Journal of Engineering and Applied Sciences 7 (4): 326-330, 2012
ISSN: 1816-949X
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Mass Transfer During Oil Extraction from Palm Kernel, Cocoa and Groundnut

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Abstract: Mass transfer rate during solvent extraction of oils from palm kernel, cocoa and groundnut were determined at varied temperature and time. Total oil content in palm kernel, cocoa and groundnut used for the study were 42.3, 24.7 and 54.6%, respectively. Oil yields after 5 h of extraction at 60, 70 and 80°C for palm kernel, cocoa and groundnut were 23.5, 33.9, 36.8; 15.4, 20.5, 20.9; 31, 42.4 and 48.1%, respectively. The coefficients of determination of regression equations ranged from 0.982-0.999. The average mass transfer coefficient for palm kernel oil at 60, 70 and 80°C were $1.5\times10^{-4}\pm9.9\times10^{-5}$, $2.0\times10^{-4}\pm4.9\times10^{-5}$ m h^{-1} and $2.5\times10^{-4}\pm9.4\times10^{-5}$, respectively. The mean coefficient for cocoa extracted 60, 70 and 80°C were $4.9\times10^{-4}\pm7.3\times10^{-5}$, $5.4\times10^{-4}\pm8.8\times10^{-5}$ and $7.9\times10^{-4}\pm9.2\times10^{-5}$, respectively. For groundnut, the mean coefficients at 60, 70 and 80°C were $1.2\times10^{-4}\pm2.9\times10^{-5}$, $2.7\times10^{-4}\pm1.5\times10^{-5}$ and $1.0\times10^{-3}\pm1.0\times10^{-4}$. Extraction temperature and duration had significant effect on mass diffusivity and transfer coefficient at $p<0.05$.

Key words: Palm kernel, cocoa, groundnut, solvent temperature, oil extraction, diffusivity, mass transfer, model

INTRODUCTION

Oil is recovered from oil bearing material by either mechanically or solvent extraction method. The kinetics of oil extraction from oilseeds and by-products is dependent on a number of factors. These include the structural and mechanical properties, composition and morphology of the raw material, temperature and duration extraction and polarity of the solvent used for extraction (Nieh and Snyder, 1991). During solvent extraction, the rate at which equilibrium is attained between the free miscella flowing past, the solid particles and the miscella absorbed within the solids can be associated to the mass transfer rate. Mass transfer studies provide a basis for design of industrial scale extraction processes (King *et al*., 1997) hence, it is important to develop models for the extraction process when the extraction operations are optimized for commercial applications since, this extraction method remains the most widely used method for solid samples. However, predictions from such optimized conditions require the establishment of model which can predict phase behavior, equilibrium, solubility, adsorption, desorption and others.

Relationships, as well as models for equipment design take into consideration the effect of fluid flow, mass and heat transfer and the phase contacting mechanisms. The development of mass transfer models requires an understanding of the diffusion coefficient of the solute (Norhuda and Omar, 2009). These properties are important in the correlation of mass transfer coefficients. Knowledge of mass transfer is required in modeling extraction kinetics at any given period and forms the basis of designing processing equipment. Studies on the solubility of seed oils have provided a basis on which to design processes for the rapid and efficient removal of oil from a variety of seed and natural product matrices. Examples of such include the extraction of oil from evening primrose seed; aqueous extraction of oil from sunflower seed (Topallar and Gecgel, 2000); moisture absorption and thermodynamic properties of palm kernel (Ajibola *et al*., 2005); extraction of protopine from Fumaria (Rakotondramasy *et al*., 2007); extraction of oil from palm kernel (Norhuda and Omar, 2009) and extraction kinetics of jatropha seed (Sayyar *et al*., 2009).

These researches explored the fundamental variables that influenced the mass transfer of solutes from solid substrates and provided the basis for several other modelling studies involving oilseed substrates. Palm kernel (*Elaeis guineensis*), cocoa (*Theobroma cacao*) and groundnut (*Arachis hypogea*) are commercially cultivated in Nigeria. Their fat extract and meal are of high economic importance. Solvent extraction is the most appropriate method in obtaining a low-fat meal in which proteins are not heat denatured (Fereidoon, 2005). It is also known that employing solvents to extract vegetable oils in large quantities are in wide use because of high efficiency. Therefore, the thrust of the research was to study the effects of extraction temperature and period on mass transfer rate of oil from palm kernel, cocoa and groundnut during solvent extraction.

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MATERIALS AND METHODS

Experimental procedure: The experiment involved the use of soxhlet apparatus for oil extraction. The apparatus are made of soxhlet extractor, condenser, heating mantle, thimble, round bottom flask, filter paper and solvent (n-hexane). Methodology adopted was AOAC 920.39C Method for fat extract determination (AOCS, 2005). About 50.0 g each of the sample was separately placed in the extractor and heated at desired temperature (60, 70 and 80°C) and duration (1-5 h). Weight of sample was measured hourly. Weight loss was taken to be the quantity of oil extracted per hour and each process was replicated thrice and mean values were recorded. Percentage oil yield was calculated using Eq. 1. Total oil contents in the seeds were determined by extending extraction duration to 10 h:

$$\text{Oil yield}(\%)=\frac{\text{Initial weight}-\text{Final weight}}{\text{Initial weight}}\times 100 \quad (1)$$

The data obtained were subjected to descriptive, regression analysis and analysis of variance at 5% level of significance. Trend study using graphs was also carried out.

Evaluation of diffusivity: The diffusion that took place during the extraction process was considered as unsteady-state in one direction in a solid, thus Fick's 2nd Law of Diffusion was applied (Eq. 2):

$$\frac{\partial C_A}{\partial t}=D_{AB}\frac{\partial^2 C_A}{\partial x^2} \quad (2)$$

General solutions of the heat conduction equation for simple shapes can be used for transient problems (King *et al*., 1997). Therefore for diffusion into or out of a cylinder (since shape of thimble that contained granules was cylindrical), Eq. 2 was reproduced by McAdams (1954) thus:

$$\frac{C_s-C}{C_s-C_o}=0.692e^{-5.78Fom}+0.131e^{-30.5Fom}+0.0534e^{-74.9Fom}+\ldots \quad (3)$$

However in cases where F_0 is >0.1, only the 1st term of the series in Eq. 3 was significant and other terms may be ignored. Thus, time required to change the concentration from C_A-C_B can be determined by rearranging Eq. 3. In applying the equation, it was assumed that surface concentration was constant and the internal resistant was also negligible:

$$t=\frac{s^2}{5.78D_v}\text{In}\,0.692\frac{[C_s-C_o]}{[C_s-C]} \quad (4)$$

And;

$$D_v=\frac{S^2}{5.78t}\text{In}\left[0.692\frac{[C_s-C_o]}{[C_s-C\,]}\right] \quad (5)$$

Analysis of mass transfer coefficients: Mass transfer coefficient is the rate of mass transfer per unit area, per unit concentration difference and is usually based on equal molar flows. This can be represented mathematically by Eq. 6 according to McCabe *et al.* (2005):

$$K_c=\frac{J_A}{C_{Ai}-C_A} \quad (6)$$

$$J_A=\frac{D_v}{B_T}[C_{Ai}-C_A] \quad (7)$$

Therefore:

$$K_c=\frac{D_v}{B_T}[C_{Ai}-C_A]x\frac{1}{C_{Ai}-C_A} \quad (8)$$

and;

$$K_c=\frac{D_v}{B_T} \quad (9)$$

Equation 9 is applicable to both steady and un-steady diffusion (McCabe *et al*., 2005)

RESULTS AND DISCUSSION

Effect of extraction temperature on oil yield: The total oil content in palm kernel, cocoa and groundnut used for the study were 42.3, 24.7 and 54.6%, respectively. From the plot of percentage oil yield against temperature as shown in Fig. 1, it was generally observed that as the Hence, temperature increased there was a corresponding increase in the oil yields of the three oil seeds, although the rate of increase in each oil seed was difference.

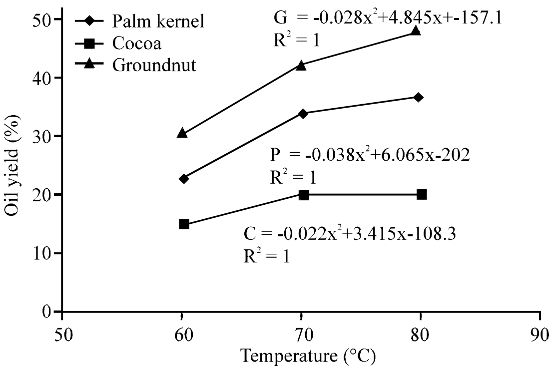

Fig. 1: Relationship between oil yield and extraction temperature

Oil yield after 5 h of solvent extraction at 60, 70 and 80°C for palm kernel, cocoa and groundnut were 23.5, 33.9, 36.8; 15.4, 20.5, 20.9; 31, 42.4 and 48.1%, respectively. This also shows that 55.1, 80.1 and 87.0% of total palm kernel oil content were extracted at 60, 70 and 80°C, respectively. Similarly, 63.2, 83.0 and 84.6% total content of cocoa oil were extracted at 60, 70 and 80°C, respectively and 56.8, 77.7 and 88.1% of total groundnut oil content were extracted at 60, 70 and 80°C, respectively. The trend of all the plots showed fitness for 2nd order polynomial with very high coefficients of determination as shown in Fig. 1. The observed variation in responses of the oilseeds to solvent extraction temperature may be attributed to differences in oil contents of each seed. In addition, degrees of solvent penetration have been reported to be dependent on cell wall thicknesses of oil seeds (Fereidoon, 2005). At higher temperature, solubility of oil in hexane increased due to a higher intermolecular interaction between hexane and oil molecules which enhanced the extraction rate, thus resulted in higher amount of oil extracted (King *et al*., 1997).

Furthermore at higher temperature, the hexane can easily penetrate into the oil-bearing seeds to be extracted, dissolve in it and carry away the soluble components. It is to be noted also that fitness of the reaction into 2nd order polynomial is an indication that optimum extraction temperature exists.

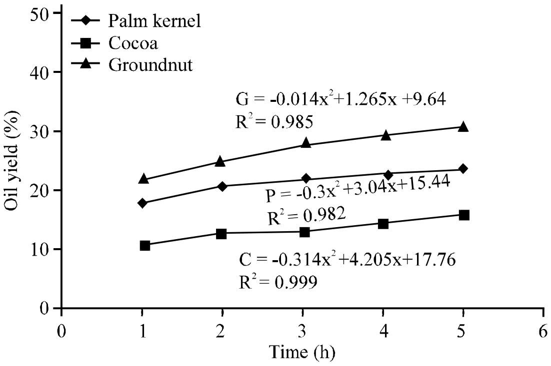

Fig. 2: Oil extraction yield at 60°C

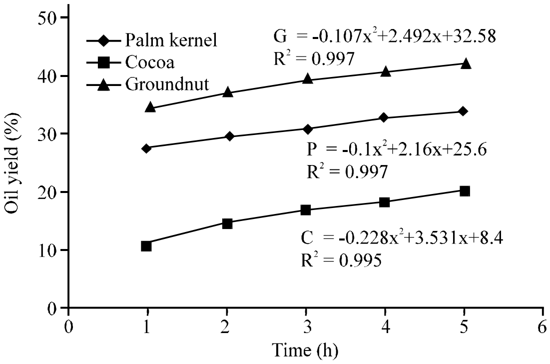

Fig. 3: Oil extraction yield at 70°C

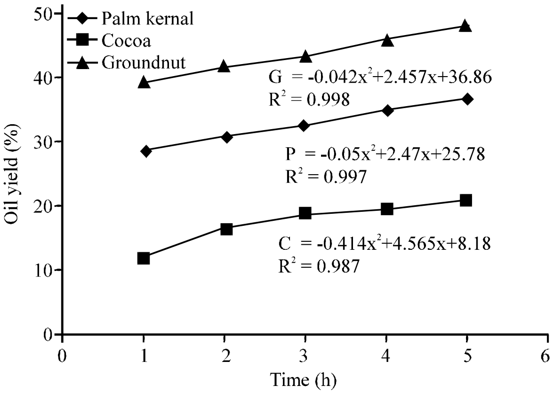

Fig. 4: Oil extraction yield at 80°C

The effect of extraction duration on oil yield: The effect of extraction on oil yield is shown graphically in Fig. 2-4. The trend of all the plots showed increase in oil yield with increase in extraction duration. However, the relationship is polynomial. The coefficients of determination of the regression R^2 equations ranged from 0.982-0.999. It was observed in this study that at 60°C solvent extraction temperature, 42.6, 43.7 and 39.6% of the total oil content in palm kernel, cocoa and groundnut were respectively extracted in the 1st 1 h. At 70°C, 65.2, 47.0 and 64.1% of the total oil content in palm kernel, cocoa and groundnut were extracted, respectively in the 1st 1 h. Percentage oil extracted in the 1st 1 h of extraction at 80°C was 66.7, 50.0 and 71.8% for palm kernel, cocoa and groundnut, respectively. The general observation was that high proportion of the extraction took place during the 1st hour of extraction (Fig. 2-4). A solid-liquid extraction process is found to be most appropriately fitted by a 2nd order model (Rakotondramasy *et al*., 2007). Similar observation was also reported by Norhuda and Omar (2009) using supercritical CO_2 for oil extraction. The observation can be explained by extraction theory which described the extraction process to occur in two stages. First, the major part of the solute gets extracted quickly because of the scrubbing and dissolution caused by the driving force effect of the fresh solvent then comes the next stage where the extraction process becomes much slower as influenced by external diffusion of the remaining solute into the solution. In kinetics study, by increasing the extraction temperature, the optimum extraction duration can be reduced as reaction occurs faster. The final concentration also increased with temperature due to the thermodynamic effect of temperature on solubilization of oil inside the solid. This means that extraction rate was

Table 1: The diffusivity and mass transfer coefficient during oil extraction from palm kernel

	Diffusivity ($m^2\,h^{-1}$)			Coefficient ($m\,h^{-1}$)		
Time (h)	60°C	70°C	80°C	60°C	70°C	80°C
1	7.13×10^{-6}	9.16×10^{-6}	7.57×10^{-5}	2.40×10^{-4}	3.05×10^{-4}	2.52×10^{-3}
2	7.06×10^{-6}	8.57×10^{-6}	2.69×10^{-5}	1.40×10^{-4}	1.50×10^{-4}	8.99×10^{-4}
3	5.81×10^{-6}	6.31×10^{-6}	1.53×10^{-5}	1.04×10^{-4}	1.40×10^{-4}	5.10×10^{-4}
4	4.43×10^{-6}	5.98×10^{-6}	1.02×10^{-5}	1.80×10^{-5}	9.90×10^{-5}	3.41×10^{-4}
5	3.46×10^{-6}	4.13×10^{-6}	7.11×10^{-6}	1.20×10^{-5}	3.80×10^{-5}	2.37×10^{-4}

Table 2: The diffusivity and mass transfer coefficient during oil extraction from cocoa

	Diffusivity ($m^2\,h^{-1}$)			Coefficient ($m\,h^{-1}$)		
Time (h)	60°C	70°C	80°C	60°C	70°C	80°C
1	5.38×10^{-5}	6.04×10^{-5}	7.15×10^{-5}	1.79×10^{-3}	2.01×10^{-3}	2.38×10^{-3}
2	4.66×10^{-5}	5.17×10^{-5}	7.49×10^{-5}	1.55×10^{-4}	3.91×10^{-4}	8.33×10^{-4}
3	4.26×10^{-6}	5.66×10^{-6}	1.42×10^{-5}	1.30×10^{-4}	1.67×10^{-4}	4.73×10^{-4}
4	3.73×10^{-6}	4.08×10^{-6}	6.14×10^{-6}	1.01×10^{-4}	1.15×10^{-4}	2.05×10^{-4}
5	1.16×10^{-6}	2.31×10^{-6}	2.85×10^{-6}	2.10×10^{-6}	3.90×10^{-6}	9.48×10^{-5}

Table 3: The diffusivity and mass transfer coefficient during oil extraction from groundnut

	Diffusivity ($m^2\,h^{-1}$)			Coefficient ($m\,h^{-1}$)		
Time (h)	60°C	70°C	80°C	60°C	70°C	80°C
1	1.19×10^{-5}	1.39×10^{-5}	8.70×10^{-5}	2.63×10^{-4}	3.97×10^{-4}	2.90×10^{-3}
2	3.59×10^{-6}	4.51×10^{-6}	3.22×10^{-5}	2.60×10^{-4}	3.60×10^{-4}	1.07×10^{-3}
3	2.74×10^{-6}	2.89×10^{-6}	1.63×10^{-5}	2.57×10^{-4}	4.80×10^{-4}	5.43×10^{-4}
4	2.11×10^{-6}	2.24×10^{-6}	9.77×10^{-6}	2.50×10^{-5}	5.44×10^{-5}	6.26×10^{-5}
5	1.23×10^{-6}	1.86×10^{-6}	6.17×10^{-6}	1.71×10^{-5}	2.20×10^{-6}	2.05×10^{-5}

fast at the beginning but reduced gradually. Fresh solvent solubilized free oil on the surface of seeds and thus, inducing a fast increase in the extraction rate (Sepidar *et al*., 2009). The behaviour can also be justified by the fact that diffusion rate is a function oil-solvent concentration.

Mass diffusivity: The mass diffusivity recorded during oil extraction from palm kernel, cocoa and groundnut are shown in Table 1-3, respectively. Polynomial relationship was observed. However, highest value of diffusivity was generally recorded during the 1st 1 h of extraction.

Test of significance between the extraction temperature impacts showed significant differences at $p<0.05$. Polynomial behaviour may be attributed to non-homogeneous nature of the oilseed being bio-material. According to Fick's 1st Law of Diffusion, mass flux per unit area of a component is proportional to its concentration. Thus, the degree of oil concentration could have influenced the diffusivity. Similar observation was reported during the frying of catla fish (Pandey *et al*., 2008). Mass diffusivity magnitudes are a function of temperature and concentration (Singh and Heldman, 2005). This implies that temperature has remarkable influence on diffusivity during solvent extraction of oil from palm kernel, cocoa and groundnut. The findings agreed with those who concluded that the most important conditions during solvent extraction of soybean oil were temperature and duration of extraction, as well as the polarity of the solvent used for extraction (Nieh and Snyder, 1991).

Mass transfer coefficient: The results of empirical determination of mass transfer coefficients during oil extraction from palm kernel, cocoa and groundnut were shown in Table 1-3. The average mass transfer coefficient for palm kernel oil extraction at 60, 70 and 80°C were $1.5\times10^{-4}\pm9.9\times10^{-5}$, $2.0\times10^{-4}\pm4.9\times10^{-5}$ m h^{-1} and $2.5\times10^{-4}\pm9.4\times10^{-5}$, respectively. Also, $4.9\times10^{-4}\pm7.3\times10^{-5}$, $5.4\times10^{-4}\pm8.8\times10^{-5}$ and $7.9\times10^{-4}\pm9.2\times10^{-5}$ were the mean coefficients for cocoa extracted 60, 70 and 80°C, respectively while for groundnut, the mean coefficients at 60, 70 and 80°C were $1.2\times10^{-4}\pm2.9\times10^{-5}$, $2.7\times10^{-4}\pm1.5\times10^{-5}$ and $1.0\times10^{-3}\pm1.0\times10^{-4}$, respectively. Extraction temperature and duration had significant effect on mass transfer coefficient at $p<0.05$.

CONCLUSION

Oil yield increased with increase in solvent extraction temperature and duration for the three oilseeds under study. High proportion of oil extraction took place during the 1st hour of extraction. The process of solvent extraction of oil from palm kernel, cocoa and groundnut was best described by 2nd order polynomial model. Groundnut had highest oil content, followed by palm kernel and cocoa in that order. The variation in oil contents influenced the rate of oil extraction. Mass diffusivity and coefficient of mass transfer during solvent extraction of oil from palm kernel, cocoa and groundnut significantly depended on solvent extraction temperature and oil concentration.

NOMENCLATURE

B_T = Thickness of layer through which diffusion occurs (m)
C_{Ai} = Concentration of component A at interface (kg mol m^{-3})
C_A = Concentration of component A (kg mol m^{-3})
C_s = Surface concentration of diffusing component (kg mol m^{-3})
C_o = Initial concentration (kg mol m^{-3})
C = Average concentration (kg mol m^{-3})
D_{AB} = Diffusivity of component A in component B (m^2 sec^{-1})
D_v = Volumetric diffusivity m^2 h^{-1}
F_{om} = Fourier number for mass transfer = D_v t sec^{-2}
t = Time (h)
K_c = Mass transfer coefficient (m sec^{-1})
S = Thickness (m)
J_A = Mass flux of component A (kg mol m^{-2})
x = Distance measured parallel with flow (m)

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