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Evaluation of the mass and moisture transport parameters of thin-layer drying of pale-fleshed, white-skinned spherical sweet potato (*Ipomoea batatas*)

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Abstract

In this study, the evaluation of mass and moisture transport parameters of hot air drying of pale-fleshed, white-skinned spherical sweet potatoes (a newly introduced variety cultivated in Burkina Faso) was investigated at air temperatures of 50, 60, 70 and 80°C for 2 and 3 cm diameter samples using an oven dryer. With the measurement data, the objective of this paper is to evaluate the transport parameters (lag factor, drying constants, moisture diffusivities and moisture transfer coefficient) of spherical sweet potatoes during hot air convective drying. Drying data analyzed were obtained in the period of falling drying rate. The moisture ratio and drying rate were influenced by the drying temperature and sample diameter. Concerning the mass moisture transport parameters results, the drying coefficient of sweet potato varied from 5.190×10^{-7} s^{-1} to 1.950×10^{-6} s^{-1} under our air-drying conditions. The lag factor of sweet potatoes varied from 1.043 to 1.083. The moisture Biot number values for sweet potatoes were in the range of 0.1232 - 0.2462. The effective moisture diffusivity for spherical sweet potatoes varied in range from 4.040×10^{-10} to 2.615×10^{-9} m^2/s, for our drying conditions. The convective mass transfer coefficient values for spherical sweet potato samples were obtained to be in the range of 7.490×10^{-8} – 7.844×10^{-7} m/s. The activation energy for moisture diffusion was 48.349 and 45.838 kJ/mol, respectively for samples with diameters of 2 and 3 cm. The activation energy for convective mass transfer was 66.474 and 62.151 kJ/mol for sweet potato samples with diameters of 2 and 3 cm, respectively.

Keywords: Convective Mass Transfer Coefficient; Drying Coefficient; Lag Factor; Moisture Diffusivity

1. Introduction

Convection drying is the process of removing water with air by a simultaneous transfer of heat, mass and momentum. The complexity of food structure and composition, the variety of transport phenomena and biological diversity make convection drying of food a real challenge. For these reasons, modelling and simulation are an appropriate technique to simplify the complexity of convection drying of food. It also allows us to aim for the best drying conditions through optimization. Modelling of food drying consists of using mathematical equations to predict the drying behavior [1,2]. Drying models are used to design new dryers or to improve existing dryers or even to control the drying process. Among these models proposed to describe drying, thin-layer models have been widely used [3]. Recently, researchers have focused on thin-layer modelling of drying of tuberous roots such as cassava, carrot, yam, and sweet potato, etc.

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Sweet potato, whose scientific name is Ipomoea batatas, is a tuberous plant with immense potential as it produces more edible energy on marginal lands than any other major food crop. It can withstand adverse abiotic and biotic stresses and does not require intensive care. It therefore plays an important role in the economy of poor households where it is a major source of income. Its cultivation has immense industrial value for starch extraction and production of feed for livestock keepers. This root offers potential for improving food and nutrition security in developing countries [4]. However, sweet potato is susceptible to microbial activities that can lead to degradation and spoilage due to its high moisture content. It is seasonal and cannot maintain optimum quality for a long period after harvest. Thus, it is used soon after harvest or preserved using hot air drying [5,6]. In the literature past, several models have been applied to this root to improve its drying behavior and capture its transport parameters. With the period of decreasing drying rate of sweet potato, moisture transfer inside its body occurs mainly by molecular diffusion captured globally by effective moisture diffusivity. Moisture diffusivity during drying is used to indicate moisture flux in sweet potato. Moisture diffusivity of sweet potato is influenced by moisture content, distance from heat source, temperature and its thickness. These values were generally obtained by solving a differential equation formulated by Fick's second law of diffusion in an unsteady state. This equation is solved by Crank with the assumption of neglected external mass resistances and with a slab of samples [7]. In addition, to obtain good drying efficiency of sweet potato, the study of quality after drying is added in the literature. The results of quality attributes of dried sweet potato have contributed to an understanding of the influence of drying techniques on drying kinetics, physicochemical properties and microstructure of this food, helping to select appropriate drying [8–10]. Through these quality studies, the recommended range of air temperature for drying sweet potato was 40 to 80 °C to obtain good quality attributes [11].

Although there are a number of existing papers in the literature on sweet potato drying, to our knowledge, few papers have been conducted to evaluate the moisture transport parameters using the drying coefficient and drying retardation factor of spherical sweet potatoes considering the internal and external moisture transfer resistances. A simple and effective approach is implemented to evaluate these moisture transfer parameters of foods subjected to drying [12]. In the past, studies have been conducted to evaluate the drying process parameters and moisture transfer parameters of some foods, including spices (e.g. saffron stigmas) [13], fruits (e.g. passion fruit, lemon, banana, and kiwi) [2,14,15], vegetables (e.g. potato, yam, eggplant, and broccoli) [15], and powders (e.g. lactose powder) [16].

Due to the need to increase the utilization of sweet potato flour, reduce annual losses of harvested sweet potato, and increase the availability of flour products throughout the year, it is essential to determine the moisture transport parameters using the drying coefficient and the retardation factor during drying of spherical sweet potatoes considering the internal and external finite resistances to mass and moisture transfer. With the measurement data, the aim of this paper is to evaluate the transport parameters (lag factor, drying constants, moisture diffusivities, and mass transfer coefficient) of spherical sweet potatoes during convection drying.

2. Materials and Methods

2.1. Raw material and processing

Sweet potato 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 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. Samples were transported and stored in refrigerated conditions (4 ± 0.5 °C) before the drying at the laboratory of materials of heliophysics and environment from Nazi Boni University. Before drying, sweet potatoes were placed in laboratory to reach room temperature (25 ± 1 °C). 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 tray. The initial moisture content on a dry basis (d.b.) of samples was obtained using the oven method at 105 ± 5 °C for 24 h [17]. Two additional repetitions of this experiment were performed on the samples to determine the initial moisture content value and the average value of these experiments was found to be 2.259 $kg_{water}/kg_{dry\ matter}$.

2.2. Drying equipment

Drying experiments were carried out in an oven (Froilabo, Model AC Standard Version, France, range 10–250°C with an accuracy of ±0.5°C) installed at the laboratory of materials of heliophysics and environment from the Nazi Boni University, previously described by Ouoba et al. (2021) [18]. Length, height and width of oven were 0.579 m, 0.640 m and 0.526 m respectively. The oven consisted essentially of a centrifugal fan to provide the desired drying air flow, a 1,000-watt electric heater to control the drying air temperature, an air filter, and a proportional-integral-derivative controller (PID controller). Air temperature in oven was regulated to ±1∘C using a temperature controller. The oven operated at dry bulb temperatures of 10°C to 250°C. The target air temperature was obtained by the operation of an electric heater and controlled by the heater control unit. The air speed was provided by the operation of a centrifugal fan and regulated by a fan speed control unit. The air passed from the heater unit and was heated to the target temperature and then channeled to the drying chamber through ventilation slots located in the rear side wall of the drying chamber. This fan located at the rear of the chamber wall produced a horizontal forced air circulation to dry the product samples to be dried. The samples were dried in a horizontal perforated tray. This stainless-steel tray was 0.3 m square. The oven was set at the target temperature for about 0.5 h before the start of the experiments in order to achieve stable conditions.

2.3. Drying procedure

Air drying temperatures were 50, 60, 70 and 80°C and air relative humidities were 5 to 20%. Air velocity was kept at a constant value of 1 to 2.0 m/s with an accuracy of ±0.03 m/s for all drying experiments. Drying process began when drying conditions reached target air temperatures. Once the parboiler reached stable conditions for set points, 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. The tray was removed from the dryer regularly, at 20-min intervals, and weighed with a digital balance, then returned to the oven. The digital balance (model 2102, SARTORIUS, France, range 0–2100 g with an accuracy of ±0.001 g) was kept very close to the dryer within 1 m [19]. Drying was continued until there was no significant temporary variation in the evolution of sample mass measurements. Experiments were terminated when the mass measurements stabilized over the measurement time, which assumes that thermodynamic equilibrium was reached. Dried samples were cooled under laboratory conditions after each drying experiment and stored in airtight jars. The water mass loss of the samples during drying was captured by moisture content on a dry basis and expressed as kg water per 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 [20]. The moisture content was calculated as follows [21]:

$$X(t) = \frac{m(t) - m_s}{m_s} \qquad \text{… … … ….} \quad [1]$$

Where X(t) is the moisture content on a dry basis (d.b.) expressed in kg of water per kg of dry matter; m(t), mass of the wet product, expressed in kg at time t and m_s, mass of dry matter of the sample (kg).

3. Drying Theory

3.1. Moisture ratio

Moisture ratio (MR) was calculated from the mass loss data of the samples during drying. Equation (2) was used to calculate the moisture ratio [22] :

$$\mathrm{MR} = \frac{\overline{X}(t) - X_e}{X_0 - X_e} \qquad \text{… … … ….} \quad [2]$$

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

Since X_e is much lower than X_0 and X, it is negligible in this paper. Then moisture ratio becomes:

$$\mathrm{MR} = \frac{\overline{X}}{X_0} \qquad \text{… … … ….} \quad [3]$$

3.2. Moisture transport analysis

Assuming the isotropic property of the drying samples with respect to moisture diffusivity, Fick's second law of unsteady state diffusion governing the process is of the same form as the Fourier equation for heat transfer, in which temperature and thermal diffusivity are replaced by moisture and moisture diffusivity, respectively. This law, used to describe moisture migration in the drying process, is as follows [13]:

$$\frac{\partial X}{\partial t} = Div[D_{eff}(gradX)] \quad \ldots\ldots\ldots\ldots \quad [4]$$

Where D_{eff} is effective moisture diffusivity of wet product (m^2 /s) and t is drying time (s).

To evaluate the drying process parameters and determine the mass transfer parameters of spherical sweet potato samples during hot air drying at different diameter and air temperature levels, Equation (4) is used under certain assumptions. These assumptions include: (a) the initial moisture content is uniform; (b) the solid retains its shape and volume; (c) the thermophysical properties of the solid and the drying air are constant; (d) the effect of heat transfer on moisture loss is negligible; (e) moisture diffusion occurs in one direction (perpendicular to the surface of the spheres); and (f) there are finite internal and external resistances to moisture transfer in the solid. Under these conditions, equation (4) expressed in axially symmetric spherical coordinates and in dimensionless form, can be written as a function of the radial direction (r) as follows [23]:

$$\frac{\partial \phi}{\partial t} = \frac{D_{eff}}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial \phi}{\partial r}\right) \quad \ldots\ldots\ldots\ldots \quad [5a]$$

$$\phi(r,t) = \frac{X(r,t) - X_e}{X_0 - X_e} \quad \ldots\ldots\ldots\ldots \quad [5b]$$

The initial and boundary conditions for solving equation (5) are [24]:

$$\phi(r,t) = 1, \quad t = 0, \quad 0 \le r \le R \quad \ldots\ldots\ldots\ldots \quad [6a]$$

$$\frac{\partial \phi(r,t)}{\partial r} = 0, \quad t > 0, \quad r = 0 \quad \ldots\ldots\ldots\ldots \quad [6b]$$

$$-D_{eff}\frac{\partial \phi(r,t)}{\partial r} = h_m\phi_s, \quad t > 0, \quad r = R \quad \ldots\ldots\ldots\ldots \quad [6c]$$

Where h_m is convective moisture transfer coefficient of wet product *(m /s)*, *r* and R are respectively the distance from the center and the radius of product *(m)*

The solution of the governing equation (i.e., equation (5)) under the initial and boundary conditions given in equation (6), with r = 0, gives dimensionless transient mean moisture ratio distributions for drying spherical sweet potato samples in the form of series solutions as follows [25]:

$$MR = \frac{\overline{X}(t)}{X_0} = \sum_{n=1}^{\infty} A_n B_n \quad \ldots\ldots\ldots\ldots \quad [7a]$$

where A_n and B_n are defined as follows [14]:

$$\begin{cases} A_n = \dfrac{2Bi\sin\mu_n}{\mu_n - \sin\mu_n\cos\mu_n} & \text{for } 0.1 < Bi_m < 100 \\ B_n = exp(-\mu_n^2 Fo) & \end{cases} \quad \ldots\ldots\ldots\ldots \quad [7b]$$

Where μ_n is the nth root of the transcendental characteristic equation (dimensionless); Bi_m and F_o are respectively the Biot number and the Fourier number for water transport which, for a spherical shape of food of radius R, are described by:

$$Bi_m = \frac{h_m R}{D_{eff}} \quad \ldots\ldots\ldots\ldots \quad [8a]$$

$$Fo = \frac{D_{eff}t}{R^2} \quad \ldots\ldots\ldots\ldots \quad [8b]$$

The above form of the series solutions can be simplified if the values of F_o > 0.2 are negligible. Thus, the infinite sum of equation (7) is well approximated by the first term only, that is [25]:

$$MR = A_1 B_1 \text{ where } \begin{cases} A_1 = G = \dfrac{2\mathrm{Bi}_m \sin\mu_1}{\mu_1 - \sin\mu_1\cos\mu_1} = \exp\left(\dfrac{0.7599\mathrm{Bi}_m}{2.1 + \mathrm{Bi}_m}\right) \text{ for } 0.1 < \mathrm{Bi}_m < 100 \\ B_1 = \exp(-\mu_1^2 Fo) \end{cases} \quad \ldots\ldots\ldots\ldots \quad [9]$$

The root μ_1 of the transcendental characteristic equation is given for the spherical product as follows [26]:

$$\begin{cases} \mu_1 = [(1.1223)\ln(4.9\mathrm{Bi}_m + 1)]^{\frac{1}{1.4}} & \text{for } 0.1 < \mathrm{Bi}_m < 10 \\ \mu_1 = \left[\dfrac{5}{3}\ln(2.199501\mathrm{Bi}_m + 152.4386)\right]^{\frac{1}{1.2}} & \text{for } 10 < \mathrm{Bi}_m < 100 \end{cases} \quad \ldots\ldots\ldots\ldots \quad [10]$$

In equation (9), G denotes the lag factor (dimensionless) and it is obtained by a regression of the dimensionless measurement data of the moisture ratio (MR) and the measurement time of the exponential model whose equation is given below. The regression uses the least squares data fitting method [24]:

$$MR = G\exp(-St) \quad \ldots\ldots\ldots\ldots \quad [11]$$

Where S denotes the drying coefficient of sweet potato samples (s^{-1}). The drying coefficient S is used to capture the drying capacity of sweet potato per unit of measurement time and the lag factor G is a means of measuring the internal resistance to moisture transfer of spherical sweet potato samples during its convective drying.

The two equations (9) and (11) have the same form and can be paralleled. Therefore, having A_1 = G and replacing the Fourier number (F_o) and B_1 by their expressions in equations (8) and (11), the moisture diffusivity values for spherical sweet potato samples are calculated by the following expression in equation (12):

$$\mathrm{D_{eff}} = \frac{SR^2}{\mu_1^2} \quad \ldots\ldots\ldots\ldots \quad [12]$$

The expression of the convective moisture transfer coefficient (h_m) during drying of spherical sweet potato samples is deduced from the mass transfer Biot number (Bi_m) and expressed by the following equation (13) [27] :

$$\mathrm{h_m} = \frac{\mathrm{D_{eff}}\mathrm{Bi}_m}{R} = \frac{\mathrm{D_{eff}}}{R}\left(\frac{1 - 1.316\ln G}{2.76369\ln G}\right) \quad \ldots\ldots\ldots\ldots \quad [13]$$

To determine the mass transport parameters for drying sweet potato samples, the following procedure is applied [24] :

- Using the least squares curve fitting method, the moisture ratio values and drying time are regressed as equation (11) and the lag factor (G) and drying coefficient (S) are determined.
- The Mass transfer Biot number (Bi_m) is calculated using equation (9).
- The value of root (μ_1) is determined from equation (10).
- Moisture diffusivity (D_{eff}) is calculated using equation (12).
- The moisture transfer coefficient (h_m) is obtained from equation (13).

3.3. Activation energy

Effective moisture diffusivity can be linked to air temperature by Arrhenius type expression [28], such as:

$$\mathrm{D_{eff}} = \mathrm{D_0}\exp\left[-\frac{\mathrm{E_{a-d}}}{\mathcal{R}(\mathrm{T} + 273.15)}\right] \quad \ldots\ldots\ldots\ldots [14]$$

Where D_0 is the constant of the Arrhenius type equation (m^2/s), E_{a-d} is the activation energy for moisture diffusion (J/mol), T is the uniform temperature of the sweet potato (°C) and $\mathcal{R}$=8, 3145 is the universal gas constant (J/mol K). Equation (14) can be rearranged into the form:

$$\ln(D_{eff}) = \ln(D_0) - \frac{E_{a-d}}{\mathcal{R}(T + 273.15)} \quad \dots\dots\dots\dots \quad [15]$$

Furthermore, a similar procedure can be adopted to describe the convective mass transfer coefficient (h_m) as a function of temperature following an Arrhenius-type equation [24] :

$$h_m = h_{m0} \exp\left[-\frac{E_a}{\mathcal{R}(T + 273.15)}\right] \quad \dots\dots\dots\dots \quad [16]$$

So,

$$\ln(h_m) = \ln(h_{m0}) - \frac{E_{a-c}}{\mathcal{R}(T + 273.15)} \quad \dots\dots\dots\dots \quad [17]$$

where h_{m0} is a constant (m/s) and E_{a-c} is the activation energy for convective mass transfer (J/mol).

3.4. Statistical analysis

Four statistical parameters were used to determine the ability of the drying model, namely: the coefficient of determination (R^2), the root mean square error (RMSE) and the sum of square errors (SSE):

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(P_{exp,i} - P_{pre,i}\right)^2}{\sum_{i=1}^{N}\left(\bar{P}_{exp} - P_{exp,i}\right)^2} \quad \dots\dots\dots\dots \quad [18]$$

$$RMSE = \left[\frac{\sum_{i=1}^{N}\left(P_{exp,i} - P_{pre,i}\right)^2}{N}\right]^{1/2} \quad \dots\dots\dots\dots \quad [19]$$

$$SSE = \sum_{i=1}^{N}\left(P_{exp,i} - P_{pre,i}\right)^2 \quad \dots\dots\dots\dots \quad [20]$$

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 [20].

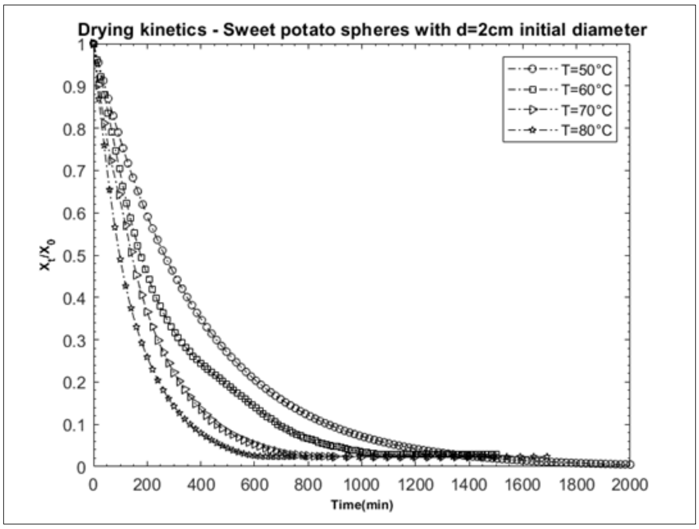
4. Results and Discussion

4.1. Moisture ratio

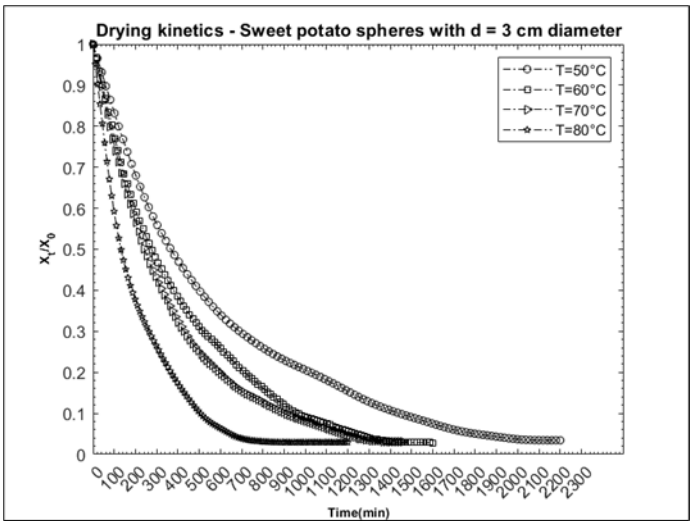
The sweet potatoes spheres were dried in an oven and dried with initial dimeters of d=2 cm and d=3 cm at selected temperature levels (50, 60, 70, and 80°C). The initial moisture contents of sweet potatoes spheres were observed to be 2.2305 (d.b.), 3.0233 (d.b.),3.4258 (d.b.) and 3.3898 (d.b.) at 50°C,60°C,70°C, and 80°C respective air-drying temperatures for 2 cm diameter samples. For 3 cm diameter samples, the initial moisture contents were found to be 2.5564 (d.b.), 2.9792 (d.b.), 3.6894 (d.b.) and 2.7938 (d.b.) at 50°C,60°C,70°C, and 80°C respective air-drying temperatures indicating perishable root tubers with high amounts of water that permit their deterioration. However, upon drying, the moisture contents were reduced to 0.0878 (d.b.), 0.0852 (d.b.), 0.0825 (d.b.) and 0.0796 (d.b.) at 50°C,60°C,70°C, and 80°C air drying temperatures respectively for 2 cm diameter samples. For 3 cm diameter samples, their moisture contents were reduced to 0.0878 (d.b.), 0.0852 (d.b.), 0.1137 (d.b.) and 0.0822 (d.b.) at 50°C,60°C,70°C, and 80°C air drying temperatures respectively.

From the curves, the sweet potatoes were completely dried during the 2000, 1376, 840, and 580 mins at 50, 60, 70 and 80°C respectively for the 2 cm diameter samples (Figure 1a). For the 3 cm diameter samples, the drying durations were found to be 2080, 1600, 1419, and 915 mins at 50, 60, 70 and 80°C respectively (Figure 1b). Therefore, moisture content in the sweet potatoes' spheres decreased to a constant point in a time that was dependent on drying temperature and diameter samples, being lowest at 80°C (during 580 min) and highest at 50°C (during 2000 min) for drying the 2 cm diameter spheres samples. For the 3 cm diameter samples, it was being lowest at 80°C (during 915 min) and highest at

50°C (during 2080 min). Thus, an increase in drying air temperature resulted in a decrease in drying time. Oven air temperature levels and wet product diameter sizes had a significant effect on the moisture content of sweet potatoes during drying. The lower moisture content of sweet potatoes in the dried samples showed decrease in volume and ease in conveying the dried samples during processing and storage. The reduction in moisture content reduced their water content which also resulted in minimizing microbial spoilage and deterioration reaction during sweet potatoes storage. These results were consistent with those of other researchers for various foods including passion fruit [29] and blackberry [17] .



(A)



(B)

Figure 1 Drying curves of sweet potatoes spheres undergoing hot-air at different temperatures for sample diameters of (a) d=2 cm and (b) d=3 cm

Diameter sizes had a significant effect on drying kinetics as showed in Figure 2. Figure 2 shows the evolution of the moisture ratio of spherical sweet potato samples as a function of drying time at an air temperature of 50 °C and for two samples of different diameters. In this figure, interestingly, the decrease in sphere diameters resulted in a reduction of the drying time. So, the 3 cm diameter sweet potato spheres consumed significantly longer time than the 2 cm diameter sweet potato spheres as showed on the Figure 1and Figure 2. For the other drying air temperature conditions, the diameter of the sweet potato increased, and the drying time was also prolonged. One explanation of this phenomenon could be indicated by the reduced water travel distance and increased sample surface area. Our results were in agreement with the drying results on the food materials sizes effects of other researchers. Royen et al. (2020) obtained upon the drying of apple slices that, while for 4 mm slices, the required degree of drying was achieved after 300 min;

for 12 mm slices, one working day (maximum 10 h) was not enough and measurement was stopped after 8.5 h and continued on the second day. The reason was due to the effect of slice thickness that became crucial by decreasing of the moisture content [30].

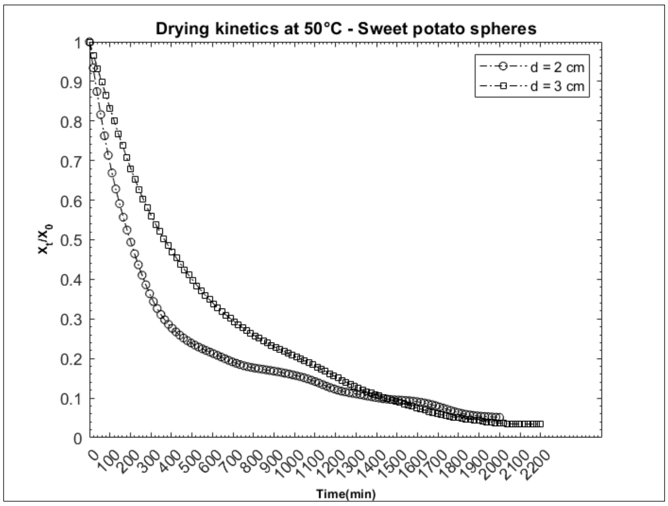


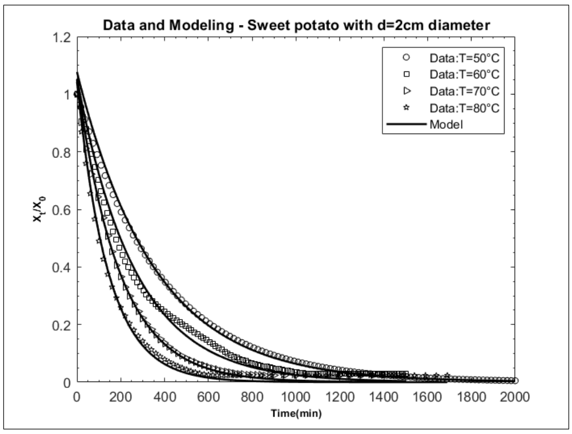
Figure 2 Moisture ratio versus drying time (min) of sweet potato spheres dried at 50 °C air drying temperatures and at different diameters

4.2. Moisture ratio fitting

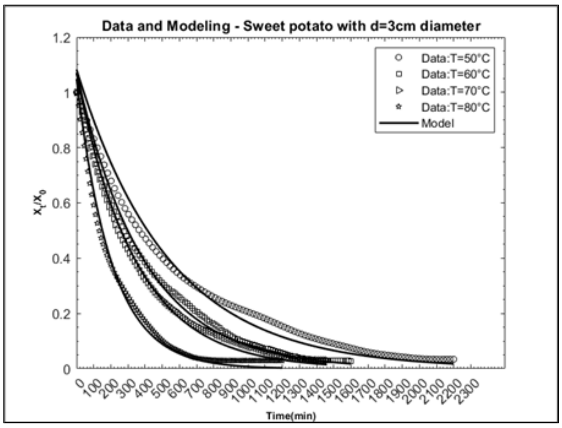
In previous sector, former analysis of the convective drying behavior of the spherical samples revealed the presence of the falling drying rate periods irrespective of the drying conditions. In these drying periods, the most widely used approach to determine the mass transfer was Crank solution from Fick's second law with neglected externe resistances assumption [29]. However, this assumption situation is not validated on condition that the moisture movement is governed by internal and external moisture resistances. Accordingly in current work, moisture transfer approach, which takes both external and internal diffusion mechanisms into account, is adopted to determine the process and transport mass parameters of spherical sweet potato samples under hot air drying. Moisture content measurement data of spherical sweet potato samples dried at air temperatures of 50 to 80 °C for samples 2 to 3 cm in diameter were converted to a dimensionless moisture content using Equation (2). The curve fitting tool of MATLAB R2023b (MathWorks, Inc., Natick, MA) and the nonlinear regression technique were used to fit the moisture content measurement data to the exponential model (Equation (11)). Then the statistical parameters including root mean square error (RMSE), correlation coefficient (R^2) and sum of squared errors (SSE) were used to evaluate the fitting quality of the exponential model. Table 1 presents the statistical data obtained by fitting the sweet potato moisture content measurement data with the exponential function. In this table, the results obtained from R^2, RMSE and SEE indicate that the exponential function is well fitted to the dimensionless moisture content measurement data of these sweet potatoes for the various drying conditions applied with higher R^2 values (0.9801–0.9958), lower RMSE values (0.0159–0.0352) and also lower SSE values (0.0142–0.1350). The drying curve (moisture ratio versus drying time) wherein there was the falling-rate period was adequately described by the exponential model at 50-80° C temperatures and for 2-3 cm diameter samples. This compatibility of the experimental value curves and the theoretical MR values calculated from the model is given in Figure 3. Our results were in agreement with the drying data fitting from literature. Thus, During the mass transfer analyzing of refractance window drying of banana puree, a good fitting between experimental and predicted moisture ratio of banana was obtained for the drying temperatures studied (70-90 °C), with higher R^2 (0.980–0.991) and lower RMSE (0.0294–0.0534) values [31]. Polatoğlu and Aral (2022) fitted experimental data from drying cornelian cherry to this model and found that it provided a good fit for drying conditions (air temperatures: 50-70 °C and air velocities: 0.4-1.0 m/s) of cornelian cherry with statistical results such as $R^2 > 0.90$ and lower RMSE [25].

Table 1 Lag factor (G) and drying coefficient (S) with MR = G exp(−St) of hot air drying of sweet potatoes at 50-80°C air temperatures and for sample diameters of 2 and 3 cm.

Diameter (cm)	**Temperature (°C)**	**Model coefficients**		**Statistical parameters**		
		G (-)	S(s^{-1})	R^2	RMSE	SEE
2	50	1.077	7.860×10^{-7}	0.9958	0.0162	0.0287
	60	1.053	1.045×10^{-6}	0.9901	0.0240	0.0626
	70	1.050	1.441×10^{-6}	0.9957	0.0159	0.0142
	80	1.043	1.950×10^{-6}	0.9923	0.0200	0.0224
3	50	1.083	5.190×10^{-7}	0.9801	0.0352	0.1350
	60	1.072	7.090×10^{-7}	0.9900	0.0257	0.0719
	70	1.068	8.120×10^{-7}	0.9911	0.0238	0.0620
	80	1.049	1.366×10^{-6}	0.9894	0.0243	0.0642



(A)



(B)

Figure 3 Experimental and predicted average moisture ratio of sweet potato for (a) 3 cm diameter samples and (b) 3 cm diameter samples under hot air drying at 50-80°C air temperatures

4.3. Drying process parameters

By using the fitting method to moisture ratio data with the model as described in previous section, the drying process parameters such as the drying coefficient (S) and the dimensionless lag factor (G) were determined for 2-3 cm diameter sweet potato samples at 50-80°C air temperatures. Their values with corresponding statistical parameters were presented in Table 1. As shown in the results in Table 1, the drying coefficient of sweet potato, which shows the ability of its sweet potatoes to dry per unit time, ranged from 5.190×10^{-7} s^{-1} to 1.950×10^{-6} s^{-1} under our air-drying conditions. The values reported in this paper are close to the data reported in the past on drying for various wet foods to be dried including apple slices with (3.30×10^{-4} –1.63×10^{-3} s^{-1}) obtained during refractory window drying and hot air drying at air temperatures of 60–90 °C [32], red dragon fruit slices with (5.627×10^{-5}–9.732×10^{-5} s^{-1}) for infrared drying at radiation intensities of 4–6 kW/m² [33] and, cornelian cherry spheres with a range of (1.138×10^{-5}–4.549×10^{-5} s^{-1}) calculated in the case of convective drying at air temperatures of 50–70 °C [25].

The lag factor of spherical sweet potato samples was a means of measuring and demonstrating the order of magnitude of the internal and external resistance to mass and moisture transfer of these sweet potatoes during the process of their convective drying. Concerning the hot air-drying process of sweet potato spherical samples and as the results showed in Table 1, the lag factor (G) of sweet potatoes varied from 1.043 to 1.083. Its factor values were between 1 and 2 when it is the case of drying spherical solid foods, which gave moisture transfer Biot numbers between 0.1 and 100. This lag factor range was indicated and recognized to represent the usual cases of non-exotic food drying applications [25]. Our lag factors showed that the moisture migration process by diffusion in sweet potato samples was delayed by both internal and external resistance to mass transfer. Because all our lag factor values were greater than 1. Moreover, this variation in calculated values, ranging from 1.043 to 1.083, reflects system specific mass transport characteristics of this sweet potato variety grown in West Africa. The lag factor data found in this paper were close to the lag factor results reported for cornelian cherry fruits (1.052 - 1.126) [25] and banana puree (1.021–1.063) [31].

4.4. Mass transfer Biot numbers

In this study, mass Biot number (Bi_m) values of sweet potato spherical samples are determined at 50-80°C drying air temperatures and for 2-3 cm sample diameters (Table 2). The Biot number values calculated for the spherical sweet potato samples ranged from 0.1232 to 0.2462. This range was in the case where $0.1<Bi_m<100$ for common case of drying application [31]. This indicated the presence of external and internal resistances to moisture diffusion in sweet potato slices. The Bi_m values obtained for sweet potatoes were closer to 0.1 indicating the effect of internal resistance on mass transfer comparatively higher than that of external resistance. The Bi_m values obtained for sweet potatoes in this paper were of the same order of magnitude as those reported by other works in the literature, i.e., Bi_m values were 0.1050 to 0.1315 for convection drying of burdock root [34] and 0.925 to 2.565 for the drying of chili pepper slices [35].

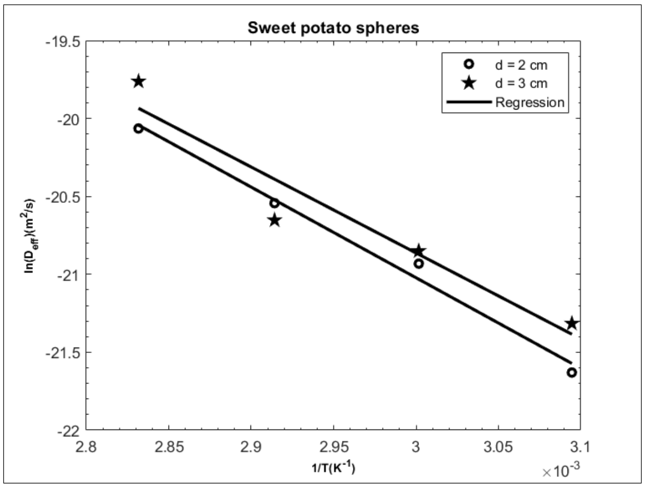
Table 2 Sweet potato mass transfer parameters obtained for our different drying conditions**.**

Diameter (cm)	Temperature (°C)	Bi_m (-)	μ_1(-)	D_{eff} (m^2 s^{-1})	h_m (m s^{-1})
2	50	0.2272	0.8827	4.040×10^{-10}	8.890×10^{-8}
	60	0.1531	0.7175	8.120×10^{-10}	2.651×10^{-7}
	70	0.1441	0.6939	1.197×10^{-9}	4.153×10^{-7}
	80	0.1232	0.6354	1.932×10^{-9}	7.844×10^{-7}
3	50	0.2462	0.9187	5.530×10^{-10}	7.490×10^{-8}
	60	0.2115	0.8512	8.810×10^{-10}	1.388×10^{-7}
	70	0.1990	0.8250	1.073×10^{-9}	1.797×10^{-7}
	80	0.1411	0.6858	2.615×10^{-9}	6.177×10^{-7}

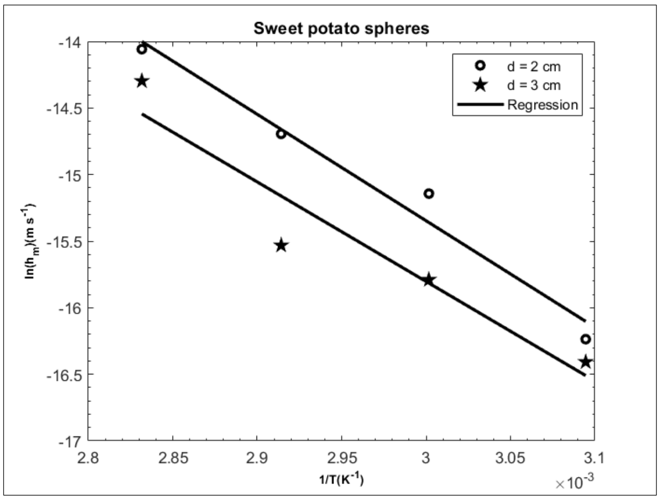
4.5. Moisture transfer parameters

The effective moisture diffusivity values of sweet potatoes, which refer to the moisture diffusion capacity of spherical samples per unit time of measurement from the inside to the outside of the samples to be dried, were calculated at air temperatures of 50 to 80 °C for samples with a diameter of 2 to 3. The results for this sweet potato variety are listed in Table 2. In this table, the effective moisture diffusivity for spherical sweet potatoes ranged from 4.040×10^{-10} to 2.615×10^{-9} m^2/s, for our drying conditions. These results lied in the range of 10^{-12}– 10^{-8} m^2/s for drying foodstuff [31].

This magnitude of effective moisture diffusivity was similar to those from previous drying works of foods i.e. 3.470×10^{-10} - 1.516×10^{-9} m^2/s for the convective drying of smelling peppers and pout peppers [36] and 1.82×10^{-10} – 5.84×10^{-10} m^2/s from Monukka seedless grapes dried in an air-impingement jet dryer [10]. However, the D_{eff} values obtained in this paper were higher than those found in other research in the literature. For example, for drying dates in an automatic solar dryer, the D_{eff} values were between 7.14×10^{-12} m^2/s to 2.17×10^{-11} m^2/s [29]. This variability in the effective moisture diffusivity values of sweet potatoes depended on the conditions of the experimental processes used, the methods of physical or chemical pretreatment of the foods to be dried, the complexity of the structure of these foods, and the initial moisture content [37].



(A)



(B)

Figure 4 Representation by the Arrhenius-type equation for drying spherical sweet potatoes: (a) of moisture diffusivity; (b) convective mass transfer coefficient

Moisture transfer between the interface of the food products to be dried and the hot drying air is a complex fact of significant water mass movement that can be the subject of experiments and scientific studies. It is globally described by a convective moisture transfer coefficient. This coefficient is defined as the rate of moisture transport from the surface of the food to the air flow during the convective drying process. The convective moisture transfer coefficient (h_m) of spherical sweet potatoes was calculated at an air temperature of 50–80 °C for samples with a diameter of 2–3 cm based on the data of D_{eff}, Bi_m and R. The values of h_m for these spherical sweet potato samples were found to be in the range of 7.490×10^{-8} – 7.844×10^{-7} m s^{-1} (Table 2). These results were within the comparable range of those available by several authors for different foods and drying conditions, such as those reported for drying burdock root slices (1.3256×10^{-7}–7.8375×10^{-7} m/s) [34] and for drying chili peppers (5.3×10^{-8} - 8.79×10^{-6} m/s) [35].

4.6. Activation energy

The Arrhenius functions expressing the variations of moisture diffusion and mass transfer coefficients for spherical sweet potatoes as a function of air temperature are determined by least-squares fits of the experimental data in Table 2 as the natural logarithms of D_{eff} and h_m as a function of the reciprocal of absolute air temperature using Equation (15) and Equation (17), respectively. The natural logarithms of D_{eff} and h_m for spherical sweet potato samples of 2-3 cm diameter were plotted against the reciprocal of absolute temperature in Figure 4. In this figure, the values of activation energy for moisture diffusion ($E_{a\text{-}d}$) and convective mass transfer ($E_{a\text{-}c}$) were obtained from the different slopes of the curves which were equivalent to the ratio of activation energy to the general gas constant. The activation energy ($E_{a\text{-}d}$) for moisture diffusion reflected the sensitivity of diffusivity to air temperature, indicating the energy required to initiate water diffusion in our drying products. The activation energy results with statistical parameters for les 2-3 diameter sweet potato samples are shown in Table 3. The activation energy for moisture diffusion ($E_{a\text{-}d}$) was 48.349 kJ/mol and 45.838 kJ/mol, respectively for 2 cm and 3 cm sample diameters with R^2 (0.9891–0.9181), RMSE (0.0846–0.2282) and SSE (0.0143–0.1041). For the same sample diameters of sweet potatoes, the activation energy for convective mass transfer ($E_{a\text{-}c}$) was 66.474 kJ/mol and 62.151 kJ/mol with R^2 (0.9725–0.9110), RMSE (0.1862–0.3237) and SSE (0.0693–0.2095), respectively (Table 3). Our energy of activation values for moisture diffusion were in the range of 12.70–110.00 kJ/ mol for most agricultural materials [22]. The activation energy ($E_{a\text{-}d}$) calculated for moisture diffusion in the present study was comparatively close to the activation energies of other works, i.e. 45.94 kJ/mol for drying paneer cubes [38] and 46.64 kJ/mol determined for thin-layer air impingement drying of American ginseng [39]

Also, our activation energy ($E_{a\text{-}c}$) for convective mass transfer was similar to $E_{a\text{-}c}$ values in literature such as 72.325-87.386 kJ mol^{-1} for drying of paddy [24]. The magnitudes of $E_{a\text{-}d}$ and $E_{a\text{-}c}$ were varied for all drying conditions applied to products. The variability of activation energy could be attributed to the characteristic diameter dimensions of sweet potatoes. These variabilities could also be due to the physical and chemical structure of the food and the water activity in this food [10,15,39].

Table 3 Activation energy for the moisture diffusion and the convective mass transfer of spherical sweet potatoes

	Moisture diffusion				**Convective mass transfer**			
Diameter(cm)	**$E_{a.\text{-}d}$(kJ/mol)**	**R^2**	**RMSE**	**SSE**	**$E_{a.\text{-}c}$ (kJ/mol)**	**R^2**	**RMSE**	**SSE**
2	48.349	0.9891	0.0846	0.0143	66.474	0.9725	0.1862	0.0693
3	45.838	0.9181	0.2282	0.1041	62.151	0.9110	0.3237	0.2095

5. Conclusion

The evaluation of the mass moisture transport parameters of spherical sweet potatoes was investigated at 50°C, 60°C,70°c and 80°C air temperatures for 2 and 3 cm diameter samples. With the measurement data, the aim of this paper is to evaluate the transport parameters (lag factor, drying constants, moisture diffusivities and moisture transfer coefficient) of spherical sweet potato samples during hot air convective drying by adopting this approach for drying modelling. In the experiments, spherical sweet potato samples were dried at several drying air temperature levels and the changes in moisture content were recorded during the drying time. These values were converted to moisture content values and used to explain the convective drying behavior of these spherical sweet potato samples. The drying process occurred generally in the decreasing rate period, but a constant rate period was not observed for all air temperature levels. The moisture content and drying rate were influenced by the drying air temperature and the sample diameter level. The drying time of sweet potatoes decreased and the drying rate increased with decreasing sample diameter and increasing drying air temperature level. The drying coefficient of sweet potato varied from 5.190×10^{-7} s^{-1} to 1.950×10^{-6} s^{-1} under our air-drying conditions. The lag factor of sweet potatoes varied from 1.043 to 1.083. The calculated moisture Biot number values for sweet potatoes were in the range of 0.1232 - 0.2462. The effective moisture diffusivity for spherical sweet potatoes varied in range from 4.040×10^{-10} to 2.615×10^{-9} m^2/s, for our drying conditions. The convective mass transfer coefficient values for spherical sweet potato samples were obtained to be in the range of 7.490×10^{-8} – 7.844×10^{-7} m/s. The activation energy for moisture diffusion was 48.349 and 45.838 kJ/mol, respectively for samples with diameters of 2 and 3 cm. The activation energy for convective mass transfer was 66.474 and 62.151 kJ/mol for sweet potato samples with diameters of 2 and 3 cm, respectively. The results of this paper are useful for optimizing the drying process parameters for commercial scale production of dried sweet potatoes using a convective oven dryer and for achieving superior quality of the dried products.

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

No conflict of interest to be disclosed.

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