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Hot air-drying characteristics of pale-fleshed, white-skinned sweet potato spheres (*Ipomoea batatas*)

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Abstract

Drying of pale-fleshed, white-skinned spherical sweet potato (Ipomoea batatas) (a newly introduced variety grown in Burkina Faso) was carried out at air temperatures of 50°C, 60°C, 70°C, and 80°C using 2 and 3 cm diameter samples to determine its drying characteristics. The results of the analysed drying data indicated that drying occurred during the decreasing rate period. The moisture content of the sample and the drying rate of sweet potato were influenced by the air-drying temperature and the spherical diameter of the samples. The drying time of sweet potato decreased and its drying rate increased with the decrease in the diameter of spherical samples and the increase in air drying temperature. The average effective moisture diffusivity values were obtained in the range of 1.4086 × 10-9 to 3.7214 × 10-9 m2/s and 2.6715 × 10-9 to 6.8775 × 10-9 m2/s for 2 cm diameter samples and 3 cm diameter samples respectively as temperatures increased from 50 °C to 80 °C. This dependence allowed the determination of the activation energy values of 2 and 3 cm diameter sweet potato samples which were found to be 30.50 and 27.71 kJ/mol, respectively.

Keywords: Sweet potato spheres; Convective drying; Moisture diffusivity; Activation energy

1 Introduction

Food security is one of the major global challenges facing the world today. There are an estimated 795 million people who are food insecure and undernourished. One of the factors leading to food insecurity is the loss of food and agricultural products due to their deterioration throughout the food and agricultural chain and/or during the post-production period. A major method to enhance food security is to reduce losses due to post-harvest spoilage of these agricultural products. To improve shelf life and reduce spoilage of agricultural products, drying is the most commonly used method [1]. Drying is an elementary process aimed at removing liquid/vapor water from a material and therefore reducing its water activity. Drying food has many advantages, such as: blocking the development and multiplication of microorganisms and food spoilage reactions by reducing water activity as well as reducing transport costs, storage and preservation through reduction of food weight/volume [2].

Hot air convection drying is the process of removing water with air via simultaneous transfer of heat, mass and momentum. The food's need for heat is achieved by contact of the food with a flow of hot air. The energy transmitted to the surface of the food by convection of hot air is transferred inside the food by diffusion and/or convection, depending

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on the physical and biological structure of the food to be dried. This heat flow causes an increase in product temperature and evaporation of surface water. Moisture is transferred from the surface of the product to the air by convection in the form of water vapor and from the interior of the product by diffusion, convection or capillarity. The drying rate and characteristics of dried foods depend on the conditions of the air-drying process such as air temperature, relative humidity of the air, air velocity, orientation/ direction of air flow and vapor pressure in air. The drying rate also depends on the characteristics of the foods to be dried such as geometry, thickness/size, shape and physical/biological configurations of the foods. The complexity of the physic-biological configurations of wet foods, the variety of transport phenomena and biological diversity make food drying a challenge. To meet this challenge, mathematical modelling and simulation can be a useful tool to examine the drying of foods and the quality of foods obtained after drying. This tool can make it possible to achieve acceptable process conditions or even better than the usual average through a procedure for optimizing the operational variables of drying. Mathematical modelling of food drying involves the use of mathematical equations to predict/capture the physics and/or behavior of drying [3]. Many mathematical models of drying processes are used to design new drying systems or to improve existing drying systems, or even to control the drying process. Among these multiple mathematical models proposed to describe the drying process, thin-layer drying models have been widely used. The term “thin layer” is applied to a single kernel freely suspended in the drying air or one layer of grain kernels. It is also applied to a poly-layer of many grain thicknesses if the temperature and the relative humidity of the drying air can be considered for the purpose of the drying process calculations, as being in the same thermodynamic state at any time of drying [4]. Thin-layer models can be classified as theoretical, semi-theoretical and empirical [5]. Recently, many researchers have focused on the mathematical modelling and experimental drying processes of various tuberous roots such as sweet potato.

Sweet potato called scientific name Ipomoea batatas is a plant cultivated mainly for its edible tubers (tuberose roots), rich in starch. These tubers produced are designated by the same name as this plant. Sweet potatoes produce more edible energy on marginal lands than any other major food crop. In addition to this useful property, these tubers can resist unwanted abiotic and biotic stresses and do not require intensive care. They therefore play an important role in the economy of poor households where they constitute a major source of subsistence and are considered a food to combat famine and child malnutrition. Besides this important function, sweet potato cultivation has immense semi-industrial/industrial value for starch extraction and animal feed production. For all these explanations, sweet potato offers great possibilities for achieving food and nutritional security in developing and underdeveloped countries where most agricultural fields belong to vulnerable population categories [6]. Sweet potatoes are important tubers rich in fiber, starch, vitamins, minerals and bioactive compounds. They contain essential carotenoid, phytochemical, anticancer and antimicrobial properties useful for human and animal health. Sweet potato raw or in its processed form can be consumed by humans as a staple food, snack or baked goods. However, sweet potato is susceptible to microbial activities which can lead to degradation and spoilage due to its high moisture content. Furthermore, sweet potato is seasonal and cannot maintain optimal quality level for a long period after harvest. Thus, it is often used shortly after harvest or preserved using the hot air convection drying method [7]. In the literature, several drying processes have been applied to different sweet potato varieties, namely, infrared and fluidized bed drying [8], convective hot air drying [9], microwave drying [10], hybrid microwave and hot air drying [11], spouted bed drying [12], sun and drum drying [13], spray drying [14], freeze-drying [15] and solar drying [16]. Pretreatments before drying have been applied to sweet potatoes including steaming [17], blanching with hot water and steam [13], soaking in sodium metabisulfite solution [18], osmotic dehydration with sucrose and sorbitol [10], immersion in citric acid solution [15], lemon juice and saline solution [19] and soaking in sodium metabisulfite solution [20]. These drying and pretreatment techniques were applied on sweet potato samples with several sliced shapes, varieties, skin and flesh colors including sweet potato cubes [21], white skin and yellow-red flesh sweet potato slices of Kratai cultivar [8], strips [22], chips [23], Nigerian variety slices [24] and Chinese local variety slices [25].

It was found that there are few articles on air drying of spherical sweet potato in this literature. The objective of this paper is to investigate the drying characteristics e.g. moisture ratio, drying rate, moisture diffusivity, activation energy of white skinned and pale fleshed spherical sweet potato, a newly introduced variety cultivated in Burkina Faso.

2 Materials and Methods

2.1 Raw Material and Processing

Sweet potato (Ipomoea batatas) was used as drying material in this study. Samples of the local variety of sweet potato with pale flesh and white-skinned, heavily consumed in low-income households, were purchased during the period of July 2023 at the fruit and vegetable market in the town of Bobo Dioulasso (Contact details: 11 ° 11′ 00″ North, 4° 17′ 00″ West), located in the Haut Bassin region of Burkina Faso. Sweet potato samples were transported and stored in refrigerated conditions (4 ± 0.5 °C) before the drying process at the GERME & TI laboratory (Study and Research Group in Energy Mechanics and Industrial Techniques) from Nazi Boni University. Before drying, sweet potato samples were placed in laboratory to reach room temperature (25 ± 1 °C). Sweet potato samples were selected, washed, peeled, cut into spheres with diameters from 1 ± 0.002 cm to 3 ± 0.002 cm, measured manually using a digital caliper. Spherical samples are immersed in distilled water to remove excess surface starch film. Excess water on the spherical samples was removed using blotting paper and these sweet potato spheres were arranged in a single layer on a drying tray. The initial moisture content on a dry basis (d.b.) of sweet potato was determined using convective oven method at 105 ± 5 °C for 24 h [26]. Triplicate samples were used for determination of moisture content and the average values were (3.0174±0.01) $kg_{water}/kg_{dry\ matter}$.

2.2 Drying Equipment

Drying experiments were carried out in an Air Performance laboratory oven (Froilabo, Model AC Standard Version, France, range 10–250°C with an accuracy of ±0.5°C) installed at GERME & TI laboratory (Study and Research Group in Energy Mechanics and Industrial Techniques) from the Nazi Boni University, Bobo-Dioulasso, Burkina Faso, previously described by Ouoba et al. [27]. Length, height and width of oven were 0.579 m, 0.640 m and 0.526 m respectively. Oven essentially consisted of a centrifugal fan to provide the desired drying air flow, a 1,000-Watt electric heater controlling the temperature of the drying air, an air filter and a proportional-integral-derivative controller (PID controller). Air temperature in convective oven was regulated to ±1∘C using a temperature controller. The oven operated at dry bulb temperatures of 10°C to 250°C. The desired drying air temperature was reached by an electric resistance and controlled by the heating control unit. The air speed was regulated by the centrifugal fan and a fan speed control unit. The air came out of the heating unit and was heated to the desired temperature, then channeled to the drying chamber through ventilation slots located in the rear side wall of the drying chamber. Fan located at the rear of chamber wall produced greater airflow and more intensive horizontal forced air circulation to dry the product samples. The samples were dried on a square perforated stainless-steel tray, having a flow cross section of 0.3 m x 0.3 m. The oven was adjusted to the selected air temperature for approximately 0.5 h before the start of the experiments in order to reach its steady state.

2.3 Drying Procedure

Air drying temperatures were 50, 60, 70 and 80°C and air relative humidity was in range from 5 to 20%. Air velocity was kept at a constant value of 2.0 m/s with an accuracy of ±0.03 m/s for all drying experiments. Drying process began when drying conditions reached constant air temperatures. Once the oven reached stable conditions for set points, sweet potato samples were placed on a tray in a single layer and measurement started from that point. Experiments were carried out with 125 ± 0.3 g of sweet potato for all tests. Tray was removed from convective dryer regularly, at 20-minute intervals, and weighed with a digital electronic balance, then placed back in oven. The tray was removed from the dryer regularly, at 20-minute intervals, and weighed with a digital electronic balance, then placed back into the oven. The electronic digital balance (model 2102, SARTORIUS, France, range 0–2,100 g with an accuracy of ±0.001 g) was kept less than 1 m from the dryer [28]. Convective hot air drying was continued until there was no longer any significant variation in the evolution of the masses of the spherical sweet potato samples. Drying tests were terminated when masses of samples were stabilized, which assumed that thermodynamic equilibrium was reached. The dried samples were cooled under laboratory conditions after each drying experiment and stored in airtight jars. The mass loss of the samples during drying was converted to moisture content on a dry basis and expressed as $kg_{water}/kg_{dry\ matter}$ according to equation (1). For each drying condition, averages of three replicates were taken as drying data. At end of each experiment, sample was heated in an oven at 105 °C for 24 h of drying to obtain the dry matter mass of this sample [29].

$$X(t) = \frac{m(t) - m_s}{m_s} \qquad \dots\dots\dots \quad (1)$$

Where X(t) is the moisture content on a dry basis (d.b.) expressed in $kg_{water}/kg_{dry\ matter}$; m (t), mass of spherical sweet potato samples, expressed in kg at time t in seconds and m_s, mass of dry matter of spherical samples (kg).

3 Drying Theory

3.1 Moisture Ratio

Moisture ratio (MR) was calculated from moisture content data of spherical sweet potato samples during drying. Equation (2) was used to calculate the moisture ratio [30]:

$$MR = \frac{X - X_e}{X_0 - X_e} \qquad \dots\dots\dots \quad (2)$$

Where X, X_0 and X_e are respectively the average moisture content at any time of drying (kg $_{water}$/kg $_{dry\ matter}$), the initial average moisture content (kg $_{water}$/kg $_{dry\ matter}$) and the equilibrium moisture content (kg $_{water}$/kg $_{dry\ matter}$).

As X_e is much smaller than X_0 and X, it is negligible in this study. The moisture ratio then becomes:

$$MR = \frac{X}{X_0} \qquad \ldots\ldots\ldots\ldots \quad (3)$$

3.2 Drying Rate

The drying rate (DR) of the spherical sweet potato samples is calculated using equation (4) [31]:

$$DR = \frac{X_{t+dt} - X_t}{dt} \qquad \ldots\ldots\ldots.(4)$$

Where X_t and X_{t+dt} are moisture contents at t and t + dt ($kg_{water}/kg_{dry\ matter}$), respectively, DR, drying rate ($kg_{water}/(kg_{dry\ matter}.\ s)$) and t is the time (s).

3.3 Effective Moisture Diffusivity

Drying of most food materials takes place during the falling rate period, and moisture transfer during drying process is controlled by internal diffusion. Fick's second diffusion equation (equation (5)) was widely used to describe drying process during falling rate period of agricultural materials [28]:

$$\frac{\partial X}{\partial t} = D_{eff}\nabla^2 X \qquad \ldots\ldots\ldots.. \quad (5)$$

Diffusion equation (equation (5)) is solved for a sphere, assuming one-dimensional volume change of moisture movement, uniform temperature and constant mass diffusivity, and negligible external resistance [32]:

$$MR = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}\exp\left[-(2n-1)^2\frac{\pi^2 D_{eff}}{4r^2}t\right] \qquad \ldots\ldots\ldots\ldots. \quad (6)$$

Where D_{eff} is the effective moisture diffusivity (m^2/s), r is the radius of the spherical sample (m), and n is the positive integer. For long drying times, equation (6) simplifies to a limiting form of the diffusion equation as follows:

$$MR = \frac{6}{\pi^2}\exp\left(-\frac{\pi^2 D_{eff}}{4r^2}t\right) \qquad \ldots\ldots\ldots\ldots\ldots. \quad (7)$$

Plotting of ln (MR) versus drying time is expressed with the dimensionless Fourier number F_0 according to equation (8).

$$\ln MR = -\ln\frac{\pi^2}{6} - \frac{\pi^2}{4}F_0 \text{ with } F_0 = \frac{D_{eff}}{r^2}t \qquad \ldots\ldots.. \quad (8)$$

Or

$$F_0 = 0.4053\ln(MR) + 0.2017 \qquad \ldots\ldots. \quad (9)$$

3.4 Activation Energy

Effective diffusivity can be linked to air temperature by Arrhenius type expression [30], such as:

$$D_{eff} = D_0\exp\left[-\frac{E_a}{R(T+273.15)}\right] \qquad \ldots\ldots. \quad (10)$$

Where D_0 is the constant of the Arrhenius type equation (m^2/s), E_a is the activation energy (J/mol), T is the uniform temperature of the sweet potato (°C) and R=8, 3145 is the universal gas constant (J/mol K). Equation (10) can be rearranged into the form:

$$\ln(D_{eff}) = \ln(D_0) - \frac{E_a}{R(T + 273.15)} \quad \text{………..} \quad (11)$$

3.5 Statistical Analysis

For the adjustment of the drying data of the spherical sweet potato samples, a regression analysis by the least squares method was carried out using MATLAB 8.0 software. Four statistical parameters were used to determine the ability of the tested model to represent the experimental data, namely: the coefficient of determination (R^2), the root mean square error (RMSE), the reduced chi-square (χ^2) and the sum of squared errors (SSE).

- The coefficient of determination(R^2)

The main goal of using R^2 in the context of statistical models is to predict future outcomes based on associated experimental data. R^2 helps capture the amount of dispersion in a drying data set which is accounted for by a mathematical model. It measures how likely future outcomes are to be predicted by this mathematical model. R^2 is rarely equal to 0 or 1, but rather somewhere between these limiting values. The closer it is to 1, the more the experimental and predicted values agree. This value is used for the comparison rule and shows the level of good fit between the measured and predicted values. This was one of the first coefficients used to select the appropriate drying model to describe food drying behavior [4].

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(P_{exp,i} - P_{pre,i}\right)^2}{\sum_{i=1}^{N}\left(\bar{P}_{exp} - P_{exp,i}\right)^2} \quad \text{……………..} \quad (12)$$

- Root Mean Square Error (RMSE)

The root mean square deviation, RMSD, or root mean square error, RMSE, is a tool for measuring the differences between the values predicted by a mathematical model and the values actually observed from drying experiments. RMSD measures the accuracy of this model well and is used to group the residuals into a single measurement of the predictive tool. It must evolve towards a zero value for a good adjustment of the drying model and can be expressed as follows [29]:

$$RMSE = \left[\frac{\sum_{i=1}^{N}\left(P_{exp,i} - P_{pre,i}\right)^2}{N}\right]^{1/2} \quad \text{……………} \quad (13)$$

- Chi-square reduced (χ^2)

This statistical coefficient of chi-square reduced (χ^2) is a tool to measure the mean square of the differences between the experimental values and those predicted from mathematical models. This makes it possible to evaluate the adequacy of this model with the experimental data. The smaller the values of χ2, the better the quality of the fit and could be expressed as follows [4]:

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(P_{exp,i} - p_{pre,i}\right)^2}{N - z} \quad \text{……………} \quad (14)$$

- Sum of Squared Errors, SSE

The sum of squared errors (*SSE*) gives the measure of the deviation of the data of an experimental sample from its theoretical values predicted by a mathematical model. This parameter is explained as the difference between the experimental data and those predicted by the drying model and expressed as [29]:

$$SSE = \sum_{i=1}^{N}\left(P_{exp,i} - P_{pre,i}\right)^2 \quad \text{……………} \quad (15)$$

Where *P* is the hot air-drying parameter, $P_{exp,i}$ is the experimental value of the parameter, $P_{pre,i}$ is the value of the parameter *P* predicted by the statistical model, $\bar{P}_{exp,i}$ is the average value of the parameter *P, N* is the number of experimental observations and z is the number of constant coefficients in the model regression. A good fit of the drying model is found for the highest values of R^2 and for the lowest values of RMSE, χ^2 and SSE [29].

4 Results and Discussion

4.1 Moisture Ratio

From the moisture ratio evolutions in

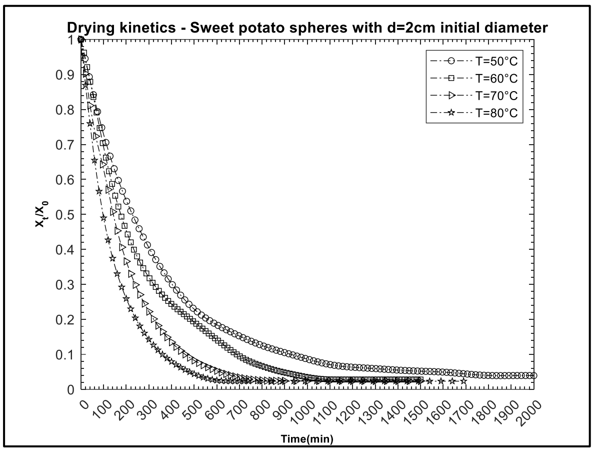
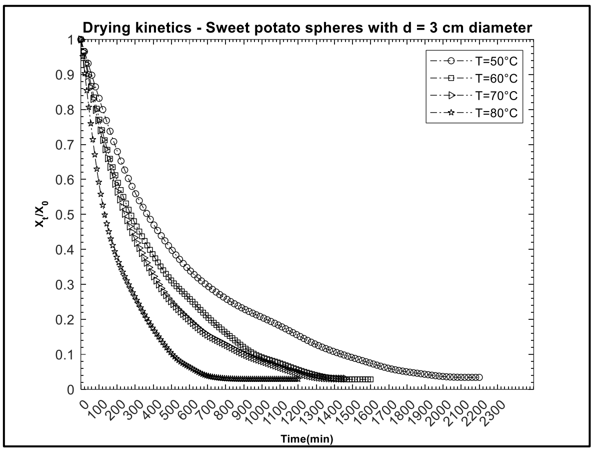
(a)	(b)
	

Figure 1a, it can be deduced that the sweet potatoes were completely dried for 2000, 1376, 840 and 580 minutes at 50 °C, 60 °C, 70 °C and 80 °C respectively for the spherical samples of 2 cm in diameter. For the 3 cm diameter samples, the drying durations were found to be 2080, 1600, 1419, and 915 minutes at 50 °C, 60 °C, 70 °C and 80 °C respectively (

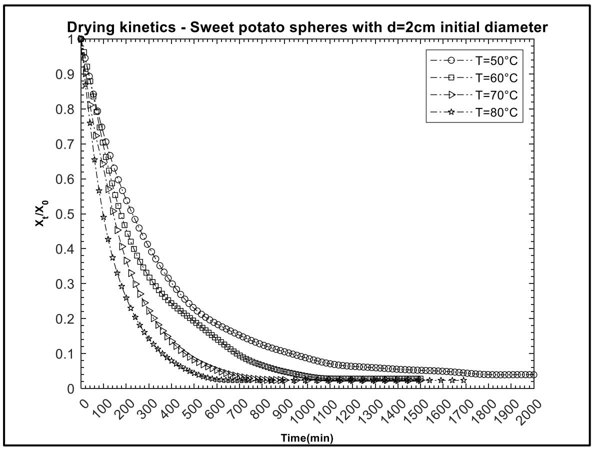
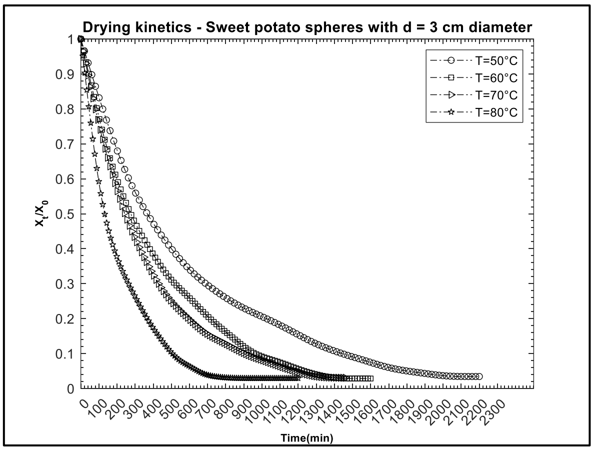
(a)	(b)
	

Figure 1b). Therefore, the moisture content of the spherical sweet potato samples decreased to a constant point in a time that depended on the air-drying temperature and the diameter of the spherical samples, with the lowest time being at 80 °C (i.e. 580 minutes) and the highest time at 50°C (i.e. 2000 minutes) during the drying of spherical samples of 2 cm in diameter. For the 3 cm diameter spherical samples, the lowest time at 80°C was 915 minutes and the highest time at 50°C was 2080 minutes. Thus, an increase in drying air temperature results in a reduction in drying time. For spherical samples of a given diameter, oven temperature levels had a significant influence on the moisture content of sweet potatoes.

(a)	(b)

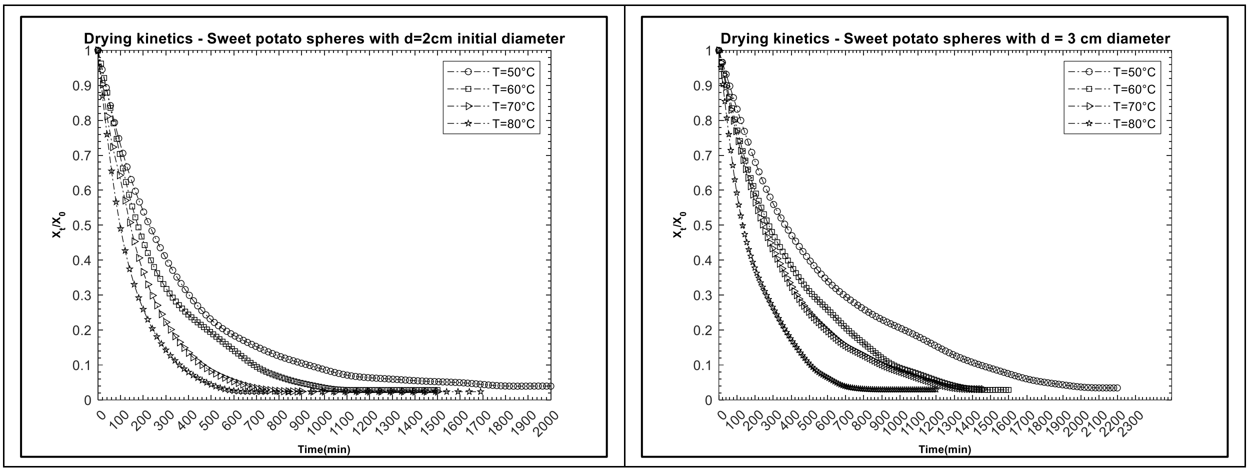


Figure 1 Drying kinetics of spherical sweet potato samples dried with hot air at temperature levels (50, 60, 70 and 80°C) with spherical samples of (a) d=2 cm and (b) d= 3 cm in diameter

The lower moisture content of dried spherical sweet potato samples showed a decrease in the volume and transportability of these dried samples during processing, preservation, and storage. The reduction in moisture content reduced their water activities, which also minimized the microbial deterioration and spoilage reaction during their storage. Our drying results of spherical sweet potatoes were in agreement with those of other researchers for various foods such as onion [29], Kiwi [33], okra [34], cassava [35], apple [36], carrot [37] and tomato [38]. In

(a) (b)

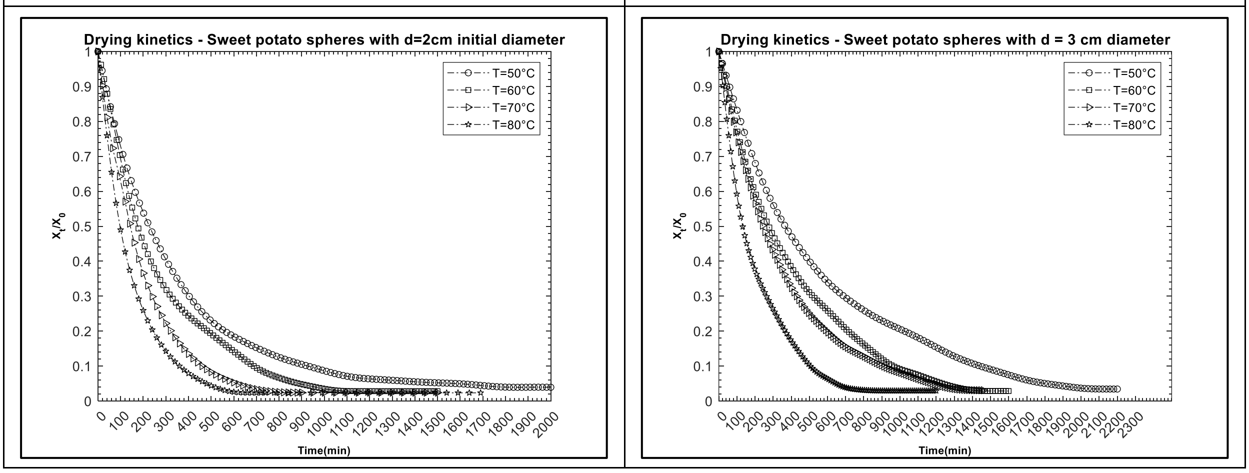


Figure 1, regarding the physical mechanism of drying, convective drying of spherical sweet potato samples did not show a constant rate period. Moisture content decreased with increasing drying time of the spherical samples during the decreasing rate period at the four temperature levels for both 2 and 3 cm diameter spherical sweet potato samples. This showed that moisture diffusion was the dominant physical mechanism of water movement in the spherical sweet potato samples during the drying process [39]. Water diffusion during the drying process could induce a decrease in absorption due to the reduction in the water content of our product to be dried [40]. Some research has been conducted on the influence of air temperature on drying kinetics. For drying pear slices in a convective dryer, Doymaz [41] investigated the influence of drying air temperature. He noted that the reduction in total drying time with increasing temperature may be due to the increase in vapor pressure inside the product with increasing temperature, which resulted in faster migration of moisture to the product surface.

4.2 Drying Rate

Drying rate is defined as mass of water removed per mass of dry matter and time [kg water/ (kg dry solid s)] under the experimental conditions. We estimated it based on equation (4) and its variations as a function of drying time at air temperatures of 50, 60, 70 and 80°C for spherical sweet potato samples of 2 cm in diameter were as shown in **Figure 2**. It could be observed on the drying kinetics a significant influence of the air-drying temperature on the drying rate of the spherical sweet potato samples. This could show that the drying rate continuously decreased with increasing drying time, except for the drying rate curve at 60°C air temperature which showed a small initial heating of the sweet potatoes.

There was no constant rate drying period in these curves and most of the drying process took place during the decreasing rate period. These results were in good agreement with previous observations of various products such as onion slices [29], grape leaves [42], pomegranate arils [43] and pomegranate peels [44]. Moisture removal inside the spherical sweet potato samples at an air temperature of 80 °C was greater and faster than at other drying temperatures studied due to the rapid movement of the moisture to the surface of the sweet potato and the high evaporation rate from the surface to the surrounding warm air. The high level of air temperature could facilitate these two physical phenomena by rapid activation of molecular diffusion of water from the sweet potato solid matrix. The bond of water molecules with the solid matrix was easily broken, allowing water molecules to exit the sweet potato samples. The removal of moisture inside the sweet potato decreased with decreasing humidity level and hence the drying rate also decreased. Additionally, shorter drying time was observed in **Figure 2** at higher temperatures due to increasing drying rate. This increase in drying rate was due to the increased heat transfer potential between the drying air and the spherical sweet potato samples, which accelerated the evaporation of water from the spherical sweet potato samples. Since the relative humidity of hot air at a higher temperature was lower than that at a lower temperature, the difference in partial vapor pressure between thin-layer sweet potato spheres and their surroundings was greater for the case of drying sweet potato at high air temperature. Similar results had earlier been reported in the others works suck as the convective drying of tomato slices [45], convective air drying of sweet potato cube [21] and the hot air drying of pear slices [46]. Torki-Harchegani et al. [47] reported that food drying occurred in the period of declining rate. During the period of decreasing rate, water migrated from areas of the food to be dried with a higher moisture content to areas of the same food where the moisture content was lower. The induced movement of water from the interior of the food to its surface was controlled by molecular diffusion of moisture. This physical phenomenon could be explained by Fick's second law. The investigation by Jiang et al. [48] explained our findings that the average moisture migration rate inside wheat grains was lower than the average evaporation rate outside the wheat grains. He et al. [49] also explained this migration by the fact that promoting the moisture transfer movement of sea cucumbers during the drying process at decreasing rate could shorten the drying time of their cucumber samples.

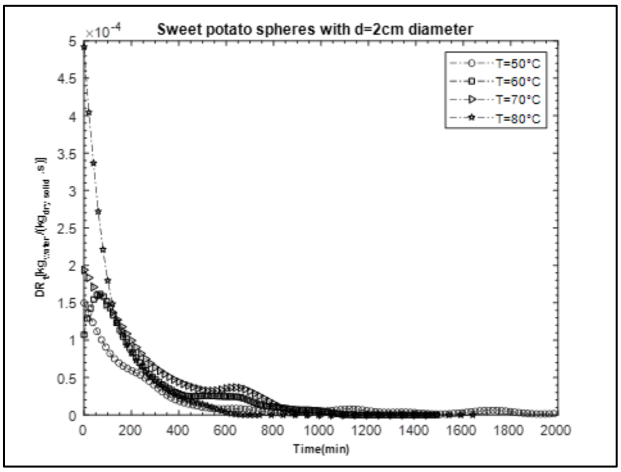


Figure 2 Drying rate curves versus time (min) for different temperature at diameter 2 cm of sweet potato spheres

The kinetics of the drying rate of spherical sweet potato samples 2 cm in diameter as a function of moisture ratio was presented in Figure 3. A constant rate period was not observed in all cases of air-drying temperature. Examination of Figure 3 revealed that, in general, two distinct drying periods were identifiable, namely the period of warming to 60 °C and the falling-rate period at all air-drying temperatures. The short initial warming period corresponding to spherical samples heated to 60 °C was due to non-isothermal drying conditions of the sweet potatoes at the start of the process. The presence of decreasing drying behavior was indicative of a progressive increase in internal resistance to mass and heat transfer [29]. A continuous decreased in drying rate as the moisture ratio decreased could be observed in Figure 3 . At the same time, the increase in drying rate was observed as the air temperature increased, as shown Figure 2. Drying rates were higher at the beginning of the process and then decreased with decreasing moisture content in the spherical sweet potato samples during the drying process. The reduction in drying rate could be due to the reduced porosity of the spherical samples. This reduced porosity originated from matrix removal from the spherical samples as the drying process progressed. This resulted in an increase in massive resistance to water migration, leading to a further decline in sweet potato drying rates [50]. The results were consistent with observations made by other researchers on drying foods such as bay leaves [51], purslane [52], by-products of pomegranate [53] and apple pomace [54]. Mrad et al. [55] reported that, upon the pears drying, the falling drying rate period resulted from the predominance of internal diffusion mechanism due to bound water at the surface and shrinkage of the product.

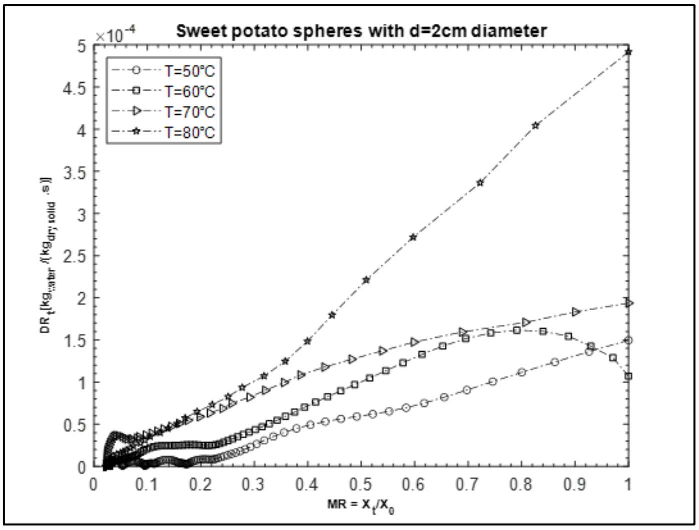


Figure 3 Drying rate curves versus moisture ratio for different temperature at diameter 2 cm of sweet potato spheres

The evolutions of drying rates as a function of humidity level for two spherical sweet potato samples with diameters (2 cm and 3 cm) at an air-drying temperature of 50 °C, are illustrated in **Figure 4**. The results of others air temperatures (60, 70, 80°C) observed similarly. Drying rate at 2 cm diameter was higher and faster than the 3 cm diameter. Shorter drying time was obtained for spherical sweet potato samples with smaller diameter, which increased their drying rate. Thus, the drying rate increased with decrease in sample diameters. The spherical diameters of the samples could influence the rate of convective drying for the same moisture content of the sweet potato: the smaller the diameter of the sample, the higher the drying rate of the sweet potato. This increase is due to the decreased mass transfer resistance of the spherical sweet potato samples, which facilitates the movement of water from the interior of the spherical sweet potato samples to their surfaces. Similar results were reported by others researches on foods. Jiang et al. [56] found when hot air-drying crabapple slices that the thickness of crabapple slices influenced the hot air-drying time. With the same moisture content, the thinner the thickness of the product slices, the higher the drying rate and the shorter the drying time of crabapple slices. Jongyingcharoen et al. [57] explained that the thinner the thickness of coconut dregs, the shorter the drying time of the process to 70 minutes. Ndisya et al. [58] found that as the thickness of their sample slices to be dried increased, the drying time of the purple-speckled coconut slices also increased. In thin layer drying of onion varieties, Sobowale et al. [59] noticed that the drying rate of white and red onion slices with increasing thickness illustrated the rate at which liquid is migrated inside-out of the bulb scales, simply through mass-transfer bound over time. Similar results on the influence of the thickness have been reported for hot air drying of banana [60], convective drying of apple slices [61], hybrid convective drying of tomato slices [62], hot air drying of “Violet de Galmi” onion slices [29], hot air convective drying of tomato slices [63] and convective hot air drying of potato, garlic and cantaloupe [64]. Compaore et al. [29] was found that the drying rate leek slices was higher at thin slices, and the total drying time reduced substantially with the decrease in slices thickness. Sadin et al. [65] reported that infrared drying rate of tomato slices was increased with increasing temperature and reduction thickness so that maximum drying time to temperature and thickness 60°C, 7 mm respectively and that minimum drying time to temperature and thickness 80 °C, 3 mm respectively. Ouoba et al. [66] indicated that, during convective drying of different sizes of sweet potato, the smaller the sample size was, the faster the drying rate was. The drying was found more efficient for small samples.

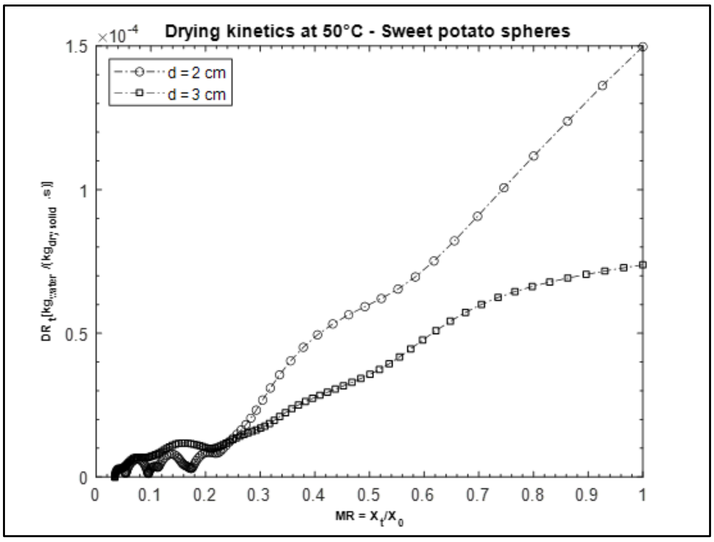


Figure 4 Kinetics of the drying rate as a function of sweet potato moisture ratio for two spherical samples of 2 and 3 cm in diameter at an air temperature of 50 °C

4.3 Average Effective Moisture Diffusivity

The average moisture diffusivity is calculated by taking the arithmetic mean of the effective moisture diffusivities which are estimated at different moisture ratios during the drying period. The average moisture diffusivity values of the spherical sweet potato samples are given in **Table 1**. The average effective moisture diffusivity values were obtained in the range of 1.4086×10^{-9} to 3.7214×10^{-9} m^2/s and 2.6715×10^{-9} to 6.8775×10^{-9} m^2/s for spherical samples of 2 cm in diameter and spherical samples of 3 cm in diameter respectively when temperatures increased from 50°C to 80°C. It can be seen that the average effective diffusivity values increase as the air temperature level and the diameter of the spherical sweet potato samples increase. Higher spherical diameter size and air temperature level cause an increase in the average effective diffusivity of moisture due to higher mass transfer for the increased air temperature. This is also due to the long migration path of moisture from the interior to the surface of the sample when the size of the spherical diameter increases. In fact, it can be attributed to the availability of more heat energy required to activate the movement of moisture from the internal part of the sweet potato to their surfaces for drying to take place, since water is loosely bound to food matrix at high temperature. Water activity increases with increasing temperature which results in increased moisture diffusivity. Similar results of the influence of drying parameters on moisture diffusivity during different drying conditions has been found in literature [67,68]. Obajemihi et al. [63] explained that the moisture diffusivity increased with increasing slice thickness from 5 to 10 mm upon tomato slices convective hot-air drying. This could result from higher moisture ratio in thick slices compared with the thinner ones. Kaveh et al. [64] found that effective moisture diffusivity values increased with increasing air velocity and air-drying temperature of potato, garlic, and cantaloupe. The increase in air temperature led to an increased in the energy transmitted for the evaporation of water molecules from the products to be dried. The evaporation of water molecules is caused by the molecular thermal agitation of the molecules due to an increase in the kinetic energy of these water molecules. For the convective drying of apple slices, Beigi [61] was discussed that the increase in temperature caused a decrease in water viscosity and increases the activity of water molecules. These phenomena facilitate diffusion of water molecules in object capillaries, consequently increasing the moisture diffusivity of apple slices. Concerning the vacuum dehydration of onion slices, it was observed that for a particular temperature as the thickness increased effective moisture diffusivity value increased and for a constant thickness, moisture diffusivity value increased with increasing temperature [69]. The values of average moisture diffusivity obtained from this study meet the standard range for food and agricultural products from 10^{-12} to 10^{-8} m^2/s [54]. Comparable values of average moisture diffusivity have been reported by other investigators: 1.51×10^{-9} to 9.28×10^{-9} m^2/s and 1.13×10^{-9} to 2.85×10^{-9} m^2/s for walnut shell and kernel at 43–75°C [70];8.9×10^{-10} to 8.4×10^{-9} m^2/s for 2-6 mm thick onion slices at 40–60°C [59]; 0.2578×10^{-9} to 0.5460×10^{-9} m^2/s for "Violet de Galmi" onion slices at 40–70°C and 20% RH [29]; 0.774×10^{-8} and 2.844×10^{-8} m^2/s for 5 mm thick tomato slices at 45-65 °C [63];1.572×10^{-10} to 2.627×10^{-10} m^2/s for (1.28 ±0.19) mm thick banana slices at 35-50°C [31] and 0.637×10^{-10} to 13.870×10^{-10} m^2/s for African oil bean seed at 40-70°C [71].

Table 1 Average effective humidity diffusivity values calculated at air temperatures of 50°C to 80°C for hot air drying of spherical sweet potato samples of (2 and 3 cm) diameter

Temperature (°C)	Average effective moisture diffusivity (m2/s)	
	Diameter: 2 cm	Diameter: 3 cm
50	1.4086×10^{-9}	2.6715×10^{-9}
60	2.3191×10^{-9}	3.8326×10^{-9}
70	3.0792×10^{-9}	4.2045×10^{-9}
80	3.7214×10^{-9}	6.8775×10^{-9}

4.4 Activation Energy

The moisture binding potential primarily determines the drying behavior of moist foods. Activation energy is the starting energy required to remove 1 mole of moisture during the drying process. It reflects the moisture-binding potential of the food and the degree of difficulty in evaporating water from it. This index is determined by the moisture content and composition of the food itself. The greater the activation energy, the more difficult it is to remove moisture [28]. The activation energy is determined by the forms in which water exists in foods, namely surface absorption and chemical absorption. The activation energy can be determined from the slope of Arrhenius plot, ln $D_{eff,ave}$ versus 1/ (T + 273.15) using equation (11). The ln $D_{eff,ave}$ as a function of the reciprocal of absolute temperature was plotted in Figure 11 for the 2 and 3 diameter sweet potatoes. The slope of the line is (-Ea/R) and the intercept is equal to ln (D_0). The results show a straight line due to the dependence on the Arrhenius type. Equations (17, 18) show the influence of air temperature on the $D_{eff,ave}$ of spherical sweet potato samples of 2 and 3 cm in diameter with the following coefficients:

For 2 cm diameter samples:

$$D_{eff,ave} = 12.887\times10^{-5}\exp\left[-\frac{3.6686\times10^{3}}{T(°C)+273.15}\right] \quad \dots\dots\dots\dots\dots.(17)$$

For 3 cm diameter samples:

$$D_{eff,ave} = 7.9999\times10^{-5}\exp\left[-\frac{3.3329\times10^{3}}{T(°C)+273.15}\right] \quad \dots\dots\dots\dots \quad (18)$$

The values of activation energy for 2 and 3 cm diameter samples found 30.50 and 27.71 kJ/mol, respectively (**Table 2**). Values of the energy of activation lie within the general range of 12.7-110 kJ/mol for food materials [72]. The differences between the results can be explained by effect of type, slice thickness, composition and tissue characteristics of the product. Our values are relatively close to those obtained in the literature on food drying: 25.01 kJ/mol for fragrant leaves and 32.35 kJ/mol for lemon basil leaves [72]; 31.01 kJ/mol for fragrant peppers and 30.11 kJ/mol for pouting peppers [73]; 31.73 kJ/mol for “Violet de Galmi” onion slices [29]; 17.6 - 29.06 kJ/mol for ginger slices [74] and 31.39 kJ/mol for pomegranate seeds and 10.60 kJ/mol for pomegranate peels [32].

Table 2 Values of activation energy and pre-exponential factor

Parameters	Activation energy (E_a) and pre-exponential factor (D_0)	
	Diameter: 2 cm	Diameter: 3 cm
D_0	12.887×10^{-5}	7.9999×10^{-5}
E_a	3.0502×10^{4}	2.7711×10^{4}
R^2	0.9644	0.9362

List of Abbreviations

d	**Diameter of the product (m)**
D_0	Constant of Arrhenius type (m^2 s^{-1})
D_{eff}	Effective moisture diffusivity (m^2 s^{-1})
$D_{eff,ave}$	Average effective moisture diffusivity (m^2 s^{-1})
DR	Drying rate (kg_{water}/($kg_{dry\ mass}$ s))
dt	Infinitesimal time (s)
F_0	Fourier number (-)
E_a	Activation energy (J mol^{-1})
m(t)	mass of wet product (kg)
min	minute (min)
m_s	Dry mass (kg)
MR	Moisture ratio (-)
n	Positive integer (-)
r	Radius (m)
R	Universal gas constant = 8314.46 J mol^{-1} K^{-1}
R^2	Coefficient of determination (-)
RMSE	Root-Mean-Square error (-)
SSE	Sum of squared error (-)
t	Tim (s)
T	Air Temperature (°C or K)
X_0	Initial mean moisture content (kg_{water}/$kg_{dry\ mass}$)
X_e	Equilibrium moisture content (kg_{water}/$kg_{dry\ mass}$)
X (t)	Moisture content (kg $_{water}$/$kg_{dry\ mass}$)
χ2	Chi-square reduced (-)

5 Conclusion

Drying of sweet potato spherical samples was carried out at air temperatures of 50°C, 60°C, 70°C and 80°C using 2 and 3 cm diameter samples to determine the drying characteristics. In experiments, different sweet potato spherical samples were dried under different drying air temperature conditions and the changes in moisture content were recorded during the drying time. They were converted to moisture content values and used to explain the convective drying behavior of sweet potato spheres. The drying process of sweet potato spherical samples showed a period of decreasing rate and not a period of constant rate for the air-drying temperatures considered. The moisture content and drying rate were influenced by the diameters of the spherical samples and the hot air temperatures. The total drying time decreased and the drying rate increased as the sample diameter decreased and the drying temperature increased. The effective moisture diffusivity was calculated from Fick's second law derived from Fick's first law and conservation of mass. The average effective moisture diffusivity values were obtained in the range of 1.4086×10^{-9} to 3.7214×10^{-9} m^2/s and 2.6715×10-9 to 6.8775×10^{-9} m^2/s for 2 cm diameter samples and 3 cm diameter samples respectively when the temperatures increased from 50 °C to 80 °C. The average effective moisture diffusivity increased as the hot air temperature and the diameter of the spherical sweet potato samples increased. The air temperature dependence of the average effective moisture diffusivity values was described by an Arrhenius-type equation. This dependence allowed to determine the values of sweet potato activation energy for samples of 2 and 3 cm diameter, which were found to be 30.50 and 27.71 kJ/mol, respectively, comparable to the reported values of various food materials. Our results of sweet potato drying could be of interest to commercial scale producers to adjust their drying process parameters and obtain better quality of dried products. It also allows to reduce energy consumption and increase profitability by saving money.

Compliance with ethical standards

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Disclosure of conflict of interest

No conflict of interest to be disclosed.

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