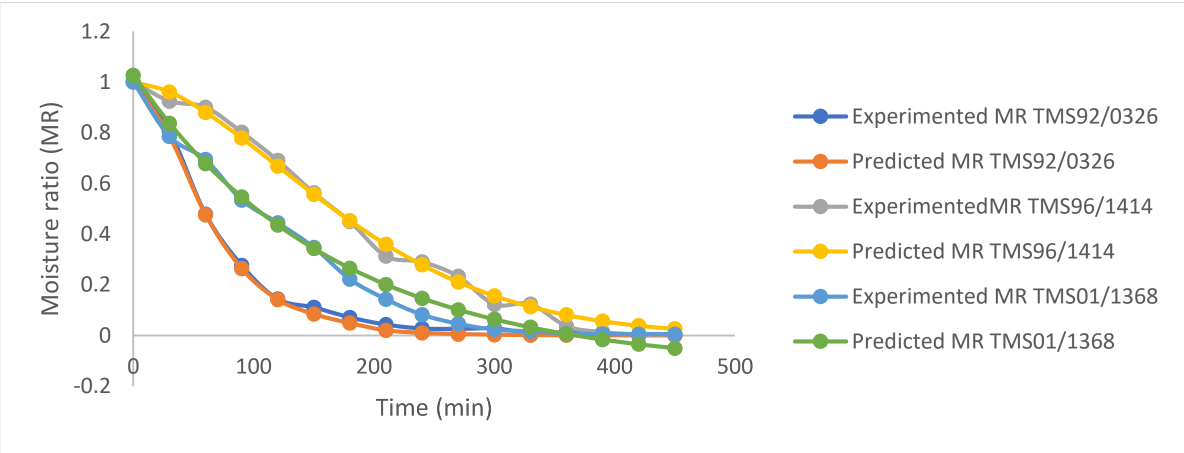

Figure 1: Experimental and predicted values of moisture ratio for best fit (Two Term exponential) model for cassava grate (TMS 96/1414, TMS92/0326 and TMS01/1368).

Drying rate of cassava grate

As the drying proceeded, the weight of the samples continued to decrease gradually due to the evaporation or loss of moisture from the cassava grate samples. Data reported show dependency of the drying time on drying temperature and thickness. Khazaei *et al.* (2008) reported the dependency of drying kinetics on air temperature, air velocity, material size, drying time, etc. The moisture ratio decreases continuously as the drying progress. Figure 2 shows the variation of drying rate as a function of time and no constant rate period was observed in the drying of the cassava grate for the three varieties; the drying process took place at a falling rate period mainly controlled by diffusion mechanisms. All the cassava varieties exhibited a single falling rate which is common to all agricultural products as reported by Karel and Lund, (2003); Ramaswamy and Marcotte (2006); Velic *et al.* (2007) and Ajala *et al.* (2012).

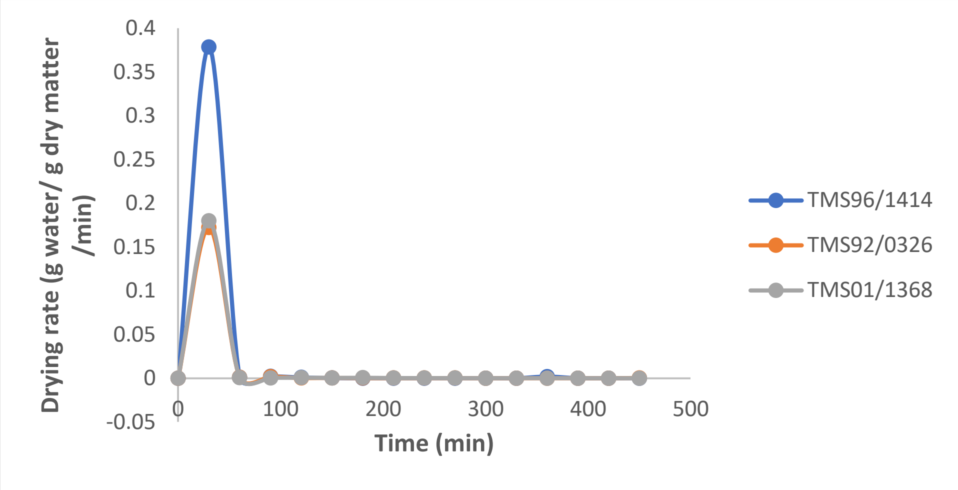

Figure 2: Drying rate versus drying duration of cassava grate (TMS 96/1414, TMS92/0326 and TMS01/1368).

Effective Moisture Diffusivity

The value of the slope (*S*) for TMS 96/1414, TMS 92/0326 and TMS 01/1368, and the value of *h*, which was determined as half of slab thickness as 0.15mm (0.0015 m) were substituted into equation and the values of effective moisture diffusivity were 6.0984x 10^{-8} m^2 s^{-1}, 7.2116 x 10^{-8} m^2 s^{-1} and 6.7184x10^{-9} m^2 s^{-1} as shown on table 4. TMS 01/1368 had the lowest moisture diffusivity value while TMS 96/1414 had the highest value. The difference in values may be attributed to the difference in variety of cassava used for the drying. It could be inferred that TMS 96/1414 had the highest resistance to moisture movement Ademiluyi *et al.*, 2007). Tunde-Akintunde and Afon (2010) reported values of 7.31×10^{-7} m^2 s^{-} 8.06×10^{-7} m^2 s^{-1} for pre-treated cassava chips. 2.43×10^{-11} m^2 $s^{-1}$to 4.52×10^{-11} m^2 s^{-1} was reported for cassava chips by Ajala *et al*. (2012). These values are slightly lower than the values gotten in this study. The values gotten from this study are within the range of effective moisture diffusivity for general range of food materials which is 10^{-7} $ms^{-1}$to $10^{-13}$$ms^{-1}$(Maroulis and Kouris. 2006; Hii *et al*., 2009).

Table 4: Effective moisture diffusivities of Cassava grate as affected by variety.

Variety	Effective Diffusivity m/s
TMS 96/1414	6.0984 x 10^{-8}
TMS 92/0326	7.2116 x 10^{-8}
TMS01/ 1368	6.7184 x 10^{-9}

Activation Energy

Figure 3 shows the plot of ln D_{eff} versus Time inverse (1/T) which produced activation energy (Ea) of the cassava grate. The slope (*S*) of the straight-line curve gave a value of –4428.5. Hence by substituting S = –4428.5 and R = 8.3143×10^{-3}kJ mol^{-1} into Equation gave the value of the Activation energy (*Ea*) for the drying of cassava grate. The value of Ea was calculated to be 36.82 kJ mol^{-1} This is the minimum energy that would be needed to effect the drying process of cassava grate and is within the range of values of 16.1 to 44.49kJ/mol reported for stone apple, cassava chips, finger millet, bell pepper and Cardaba Banana Peels (Rayaguru and Routray, 2012; Ajala *et al*., 2012; Rhadika *et al*., 2011; Taheri-Garavand *et al*., 2011). Activation energy value ranges from 12.7 to 110 kJ/mol for most food material (Akpinar and Bicer, 2007). The value is higher than 28.576kJ mol^{-1} that was obtained by Ezeanya *et al.* (2018) for tapioca. Activation energy is the minimum energy that would be required to effect drying in food materials that is activation energy is the amount of energy needed to trigger moisture removal from a solid matrix during drying (Tanko *et al*., 2005); the energy barrier that must be overcome in order to activate moisture diffusion. By increasing the temperature and hence the drying rate this energy barrier can be easily overcome but Hii *et al.* (2009) stated that compromise between high temperature and acceptable product quality must be reached. The higher the activation energy of the sample, the higher the energy that would be needed in drying the cassava grate samples (Engkos *et al.*, 2020).

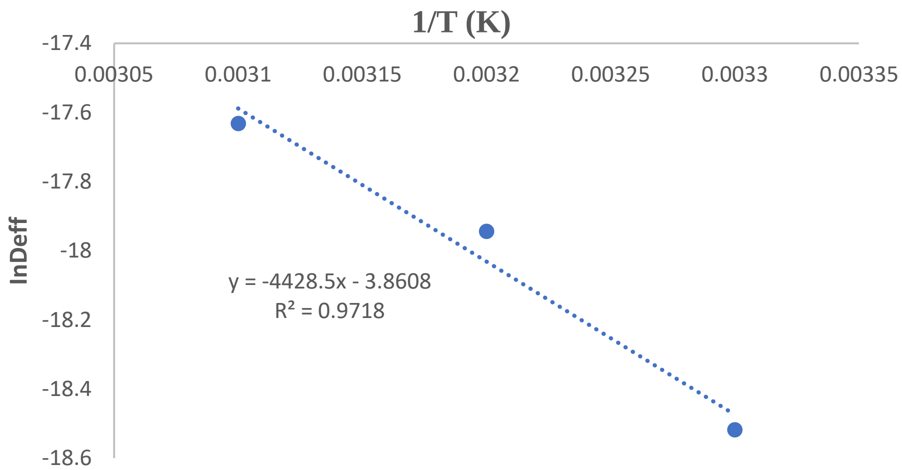

Figure 3: Graphical plots of lnDeff versus 1/T

Conclusion

Cassava grate from TMS 96/1414, TMS92/0326 and TMS 01/1368 were dried in a hybrid solar dryer at 50°C. From the experimental analysis, it was observed that drying took place at falling rate period. The effective moisture diffusivity and the activation energy for the three varieties of cassava grate samples were within the range of other agricultural products.
Among 17 models, the Two Term exponential model gave the best results and showed good agreement with the experimental data obtained from the experiments including the thin layer drying process for the three varieties of cassava grate samples in the hybrid solar dryer. In future the drying kinetics should be done at varied period of the year due to change in weather to determine if the two term exponential model will give best fit.

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