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TEMPERATURES DEPENDENT DRYING KINETICS OF COCOA BEANS VARIETIES IN AIR-VENTILATED OVEN

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ABSTRACT

The drying kinetics of three varieties of cocoa beans (N38, F and WA) at 40, 50 and 60 degree centigrade was investigated experimentally. The three different varieties were dried using laboratory air oven UF Memmert and the moisture content determined according to AOAC standards. The results show that drying processes occur mainly in the range of the falling-rate period and the drying rates were observed to be faster at higher drying temperature. The effective diffusivities of the three cocoa beans varieties determined at 40, 50 and 60 degree centigrade ranged between 9.9269 x 10^{-11} and 4.4671 x 10^{-10} metre square per second. The predicted Arrhenius constant and activation energy were 2.47 x 10^{-10} metre square per second and 23.61 kilojoule per mole.

Keywords: Drying kinetics, drying rate, cocoa beans, drying temperature, moisture content, cocoa varieties

1. INTRODUCTION

Cocoa beans are seeds of *Theobroma cacao L.*, which is one of the most important cash crop trees in many tropical countries including Nigeria, Cote D'voire, Ghana, Indonesia, Cameroun, Brazil, Ecuador, Malaysia, Sierra-Leone and Republic of Benin. The return of civilian administration in Nigeria in 1999 ushered in a good fortune for cocoa industry with the establishment of the National Cocoa Development Committee (NCDC) in 2000 which is domiciled in the Federal Ministry of Agriculture and Rural Development (FMA&RD) (Alamu, 2013).

In order to promote the production of cocoa to meet the needs of expanding industrial sector and export market, a special programme tagged cocoa re-birth was launched in 2005. The policy thrust of the programme was to promote the production of cocoa to meet the needs of an expanding industrial sector and export market (Alamu, 2013). The programme also aimed at creating jobs and wealth to enhance farmers' income and reduce poverty in the country (FGN, 2006). The end products of cocoa beans especially chocolate and beverages are considered among the basic food in many countries of the world and the quality of these end products is a function of how they are processed. The processes to condition cocoa beans for industrial use include a series of steps to develop sensorial properties. The steps include an adequate pod maturity, pod cracking and seed extraction, fermentation, drying, selection and storage (Schwan *et al.*, 1995).
Among these postharvest processing steps, fermentation and drying are the major steps that must be carried out.

Drying, being the most important among other postharvest steps, is a complex thermal process in which unsteady heat and moisture transfer occur simultaneously. This complex process depends on different parameters such as air temperature, relative humidity, air velocity, physical properties and initial moisture content of the product (Akpinar *et al.,* 2003). The main purpose of drying process is to reduce water activity of the material so as to prevent the growth of microorganisms and to lower the activity of enzyme, thereby prolonging the shelf life at room temperature (Hamrouni-Sellami *et al*., 2013). In drying process, heat is supplied for vaporization of water with unheated and heated forced air. This process through which vaporization of water occur as a result of heat supply to the product is known as simultaneous heat and mass transfer (Hall, 1980). The challenge of cocoa drying has been one of using available sources of energy efficiently to reduce moisture to safe storage levels, while producing beans of acceptable quality (Bonaparte, 1998). In many processes, improper drying may lead to irreversible damage to product quality and hence a non-sellable product (Fagunwa *et al.,* 2009). These are likely consequences of under-drying or over-drying of the product when suitable drying conditions such as drying air temperature are not applied.

Several research works have been reported on the drying kinetics of cocoa beans under different conditions (Chineye *et al.,* 2010; Hii *et al.,* 2009; Fagunwa *et al.* 2009; Hii *et al.* 2012; Hii *et al*., 2010; Hii *et al.,* 2013; Dina *et al.*, 2015; Komolafe *et al.*,2014) and other agricultural products such as fish (Komolafe *et al.,* 2013; Komolafe *et al.,* 2011), pepper (Darvish *et al.,* 2013), beetroot (Kaur and Singh, 2014), banana (Adewale *et al.,* 2015), persimmon fruits (Sampauo *et al.,* 2016), carrot slices (Doymaz, 2016), green soybean seeds (Zhao, 2017), grain sorghum (Sadaka and Atungulu, 2018), asparagus root (Kohli *et al.*, 2018), banana peels (Lin and Cze, 2018) and sage leaves (Doymaz and Karasu, 2018). A search through the literature shows that work has not been reported on the drying kinetics of these three varieties of cocoa beans (N38, F3 and WA) under oven-drying conditions. This paper presents the drying kinetics of three varieties of cocoa beans under air-

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ventilated oven drying condition at different temperature. The general objective was to determine the best drying condition for each variety using air-ventilated oven.

2. MATERIALS AND METHODS

2.1. Sample preparation

Firm, ripe, mature, undamaged, cocoa pods, free from infection (visually detected) were collected from Cocoa Research Institute of Nigeria (CRIN), the beans were removed and fermented for six days inside perforated wooden boxes. At every 48 hours, the beans in the boxes were mixed for better fermentation (Hii and Tukimon, 2002; Hii *et al.* 2010). The three varieties of cocoa beans were fermented separately for 6 days. After the fermentation process, the beans were cleaned of the pulp by soaking in running water (Abdullah, 2003).

2.2. Drying procedure

The initial and final moisture content of the three different varieties of cocoa beans (Amelonado, N38; F3 Amazon, F and WACRI Series, WA) were determined by drying samples with laboratory air-ventilated oven (UF. 75 Memmert, Schwabach, Germany, Number: F.-∴0109.0088) at temperature 40, 50 and 60 °C and air velocity 2.7 m/s. The experimental set up is as shown in Fig. 1. The setting temperature of the universal oven ranged between 20 and 300 °C. Prior to placing the samples in drying chamber after fermentation, the oven pre-set at 40 °C was allowed to run for at least 30 minutes to obtain steady condition. Thereafter, 0.5 kg each of cocoa beans from the three varieties already spread on clean aluminum tray was placed on the shelves inside the oven. The reduction in weight was taken at 30 minutes interval using an electronic scale DT-1000 with a precision of 0.01 g until no further changes in mass were observed. Losses in samples weight were recorded for moisture content determination. The same procedure was repeated for the varieties at 50 and 60 °C drying temperatures. To measure the mass of sample at any time during experimentation, sample inside the aluminum tray was taken out of the drying chamber and weighted on the digital/electronics scale (DT-1000) with accuracy of 0.1 g positioned very close to the oven and then placed back into the drying chamber. The procedure was repeated until a constant weight was obtained.

2.3. Drying kinetics

The moisture content on wet basis was calculated according to AOAC (2000) as:

$$M_t = \frac{W_i - W_{bd}}{W_i} \quad (1)$$

where M_t is the moisture content (% w.b.); W_i the initial weight of the sample (g) and W_{bd} the bone dried weight of sample (g).

The dimensionless moisture ratio (MR) of cocoa beans was calculated according to Dinani *et al.* (2014) using:

$$MR = \frac{M_t - M_e}{M_o - M_e} \quad (2)$$

where M_i, M_e, and M_t are the initial moisture content, equilibrium moisture content and the moisture content measured at time t, respectively. The value of M_e is very small compared to M_t or M_i for long drying time. Thus Eqn. (2) can be written in a more simplified form according to El-Sebaii and Shalaby [33] as:

$$MR = \frac{M_t}{M_o} \quad (3)$$

The drying rate (DR) of cocoa beans was calculated using eqn. (4) (Doymaz, 2009; Fernando and Amarasinghe, 2016):

$$DR = \frac{M_t - M_{t+dt}}{dt} \quad (4)$$

where M_{t+dt} is moisture content (g water/g wet solid) at $t + dt$, t is the time (hr) and dt is time difference (hr).

The drying rate is defined as diffusion of moisture from the inner to the surface layer. This can be explained by Fick's second law of diffusion for unsteady state diffusion.

2.4 Moisture diffusivity

The experimental data were fitted to determine the moisture diffusivity by using the Fick's second law of diffusion:

$$\frac{\partial M}{\partial t} = D_{eff} \nabla^2 \quad (5)$$

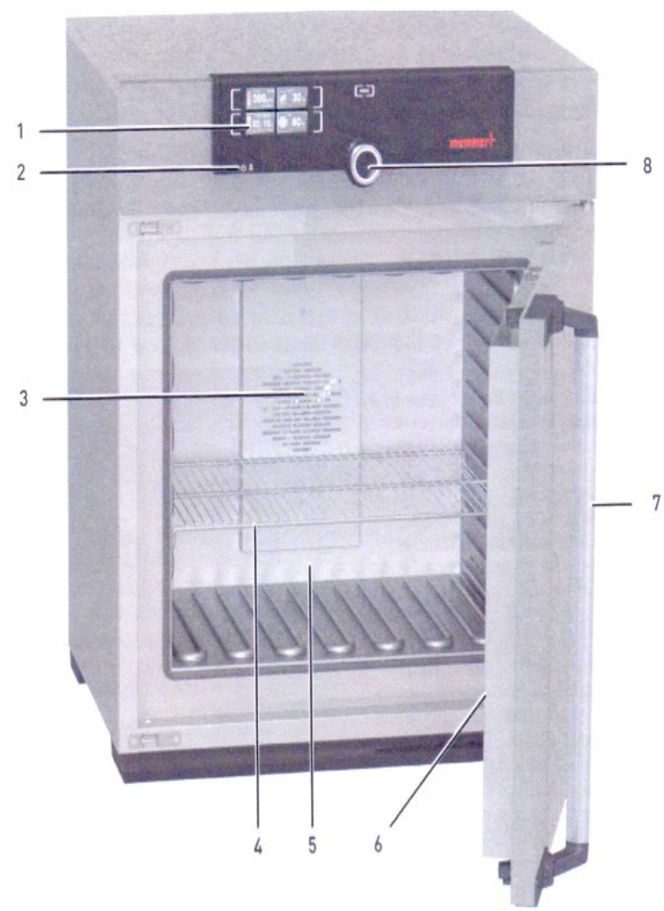

Fig. 1: Features of Memmert oven (1. Control Cockpit with capacitive function key; 2. On/Off switch; 3. Working chamber fan; 4. Steel grid; 5. Working chamber; 6. Nameplate; 7. Door handle; 8. Turn control with confirmation key)

Source: (Memmert Expert in Thermostatics , 2013)

The analytical solution of Eqn. (5) was given by Crank (1975) for slab geometry with uniform initial moisture distribution, negligible external resistance, constant diffusivity and negligible shrinkage as:

$$MR = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{2n-1}\exp\left(\frac{(2n-1)^2\pi^2 D_{eff}\, t}{4L^2}\right) \tag{6}$$

where L is half-thickness of the samples (m), t is the time (s), n is a positive integer and D_{eff} is effective diffusivity.

Linearizing Eqn. (6) (Clement et al. 2009; Doymaz, 2005) yields:

$$ln\ (MR) = ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 t\, D_{eff}}{4L^2}\right) \tag{7}$$

The slope of the curve from the plot of ln (MR) versus drying time was used to determine the effective diffusivity as follows:

$$D_{eff} = slope\ \times \frac{4L^2}{\pi^2} \tag{8}$$

The activation energy (E) for diffusion was determined using the Arrhenius equation:

$$De_{ff} = D\ exp\left(-\frac{E}{RT}\right) \tag{9}$$

where D is the pre-exponential factor of the Arrhenius equation (m^2/s), E is activation energy (J/mol), R is universal gas constant (8.314 J/mol/K), T is absolute temperature (K).

The Microsoft Excel SOLVER tool was used for the prediction of the Arrhenius constant and activation energy.

3. RESULTS AND DISCUSSION

Figures 2-4 depict the variation of moisture contents (w.b.) with the drying time during air-oven drying process of three varieties of cocoa beans at 40, 50 and 60 °C drying air temperature. In all cases it can be seen that the moisture contents decrease exponentially with time as reported for most agricultural products by Toujani *et al.* (2013). The continuous decrease in the moisture content with drying time and increase in temperature resulted in the reduced drying time. At 40 °C, it took 25 hours to reduce the moisture content of N38, F3 and WA from the initial values of 53.8, 52.4 and 50.5% w.b. to 7.5, 4.1 and 6.4% w.b., respectively. Similarly, at 50 °C, the reduction of initial moisture content from 53.7, 53.6 and 53% w.b. to 2.7, 2 and 3.1%, respectively took 20 hours, while at 60 °C, it took 12 hours to reduce the initial moisture content of the cocoa beans from 52.6, 51.8 and 49.6% to 2.6, 2.8 and 5.0, respectively. The drying processes at 40, 50 and 60 °C occur mainly in the range of the falling-rate period. This shows that diffusion is the dominant physical mechanism governing moisture movement in the drying samples. The curves show that the increase in drying temperature resulted in the decrease in the drying time since both the thermal gradient inside the object and the evaporation rate in the product increased. The drying time at 50 °C is more than one and half times that at 60 °C and double at 40 °C. However, McDonald *et al.* (1981) stated that drying within a very short time is not recommended and it should be avoided because adequate time is required for oxidation process to occur within the beans in order to ensure full brown of the interior.

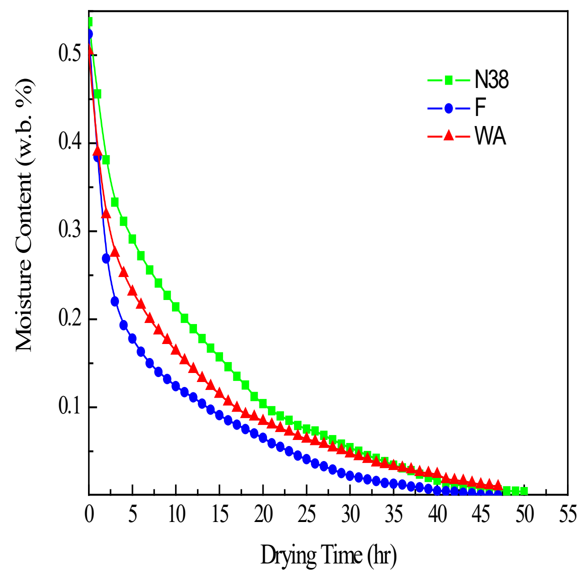

Fig. 2: Variation of moisture content with drying time at 40 °C drying temperature

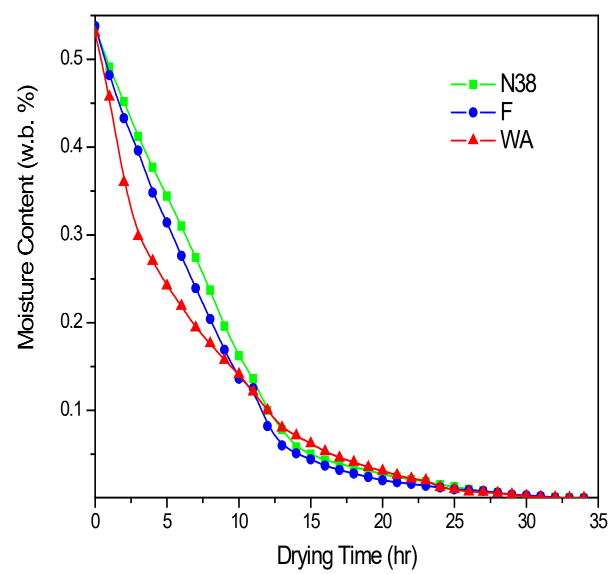

Fig. 3: Variation of moisture content with drying time at 50 °C drying temperature

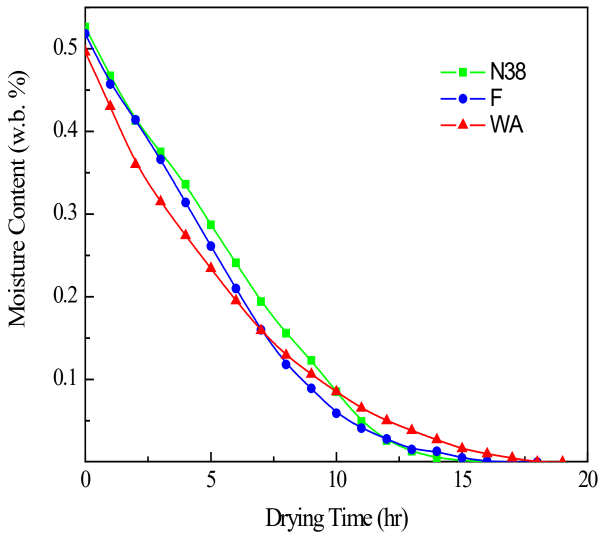

Fig. 4: Variation of moisture content with drying time at 60 °C drying temperature

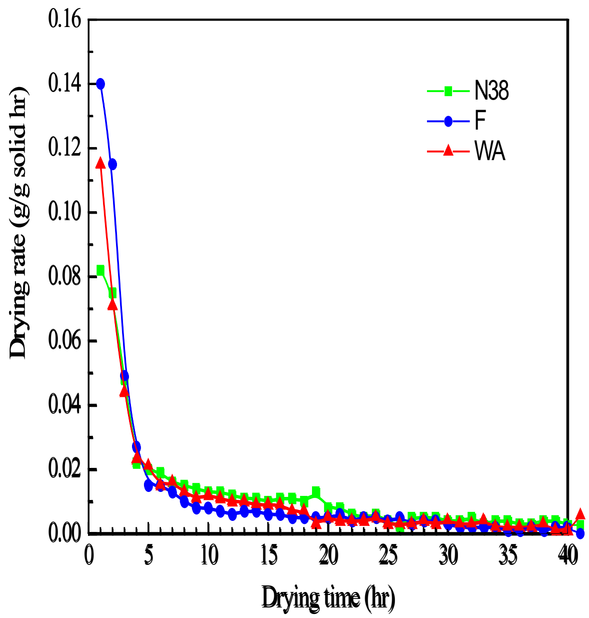

Fig.5: Drying rate as a function of time at 40 °C drying temperature

Figures 5-7 are plots of the drying rate against the drying time. As expected, the drying temperature has significant effects on the drying kinetics of the varieties. As expected, the highest drying rates occurred during the early hours of the drying processes at 40, 50 and 60 °C for the three varieties (N38, F3 and WA) as presented in Table 1. It was observed that among the three tested varieties, the WA has the highest drying rates at 50 and 60 °C during the early hour of the drying process.

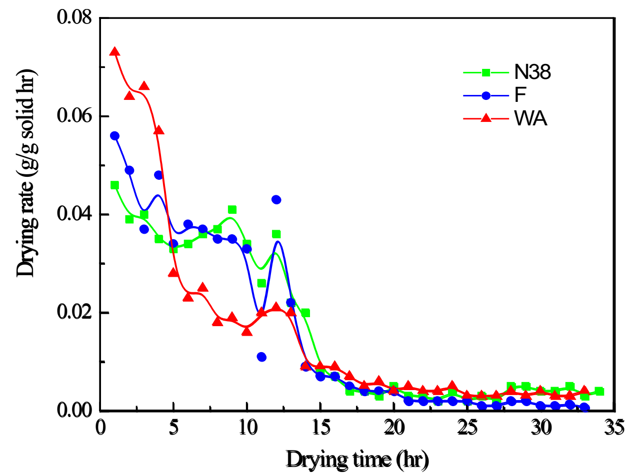

Fig.6: Drying rate as a function of time at 50 °C drying temperature

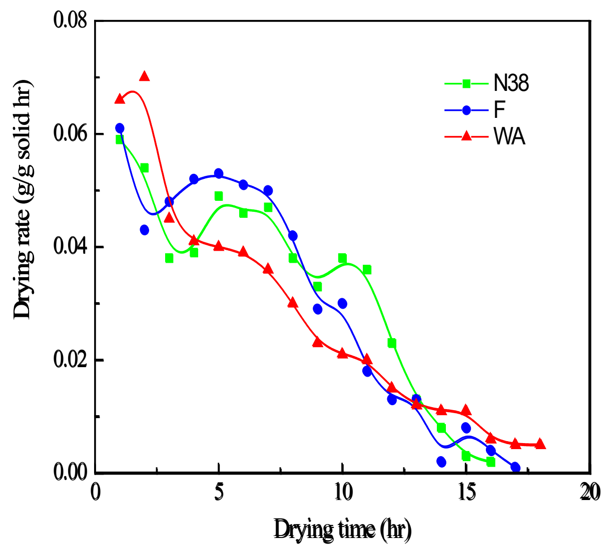

Fig.7: Drying rate as a function of time at 60 °C drying temperature

Table 1: Calculated drying rate (g water /g wet solid hr) for the different varieties of cocoa beans

Temp. (°C)	Drying rate (g water /g wet solid hr)		
	N38	F3	WA
40	0.082	0.115	0.115
50	0.046	0.056	0.073
60	0.059	0.043	0.070

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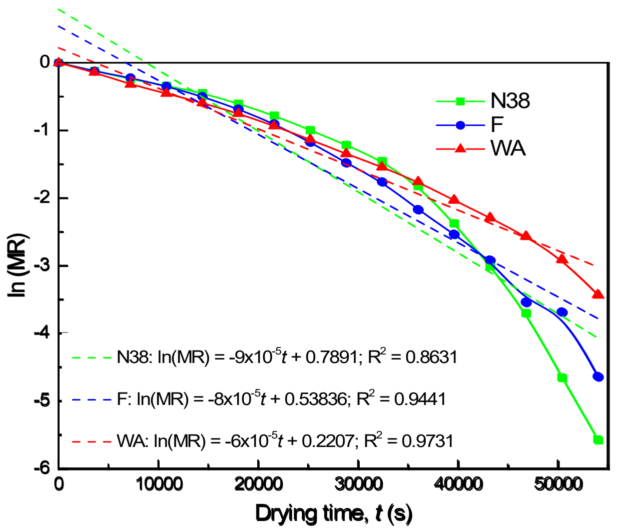

Fig. 8: Variation of logarithm of moisture ratio with drying time at 40 °C drying temperature

Figures 8-10 present the variation of logarithm of moisture ratio with drying time at 40, 50 and 60 °C drying air temperature. It is clearly evident from the figures that the logarithm of moisture ratio decreased with increase in drying time. The calculated effective diffusivities for cocoa beans at 40, 50 and 60 °C are shown in Table 2. The values of D_{eff} obtained from this study lie within the general range 10^{-12} to 10^{-8} for drying of garlic slices and food materials as presented by Madamba *et al.* (1996) and Zogzas *et al.* (1996). Also, the values lie within the effective diffusivity range 7.46×10^{-11} to 1.87×10^{-10}; 8.94×10^{-11} to 9.63×10^{-11}; 3.70×10^{-11} to 5.80×10^{-11} and 6.137×10^{-10} to 2.1855×10^{-9} m^2/s reported by Hii *et al.* (2013); Dina *et al.* (2015); Clement et al. (2009) and Chinenye *et al.* (2010) during oven-drying at 60, 70 and 80 °C; solar drying integrated with absorbent and adsorbent; sun drying; and heated batch drying of cocoa beans, respectively.

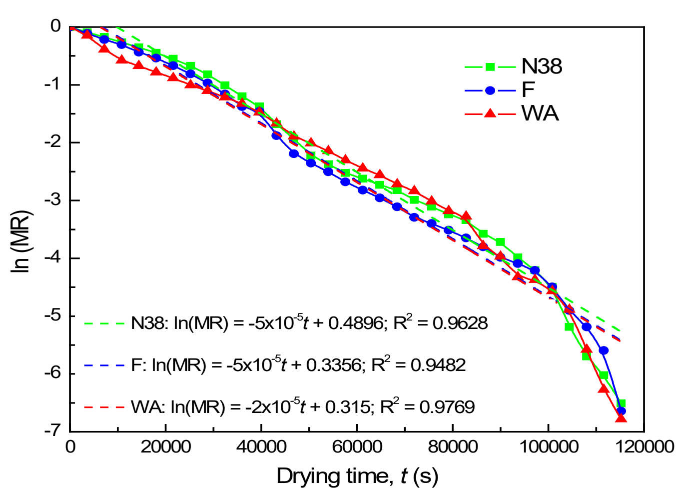

Fig.9: Variation of logarithm of Moisture ratio with drying time at 50 °C drying temperature

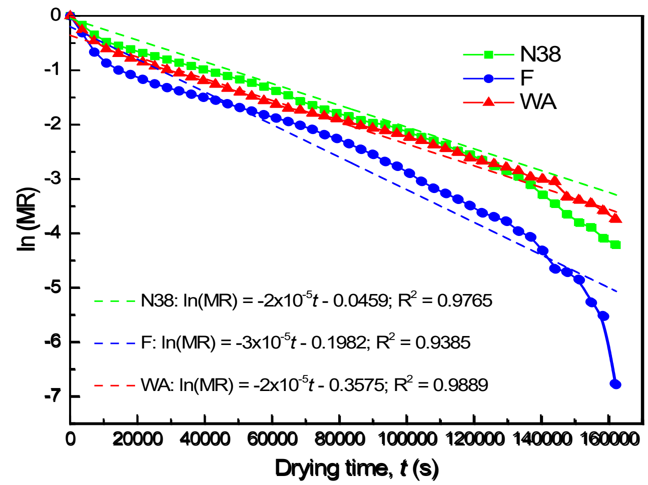

Fig.10: Variation of logarithm of moisture ratio with drying time at 60 °C drying temperature

Table 2: Calculated moisture diffusivity, D_{eff} (m^2/s) for the different varieties of cocoa beans

Variety	Diffusivity (D_{eff}) (m^2/s)		
	40 °C	50 °C	60 °C
N38	9.9269×10^{-11}	2.4817×10^{-10}	4.4671×10^{-10}
F3	1.1681×10^{-10}	1.9469×10^{-10}	3.1150×10^{-10}
WA	8.0408×10^{-11}	2.0102×10^{-10}	2.4122×10^{-10}

4. CONCLUSION

Drying kinetics of cocoa beans varieties at different drying temperatures using air-oven has been experimentally studied. The drying processes of three varieties of cocoa beans at 40, 50 and 60 °C occur mainly in the range of the falling-rate period. The drying time at 50 °C is almost doubled that at 60 °C and more than double at 40 °C. The drying rate of the three varieties at drying temperatures ranged between 0.001 and 0.140 g water/ g wet solid hr. The calculated effective diffusivities for three cocoa beans varieties at 40, 50 and 60 °C ranged from 9.9269×10^{-11} to 4.4671×10^{-10} m^2/s. The predicted Arrhenius constant (D_o) and activation energy (E_a) were 2.47×10^{-10} m^2/s and 23.61 kJ/mol. These results would be of help in the design of equipment or processes involving drying of different varieties of cocoa beans under forced convection at varying temperature.

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NOMENCLATURE

D	Arrhenius constant (m^2/s)
D_{eff}	moisture diffusivity (m^2/s)
DR	drying rate (g H_2O/g wet solid h)
E	activation energy (kJ/mol)
M	moisture content (%)
W	weight of sample (g)

Subscripts

bd	bone dried
dt	change in time (hr)
e	equilibrium
f	final
L	half thickness of slab (mm)
i	initial
m	moisture
MR	moisture ratio (dimensionless)
R	Universal gas constant (8.314 J/mol.K)
t	time (s)
T	temperature (K)

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