A mathematical model for predicting the drying rate of cocoa bean (*Theobroma cacao L.*) in a hot air dryer

Nnaemeka Reginald Nwakuba[1*], Prince Kelechi Ejesu[2] and Victor Chijioke Okafor[2]

(1. *Department of Agricultural and Bioresources Engineering, Michael Okpara University of Agriculture, Umudike, P.M.B.7267 Umuahia, Abia State, Nigeria*;

2. *Department of Agricultural and Bioresources Engineering, Federal University of Technology, P.M.B. 1526 Owerri, Imo State, Nigeria*)

Abstract: Development of a mathematical model for predicting the drying rate of a thin layer cocoa bean in a convective hot air dryer using dimensional analysis based on the Buckingham's π theorem was presented. Results obtained showed that drying rate decreased as the moisture level reduced due to the increase in the intra-particle resistance to internal moisture migration of the cocoa beans. High coefficients of determination of 94.7%, 99.8% and 99.5% at temperatures of 60°C, 70°C and 80°C respectively between the predicted and experimental values showed that the method was good. The model was validated with data obtained from an existing prototype thin layer convective dryer and there was no significant difference between the experimental drying rate and the predicted values at 5% level of significance. Two-tail test showed that t-calculated was less than t-tabulated at 5% degree of freedom, which indicated the suitability of the model at the studied temperatures. It was generally observed that drying cocoa bean at increasing drying temperature, decreasing moisture contents and constant air velocity resulted in a low drying rate.

Keywords: Cocoa bean, thin layer drying, dimensional analysis, drying rate, prediction equation

Citation: Nwakuba, N. R., P. K. Ejesu, and V. C. Okafor. 2017. A mathematical model for predicting the drying rate of cocoa bean (*Theobroma cacao L.*) in a hot air dryer. Agricultural Engineering International: CIGR Journal, 19(3): 195–202.

1 Introduction

Cocoa (*Theobroma cacao L.*) is a perennial cash crop that naturally grows in the humid tropical climate that is within 20° of latitude of the equator in countries such as Nigeria, Cote D' Ivoire, Ghana, Brazil, Cameroun etc. (Ndukwu et al., 2010; Oke and Omotayo, 2012). In these countries, cocoa is harvested all the year round and the beans are dried immediately after fermentation to prevent postharvest mass losses and subsequent spoilage. The final products from cocoa beans are mainly consumed as chocolate and widely used in beverages, cosmetics, pharmaceuticals and toiletry products. It is also associated with health benefits such as anti-carcinogenic, anti-athergenic, anti-ulcer, anti-thrombotic, anti-inflammatory, immune modulating, anti-microbial, vasodilatory, and analgesic (Porter, 2006; Taubert et al., 2007; Oke and Omotayo, 2012). However, the qualities of these final products depend on the processing method (Ndukwu et al., 2010).

Fermentation and drying are considered as two major critical steps in the sequence of cocoa processing. Fresh cocoa beans are usually fermented using the heap, tray or box methods for 5 to 7 days depending on the condition of the beans (Opeke, 1987; Oke and Omotayo, 2012). During fermentation, the temperature of the beans usually rises from ambient to about 50°C to 55°C due to the exothermic oxidation reaction (Wood and Lass, 1985; Oke and Omotayo, 2012). During these stages, the cocoa beans undergo various chemical and biochemical changes that form the necessary flavor precursors needed during processing (Hii, Law, and Cloke. 2009). Drying techniques vary among cocoa farmers and it ranges from the natural sun drying technique to the artificial hot-air technique. Currently, sun drying is mostly used by

Received date: 2016-11-05 **Accepted date:** 2016-12-13

*** Corresponding author: N. R. Nwakuba,** Department of Agricultural and Bioresources Engineering, Michael Okpara University of Agriculture, Umudike, Abia State., zip code: 440109, Nigeria. Email: nrnwakuba@gmail.com. Tel: +234 803 660 8510.

Nigerian cocoa farmers due to its simplicity, low cost set up and requires only direct sunlight which is abundant, regular and free (Opeke, 1987). The artificial hot air (forced convection) drying requires mechanical or electrical power to provide air flows. It is concerned with the transfer of heat energy between a moving fluid and a product surface.

Different thin layer drying models of different agricultural products have been modified and adapted to simulate the drying kinetics of many agricultural products (Akpinar et al., 2003; Jain and Pathare, 2007; Ndukwu et al., 2010). In the past, most published literature on cocoa focused on flavour extraction, design and development of dryers, quality and bean acidity (Faborode et al., 1995; Hii and Tukimon, 2002; Ndukwu et al., 2010). Fotso et al. (1994), Wan Daud et al. (1996) reported the characteristic drying curves of cocoa beans at various external conditions with critical moisture contents identified in their studies. Ndukwu (2009) reported the effects of the drying air temperature and air velocity on the drying rate and drying constant of cocoa beans. He generated an empirical equation for calculating the drying constant during the falling rate period and concluded that temperature had greater effect on the drying rate of cocoa beans. Most crops exhibit the constant rate drying characteristics at their critical water content, therefore cocoa is not an exception. However, Bravo and McGaw (1982), Baryeh (1985) stated that cocoa exhibited constant rate behavior during drying, from a moisture content of 70% - 100% dry basis (d.b.). Most cocoa beans drying followed the falling rate characteristics since the initial moisture content hardly reached the critical value and most of the drying models simulated this characteristic. On the contrary, Hii, Law, Cloke, and Suzannah (2009) stated that studies on the drying kinetics of cocoa drying were scarce in published literature. This present study therefore focused on the modeling of the artificial drying process of cocoa beans with the inclusion of tempering using a semi theoretical model known as the Buckingham Pi Model (BPM). Product quality attributes were investigated for appearance, pH (test of acidity, neutrality and alkalinity) cut test as these were the basic parameters used by chocolate manufacturers to assess incoming bean quality. These quality attributes contributed significantly to the quality of the finished products (Hii et al., 2009a).

2 Materials and Methods

2.1 Experimental Procedure

The materials and methods used in this research were similar with the approach of Hii and Tukimon (2002). The fermented cocoa beans weighing 600 g were dried using an air-ventilated oven dryer (Memmert, D06836, Germany) at air temperatures of 60°C, 70°C and 80°C with natural convective air flow of 0.01 m s^{-1} (Figure 1). The relative humidity of the drying air was measured with a humidity probe at each temperature (6%, 4.7% and 2.9%, respectively). The cocoa beans were thinly spread in a single layer (about 1.05 cm thick) on a meshed drying tray with square openings measuring 0.4×0.4 cm^2. Heat was generated by the heating unit integrated into the walls of the oven and the distributor fan was not switched on in order to simulate the natural convective environment of the commercial cocoa dryer. The exhaust air escaped through a ventilation hole (diameter = 4 cm) at the back of the oven. Drying was conducted for 8 hours daily and the beans were tempered at room temperature overnight. The purpose of this step was for the intra-particle moisture of the beans to redistribute from the internal matrix to the outermost layer of the beans (testa) since the testa would generally dry faster than the cotyledon layer in hot air drying. Drying was terminated when the desired moisture content of about 7.5% dry basis was achieved.

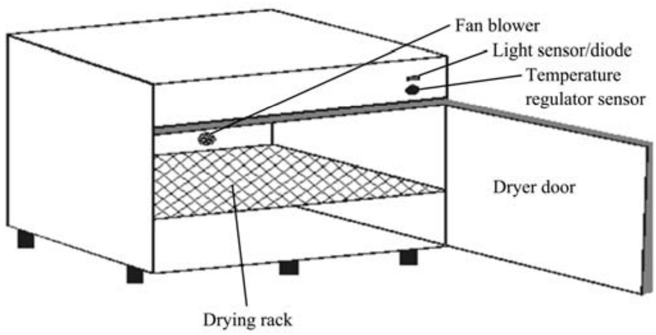

Figure 1 Schematics of the thin-layer dryer

2.1.1 Moisture Content

The beans used in each experiment were weight every two hours during drying by using an analytical balance

(AND instrument, MX50, USA). The moisture content of the beans was determined with reference to the bone-dry weight of the beans using the Equation 1 below according to AOAC (2000).

$$\text{Moisture content} \frac{W_i - W_{bd}}{W} \times 100 \text{ (\% wet basis)} \quad (1)$$

where, W_i = weight of beans at $t = t_i$ (g) and W_{bd} = bone-dry weight of the beans (g).

The equilibrium moisture content (M_e) was determined by prolonging the drying process until no further change in weight was observed for the beans in each treatment. The M_e values determined were 6.3%, 5.74% and 3.6% for the oven drying at 60 °C, 70 °C and 80°C, respectively.

2.1.2 pH

Ground nibs (5 g) were homogenized in 45 mL boiled distilled water. The mixture was filtered with whatman No. 4 filter paper and cooled to 20°C-25°C. The resulting filtrate was measured for pH using a pH meter (Schott Instruments, D-55122, Germany) which had been calibrated with buffer solutions of pH 4 and 7.

2.1.3 Drying Rate

The drying rates were calculated based on the Equations (2), (3) and (4). (Ojha and Michael, 2005):

$$\frac{dM}{dt} = -K(M - M_e) \quad (2)$$

By separable variables, Equation (3) yields:

$$\frac{dM}{M - M_e} = -Kt \quad (3)$$

By applying integral to both sides we have Equation (4) rewritten as:

$$\frac{M - M_e}{M_o - M_e} = e^{-kt} \quad (4)$$

where, $\frac{dM}{dt}$ is the drying rate (hr^{-1}); M is the moisture content at any time (%); M_o is the initial moisture content (%); M_e is the equilibrium moisture content (%); t is the time (hr) and; k is the drying constant (hr^{-1}).

$$K = -0.00709 + 0.000170Rh + 0.0003433T - 0.00000433RhT \quad (5)$$

where, Rh is the relative humidity (%) and T is the temperature of the dryer (°C)

The equilibrium moisture content was expressed using Equation (6):

$$M_e = \left(\frac{1}{0.1560}\right)\ln\left\{\frac{-(T - 7.3988)}{190.44}\ln\left(\frac{RH}{100}\right)\right\} \quad (6)$$

2.2 Model Development

The drying rate of the cocoa beans was modeled using a semi-theoretical approach known as the Buckingham Pi theorem model (BPM). The model variables were presented in Table 1.

Table 1 Dimensions of variables influencing drying rates of cocoa pod

Variables	Symbols	Dimensions
Time	t	$M^oL^oT^1\,\Theta^0$
Moisture content of cocoa pod at any time, t	M	$M^oL^oT^o\,\Theta^0$
Initial moisture content	M_o	$M^oL^oT^o\,\Theta^0$
Drying constant	K	$M^oL^oT^{-1}\,\Theta^0$
Temperature	T	$M^oL^oT^o\Theta^1$
Air velocity	V	$M^oLT^{-1}\,\Theta^0$
Equilibrium moisture content	%	$M^oL^oT^o\,\Theta^0$
Relative humidity	RH	$M^oL^oT^o\,\Theta^0$

The following assumptions were made in the development of the model:

i. The mechanism of moisture transportation is diffusion.

ii. Heat transfer equations are neglected.

iii. Moisture diffusivity is constant although the drying process.

iv. Shrinking of the cocoa beans during the drying process is negligible.

v. The cocoa bean dimension is constant at the same moisture content.

The number of important variables that determined the drying rate of the cocoa beans was 8 and the number of fundamental units was 4, therefore the number of π-terms was given as Equation (7):

$$N^{\pi} = n - m = 8 - 4 = 4\pi\text{-terms.} \quad (7)$$

where, m = number of fundamental units required for the modeling; n = number of variables considered for the study. Hence, the number of repeating π-terms is 4 (i.e. temperature, air velocity, moisture content at any time and drying time interval).

The drying rate $\left(\frac{dM}{dt}\right)$ was therefore expressed as

Equation (8):

$$\frac{dM}{dt} = f\left(t, M, RH, M_o, K, T, v, M_e\right) \tag{8}$$

The π-terms are therefore expressed as Equations (9), (10), (11) and (12):

$$\pi_1 = \frac{M_o}{T^a v^b M^c t^d} \tag{9}$$

$$\pi_2 = \frac{K}{T^a v^b M^c t^d} \tag{10}$$

$$\pi_3 = \frac{RH}{T^a v^b M^c t^d} \tag{11}$$

$$\pi_4 = \frac{M_e}{T^a v^b M^c t^d} \tag{12}$$

The dimensionless groups based on the Buckingham-π theorem were expressed as Equations (13)-(16) as:

$$\pi_1 = M_o \tag{13}$$

$$\pi_2 = Kt \tag{14}$$

$$\pi_3 = RH \tag{15}$$

$$\pi_4 = M_e \tag{16}$$

Hence the drying rate in terms of the π-terms was given as Equation (17):

$$\frac{dM}{dt} = f(\pi_1, \pi_2, \pi_3, \pi_4) \tag{17}$$

Substituting the π-terms into Equation (18) yields:

$$\frac{dM}{dt} = f(M, Kt, RH, M_e) \tag{18}$$

According to shefh et al. (1996) the dimension terms can be reduced to a manageable level either by multiplication or division by combining the π-terms. Hence, we had the π terms rewritten as Equations (19) and (20):

$$\pi_{13} = \pi_1 * \pi_3 = M_o RH \tag{19}$$

$$\pi_{24} = \pi_2 * \pi_4 = M_e Kt \tag{20}$$

3 Results and Discussions

The drying rate of the cocoa beans in an oven dryer at different moisture contents and air temperatures were presented in Table 2. Moisture content and moisture loss of the sample decreased as drying time progressed for each temperature regime due to the increase of vapour pressure in the samples, which resulted in high migration of internal water to surface evaporation. With increased drying air temperature, the drying rate increased to a given moisture level. As drying progresses, the moisture content, moisture loss and drying rate decreased as a result of the increase in the intra-particle resistance to moisture migration to the surface of the sample beans, as well as due to low thermal conductivity of food materials in the falling rate drying period during conventional heating (Nwakuba et al., 2016). However, the minimum drying rate of 0.01 g hr^{-1} was obtained when the samples were dried at a temperature of 60°C at a constant air velocity of about 1.5 m s^{-1} while the maximum drying rate of 0.079 g hr^{-1} was obtained when the cocoa beans were dried at a temperature of 80°C. This was an indication that the dryer could dry off about 564 g of water contained in a 600 g of cocoa beans samples in a day with the above desired drying conditions. These observations were similar to the findings of Musa (2012), Ndukwu et al. (2012), Firihu and Sudiana (2016) for the same sample.

Table 2 Experimental results of the effects of different moisture contents and temperatures on drying rates of cocoa beans

Moisture content, %db.	Time, hours	Moisture loss, kg	Drying rate at different temperatures, g hr^{-1}		
			Temperature, °C		
			60	70	80
37.5	1	7.8	0.039	0.047	0.079
30.0	2	6.1	0.031	0.038	0.048
22.5	4	5.3	0.026	0.028	0.031
15.0	6	4.7	0.010	0.019	0.023
7.5	8	2.1	0.005	0.008	0.009

3.1 Prediction Equation

The prediction equation was established by allowing one π-term to vary at a time while keeping the other constant and observing the resulting changes in the function (Shefh et al., 1996). This was achieved by potting the values of experimental drying rate against dimensionless constants shown in Table 3. The values of experimental drying rate was plotted against dimensionless constant π_{13} while keeping π_{24} constant and also plotting drying rate against π_{24}; keeping π_{13} constant for the three temperatures as illustrated in Figures 2 to 4.

Table 3 Dimensionless and experimental results for drying rate of the thin-layer dryer for different moisture contents and temperatures of cocoa beans

Moisture content, %db.	Temperatures, °C								
	60			70			80		
	π_{13}	Π_{24}	$\left(\frac{dM}{dt}\right)_e$	π_{13}	Π_{24}	$\left(\frac{dM}{dt}\right)_e$	π_{13}	Π_{24}	$\left(\frac{dM}{dt}\right)_e$
7.5	0.0045	0.001701	0.005	0.003525	0.0338	0.008	0.00203	0.041	0.009
15.0	0.0090	0.003402	0.010	0.00705	0.0676	0.019	0.00405	0.082	0.023
22.5	0.00135	0.005103	0.026	0.0106	0.1014	0.028	0.00608	0.012	0.031
30.0	0.018	0.006804	0.031	0.0141	0.1352	0.038	0.0081	0.163	0.048
37.5	0.0225	0.008505	0.039	0.0176	0.169	0.047	0.01013	0.204	0.079

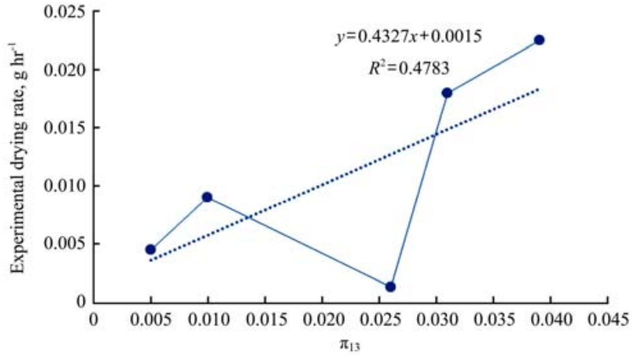

Figure 2a Graph of drying rate $\left(\frac{dM}{dt}\right)_e$ against dimensionless π_{13} at 60°C

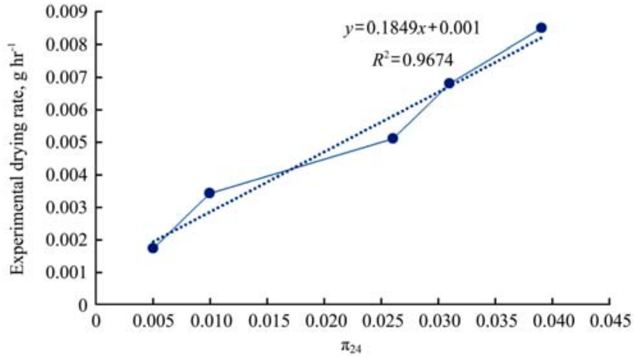

Figure 2b Graph of drying rate $\left(\frac{dM}{dt}\right)_e$ against dimensionless π_{24} at 60°C

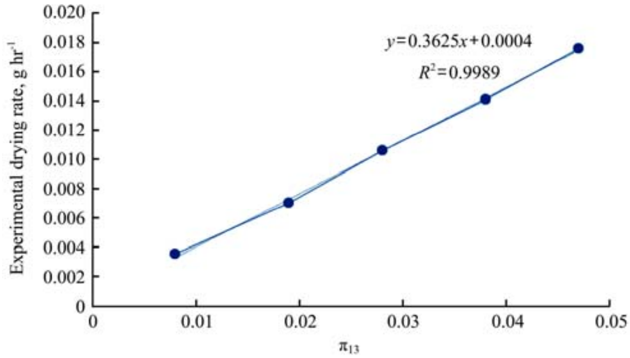

Figure 3a Graph of drying rate $\left(\frac{dM}{dt}\right)_e$ against dimensionless π_{13} at 70°C

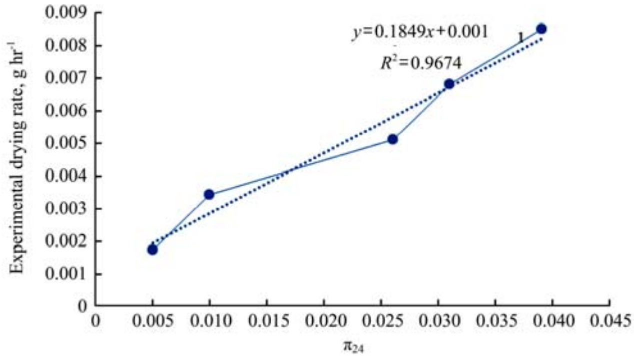

Figure 3b Graph of drying rate $\left(\frac{dM}{dt}\right)_e$ against dimensionless π_{24} at 70°C

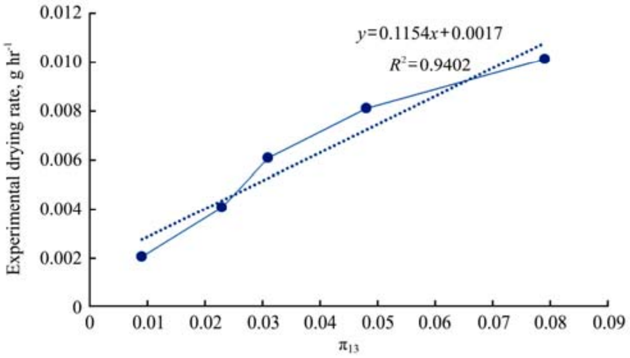

Figure 4a Graph of drying rate $\left(\frac{dM}{dt}\right)_e$ against dimensionless π_{13} at 80°C

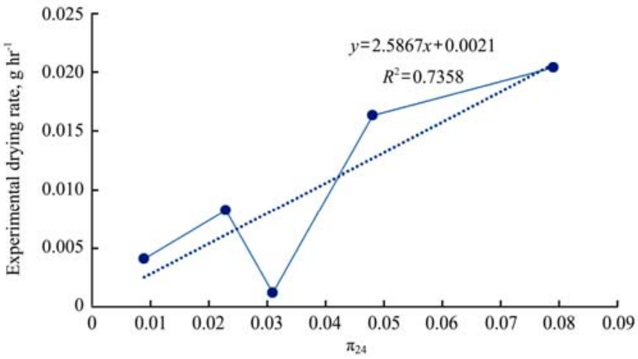

Figure 4b Graph of drying rate $\left(\frac{dM}{dt}\right)_e$ against dimensionless π_{13} at 80°C

The model equations obtained from the linear functions were expressed as Equations (21)-(23):

$$\left(\frac{dM}{dt}\right)_{e,13} = 0.4327\pi_{13} + 0.0015 \text{ and} \quad \left(\frac{dM}{dt}\right)_{e,24} = 0.1439\pi_{24} + 0.0015, \text{ for } 60°C \tag{21}$$

$$\left(\frac{dM}{dt}\right)_{e,13} = 0.3625\pi_{13} + 0.0004 \text{ and} \quad \left(\frac{dM}{dt}\right)_{e,24} = 3.4805\pi_{24} + 0.0039, \text{ for } 70°C \tag{22}$$

$$\left(\frac{dM}{dt}\right)_{e,13} = 0.1154\pi_{13} + 0.0017 \text{ and} \quad \left(\frac{dM}{dt}\right)_{e,24} = 2.5867\pi_{24} + 0.0021, \text{ for } 80°C \tag{23}$$

where, $\left(\frac{dM}{dt}\right)_e$ was the experimental drying rate (g hr^{-1}).

The plot of the π-terms formed a plane surface in linear space. According to Musa (2012), it implied that their combination supported either summation or subtraction. Therefore, the component equation was combined by summation and the combined equation gave the predicted equations was presented as:

$$\left(\frac{dM}{dt}\right)_p = \left(\frac{dM}{dt}\right)_{e,13} + \left(\frac{dM}{dt}\right)_{e,24} \tag{24}$$

$$\left(\frac{dM}{dt}\right)_p = 0.4327\pi_{13} + 0.1439\pi_{24} + 0.003 \text{ for } 60°C \tag{25}$$

$$\left(\frac{dM}{dt}\right)_p = 0.3625\pi_{13} + 3.4805\pi_{24} + 0.0043 \text{ for } 70°C \tag{26}$$

$$\left(\frac{dM}{dt}\right)_p = 0.1154\pi_{13} + 2.5867\pi_{24} + 0.0038 \text{ for } 80°C \tag{27}$$

where, $\left(\frac{dM}{dt}\right)_p$ was the predicted/modeled drying rate.

Substituting the values of π_{13} and π_{24} into Equations (25), (26) and (27), the predicted equations were obtained as expressed in Equations (28)-(30):

$$\left(\frac{dM}{dt}\right)_p = 0.4327M_oRH + 0.1439M_ekt + 0.003 \text{ for } 60°C \tag{28}$$

$$\left(\frac{dM}{dt}\right)_p = 0.3625M_oRH + 3.4805M_ekt + 0.0043 \text{ for } 70°C \tag{29}$$

$$\left(\frac{dM}{dt}\right)_p = 0.1154M_oRH + 2.5867M_ekt + 0.0038 \text{ for } 80°C \tag{30}$$

3.2 Validation of Data

The mathematical model was validated using experimental data generated from the dryer. The validation parameter used for this research was a two-tail test, which was a statistical tool for testing validation. The model validation was done at five different levels of moisture content and at three different ambient air temperatures of 60°C, 70°C and 80°C. Microsoft Excel 2007 statistical package for windows vista was used for the statistical analysis based on General Linear Model (GLM). The experimental and predicted values of the drying rate of the cocoa beans were shown in Table 4 for the different air temperatures considered in this study. It can be observed that the predicted and experimental values had very high coefficient of correlation (R^2) value of 0.967, 0.998 and 0.937 for 60°C, 70°C and 80°C, respectively. The predicted and experimental values were compared using the least significant difference (LSD) at 1% and 5% levels of significance. There was no statistical difference since the calculated "*t*" value was less than the tabulated "*t*" value. Also, the validity of the model equations was examined by testing if the intercept and the slope were statistically significantly different from 0 and 1.0 respectively in the 1:1 model equation (Simonyan et al., 2010). The slope was found to be insignificant at 5% level of probability. The regression equations were then obtained by the least square method for the three air temperatures for this study as shown in Figure 5.

Table 4 Predicted and experimental drying rate values for different moisture contents and temperatures

Time, hours	Moisture content, %db.	Temperature, °C					
		60		70		80	
		$\left(\frac{dM}{dt}\right)_p$	$\left(\frac{dM}{dt}\right)_e$	$\left(\frac{dM}{dt}\right)_p$	$\left(\frac{dM}{dt}\right)_e$	$\left(\frac{dM}{dt}\right)_p$	$\left(\frac{dM}{dt}\right)_e$
1	7.5	0.013	0.005	0.009	0.008	0.0098	0.009
2	15.0	0.023	0.010	0.022	0.019	0.029	0.023
4	22.5	0.029	0.026	0.030	0.028	0.034	0.031
6	30.0	0.036	0.031	0.041	0.038	0.051	0.048
8	37.5	0.042	0.039	0.049	0.047	0.082	0.079

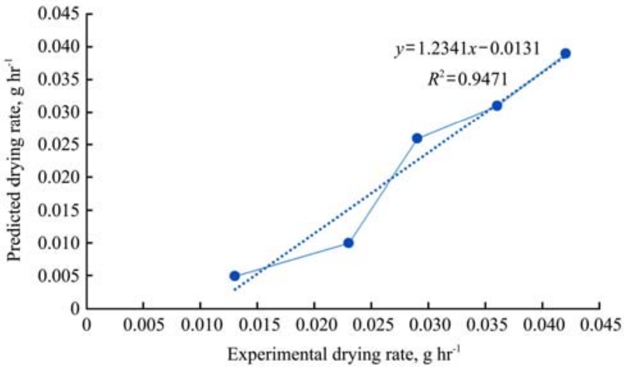

Figure 5a Graph of $\left(\frac{dM}{dt}\right)_p$ against $\left(\frac{dM}{dt}\right)_e$, at 60°C

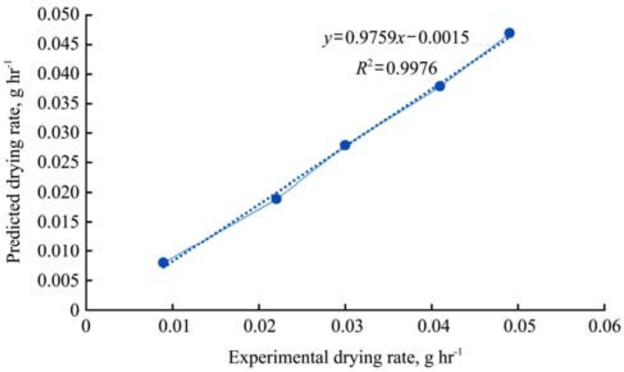

Figure 5b Graph of $\left(\frac{dM}{dt}\right)_p$ against $\left(\frac{dM}{dt}\right)_e$, at 70°C

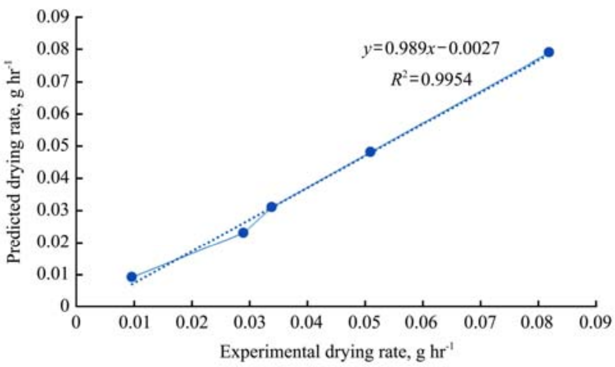

Figure 5c Graph of $\left(\frac{dM}{dt}\right)_p$ against $\left(\frac{dM}{dt}\right)_e$, at 80°C

Between the moisture contents of 7.5% to 37.5% and dryer air temperatures of 60°C, 70°C and 80°C, the linear equations relating the predicted and experimental values of the drying rate of cocoa beans were given Equations (31)-(33) as:

$$\left(\frac{dM}{dt}\right)_p = 1.2341\left(\frac{dM}{dt}\right)_e - 0.0131 \text{ for } 60^{\circ}\text{C} \quad (31)$$

$$\left(\frac{dM}{dt}\right)_p = 0.9759\left(\frac{dM}{dt}\right)_e - 0.0015 \text{ for } 70^{\circ}\text{C} \quad (32)$$

$$\left(\frac{dM}{dt}\right)_p = 0.989\left(\frac{dM}{dt}\right)_e - 0.0027 \text{ for } 80^{\circ}\text{C} \quad (33)$$

4 Conclusion

A mathematical model using dimensional analysis based on the Buckingham's-π theorem has been developed for thin layer drying of cocoa beans in a hot air dryer. Results obtained showed that moisture content decreased as drying time progresses for each temperature regime due to the increase of vapour pressure in the samples, which resulted in an increased diffusion rate of the internal water. Additionally, the drying rate decreased as the moisture reduced due to the increase in the intra-particle resistance to moisture migration to the surface of the sample products. The functional relationship between thin layer dryer and cocoa bean parameters was established. Prediction equation was established by varying one π-term at a time while keeping the other constant in order to observe the resulting changes in the model relationship. The model was validated with data from an existing thin layer dryer, yielding a high value of coefficient of determination (R^2) of 0.947, 0.998 and 0.995 obtained for the drying air temperatures of 60°C, 70°C and 80°C, respectively. The parameters used for the model validation were moisture content, drying constant, drying time, drying temperature, bulk density and particle density. It can be concluded that drying cocoa beans in thin layers at increasing drying temperature, decreasing moisture contents and constant air velocity leaded to a low drying rate.

References

Akpinar, E. K. 2006a. Determination of suitable thin layer drying curve model for some vegetables and Fruits. *Journals of Food Engineering*, 73(1): 75–84.

Akpinar, E. K. 2006b. Mathematical modeling of thin layer drying process under open sun of some aromatic plants. *Journal of Food Engineering*, 77(4): 864–870.

Akpinar, E. K., Y. Bicer, and C. Yildiz. 2003. Thin layer drying of red pepper. *Journal of Food Engineering*, 59(1): 99–104.

Baryeh, E. 1985. Cocoa drying and storage, using charcoal and solar heated rods. *Journal of Agricultural Mechanization in Asia, Africa and Latin America*, 16(1): 23–28.

Bravo, A., and D. R. McGaw. 1982. Drying characteristics of agricultural materials with a protective shell. In *Proc. 3rd International Drying Symposium*, Pp. 319–327. Dakar, Senegal, 12th June.

Chinenye, N. M., A. S. Ogunlowo, and O. J. Olukunle. 2010. Cocoa bean (T*heobroma cacao L.*) drying kinetics. *Chilean Journal of Agricultural Research*, 70(4): 633–639.

Eastop, T. D., and A. McConkey. 1993. *Applied Thermodynamics for Engineering Technologists (5th ed)*. New York, USA: Prentice Publishers.

Faborode, M. O., J. F. Favier, and O. A. Ajayi. 1995. Effects of forced air drying on cocoa quality. *Journal of Food Engineering*, 25(4): 455–472.

Firihu, M. Z., and I. N. Sudiana. 2016. 2.45 GHZ microwave drying of cocoa bean. *ARPN Journal of Engineering and Applied Sciences*, 12(19): 11595–11598.

Fotso, P. J., D. Lecomte, L. Pomathios, and J. Nganhou. 1994. Convective drying of cocoa beans: Drying curves for various external conditions. *In Proc. 9th International Drying Symposium*, 937-944. Gold Coast, Queensland, Australia, 1-4 August.

Hii, C. L., C. L. Law, and M. Cloke. 2009. Modeling using a new thin layer drying model and product quality of cocoa. *Journal of Food Engineering*, 90(2): 191–198.

Hii, C. L., C. L. Law, and M. Cloke, and S. Suzannah. 2009. Thin layer drying kinetics of cocoa and dried product quality. *Biosystems Engineering*, 102(2): 153–161.

Hii, C. L. and M. B. Tukimon, 2002. Evaluation of fermentation techniques practical by the cocoa smallholders. *The Planter*, 78(910): 13–22.

Hu, Q. G., M. Zhang, A. S. Mujumdar, and G. N. Xiao, 2006. Drying of *edamames* by hot air and vacuum microwave combination. Available at: www.agris.fao>agris-search> search.

Jain, D., and P. B. Pathare, 2007. Study the drying kinetics of open sun drying of fish. *Journal of Food Engineering*, 78(4): 1315–1319.

Musa, N. A. 2012. Drying characteristics of cocoa bean using an artificial dryer. *Journal of Engineering and Applied Science*, 7(2): 194–197.

Ndukwu, M. C. 2009. Effect of drying temperature and drying air velocity on the drying rate and drying constant of cocoa bean. *CIGR Journal,* 1091(11): 1–7.

Ndukwu, M. C., K. J. Simonyan, and V. I. O. Ndirika. 2012. Investigation of the structural changes of cocoa bean (with and without seed coat) during convective drying. *CIGR Journal*, 5(3): 75–82.

Nwakuba, N. R., S. N. Asoegwu, and K. N. Nwaigwe. 2016. Energy requirements for drying of sliced agricultural products: a review. *CIGR Journal*, 18(2): 114–155.

Official Methods of Analysis, 17th ed. 2000. Washington DC, USA: Association of Official Analytical Chemistry.

Ojha, T. P., and A. M. Michael. 2005. *Principles of Agricultural Engineering (5th ed)*. New Delhi, India: Jain Publishers.

Oke, D. O., and K. F. Omotayo. 2012. Effect of forced-air artificial intermittent drying on cocoa beans in South-Western Nigeria. *Journal of Cereals and Oil seeds*, 3(1): 1–5.

Opeke, L. K. 1987. *Tropical Tree Crops*. Chichester: John Willey and Sons.

Porter, L. L. 2006. Benefits of cocoa polyphenols. *Manufacturing Confectioner*, 86(6): 49–53.

Shefh, S., S. K. Upadhyaya, and R. E. Garret. 1996. The importance of experimental design to the development of empirical prediction equations: A case study. *Transaction of ASABE*, 39(2): 377–384.

Simonyan, K. J., Y. D. Yilijep, and O. J. Mudiare. 2010. Development of mathematical model for predicting the cleaning efficiency of stationary grain threshers using dimensional analysis. *Applied Engineering in Agriculture*, 26(2): 35–44.

Taubert, D., R. Roesen, and E. Schömig. 2007. Effect of cocoa and tea intake on blood pressure: a meta-analysis. *Achieves of Internal Medicine*, 167(7): 626–634.

Wan Daud, W. R., M. Z. Mcor-Talib, and M. H. Ibrahim. 1996. Characteristic drying curves of cocoa beans. *Drying Technology*, 14(10): 2387–2396.

Wood, G. A. R., and R. A. Lass, 1985. *Cocoa (4th Edition)*. New York, USA: Longman Inc.