Modeling and Evaluation of Palm Nut Drying Rate during Mechanical Cracking.

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ABSTRACT

Palm tree has multiple uses in the sense that all part of the tree has economic value. Palm kernel production potentials of several countries are yet to be fully exploited. Palm kernel oil (PKO) has been considered globally as viable alternative to groundnut and soybean oils. A major challenge facing palm kernel production is the difficulty in extracting a whole kernel from the shell. Damaging the kernel during mechanical cracking influences microbial reaction and thereby greatly reduces its market value. This research is aimed at modelling drying parameters so as to generate equations that governed palm nut drying rates. This provides the basis for the design of effective palm nut cracker for quality kernel production. Performance evaluation of the machine showed that in tenera; functional efficiency was as high as 99.07%, quality performance efficiency was as high as 98.80% and mechanical damage was as low as 0.20%. In dura; functional efficiency was as high as 96.40%, quality performance efficiency was as high as 95.30% and mechanical damage was as low as 1.40%. The preliminary test showed appreciable result which influenced whole kernel recovery remarkably.

(Keywords: palm, kernel, modeling, drying rate performance evaluation)

INTRODUCTION

Oil palm was initially found growing widely in the central rain forest of the southern part of Nigeria. This region provides a good habitat for the tree, the benefits of this important crop enhances its high demand. This led to the establishment in 1939 of the pioneer palm oil research institute known as West Africa Institute for Oil palm Research (WAIFOR) which later became Nigeria Institute for Oil Palm Research (NIFOR). Palm oil is currently planted in all African countries, Asia, America and Oceania (Jimoh and Olukunle, 2013). The oil palm thrives in worm temperature and high rainfall in the tropical forest areas. It grows best where rainfall is not less than 1500 mm and is evenly distributed throughout the year (FAO, 2002). The ideal temperature is 27^0C to 35^0C and it will tolerate even higher temperature provided there is adequate moisture. Investigation further reported that oil palm thrives under condition of high relative humidity; yield adversely influenced when the crop is exposed to dry Harmattan wind. It has fibrous root system and benefits from deep and fertile soil free from iron concentrations.

There are three varieties of oil palm namely *dura*, *tenera,* and *pisifera*. *Dura* is characterized by thin mesocarp, thick endocarp (shell) with generally large kernel. The *dura* type is genetically homozygous and dominant for shell. *Tenera* possesses think mesocarp, thin endocarp with large kernel. This is a dual-purpose palm for the production of mesocarp oil and kernel. It is genetically heterozygous. *Pisifera* possesses thick mesocarp with very little oil content, no endocarp (shell less) with small Kernel, the female flowers are often sterile, this results in bunch failure and it is genetically homozygous and recessive for shell (Jimoh and Olukunle, 2012). Olukunle, *et al.,* (2008) stated that typical African *dura* is about 8-20 mm in length and has a fairly uniform shell thickness of about 2 mm. The *tenera* is about 7-15 mm in length with shell thickness of 1.2 mm.

Research investigation revealed as reported by (Akpobi and Oniah, 2009) that efficient processing of Palm fruit is a pre-condition for high efficiency in palm nut cracking. That is smoothness of the shell, freedom of nut from fibre and degree of shrinkage of the kernel affect the cracking efficiency of palm nut. At maturity, the fruit is reddish-orange to red colour and consist of the mesocarp and the nut. The nut gives three useful products after certain processing: the shell, the kernel oil and the residue cake. Kernel is the innermost part of palm fruit covered by hard shell; the kernel size varies greatly and depends on the size of the nut. Palm oil and kernel oil have continuously been a source of revenue for so many countries in the international market. They have proved to be a source of raw material for so many industries across the globe. Palm kernel is used in the production of palm kernel oil (PKO), palm kernel cake which is used in making feed for life stocks and manures for plant (Baegale, 2004). At present, the palm kernel production is far below estimated demand as more economic and domestic values are been discovered.

In general, palm nuts have relatively high moisture content 15-20% when freshly picked from the tree (Ituen and Modo, 2000). Since palm nut is close to a sphere in shape and the kernel is in close contact with the shell, dried palm nut can be considered approximately to be a hollow spherical shell. To reduce the possibility of crushing the kernel during shearing of the nut, palm nuts are therefore dried to reduce its moisture content. The drying must be in such a way that it does not affect the determination and fracture of the shell and that palm kernel oil is intact. As a biological material, the microstructure of palm nut shell appears similar to wood in general. It is a cellular solid with relatively low density and high strength, but its structure is reasonably isotropic and uniform.

Each variety of palm nut exhibits different physical and mechanical properties that influence functional and quality performance efficiency during cracking. In most places, particularly in Nigeria and West Africa in general, extraction of palm kernel from the nut is usually done by hand (Jimoh and Olukunle, 2012). Cracking is done by placing the nut on top of a stone and striking it using another stone with an impact force which causes the shell to split along the line of impact. This method is labor intensive, less productive, exposes someone to danger of flying shells. With this method, one can hardly extract up to 100 kg of kernel per day. However, due to the rising demand of kernel and shell, several efforts have been stepped up to develop mechanical cracking machine to meet up with the current challenge. These efforts include development of prototype cracking machines on principle of hammer and centrifugal impact as reported by: (Babatunde and Okoli, 1988; Badmus, 1990 and Akpobi and Oniah, 2009). The evaluation of these machines show high mechanical damage ranges from 6.0-14.7%. In view of this loss, this research identified and modeled parameters that influenced palm nut drying so as to investigate the effect of these variables on palm kernel quality production during mechanical cracking of different varieties of palm nut.

DRYING CONCEPT

When a temperature gradient exists in a body, experience has shown that there is an energy transfer from the high-temperature region to low-temperature region. The energy transferred across nut shell is by conduction and that the heat-transfer rate per unit area is proportional to the normal temperature gradient:

$$\frac{q}{A} = \frac{\partial T}{\partial x} \tag{1}$$

When proportionality constant is introduced,

$$q = -kA\frac{\partial T}{\partial x} \tag{2}$$

for shell thickness *dx,* as shown in Figure 1, the following energy balance can be made for one dimensional heat-conduction analysis as reported by (Jimoh and Olukunle, 2012):

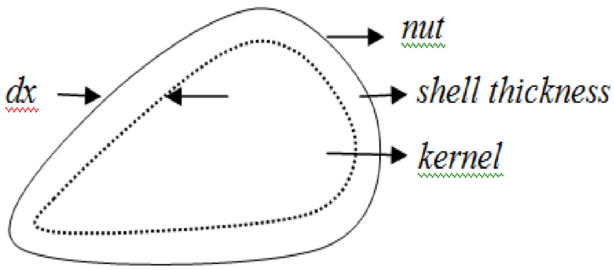

Figure 1: Physical Structure of Palm Nut.

Source: Jimoh and Olukunle, 2012

Heat conducted into shell + energy generated within shell = change in internal energy + energy conducted out of shell.

Energy conducted into shell,

$$(q) = -kA\frac{\partial T}{\partial x} \qquad \textbf{(3)}$$

Where k = thermal conductivity of the shell and minus sign indicated shows that it obey second law of thermodynamics, A = cross sectional area through flow, $\partial T/\partial x$ = temperature gradient in the direction of heat flow.

Energy generated within shell = $qAdx$ **(4)**

Where q = energy generated per unit volume, w/m^3

Change in internal energy = $\rho cA\frac{\partial T}{\partial \tau}dx$ **(5)**

Where ρ = density of shell, kg/m^3, c = specific heat of shell, J/kg ^oC and $\frac{\partial T}{\partial t}$ = change in temperature with respect to time.

Energy conducted out of shell,

$$q + dx = -kA\left[\frac{\partial T}{\partial x}\right]_{x+dx} \qquad \textbf{(6)}$$

$$= -A\left[k\frac{\partial T}{\partial x} + \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)dx\right] \qquad \textbf{(7)}$$

Therefore energy conducted into shell is proportional to the temperature from heat source while energy conducted out of shell is inversely proportional to the thickness of the shell. In other word part of energy conducted is converted to internal energy.

The conditions of the air do not remain constant in a drying chamber during drying process. Heat and mass balances are used to estimate conditions of air entering the chamber. Considering uniform trays loaded with fresh palm nut arranged in an oven, a differential length dL, and a section of thickness z, which can be expressed as:

$$dq = GC_s(zb)dT \qquad \textbf{(8)}$$

Where G is the mass flux of air, b is the distance between trays, z is the thickness of the tray, q is the heat flux, T is the temperature, and C_s is the specific wet heat of the air-water mixture. The heat flux can also be expressed as:

$$dq = h(zdL_t)(T - T_W) \qquad \textbf{(9)}$$

Here, h is the heat transfer coefficient, T_W is the wet bulb temperature and L_t is the length of the tray. Assuming that h and C_s are constants, when combining these two equations, the following can be obtained by integration:

$$\frac{hL_t}{GC_sb} = \ln\left(\frac{T_1 - T_W}{T_2 - T_W}\right) \qquad \textbf{(10)}$$

In which T_1 and T_2 are the temperature of air at the inlet and outlet of the tray, respectively. The mean logarithmic temperature is defined by:

$$\Delta T_{ml} = (T - T_W)_{ml} = \frac{(T_1 - T_W) - (T_2 - T_W)}{\ln\left(\frac{T_1 - T_W}{T_2 - T_W}\right)} \qquad \textbf{(11)}$$

Combining Equation 10 and 11:

$$(T - T_W)_{ml} = \frac{(T_1 - T_W)\left(1 - \exp\frac{-hL_t}{GC_sb}\right)}{\left(\frac{hL_t}{GC_sb}\right)} \qquad \textbf{(12)}$$

The heat flow reaching palm nut surface from the hot air can be expressed as:

$$\frac{Q}{t} = hzL_t\Delta T_{ml} \qquad \textbf{(13)}$$

This heat is used to evaporate water from surface of the nut. The total heat required to change from initial moisture content Y_1 to final moisture corresponding to the critical moisture content Y_B is:

$$Q = (zL_t x\rho)\lambda_W(Y_1 - Y_B) \qquad \textbf{(14)}$$

From Equation 13 and 14 and taking into account Equation 12, it is obtained that the drying time for the constant rate period is given by:

$$t_B = \frac{x\rho_s L_t \lambda_W (Y_1 - Y_B)}{GC_s b(T_1 - T_W)\left(1 - \exp\left(\frac{-hL_t}{GC_s b}\right)\right)} \quad \textbf{(15)}$$

Where Y_1 is the initial moisture content of the nut, Y_B is the critical moisture content, x is the thickness of the nut, ρ_s is the density of the nut, λ_W is the latent heat of vaporization at the temperature T_W.

Drying rate, *R* is determined as follows (Ibarz and Barbosa-Canovas, 2003):

$$R = \frac{-w_s}{A}\frac{dY}{dt} \quad \textbf{(16)}$$

Where w_s is weight of nut in the oven, A is the area of the drying surface and dY/dt is the change in moisture content with time. This can also be written as expressed by (Barbosa-Canovas and Vega-Mercado, 1996):

$$R = \frac{h}{\lambda_W}(T - T_W)_M \quad \textbf{(17)}$$

Here the drying rate is expressed as a function of mean temperature increment. Combining these equations and assuming that the drying velocity is a linear function of Y, when integrating on the boundary condition t = 0, $Y = Y_B$ and $t = t_C$, $Y = Y_F$, the drying time for the falling rate is obtained:

$$t_C = \frac{w_s \lambda_W Y_B \ln\left(\frac{Y_B}{Y_F}\right)}{Ah(T - T_W)_M} \quad \textbf{(18)}$$

If the mean difference of temperature is logarithmic, it can be substituted in equation 12 to obtained:

$$t_C = \frac{x\rho_s L_t \lambda_W Y_B \ln\left(\frac{Y_B}{Y_F}\right)}{GC_s b(T_1 - T_W)\left(1 - \exp\left(\frac{-hL_t}{GC_s b}\right)\right)} \quad \textbf{(19)}$$

Where Y_F represents the final moisture of the product. The total drying time of the nut to change from moisture content Y_1 to final moisture content Y_F is obtained by adding Equations 15 and 19, the total drying time being equal to:

$$t_s = t_B + t_C \quad \textbf{(20)}$$

DRYING PROCESS

The moisture content of the product is defined as the relationship between the amount of water in the nut and the amount of dry nut, expressed as:

$$Y_t = \frac{w_T - w_s}{w_s} \quad \textbf{(21)}$$

Where w_T is the total weight of the material at a determined given time, w_s is the weight of dry nut, and Y_t is the moisture expressed as water weight/dry nut weight. A very important variable in the drying process is the free moisture content, Y, expressed as:

$$Y = Y_t - Y_{eq} \quad \textbf{(22)}$$

Where Y_{eq} is the moisture content when equilibrium is reached.

The drying rate, R is proportional to the change in moisture content with time. Thus, R for respective free moisture content during drying of dura and tenera palm nut were taken so as to determine constant rate and falling rate period.

MACHINE PERFORMANCE EVALUATION

The machine was tested on the two varieties of palm nut at low machine speed 1840 rpm and with power rating 5 kW. The effect of this modeling on machine parameters such as functional efficiency, quality performance efficiency and mechanical damage was determined. During shearing, weight of completely cracked nut, weight of unbroken kernel, weight of broken kernel, weight of partially and un-cracked nut were taken. In other word, five tests were carried out for each variety. Machine parameters were determined as follow:

Functional efficiency,

$$E_f = \left[\frac{W_{CC}}{W_{LO}} \times 100 \right] \tag{23}$$

Quality performance efficiency,

$$E_p = \left[\frac{W_U}{W_{LO}} \times 100 \right] \tag{24}$$

Mechanical damage,

$$M_d = \left[\frac{W_{CC} - W_U}{W_{LO}} \times 100 \right] \tag{25}$$

Where:
W_{cc} = Weight of completely cracked nut / kg
W_{LO} = weight of kernel for each loading / kg
W_u = weight of unbroken kernel / kg

RESULTS AND DISCUSSION

Data obtained were plotted; drying rate (g water/s mm^2) on vertical axis and free moisture (g water/g dried nut) on horizontal axis for both *dura* and *tenera* as shown in Figure 2 and 3, respectively.

Point A on the graphs represents conditions of equilibrium temperature of the nut surface. Line AB on the curves represents the constant drying rate period and is usually associated with the removal of unbound water in the nut. Initially, the surface of the nut is wet with water activity approximately one.

The constant rate period continues while evaporated water at the surface can be compensated for internal water. The temperature at the surface of the nut corresponds to the wet-bulb temperature. When drying rate cannot longer be constant as a result of fallen in water activity on surface of the nut (less than one), it decreases as represented in line BD. Here, the drying rate decreases when the moisture content of the nut is lower than its critical moisture content, YB. Falling rate is divided into two stages while point B represents the start of the falling rate period.

The first stage occurs when wet points on the surface of the nut decrease continuously until the surface is completely dry as shown in point C. The second stage of the falling rate period begins at point C where the surface is completely dry and the evaporation plane moves to interior of the nut at point D. Line BC is shorter in *tenera* than that of *dura* simply the drying is faster and evaporation plane to the interior takes shorter time.

This outstanding difference in the two varieties causes line CD in *tenera* to be more deflected from line BC as shown in Figure 3. Difference in the falling rate is as a result of variation in shell thickness. Previous research revealed that average shell thickness in *tenera* is 1.2 mm while that of *dura* is 2 mm (Jimoh and Olukunle, 2013). Further dry causes surface of the nut to be oily and this indicates movement of palm kernel oil (PKO) from the inside to the interior.

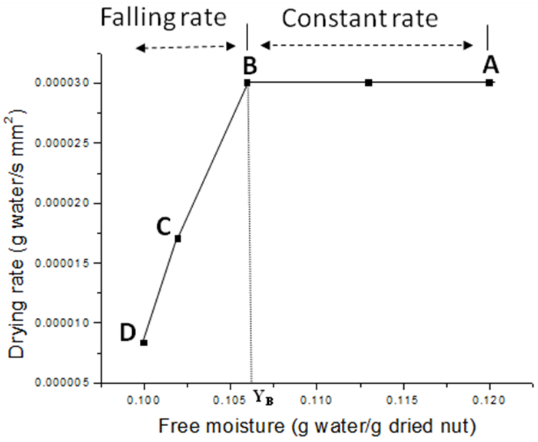

Figure 2: Drying Rate Curve of *Dura* Nut.

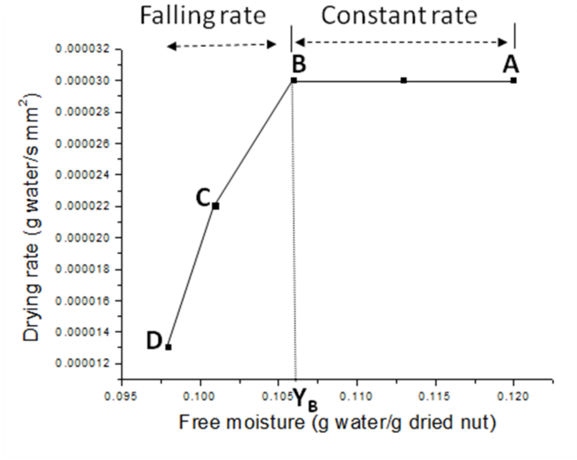

Figure 3: Drying Rate Curve of *Tenera* nut.

The dry mechanism introduced to the nut prior cracking is commendable. It produces desired effect during mechanical cracking. The result of machine performance showed that in *dura*, as the moisture content decreased from 12.00 - 9.00%; machine cracking efficiency increased from 92.30 - 96.40% as shown in Figure 4, quality performance efficiency increased from 91.00 - 95.30% as shown in Figure 5 and mechanical damage decreased from 2.47 - 1.40% as shown in Figure 6. Similarly, in *tenera*, as the moisture content decreased from 12.00 - 8.20%; cracking efficiency increased from 95.50 - 99.07%, quality performance efficiency increased from 95.50 - 98.80% and mechanical damage decreased from 1.16 - 0.20%. The rate at which moisture content reduced under the same timing is inherently different in the two varieties as a result of differences in shell thickness.

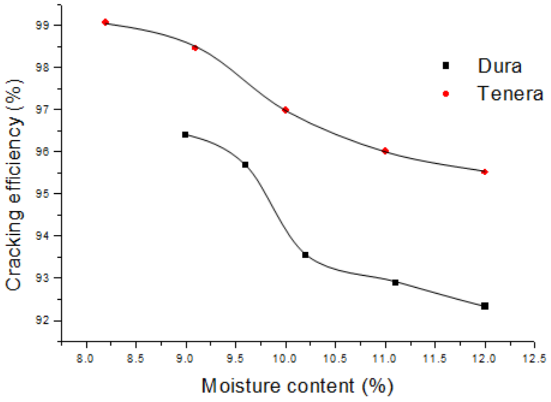

Figure 4: Effect of Nut Drying on Cracking Efficiency.

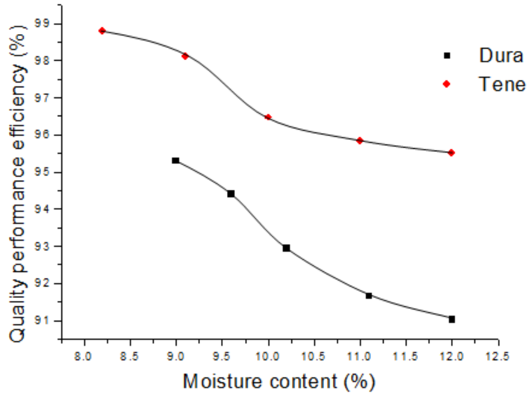

Figure 5: Effect of Nut Drying on Quality Performance Efficiency.

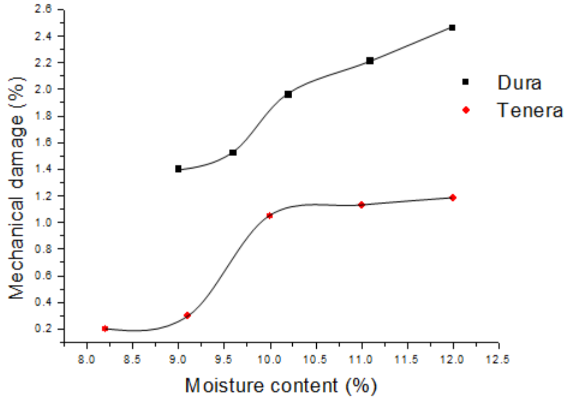

Figure 6: Effect of Nut Drying on Mechanical Damage.

CONCLUSIONS

1. The movement of water through the nut during drying depends on shell thickness/porous structure as well as interaction of water within the nut matrix.

2. The drying rate is governed by the diffusion of liquid due to concentration gradient.

3. Inadequate dry of palm nut causes mechanical damage to the kernel during cracking and over dry cause's loss of the kernel oil.

4. The drying concept enhanced whole kernel recovery during cracking with little or no mechanical damage.

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