Modeling the effect of dryer configurations on the thin-layer solar drying kinetics of *ogbono* seeds (*Irvingea gabonensis*)

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Abstract: Effective drying methods for agricultural products have been a major global concern. A study on modeling the effect of dryer configurations on the thin-layer solar drying kinetics of *ogbono* seeds was presented in this paper. *Ogbono* seeds were dried using a solar drying system, which was a forced convection distributed type solar collector, equipped with a sun-tracking mechanism. The seeds were dried at four different tilt angles of 0, 5, 10, and 15°; two absorber plate thicknesses of 1.5 mm and 2.7 mm; and a constant air velocity of 2 m s^{-1}. The drying data obtained from the experiment was fitted to six thin-layer drying predictive models. The effective moisture diffusivities at varying treatments as well as the activation energy of the *ogbono* seeds were determined. Results from the experiment revealed that the drying kinetics of the seeds varied with the different tilt angles and plate thicknesses. All six drying models fitted fairly accurately with the drying data of *ogbono* seeds. However, the Wang and Singh model with the highest coefficient of determination (R^2) value of 0.9994 and least root mean squared error (RMSE) value of 0.007 was the best-fitted model for the thin-layer solar drying of *ogbono* seeds. The effective moisture diffusivities determined for the seeds ranged from 2.03×10^{-11} to 3.24×10^{-11} m^2 s^{-1}. The research results revealed that these values increased with the absorber plate thickness of the dryer. The activation energy of 59.724 kJ mol^{-1} was determined for the *ogbono* seeds. The results obtained from this research showed that a solar drying system in alliance with a good predictive model could be employed in food processing industries for better dryer designs and more efficient product drying.

Keywords: drying kinetics, forced convection, ogbono seeds, effective moisture diffusivity, activation energy

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1 Introduction

Drying of crops enables them to be kept at a safe storage moisture content thus preventing the deteriorating activities of microorganisms on the food matrix. The sun provides a relatively cheap and large supply of energy (solar energy) which can be utilized raw for drying and heating materials. The conversion of solar energy to heat energy by a solar cell is the principle of operation of a solar dryer used for the drying of agricultural materials and the heating of houses. The relatively low operating requirements and the low cost of running a solar dryer justify its economic usage in the rural farming environment of Nigeria.

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The African wild mango or *ogbono* as locally called in the South Eastern part of Nigeria is known botanically as *Irvingea Gabonensis*. It is found in the Southern parts of Nigeria and some parts of West Africa. It is a wide forest tree with dark green foliage and yellowish fragrant flowers. The fruit is approximately spherical with a smooth yellow fragrant mesocarp and a hard endocarp when ripe. The kernel of *irvingea* is important economically and is popularly used as soup thickeners, they are also processed into cakes and meals (Harris, 1996; Adedeji, 2017). The drying and preservation of *ogbono* are traditionally achieved in many parts of Nigeria through sun drying. Another method practiced in those days was the drying of *ogbono* and other agricultural materials using heat from the fireplace in the kitchen. These traditional methods have the disadvantage of producing poor-quality products, taking a lot of time to dry materials and exposing the materials being dried to the attack of insects and rodents (Ezeanya et al., 2012; Chukwunonye et al., 2016). These inadequate methods also lead to huge losses and spoilage of these seeds during the harvesting period.

According to Karathanos and Belessiotis (1999), mathematical modeling and simulation of drying curves under different conditions are important to obtain better control of unit operations and overall improvement of the quality of the final product. Models are generally used to study the variables involved in a process, predict the drying kinetics of the product and optimize the operating parameters and circumstances (Karathanos and Belessiotis, 1999; Belessiotis and Delyannis, 2011). Research by Oje and Osunde (2005) established that dryer configurations like tilt angle affect the performance of solar collectors. Therefore, several pieces of research have been done on modelling the drying kinetics of various crops like cassava noodles, tomato slices, soybean and yam slices (Ezeanya et al., 2018; Nwakuba et al., 2018; Khama et al., 2022; Falade et al., 2008; Darvishi, 2017).

A few research have been done on the drying of *ogbono*. Research by Ezeanya et al. (2012) worked on the analysis of the effects of a flat plate solar dryer geometry on the drying rate of *ogbono* seeds. Findings from this research revealed that the drying rate of *ogbono* seeds varied with varying tilt angles, collector surface areas, and absorber plate thicknesses. Research by Famurewa and Faboya (2017) investigated the effects of drying temperature on the physicochemical properties of *ogbono* (*Irvigea gabonensis*). A study according to Ogunbusola et al. (2014) investigated the effect of drying on the physicochemical properties of ready-to-cook *ogbono* mix (*Irvingeaa gabonensis*). Their research findings revealed that drying enhanced the water and oil absorption capacities of the *ogbono* mix. However, information on modeling the effect of tilt angle and absorber plate thickness on thin-layer solar drying kinetics of *ogbono* is scarce in the literature. Therefore, this study aims to develop suitable predictive models for the drying behaviour of *ogbono* seeds at varying dryer configurations. It will further explain the effect of process variables on the energy aspects and moisture diffusion kinetics of the seeds.

2 Material and methods

The materials used for the experiment are *ogbono* fruits, a knife, a small hammer, a digital weighing balance (OHAUS) of capacity 4.1 kg and sensitivity of 0.01 g, a solar dryer, and a digital thermometer of sensitivity 0.01°C.

2.1 Equipment description

The equipment used in this study is a forced convection distributed type solar collector (Figure 1), developed at the Federal University of Technology, Owerri, Nigeria (latitude 5° 27’ North, longitude 7° 2’ East and altitude of 90.91 m above sea level). It consists of a solar collector chamber for absorbing the sun’s heat, a dryer chamber where the seeds are dried, a sun-tracking mechanism which enables the collector chamber to follow the sun’s direction, the fan, the support, and a rechargeable battery for powering the fan and tracking mechanism.

2.2 Experimental procedure

The experiment was designed as a 4×2 factorial in a completely randomized design in three replications with factors: tilt angle of the dryer (0°, 5°, 10°, and 15°) and absorber plate thickness (1.5 and 2.7 mm). The *ogbono* fruits were bought from the village markets around Owerri town. The fleshy fruits were peeled off with a knife, subsequently, the remaining hard shells were cracked to obtain the seeds. At the beginning of the experiment, the equipment was placed in an open place to minimize the shading effect. It was placed along the North-South axis and positioned to face the south as recommended by Duffie and Beckman (2006); and Tiwari (2012). The dryer was allowed to operate under no-load conditions for 30 minutes to enable the dryer chamber to attain stable state conditions. 84 g of the *ogbono* seeds were placed in the drying trays inside the dryer. The average initial moisture content of the seeds was determined as 52.5% (wet basis) by the standards of AOAC (2015). The masses of the dried seeds inside the dryer were weighed at hourly intervals to determine the loss of moisture. The experiment continued until the equilibrium moisture content of 8.8% of the seeds was attained. This point was characterized by two constant consecutive mass readings of the seeds. Also, the temperature readings were taken periodically using a digital thermometer.

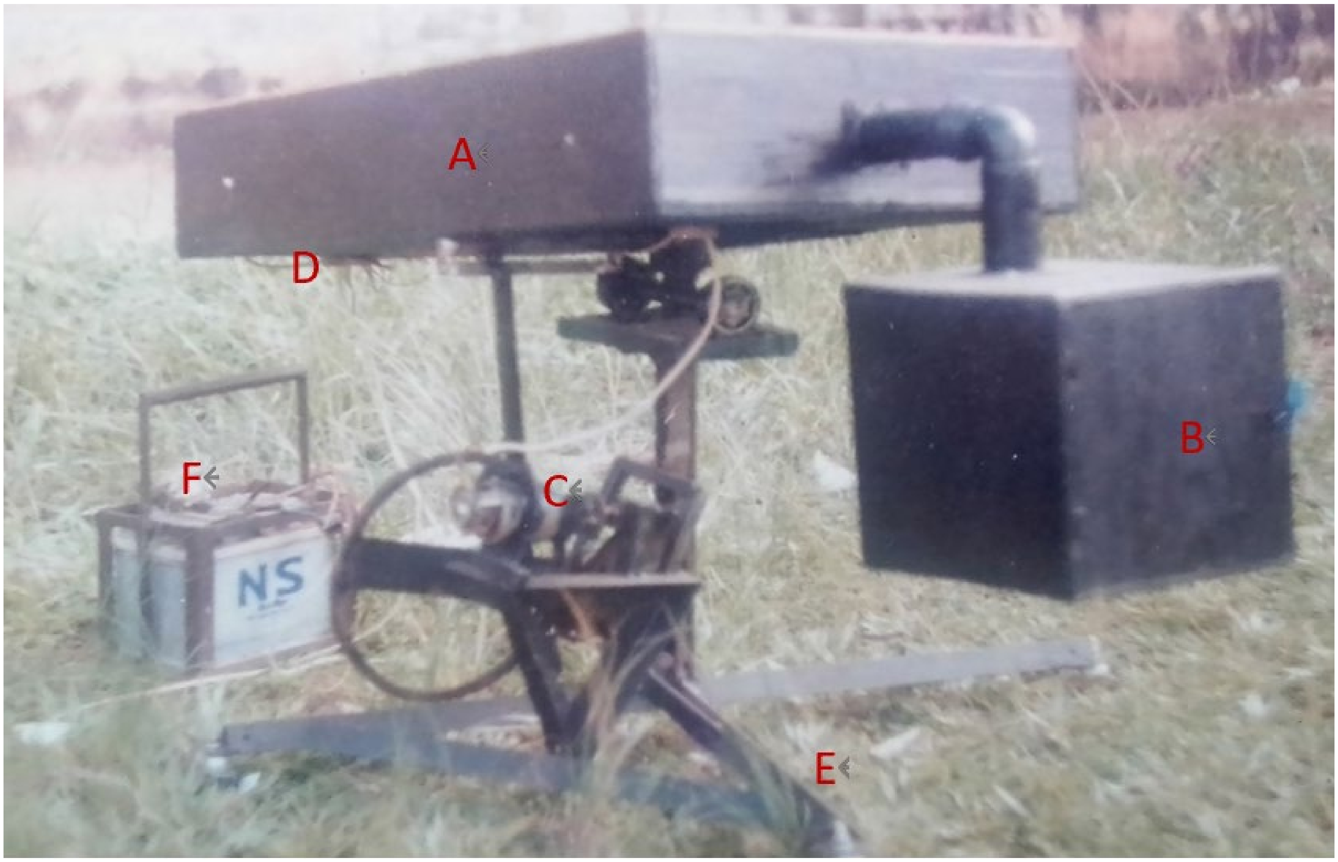


Figure 1 Pictorial representation of the experimental set-up

Notes: A - solar collector chamber, B - drying chamber, C - sun tracking mechanism, D - fan unit, E - support, F - battery for powering the tracking mechanism and fan.

The samples were oven-dried by the standards of AOAC (2015) for moisture content determination. This procedure was repeated for all the experimental treatments. The base of the collector plate was made adjustable to set different tilt angles. The speed of 2 m s^{-1} was achieved by using a fan with a variable speed selector. The 2 m s^{-1} speed was achieved by calibration using an air-flow meter. The moisture content wet basis (M_{wb} *% w.b*) of the samples was determined using Equation (1).

$$M_{wb} = \frac{m_{ws} - m_{ds}}{m_{ws}} \tag{1}$$

Where m_{ws} is the mass of the wet sample (g), m_{ds} is the mass of the dry sample (g)

The moisture ratio (*MR*) of the samples was determined using Equation 2.

$$MR = \frac{M_t - M_e}{M_i - M_e} \tag{2}$$

Where *Mt* is the moisture content at a given time *t* (%), *Mi* is the initial moisture content (%), and *Me* is the equilibrium moisture content (%).

Equation 2 was modified according to Midilli et al. (2002); and Kingsley and Singh (2007) and expressed as:

$$MR = \frac{M_t}{M_i} \tag{3}$$

Where MR is the dimensionless moisture ratio.2.3 Model fitting and data analysis

A total of six thin-layer drying models as shown in Table 1 were fitted to the drying data of *ogbono*, using MATLAB 2015 software. The criteria for selection of the best-fitted model were based on the highest value of the coefficient of determination (R^2), and the lowest values of the root mean squared error (RMSE) and standard error of estimate (SEE) as reported by Tunde-Akintunde and Afon (2010).

Table 1 The six drying models that were fitted to the drying data of *ogbono* seeds

S/n	Model name	Equation	Source
1	Henderson & Pabis	$MR= a \exp(-kt)$	Saeed et al. (2008)
2	Logarithmic	$MR= a \exp(-kt) + c$	Toğrul and Pehlivan (2002)
3	Two-term	$MR= a \exp(-k_0 t) + b \exp(-k_1 t)$	Wang et al. (2007)
4	Page	$MR= \exp(-kt^n)$	Saeed et al. (2008)
5	Wang and Singh	$MR= 1 + at + bt^2$	Wang and Singh (1978)
6	Modified Aghbashlo	$MR= \exp-\{(k_1 t)/(1+k_0 t)\} + ct$	Ezeanya et al. (2018)

2.4 Determination of effective moisture diffusivity of *ogbono* seed

The diffusivity of sample moisture is a key transport property for modeling the drying behaviour of plant-based materials. The effective moisture diffusivity was calculated by plotting experimental drying data in terms of ln (*MR*) versus drying time (secs), and the slope (*S*) was determined. The effective moisture diffusivity (D_{eff}) was calculated by using the method of slopes according to Maskan et al. (2002) and Doymaz (2004) and expressed as:

$$Slope\ (S) = \frac{D_{eff}\pi^2}{4L^2} \tag{4}$$

Where, *L* is the half of the slab thickness (m).

2.5 Determination of activation energy of *ogbono* seed

The energy of activation refers to the ability of water molecules to exceed the energy barrier during product intra-cellular moisture transport (Nwakuba et al., 2020a and 2020b). Greater diffusivity of product moisture is a result of a reduction in activation energy value. This is caused by a rise in the mean energy value of the water molecules (Nwakuba and Okafor, 2020). The activation energy was calculated using the Arrhenius equation (Akpinar et al., 2003) as given in Equation (5).

$$D_{eff} = D_o \exp\left(-\frac{E_a}{RT_a}\right) \tag{5}$$

Where: E_a is the activation energy (kJ mol^{-1}), *R* is the universal gas constant (8.3143×10^{-3} kJ mol^{-1} K^{-1}), T_a is absolute air temperature (*K*), and D_0 is the pre-exponential factor of the Arrhenius equation (m^2 s^{-1}). Equation (5) was rearranged by finding the natural logarithm of each component in the equation and expressed as:

$$lnD_{eff} = lnD_o - \frac{E_a}{RT_a} \tag{6}$$

The activation energy was determined from the slope of the Arrhenius plot of *ln* (D_{eff}) versus $1/T_a$. From Equation (6), a plot of *ln* D_{eff} versus $1/T_a$ gives a straight line graph whose slope (S_A) is given as:

$$S_A = \frac{E_a}{R} \tag{7}$$

Consequently, a plot of *ln* (D_{eff}) versus $1/T_a$ was done, and the slope (S_A) obtained was substituted into Equation (7) to determine the activation energy (E_a) for the *ogbono* seed.

3 Results and discussion

3.1 Drying behavior of *ogbono* seeds

This characteristic behavior is attributed to the various forms and levels in which water is present in food materials (Tunde-Akintunde and Afon, 2010). It also depicts the energy with which the water molecules are held to the food matrix at a given stage of the drying process. This characteristic behavior is similar to previous drying experiments done on other agricultural materials like cassava noodles, pre-treated cassava chips, Rossale, and tomato slices (Ezeanya et al., 2016; Tunde-Akintunde and Afon, 2010; Saeed, 2010; Nwakuba et al., 2018). The exponential drops in moisture ratio with rising drying time at varying angles of tilt of the solar collector, possibly indicate similar sample moisture diffusion mechanisms from the product matrix to the surface (Nwakuba et al., 2020a and 2020b). A higher rate of moisture migration is recorded for the collector tilt angle of 5° and less for the 15° tilt angle. This is probably a result of the high solar flux collection at a lower tilt angle of the collector which creates an upsurge in the thermal gradient of the drying chamber, hence a higher moisture transport rate, less drying time and significant savings in specific energy demand (Nwakuba et. al., 2017).

The time taken for the seeds to dry to a constant mass varied with the various dryer configurations of tilt angle and plate thickness. A maximum drying rate of 7.38% mc hr^{-1} was obtained for the seeds that were dried at a 5° tilt angle and absorber plate thickness of 2.7 mm. The moisture desorption curves for *ogbono* seeds dried at an absorber plate thickness of 1.5 mm are shown in Figure 2. The curves sloped downwards from the left to the right hand of the page, indicating an initial high rate of drying, which was later followed by a slower drying rate until the end of the drying process.

Table 2 Variation of moisture ratio with drying time at a constant air velocity of 2 m s^{-1} for ogbono seeds

Time (hrs)	Moisture Ratio (MR)							
Thickness (mm)	1.5				2.7			
Angle, α°	0	5	10	15	0	5	10	15
0	1	1	1	1	1	1	1	1
1	0.82	0.74	0.80	0.85	0.79	0.73	0.77	0.79
2	0.69	0.64	0.64	0.71	0.63	0.57	0.61	0.67
3	0.58	0.45	0.57	0.61	0.48	0.42	0.50	0.55
4	0.47	0.33	0.44	0.51	0.38	0.32	0.39	0.42
5	0.37	0.23	0.35	0.42	0.28	0.23	0.29	0.33
6	0.30	0.20	0.25	0.34	0.21	0.17	0.21	0.25
7	0.24	0.17	0.19	0.28	0.17	0.17	0.17	0.20
8	0.20	0.17	0.17	0.21	0.17		0.17	0.17
9	0.17		0.17	0.17				0.17
10	0.17			0.16				
11				0.16				

Note: α— tilt angle (°), T— absorber plate thickness (mm).

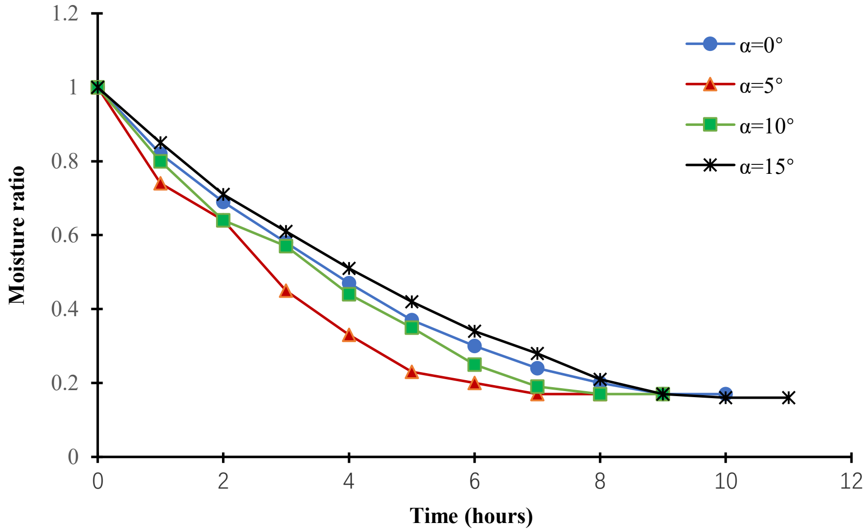


Figure 2 Moisture desorption curve for *ogbono* seeds dried at a thickness of 1.5 mm

3.2 Curve fitting of experimental data

The statistical parameters and the model constants obtained from fitting the drying data of ogbono seeds to the six thin-layer drying models are summarized in Table 3. From Table 3, it was observed that all six models predicted fairly accurately the kinetics of the thin layer drying of the seeds. The results also revealed that the statistical parameters obtained for the various predictive models varied with the different treatments in the experiment.

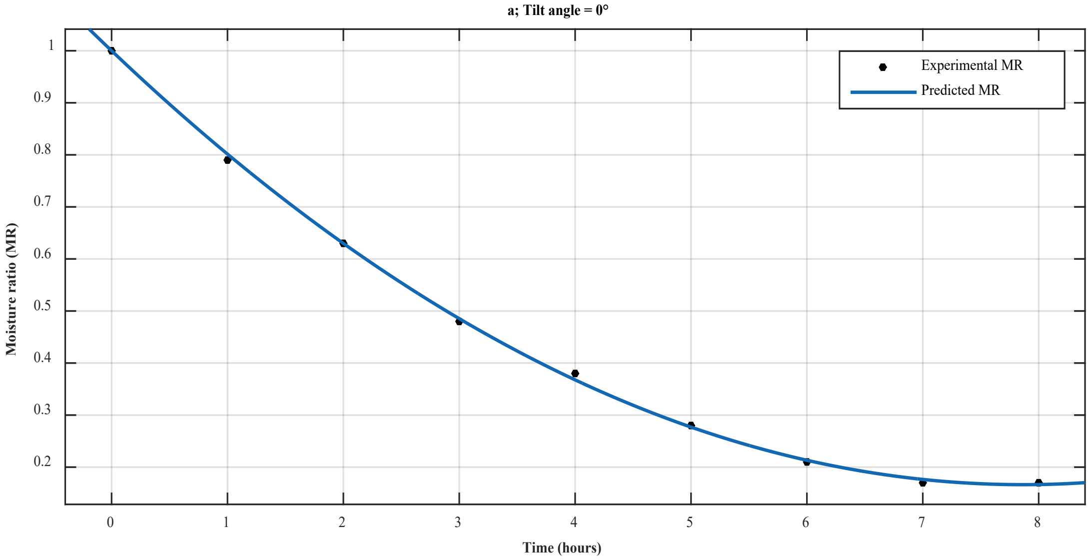
Table 3 Results of thin-layer modeling of *ogbono* seeds

Model	T(mm)	α°	R^2	RMSE	SSE	Model constants					
						a	b	c	k	k_0	k_1
Henderson & Pabis	1.5	0	0.9975	0.015	0.00203	1.005			0.1949		
		5	0.9893	0.0328	0.0075	0.9954			0.2614		
		10	0.9934	0.0265	0.0049	1.002			0.5297		
		15	0.9964	0.0181	0.0033	1.016			0.1813		
	2.7	0	0.9974	0.0162	0.0018	1.007			0.2463		
		5	0.9968	0.018	0.0019	0.9909			0.2803		
		10	0.9969	0.0173	0.002	0.9955			0.2418		
		15	0.9957	0.0201	0.0032	1.003			0.2172		
Logarithmic	1.5	0	0.9975	0.0159	0.002	1.006		0.0008	0.1946		
		5	0.9902	0.0338	0.0069	0.9603		0.2901	0.044		
		10	0.9937	0.0261	0.0048	1.026		-0.029	0.2019		
		15	0.9969	0.0177	0.0028	1.05		-0.041	0.167		
	2.7	0	0.9974	0.0175	0.0018	1.001		0.0064	0.2497		
		5	0.9978	0.0164	0.0014	0.9598		0.0414	0.3115		
		10	0.9969	0.0186	0.0021	0.9902		0.0064	0.2452		
		15	0.9957	0.0215	0.0032	1.01		-0.008	0.2135		
Two-term	1.5	0	0.9975	0.017	0.002	-0.009	1.014			0.096	0.194
		5	0.9887	0.0398	0.00795	4.002	-3.01			0.216	0.203
		10	0.9934	0.0287	0.0049	0.8601	0.142			0.214	0.209
		15	0.9964	0.0202	0.0032	2.683	-1.67			0.176	0.174
	2.7	0	0.9928	0.0317	0.005	-10.31	11.28			0.119	0.127
		5	0.9968	0.0221	0.0019	1.3	-0.309			0.279	0.278
		10	0.9969	0.0204	0.002	1.02	-0.03			0.244	0.361
		15	0.996	0.0223	0.003	1.062	-0.07			0.227	0.67
Page	1.5	0	0.9976	0.0146	0.0019	1.025			0.1859		
		5	0.9894	0.0327	0.0075	0.9788			0.2705		
		10	0.9937	0.0244	0.0047	1.029			0.2043		

Model	T(mm)	α°	R^2	RMSE	SSE	Model constants					
						a	b	c	k	k_0	k_1
		15	0.9975	0.0152	0.0023	1.072			0.1572		
	2.7	0	0.9975	0.0159	0.0018	1.027			0.2353		
		5	0.9976	0.0157	0.0015	0.9529			0.3041		
		10	0.9969	0.0172	0.0021	0.9886			0.2471		
		15	0.9959	0.0197	0.0031	1.026			0.2078		
Wang & Singh	1.5	0	0.9992	0.0083	0.0006	-0.168	0.008				
		5	0.9945	0.0234	0.0038	-0.231	0.016				
		10	0.9951	0.0214	0.0037	-0.183	0.01				
		15	0.999	0.0093	0.0009	-0.151	0.007				
	2.7	0	0.9994	0.007	0.0038	-0.212	0.014				
		5	0.9967	0.018	0.002	-0.250	0.019				
		10	0.9966	0.018	0.0023	-0.211	0.013				
		15	0.998	0.014	0.0015	-0.187	0.011				
Modified Aghbashlo	1.5	0	0.9991	0.0094	0.0007			0.0127	0.182	-0.045	
		5	0.9945	0.0255	0.0038			0.0199	0.2402	-0.072	
		10	0.9947	0.0238	0.0039			0.0124	0.1974	-0.048	
		15	0.9988	0.011	0.0011			0.0109	0.1585	-0.046	
	2.7	0	0.9993	0.0092	0.0005			0.0165	0.2284	-0.059	
		5	0.9988	0.0154	0.0012			0.0117	0.2942	-0.029	
		10	0.9972	0.018	0.0019			0.0089	0.24	-0.029	
		15	0.9977	0.0156	0.0017			0.0148	0.2	-0.055	

However, the Wang and Singh model was the best-fitted model for the thin-layer solar drying of *ogbono* seeds at a tilt angle of 0° and absorber plate thickness of 2.7 mm. At this treatment combination, it produced the highest R^2 value of 0.9994 and the lowest RMSE of 0.007. The Wang and Singh model was originally developed for thin layer modeling of rice (Wang and Singh, 1978). The predicted and experimental values of moisture ratio using the Wang and Singh model are represented in Figures 3 and 4. It was evident from the curves (Figures 3 and 4) that the prediction of the drying behavior of the seeds by the Wang and Singh model exhibited a slight lack of correlation to the experimental MR values in the middle phase of the drying process, whereas proper curve fitting of the experimental data was illustrated by the Wang and Singh's model using the 0° tilt angle. A similar correlation was observed for the specific form of this model was obtained by substituting the values of the constants a and b into the Wang and Singh model and expressed as Equation (8).

$$MR = 1 - 0.212t + 0.014t^2 \tag{8}$$



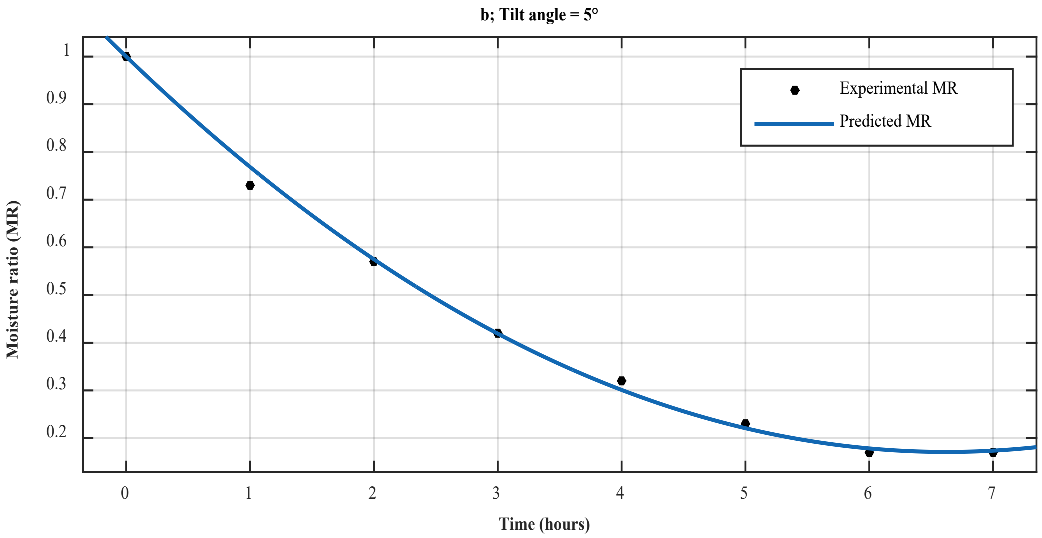


Figure 3 Predicted and experimental moisture ratios obtained from the study using the Wang and Singh model for samples dried at a plate thickness of 2.7 mm

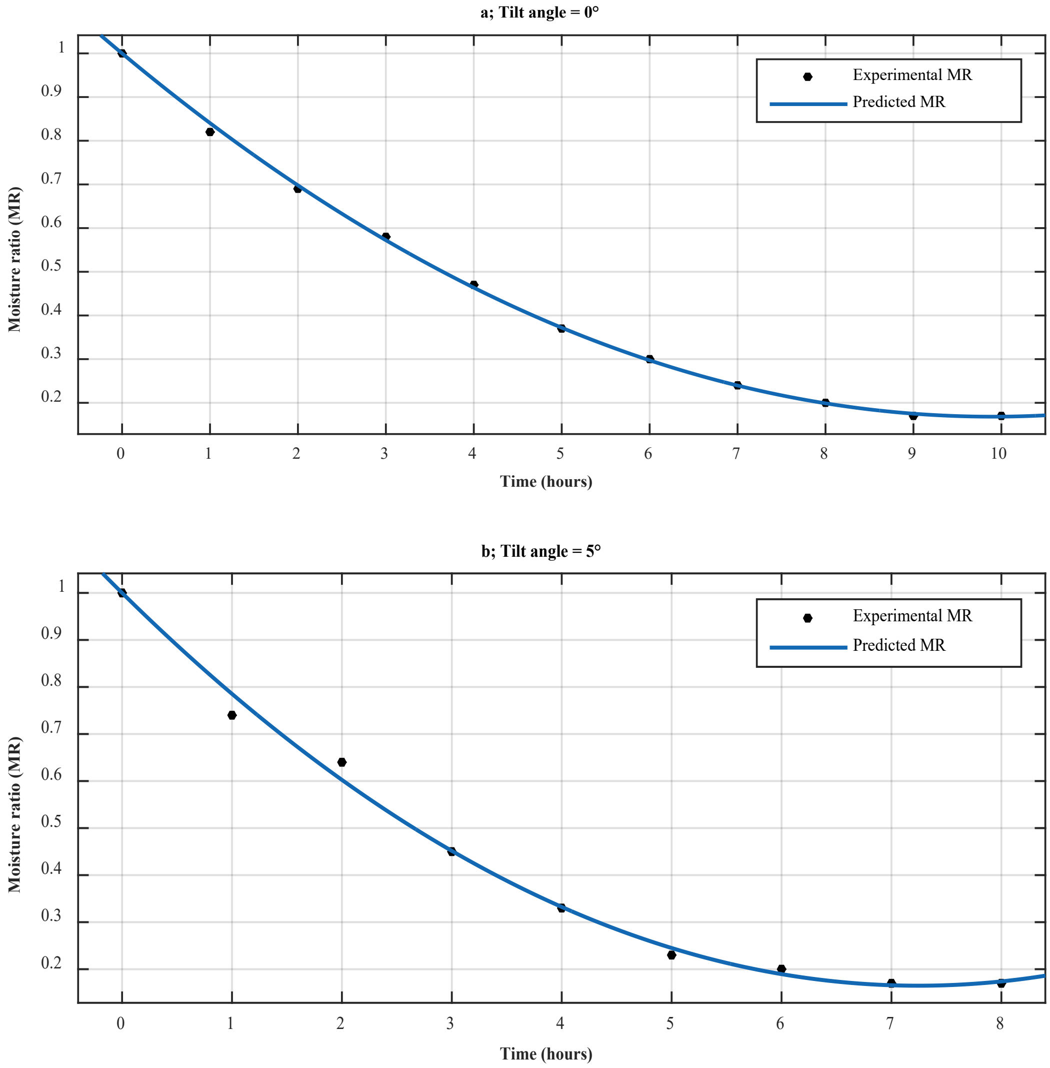


Figure 4 Predicted and experimental moisture ratios obtained from the study using the Wang and Singh model for samples dried at a plate thickness of 1.5 mm.

3.3 Effective moisture diffusivity of *ogbono* seeds

The effective moisture diffusivity values obtained for the seeds are summarized in Table 4. The effective moisture diffusivities obtained for the *ogbono* seeds ranged from 2.03 × 10^{-11} to 3.24 × 10^{-11} m^2 s^{-1}. This range of values is similar to the values of 10^{-5} to 10^{-11} m^2 s^{-1} obtained for other agricultural materials (Tunde-Akintunde and Afon, 2010).

Table 4 Effective moisture diffusivities of the *ogbono* seeds

T(mm)	α°	D_{eff} (m^2 s^{-1}) × 10^{-11}
1.5	0	2.03
	5	2.84
	10	2.43
	15	2.03
2.7	0	2.84
	5	3.24
	10	2.84
	15	2.43

Some of the results of effective moisture diffusivities obtained for other agricultural materials include 4.93× 10^{-11} to 8.82 × 10^{-11} m^2 s^{-1} obtained for cassava noodles (Ezeanya et al., 2018); 7.31 × 10^{-7} to 8.06 × 10^{-7} m^2 s^{-1} obtained for pre-treated cassava chips (Tunde-Akintunde and Afon, 2010); 4.9541 × 10^{-9} to 7.5726 × 10^{-9} m^2 s^{-1} obtained for tomato slices (Nwakuba et al., 2018); and 9.92 × 10^{-8} to 1.298 × 10^{-5} m^2 s^{-1} obtained for yam slices (Falade et al., 2008). The relatively low values of effective moisture diffusivities obtained for the *ogbono* seeds could be attributed to the special texture and quality of the seeds.

It was evident from both Table 4 and Figure 5 that the effective moisture diffusivities of the *ogbono* seeds generally increased with the increase in absorber plate thicknesses of the dryer, whereas it increased slightly with the tilt angle. For the plate thickness of 1.5 mm, the D_{eff} values increased from 2.03 × 10^{-11} m^2 s^{-1} at 0° tilt angle to 2.84 × 10^{-11} m^2 s^{-1} at 5° tilt angle, after which the values decreased slightly. The same trend was observed for D_{eff} values obtained by using the plate thickness of 2.7 mm. For the two plate thicknesses, maximum D_{eff} values were obtained at a 5° tilt angle. This tilt angle is approximately the latitude of the experimental location. Previous research has shown that maximum insolation is normally harnessed by a solar collector when tilted at an angle that approximates the local latitude (Duffie and Beckman, 2006; Oje and Osunde, 2005). This trend in the D_{eff} values of *ogbono* seeds is in agreement with previous research findings which showed that D_{eff} values normally increase with the increase in the drying air temperatures (Nwakuba et al., 2020a).

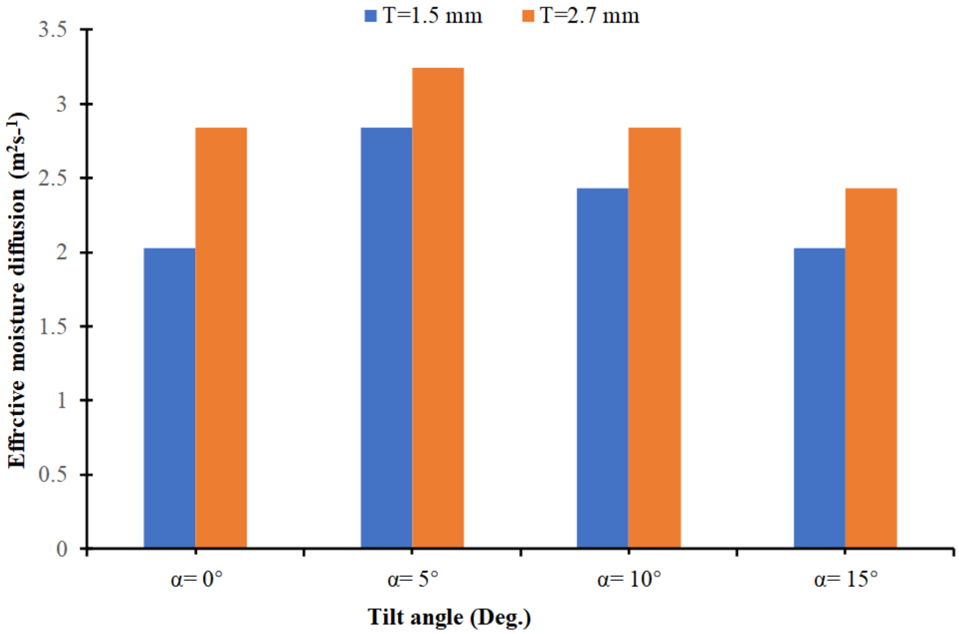


Figure 5 Variation of the effective moisture diffusivities of *ogbono* seeds with varying dryer configurations

3.4 Activation energy of *ogbono* seeds

The activation energy was determined from Equation 7 as 59.724 kJ mol^{-1}. The value is within the range of 10 to 100 kJ mol^{-1} obtained for other agricultural materials (Ezeanya et al., 2018; Tunde-Akintunde and Afon, 2010).

4 Conclusion

This research aimed to dry *ogbono* seeds using a solar drying system and to select a suitable model to predict the drying behaviour of *ogbono* seeds. The research findings from the study revealed that the solar drying system successfully dried the *ogbono* seeds from an average initial moisture content of 52.5% (wb) to a safe storage moisture content of 8.8% (wb). The Wang and Singh model was best suited for predicting the drying behaviour of the *ogbono* seeds with an R^2 value of 0.9994 and an RMSE value of 0.007. The values of the effective moisture diffusivities obtained ranged from 2.03×10^{-11} to 3.24×10^{-11} m^2 s^{-1}. They also varied with the configurations of the dryer. Also, the activation energy of the seeds was determined as 59.724 kJ mol^{-1}. It is hereby recommended that this experiment should be replicated using other heat sources like electricity, biomass and microwave. The effect of factors like dryer air temperature and air velocity should also be considered in future research in this field.

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