Effect of drying conditions on energy utilization during cocoyam drying

Tinuade Afolabi, Toyosi Tunde-Akintunde, Bosede F Olanipekun

(*Department of Food Science and Engineering, Ladoke Akintola University of Technology, PMB 4000, Ogbomoso, Oyo State, Nigeria*)

Abstract: Cocoyam samples soaked in sodium metabisulphite (SM) and water blanched (WB) were oven dried at 50, 60 and 70 ℃ and microwave power levels of 385, 540 and 700 W while untreated samples were sun dried. The effects of drying on selected properties of cocoyam were studied. The drying time generally reduced with increase in drying temperature and power level used. The use of SM pretreatment resulted in lower drying times compared with WB pretreatment. Effective moisture diffusivity values (D_{eff}) for all the drying conditions varied from 5.27×10^{-8} to 2.07×10^{-6} m^2/s and SM samples had higher values than WB samples. Activation energy values for oven drying were 37.41 kJ/mol and 61.79 kJ/mol and that for microwave drying were 38.59 and 41.91 W/g for SM and WB samples respectively. The energy consumption varied from 30 to 50 kWh for oven drying and 308 to 396.7 Wh for microwave drying while that of specific energy requirement varied from 86.2 to 106.5 kWh/kg and 1.49 to 2.03 kJ/kg water for oven drying and microwave drying respectively.

Keywords: oven, microwave, pretreatment, activation energy, energy consumption

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1 Introduction

Roots and Tubers which include cassava, yam, cocoyam and sweet potatoes are plants whose edible portions are the underground roots or tubers which are generally high in carbohydrate (Akanbi et al. 2004). The large proportion of the inhabitants of the tropics depends on tuber crops for the supply of carbohydrate in their diet, especially in the rain forest zone of the tropics where the growing of cereals is difficult (Akanbi et al. 2004). Root and tuber crops are rank next in importance to the cereal grains in providing the major part of the daily caloric needs of people in the tropics (Ngoddy and Ihekoronye, 1985). However unlike grains, root and tuber crops have high water content which is probably the major drawback in improving the utilization potential of the crops (Ngoddy and Ihekoronye, 1985).

Cocoyam (*Colocasia esculenta*) is a root and tuber crop that belongs to the family Araceae (Akanbi et al., 2004). Cocoyam as a food provides digestible starch and contains relatively high levels of protein compare to most root and tuber crops (Susan and Anne, 1988). They are good source of dietary carbohydrates, proteins, vitamins A and C, thiamine, niacin, calcium, phosphorus and iron (Ngoddy and Ihekoronye, 1985). They are however rich in fat in which linoleic acid is the most abundant among the fatty acids (Ngoddy and Ihkoronye, 1985). Cocoyam corms and cormels can be prepared domestically in different ways: pounding, either pure or mixed with yam and cassava, boiled, roasted. It is also used in preparing cocoyam chips ('achicha'). Porridge is also a popular form of consuming cocoyam corms while cocoyam flour is another product that can also be produced from it. However, one of the major limitations in its utilization potential is the high water content. The high water content which ranges from 70 to 80% however, leads to problems of storage as well as dehydration prior

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Corresponding author: T. J. Afolabi, Department of Food Science and Engineering, Ladoke Akintola University of Technology, PMB 4000, Ogbomoso, Oyo State, Nigeria. Email: toyositunde@yahoo.co.uk.

to subsequent processing (Ngoddy and Ihekronye, 1985). In recent times, the degradation of most food crops including cocoyam in developing countries was estimated to be 30% - 40% of production (Tunde-Akintunde and Ogunlakin, 2011). Hence, there is need for preservation.

Drying is the most accepted and probably the oldest method of preservation. Drying methods include domestic drying (mainly sun drying) and industrial drying (solar drying, tunnel drying, vacuum oven drying and cabinet drying among others). Drying of large quantities of food products improves shelf life, retain original flavor, reduce packaging costs, lower weights, enhance appearance, and maintain nutritional value (Baysal et al. 2003). The drying of food materials also has advantage on quality control, achievement of hygienic conditions and reduction of product loss. Factors that mostly affect drying are related to drying air, i.e. temperature, relative humidity and velocity in addition to the product initial moisture content. However, utilization of high amount of energy in the drying industries makes drying one of the most energy-intensive operations with great industrial significance (Carsky, 2008). Thus, reduction in the energy utilization during drying is important in order to conserve the remaining little energy for other process requiring energy. Thereby maximizing the production and minimizing the cost of energy.

Kinetics of drying process for food products have been undertaken by several researchers (Akpinar et al. 2003; Ertekin and Yaldiz, 2004; Midili and Kucuk, 2003a; Togrul and Pehlivan, 2003). Kinetics of drying is useful in design and analysis of mass and heat transfer processes during drying. Thermodynamics analysis, however has appeared to be an essential tool for system design, analysis and optimization of thermal systems (Dinner and Sahin, 2004). Thus this study is carried out to optimize cocoyam drying process by determining the drying method and pretreatment of cocoyam that utilizes a minimum amount of energy for maximum moisture removal.

2 Materials and Methods

2.1 Material selection and preparation

Cocoyam samples were obtained from Sabo market in Ogbomoso, Oyo state and were washed in a bowl of clean water and peeled with table knife under water. The peeled cocoyam were sliced into uniform thickness of about 3 cm×5 cm×5 cm. The sliced cocoyam was pretreated using two methods: (i) one set was soaked for 5 min in 0.2% sodium metabisulphite solution; (ii) the second set was water blanched for 5 min at a temperature of 100 ℃; while a set of untreated cocoyam slices were used as control. After pretreatment, cocoyam samples were dried in a hot air oven or a microwave dryer.

For oven drying, cocoyam samples were placed in perforated oven tray and placed in a hot-air oven for drying. The oven was preheated for about 1 hour before the samples were placed in the oven to ensure that steady state conditions in the dryer had been reached. The hot air flow at a velocity of 1.5 m/s which passed across the surface of the drying material and perforated bottom of the drying tray was parallel to the samples. The drying temperatures for cocoyam slices utilized in this study were 50 ℃, 60 ℃ and 70 ℃.

The cocoyam slices were placed in a microwave dryer which was operated by a control terminal which could be used to choose the microwave power level. The oven has a fan for air flow in drying and moisture from the drying cavity was removed using the fan by passing it through the openings on the right side of the oven wall to the outer atmosphere. During each drying experiment, weight reduction of the slices was measured at regular time interval of 30 min using a PH Mettler digital balance (which had an accuracy of ±0.01 g). The drying process was terminated when three consecutive readings had constant values. Drying was carried out in triplicates and the mean values were used to plot the drying graphs.

2.2 Analysis

The AOAC (1990) method (drying in a hot-air oven at 100°C for 18h) was used to calculate the initial moisture content, M_i, of 1.5 kg water/kg dry matter and the moisture content values at time t, during the drying process were determined using the following equation:

$$M_t = M_i - \frac{w_l}{w_d} \tag{1}$$

where, M_t is the moisture content at any time of drying (kg water/kg dry matter); M_i is the initial moisture content (kg water/kg dry matter); w_l is the loss in weight at time t (kg) and w_d is the dry matter weight (kg).

The moisture ratio drying curves having an initial value of 1 for all the drying experiments were used to plot the drying curves instead of the moisture content of its uniformity. The moisture ratio during drying was obtained from the moisture content values using the following equation:

$$M_R = \frac{M_t - M_e}{M_i - M_e} = \exp(-Kt) \quad (2)$$

where, M_R is the dimensionless moisture ratio; M_t is moisture content at any time of drying (kg water/kg dry matter); M_i is the initial moisture content (kg water/kg dry matter) and M_e is the equilibrium moisture content (kg water/kg dry matter), respectively.

The equilibrium moisture contents (EMCs) were obtained when no further change in weight was observed for the cocoyam slices during each drying experiment (Hii et al. 2009).

2.3 Effective Moisture Diffusivity

Drying of cocoyam slices took place in the falling-rate drying period and as a result the Fick's second law of diffusion equation was used to determine the effective moisture diffusivity. Crank (1975) gave a solution for the Fick's equation assuming that there is uniform initial moisture distribution; moisture migration by diffusion, negligible external resistance, negligible shrinkage, constant diffusivity and temperature. The diffusivity coefficient, D_{eff}, was thus determined by using the equation below

$$M_R = \frac{M_t - M_e}{M_i - M_e} = \frac{8}{\pi^2} \exp\left(\frac{-\pi^2 D_{eff} t}{4L^2}\right) \quad (3)$$

where, M_R is the dimensionless moisture ratio; D_{eff} is the effective moisture diffusivity (m^2/s); t is the drying time (s) and L is half of the slab thickness (m).

The graph of Ln(MR) against time for the drying experiments carried out at different temperatures was plotted and the method of slopes was used to determine the diffusion coefficient (Doymaz 2007). The effective diffusivity coefficient, D_{eff}, was determined from the slope of the graph using the equation below

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

2.4 Determination of Energy Requirement

An Arrhenius type equation (Doymaz 2010) which predicts the dependence of the effective diffusivity on the different drying temperature was used to calculate the energy of activation as indicated in the equation below:

$$D_{eff} = D_o \exp\left[\frac{-E_a}{R_g T_{abs}}\right] \quad (5)$$

where, D_{eff} is the effective moisture diffusivity (m^2/s); D_o is a constant (the pre-exponential factor of Arrhenius equation or maximum diffusion coefficient (at infinite temperature) in m^2/s); E_a is the energy of activation (kJ/mol); R_g is the universal gas constant (8.3143 kJ/mol) and T_{abs} is the absolute air temperature (K).

The logarithm of the linear form of the equation above is given as follows:

$$\text{Ln}(D_{eff}) = \text{Ln}D_o + \frac{E_a}{R_g T_{abs}} \quad (6)$$

The activation energy is calculated from the slope, K_2 of the graph of LnD_{eff} against 1/T_{abs} using the following equation;

$$K_2 = \frac{E_a}{R_g} \quad (7)$$

The total needed energy for drying one charge of the heater and energy requirements for drying 1 kg of fresh cocoyam slices in a hot-air oven for each of the drying experiments were calculated from the following Eqns. (8) and (9), respectively:

$$E_t = A\upsilon\rho_a c_a \Delta T D_t \quad (8)$$

where, E_t is the total needed energy for drying at each experimental condition (kWh); A is the tray area (m^2); υ is the air velocity (m/s); ρ_a is the air density (kg/ m^3); c_a is the specific heat of air (kJ/kg°C); ΔT = temperature differences and D_t is the total drying time (s)

$$E_{kg} = \frac{E_t}{W_o} \quad (9)$$

where, E_{kg} = specific energy requirement (kWh/kg) and W_o = initial weight of samples (kg).

The total energy consumption in each drying experiment and specific energy consumption (energy needed to evaporate a unit mass of water (Soysal et al.

2006) for the microwave drying were determined by the following equations:

$$E_c = P \times \frac{t}{60} \tag{10}$$

and

$$E_s = \frac{P \times t}{m_w} \tag{11}$$

where, E_c is the energy consumption (Wh) during each drying operation using the microwave and E_s is the specific energy consumption (J/kg water); P is the microwave power (W); and m_w is the total mass of evaporated water (kg).

2.5 Statistical Analysis

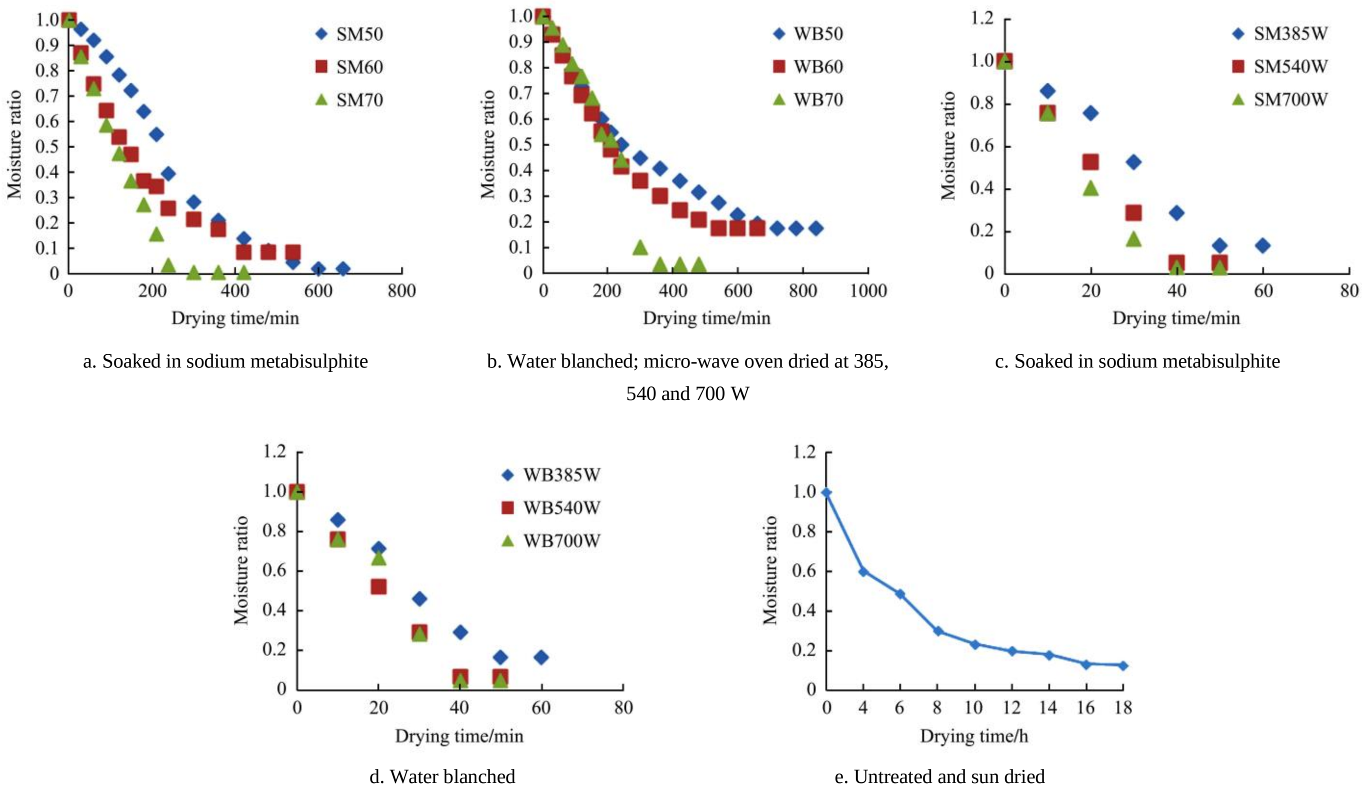
The effect of pretreatment and drying method on drying time, moisture diffusivity and energy requirement was determined by using the analysis of variance using the SAS program (SAS 1985) at a confidence level of 95%. Duncan's multiple tests at the same confidence level of 95% was used to compare the means.

3 Results and Discussion

3.1 Drying kinetics

The reduction in moisture ratio values with increase in drying time for various drying experiments are as shown in Figure 1. From the drying curves, it can be observed that the moisture ratio decreases continuously with drying time as drying proceeds. This is because of the decrease in free water present in the drying material as drying continues. This reduction in free water as drying continues also resulted in rapid moisture removal at the initial stages of drying and a reduction in moisture removal as drying progresses till the end of the drying process when no moisture is removed. This is because the free water in the product, would was evaporated leaving the bound water which is not available.

The air temperature was observed to enhance the drying process significantly, since an increase in the drying temperature resulted in a more rapid drying. This is probably due to the fact that higher drying temperatures result in a greater heat transfer and also a larger water vapour pressure deficit. This is because the higher the drying air temperature, the bigger the difference between the saturated and partial pressure of water vapor in the drying-air thus increasing the maximum amount of water (saturation) that air can hold at that temperature. This is in agreement with the reports made by several authors (Vega-Gálvez et al. 2011; Rayaguru et al. 2012; Darvishi et al. 2013).



a. Soaked in sodium metabisulphite

b. Water blanched; micro-wave oven dried at 385, 540 and 700 W

c. Soaked in sodium metabisulphite

d. Water blanched

e. Untreated and sun dried

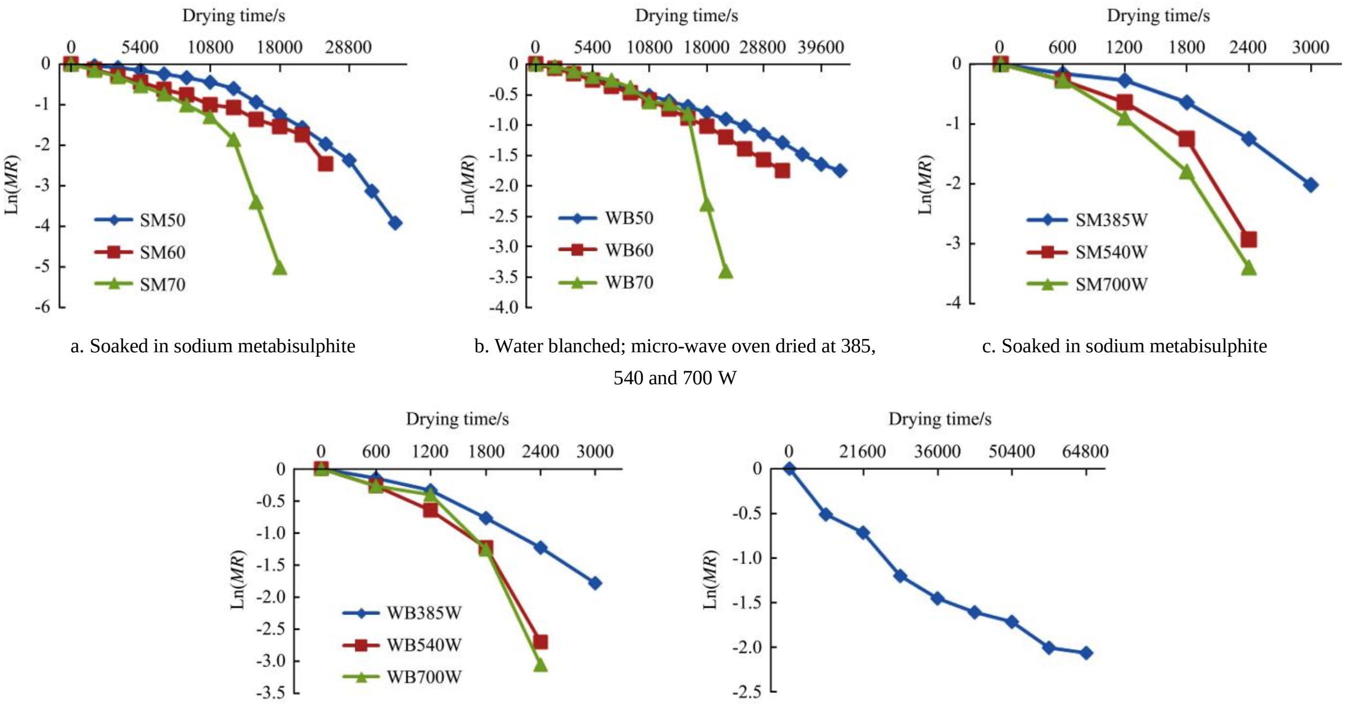
Figure 1 Cocoyam drying curves for oven dried at 50, 60 and 70 ℃

Higher microwave power level also resulted in a more rapid drying of the cocoyam slices. The decrease in drying time with an increase in the microwave power density has been reported for other food materials, including tomato pomace (Al-Harahsheh et al. 2009), onions (Arslan and Ozcan, 2010), and potatoes slices (Darvishi, 2012). This decrease in drying time with increase in power level is due to the mass transfer within the sample which progresses more rapidly during higher microwave power heating. This is because of the generation of more heat within the sample which creates a larger vapor pressure difference between the center and the surface of the slices due to the characteristic microwave volumetric heating.

The time required for drying cocoyam slices also decreased as the drying-air temperature increased. This is because since faster moisture removal was observed at higher temperatures, the drying time needed to reach a specified moisture ratio decreased. This is similar to the observations of other authors (Lee and Kim, 2009; Doymaz, 2010). The time taken to reach a moisture ratio value of about 0.2 was approximately 720, 540 and 300 min at temperatures of 50, 60 and 70℃ for water blanched cocoyam slices. This implies that an increase in drying temperature from 50 to 60℃ and then to 70℃ reduced the drying time by about 25% and 58% respectively. Pretreatment of cocoyam samples also was observed to have a significant effect on the drying time. Cocoyam slices soaked in SM dried faster than that of water blanched samples. At the same drying temperatures of 60℃, a moisture ratio of 0.2 was reached by WB and SM samples at 480 and 320 min respectively, which indicates that the drying time for SM is a reduction of drying time of WB by 33%.

3.2 Effective moisture diffusivity

The effective moisture diffusivity, D_{eff}, of cocoyam slices at corresponding moisture contents under different drying conditions was determined using the method of slopes. The graph of Ln(*MR*) plotted against drying time (*t*) is shown in Figure 2.



a. Soaked in sodium metabisulphite
b. Water blanched; micro-wave oven dried at 385, 540 and 700 W
c. Soaked in sodium metabisulphite
d. Water blanched
e. Untreated and sun dried

Figure 2 Graphs of Ln(*MR*) against drying time: oven-dried at 50, 60 and 70°C

The effective moisture diffusivity values for the various pretreatments and drying method which varied from 5.27×10^{-8} to 2.07×10^{-6} m^2/s are shown in Figure 3. These values are within the range generally obtained for drying of food materials (Doymaz, 2010). The D_{eff} values for oven and microwave-oven drying were generally higher than that of sun drying while the D_{eff} values increased with increase in temperature of oven or power level of micro-wave oven thus resulting in lower drying times at higher oven drying temperatures and microwave power levels.

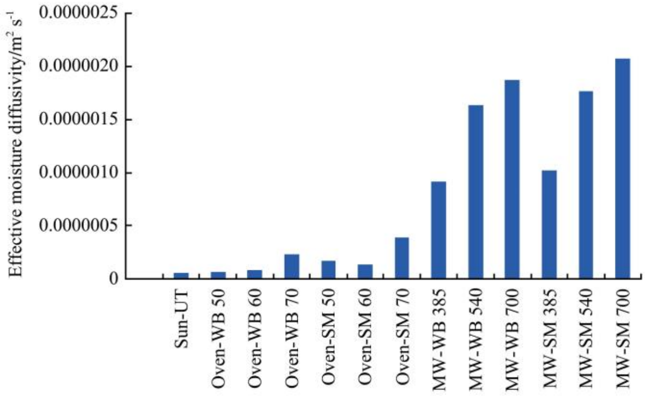


Figure 3 D_{eff} values for cocoyam drying (UT-untreated, WB-water blanched, SM-soaked in sodium metabisulphite, 50, 60 and 70 are oven drying temperatures (°C) and 385, 540 and 700 are the power ranges (W) for the microwave)

A similar effect of increase in moisture diffusivity values with increase in air drying temperature for oven drying is also reported apricots (Doymaz, 2004a), peaches (Kingsly et al. 2007), plums (Goyal et al. 2007), berberis fruit (Aghbashlo et al. 2008), corn (Chayjan et al. 2011) and stone apple slices (Rayaguru et al. 2012).

Effective moisture diffusivity values for the oven drying of cocoyam are within the range reported for oven drying of other root and tuber crops i.e. 1.013 to 3.799 × 10^{-8} m^2/s for potato (Darvishi et al., 2013), 4.87 × 10^{-11} m^2/s to 1.29 × 10^{-9} m^2/s for corn (Chayjan et al., 2011), 7.31 × 10^{-7} m^2/s to 8.06 × 10^{-7} m^2/s for cassava (Tunde-Akintunde and Afon, 2009) but higher than the values reported for fruits. Effective moisture diffusivity values for root crops should not normally be higher than that of fruits but this occurrence could be as a result of the experimental conditions employed in the studies carried out. The values obtained for some of the fruits includes 3.7317 × 10^{-10} m^2/s to 6.675 × 10^{-10} m^2/s for stone apple slices (Rayaguru et al., 2012), 3.04 × 10^{-10} to 4.41 × 10^{-10} m^2/s for hot-air drying of plums at 55–65 ℃ (Goyal et al., 2007), 5.65 to 7.53 × 10^{-10} and 3.91 to 6.65 × 10^{-10} m^2/s for pretreated and untreated tomatoes (Doymaz 2007), 3.320 × 10^{-10} to 9 × 10^{-9} m^2/s for berberis (Aghbashlo et al., 2008), 6.92 × 10^{-9} and 14.59 × 10^{-9} m^2/s for radish slices (Lee and Kim, 2009) and 2.93 × 10^{-10} m^2/s and 6.08 × 10^{-10} m^2/s for red apples (Doymaz, 2010).

The increase in D_{eff} with increase in microwave power might be due to the increased heating energy, which would increase the activity of the water molecules leading to higher moisture diffusivity when samples were dried at higher microwave power (Darvishi et al., 2013). The D_{eff} values for microwave drying of cocoyam (9.09 × 10^{-7} to 2.07 × 10^{-6} m^2/s) is higher than that of 7.04 × 10^{-8} to 24.22 × 10^{-8} m^2/s for microwave drying of potato cylinders (Aghbashlo et al., 2009a) and 1.013 × 10^{-8} to 3.799 × 10^{-8} m^2/s for microwave drying of potato slices (Darvishi et al., 2013).

3.3 Activation energy

The activation energy which is the energy needed to initiate internal moisture diffusion is an indication of the temperature sensitivity of D_{eff}. The activation energy for hot-air oven drying of cocoyam at temperatures of 50, 60 and 70 ℃ which was determined from the graph of LnD_{eff} against $1/T_{abs}$ (Figure 4) was 61.79 kJ/mol for water blanched samples and 37.41 kJ/mol for samples soaked in sodium metabisulphite. The forms in which water exists in foods which are mainly surface absorption and chemical absorption determine the value of the activation energy. The high E_a values obtained for cocoyam is due to the following: its initial moisture content (1.513 g water/g dry matter), the form in which water is present in cocoyam, the tissue or starchy structure of cocoyam and the changes of D_{eff} value for air temperature levels at constant air velocity. This is similar to the observation of Chayjan et al. (2011) for high moisture corn.

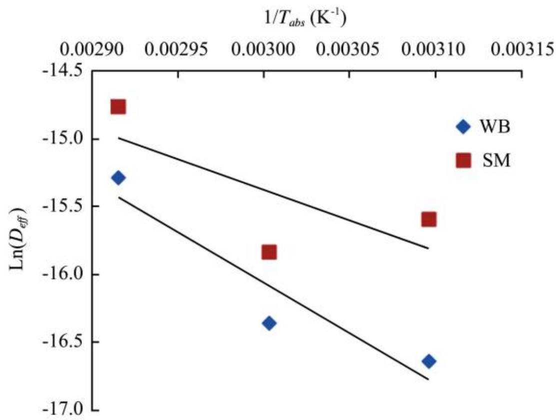


Figure 4 Ln(D_{eff}) *versus* $1/T_{abs}$ for oven drying of cocoyam (SM-soaked in sodium metabisulphite, WB-water blanched)

The E_a value is higher than that 28.15 kJ/mol for tiger nut (Tunde-Akintunde and Oke, 2012), 28.36 kJ/mol for carrot (Doymaz 2004b), 16.1 kJ/mol for stone apple slices (Rayaguru et al., 2012), 16.49 and 20.26 kJ/mol for radish slices (Lee and Kim 2009). These values are within the range of 56.61 and 35.23 kJ/mol for untreated and blanched FHIA-21 plantain (Dzisi et al. 2012), 48.47 kJ/mol for figs (Babalis and Belessiotis 2004) and green peppers (51.4 kJ/mol) (Kaymak-Ertekin 2002). This E_a value is however lower than that of 110.837 to 130.61 kJ/mol for berberis fruits (Aghbashlo et al. 2008). The activation energy obtained for each variety is within the general range of 12.7-110 kJ/mol (Aghbashlo et al., 2008) for most agricultural and food materials as presented by several other reports.

The activation energy for the microwave drying was determined by the method employed in Darvishi et al. (2013) in which the natural logarithm of D_{eff} was plotted against sample amount/power (m/P) as shown in Figure 5. The range of microwave power employed in this experiment gave a straight line graph which indicates an Arrhenius dependence. The dependence of the effective diffusivity of cocoyam on the microwave power can then be represented by the following equations:

$$\mathrm{Ln}(D_{eff}) = 3.104\times10^{-6}\exp\left(41.91\frac{P}{m}\right) \text{ for WB sample, } R^2 = 0.965 \quad (11)$$

$$\mathrm{Ln}(D_{eff}) = 3.393\times10^{-6}\exp\left(38.59\frac{P}{m}\right) \text{ for SM sample, } R^2 = 0.965 \quad (12)$$

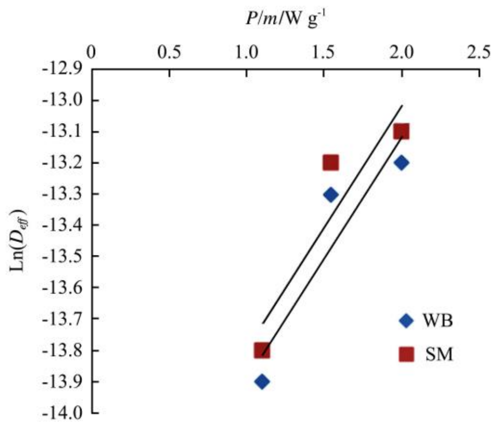


Figure 5 Ln(D_{eff}) *versus P*/*m* for microwave oven drying of cocoyam (SM-soaked in sodium metabisulphite, WB-water blanched)

The activation energy for cocoyam slices which was 38.59 W/g and 41.91 W/g for SM and WB respectively is higher than that of 5.54 W/g for okra (Dadali et al., 2007), 12.284 W/g for mint leaves (Ozbek and Dadali, 2007), 13.6 W/g for pandanus leaves (Rayaguru and Routray , 2011), 16.675 and 24.222 W/g for sweet and sour pomegranate (Motevali et al., 2011) and 14.945 W/g for potato samples (Darvishi et al., 2013). The value of activation energy at the microwave levels and that at the oven drying temperatures shows that microwave drying had lower activation energy values which is in agreement with its higher moisture diffusivity values since lower the activation energy the higher the moisture diffusivity in the drying process (Sharma and Prasad, 2004).

3.4 Energy requirement

Optimisation of the drying process involves the use of minimum amount of energy for maximum moisture removal. The total energy needed for each drying experiment as indicated by Figure 6 was determined using equation (8). Figure 7 however shows the specific energy required for drying 1 kg of cocoyam slices using a hot-air oven and this was determined using equation (9). The total energy required for each drying condition (temperatures and pretreatments used) ranged between 30 kWh and 50 kWh. The specific energy requirement for the drying temperatures and pretreatments investigated in this study was from 86.2 kWh/kg to 142.8 kWh/kg. The lowest value of both properties was obtained for pretreated samples dried at 50℃ while the highest was for samples dried at 60℃. The values obtained for the pretreatments and drying temperatures were significantly different at P<0.05.

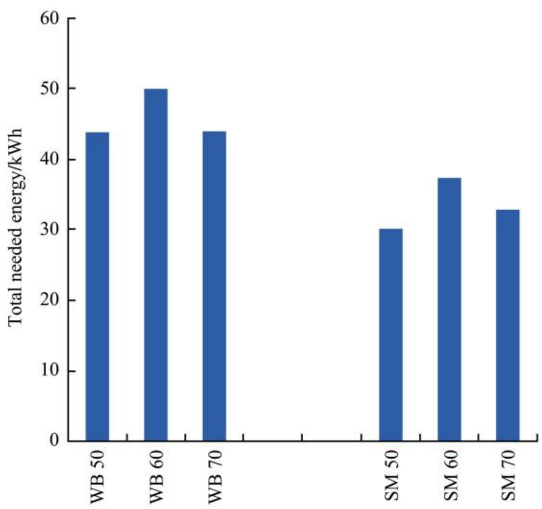


Figure 6 Total required energy for drying of cocoyam slices at different air drying temperatures (50, 60 and 70°C) and pretreatment (WB- water blanching; SM- soaking in sodium metabisulphite)

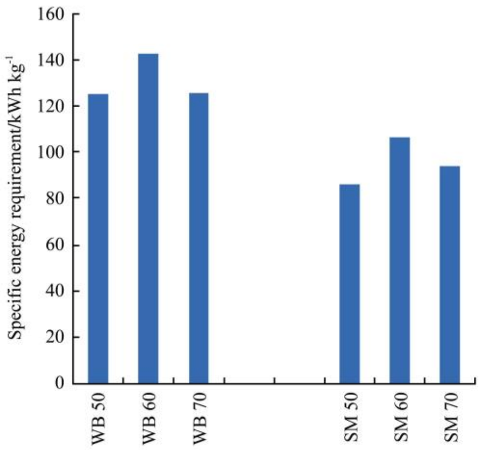


Figure 7 Specific energy requirement for drying 1 kg of cocoyam slices at different air drying temperatures (50, 60 and 70°C) and pretreatment (WB- water blanching; SM- soaking in sodium metabisulphite)

The values obtained for soaking in sodium metabisulphite were generally lower than that obtained for the water blanching pretreatment. This indicates that soaking in sodium metabisulphite results in a higher reduction of energy utilization during drying. An increase in temperature from 50 to 60℃ for the two pretreatments resulted in an increase in total energy required and specific energy requirement while a further increase to 70℃ resulted in a decrease in the values.

The variation of energy efficiency with respect to drying time for microwave drying of cocoyam slices is shown in Figure 8 and 9. The energy consumption ranged from 308 Wh to 396.7 Wh while the specific energy consumption ranged from 1.49 kJ/kg to 2.03 kJ/kg water for the microwave power levels and pretreatments considered.

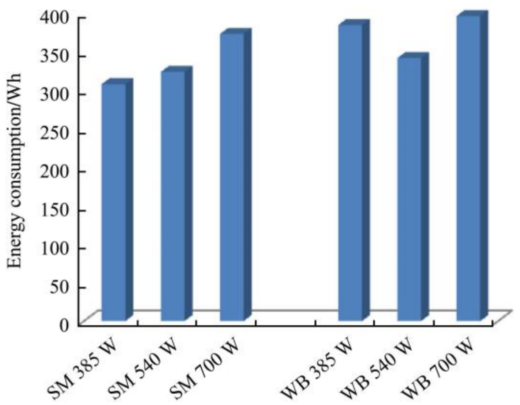


Figure 8 Energy consumption for drying of cocoyam slices at different microwave power levels (385, 540 and 700 W) and pretreatment (WB- water blanching; SM- soaking in sodium metabisulphite)

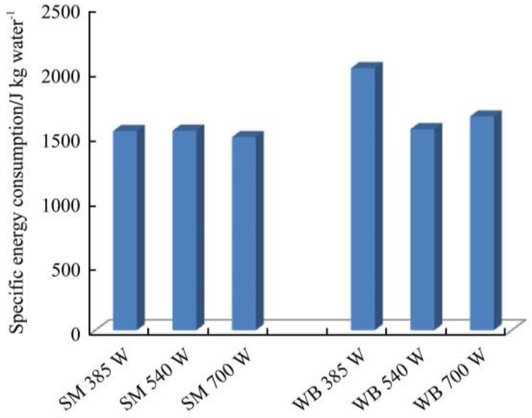


Figure 9 Specific energy consumption for drying of cocoyam slices at different microwave power levels (385, 540 and 700 W) and pretreatment (WB- water blanching; SM- soaking in sodium metabisulphite)

The lowest values were obtained from soaking in sodium metabisulphite pretreatment which is in agreement with the results of oven drying. The use of this form of pretreatment during drying of cocoyam slices will result in the optimal use of energy which will be economically beneficial to processors especially the low and middle scale ones.

4 Conclusion

The moisture ratio was observed to decrease continuously with drying time as drying proceeds in agreement with the general trend for food materials. An increase in oven drying temperature and microwave power level resulted in a decrease in drying time and an increase in D_{eff} values. Cocoyam slices soaked in sodium metabisulphite (SM) generally dried faster; thus, had lower drying times and higher D_{eff} values than water blanched (WB) samples. The E_a values for the water blanching pretreatment were generally higher than that of soaking in sodium metabisulphite pretreatment. SM samples had lower energy consumption values when compared with WB samples, which indicates that the use of soaking in sodium metabisulphite pretreatment is suitable for optimization of the cocoyam drying process since it results in a higher reduction in energy utilization during the process.

Nomenclature

A tray area (m^2)

c_a specific heat of air (kJ/kg ℃)

D_o constant (m^2/s)

D_{eff} effective moisture diffusivity (m^2/s)

D_t total drying time (s)

E_a energy of activation (kJ/mol)

E_c energy consumption (Wh) during each microwave drying operation

E_{kg} specific energy requirement (kWh/kg)

E_s specific energy consumption for microwave drying (J/kg water)

E_t total needed energy needed (kWh)

K_1, K_2 slopes of straight line

L half of the slab thickness (m)

M_e equilibrium moisture content (kg water/kg dry matter)

M_i the initial moisture content (kg water/kg dry matter)

M_t the moisture content at any time (kg water/kg dry matter)

m_w total mass of evaporated water (kg)

MR moisture ratio (dimensionless)

P microwave power (W)

R_g universal gas constant (8.3143 kJ/mol)

T_{abs} absolute air temperature (K)

t time of drying (s)

w_l loss in weight at time t (kg)

w_d dry matter weight (kg)

W_o initial weight of samples (kg)

ρ_a air density (kg/m^3)

υ air velocity (m^2/s)

ΔT temperature differences (℃)

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