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Influence of temperature and diameter of pale-fleshed, white-skinned spherical sweet potato (*Ipomoea batatas*) on the mass moisture transport parameters of hot air convection

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Abstract: The aim of this study is to the influence of air temperature and samples diameter on the moisture and mas transport parameters for spherical sweet potatoes subjected to drying. In this study, the influence of drying parameters such as air temperature and sample diameter on the mass moisture transport parameters of hot air drying of pale-fleshed, white-skinned spherical sweet potato of 'BF 13' variety, (a variety newly introduced and grown in Burkina Faso), were investigated at 50-80°C air temperatures on 2-3 cm diameter samples. Drying experiments were carried out in an air convective oven by measuring the sample weights according to the time. The averages of three replicates were taken as experimental data. As results, the drying coefficient of sweet potato samples increased up to 1.950×10^{-6} s^{-1} with increasing drying temperature regardless of the employed sample diameters. At almost all air temperatures, reducing the sweet potato diameters caused the drying coefficient to increase. The increase in air temperature from 50 to 80 °C and decrease in sample diameter from 3 to 2 cm decreased the lag factor from 1.083 to 1.043. The Biot number values decrease from 0.2462 to 0.1232 with increase in the air temperature for all sample diameters. When sample diameter increases, the Biot number values increased regardless of drying air temperature. Moisture diffusivity values increased with increased air temperature from 50°C to 80°C and increased sweet potato sample diameter from 2 cm to 3 cm. The moisture diffusion and convective mass transfer activation energy values were decreased with increasing samples diameter for all drying conditions applied.

Keywords*:* drying coefficient, lag factor, moisture diffusivity and convective mass transfer coefficient.

Abbreviations:

Bi_m	Biot number of moisture transport (-)
d	Diameter of the product (m)
d.b.	dry basis
D_0	Constant of Arrhenius type equation for moisture diffusion (m^2 s^{-1})
D_{eff}	Effective moisture diffusivity (m^2 s^{-1})
$E_{a\text{-}c}$	Activation energy for convective mass transfer (J mol^{-1})
$E_{a\text{-}d}$	Activation energy for moisture diffusion (J mol^{-1})
Fo	Fourier number of moisture transport (-)
G	Lag factor (-)
h_m	Convective moisture transfer coefficient of wet product (m s^{-1})
h_{m0}	Constant of Arrhenius type equation for convective moisture transfer (m s^{-1})
min	minute (min)
MR	Moisture ratio (-)

m_s	Dry mass (kg)
$m(t)$	mass of wet product (kg)
n	Integer number (-)
N	Number of experimental observations (-)
$P_{exp,i}$	Experimental value of the parameter P (-)
$\bar{P}_{exp,i}$	Average experimental value of the parameter P(-)
r	Space variable from product centre (m)
R	Radius (m)
$\mathcal{R}$	Universal gas constant = 8314.46 J mol^{-1} K^{-1}
R^2	Coefficient of determination (-)
$RMSE$	Root-Mean-Square error (-)
S	Drying coefficient (s^{-1})
SSE	Sum of squared error (-)
t	Tim (s)
T	Air Temperature or uniform product 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$_{dry\ mass}$)
$\bar{X}\ (t)$	Average or mean moisture content (kg $_{water}$/kg$_{dry\ mass}$)
z	Number of constant coefficients in the model regression (-)
μ_n	nth root of the transcendental characteristic equation (-)
μ_1	first root of the transcendental characteristic equation (-)
χ^2	Reduced chi-square (-)

Introduction

Drying is a unitary operation aimed at eliminating water from a product and consequently reducing its water activity. Drying food products has many advantages, such as: inhibiting the growth of microorganisms and spoilage reactions by reducing water activity as well as reducing transportation and storage costs due to the reduction in weight and volume of products (Compaore et al., 2017). Convective drying is the process of removing water with air via simultaneous transfer of heat, mass and momentum. The necessary heat is transmitted to the food by a flow of hot air. Energy is transferred to the surface of the product by convection and then transferred to the interior of the product by diffusion or convection, depending on the biological configuration of the wet product. 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 properties of the dried product depend on the external air conditions of the drying process such as temperature, humidity, velocity and direction of flow. Additionally, the drying rate depends on internal conditions of moist product such as geometry, thickness, shape and structure of the product. The complexity of the structure and composition of wet foods, the variety of transport phenomena and biological diversity make food drying a challenge (Li et al., 2024; Onwude et al., 2021). To address this challenge, many researchers have been interested in investigating various experimental processes of drying foods such as the tuberous roots category (Amagloh et al., 2021; Antal, 2023; Ayonga et al., 2023).
Sweet potato tuber (*Ipomoea batatas*) offers great possibilities for achieving food and nutritional security in developing and underdeveloped countries where most agricultural fields belong to vulnerable population categories (Amagloh et al., 2021). Sweet potatoes are important tubers rich in fibre, 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 (Onwude et al., 2019). In the literature, several drying processes have been applied to different sweet potato varieties, namely, infrared and fluidized bed drying (Thao and Noomhorm, 2011), convective hot air drying (Adie & Inyang, 2024), microwave drying (Junqueira et al., 2022), hybrid microwave and hot air drying (Tüfekçi & Özkal, 2023), spouted bed drying (Rezende et al., 2024), sun and drum drying (Badiora et al., 2023), spray drying (Arebo et al., 2023), freeze-drying (Antal, 2023) and solar drying (Sakouvogui et al., 2023). Pretreatments before drying have been applied to sweet potatoes including steaming (Dinrifo, 2012), blanching with hot water and steam (Badiora et al., 2023), soaking in sodium metabisulfite solution (Edeani and Anyaene, 2023), osmotic dehydration with sucrose and sorbitol (Junqueira et al., 2022), immersion in citric acid solution (Antal, 2023), lemon juice and saline solution (Ayonga et al., 2023) and soaking in sodium metabisulfite solution (Shamala and Fouda, 2023). These drying and pretreatment techniques were applied on sweet potato samples with several sliced shapes, varieties, skin and flesh colours including sweet potato cubes (Singh and Pandey, 2012), white skin and yellow-red flesh sweet potato slices of Kratai cultivar (Thao and Noomhorm, 2011), strips (Obregon et al., 2020), chips (Souza et al., 2019), Nigerian variety slices (Olawale and Omole, 2012), and Chinese local variety slices (Fan et al., 2015). It was found that there are few papers on air drying of spherical sweet potato in the literature. To our knowledge, no paper was found to

determine the effects of drying conditions on moisture transport parameters using lag factor and drying coefficient during convection drying of spherical sweet potatoes with white skin and pale flesh. Using the experimental data, the aim of this study is to determine the influence of air temperature and sample diameter on the moisture transport parameters (lag factor, drying constants, moisture diffusivities, and moisture transfer coefficient) for spherical sweet potatoes subjected to convective drying.

Results and Discussion

Moisture ratio fitting

Understanding the optimum operating conditions to obtain good quality dried sweet potatoes requires knowledge of the influence of the process parameters on the mass transfer rates. In literature, former analysis of the convective drying behaviour of the sweet potatoes revealed the presence of the falling drying rate periods irrespective of the drying conditions (Fan et al., 2015; Junqueira et al., 2022; Obregon et al., 2020; Edeani and Anyaene, 2023). In these drying periods, the most widely used approach to determine the mass transfer is Crank solution from Fick's second law with neglected externe resistances assumption (Metwally et al., 2024). 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, was adopted to determine the process and transport mass parameters of spherical sweet potato samples under hot air drying.

The experimental moisture content values of the spherical sweet potato's samples dried at 50-80°C air temperatures for 2-3 cm diameter samples were converted to moisture ratio using Equation (2) (Jibril et al., 2024). The moisture ratio data were fitted with the exponential function from 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** indicates the statistic results obtained by fitting experimental moisture ratio data with the model. In this table, the obtained values of R^2, RMSE and SEE show that the exponential equation is satisfactorily fitted the experimental data for the different drying conditions employed with higher R^2 (0.9801–0.9958), lower RMSE (0.0159–0.0352) and lower SSE (0.0142–0.1350) values. 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 values and the MR values calculated from the model is given in **Error! Reference source not found.**. Our results were in agreement with the drying data fitting from the literature (Rajoriya et al., 2021; Polatoğlu and Aral, 2022). Thus, during the mass transfer analysing 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 (Rajoriya et al., 2021). 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 (Polatoğlu and Aral, 2022).

Influence of temperature and diameter on drying process parameters

By using the fitting method to experimental 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 the corresponding statistical parameters, were presented in **Table 1**. As shown in **Table 1**, the drying coefficient of sweet potato which shown the capability of its sweet potatoes drying per unit time varied from 5.190×10^{-7} s^{-1} to 1.950×10^{-6} s^{-1} under our air-drying conditions. Some factors such as indigenous properties, initial and final moisture content of the product, drying method and drying conditions could affect the drying parameters of food materials. In our case and with the results in **Table 1**, the drying coefficient of sweet potatoes increased with increasing drying temperature whatever the employed sample diameters. An increase in drying temperature leads to an increase in heat and mass transfer between the hot air and the sweet potato spherical samples and consequently, a higher drying capability of these sweet potatoes. Our results were consistent with the influence of drying air temperatures on drying coefficients (S) from literature. Polatoğlu and Aral (2022) reported same results in term of the drying temperature on convective drying coefficient of cornelian cherry slices. Increasing air temperature enhanced heat transfer from air to the cornelian cherry which caused an increase in the evaporation rate of moisture in this fruit (Polatoğlu and Aral, 2022). Rajoriya et al. (2021) reported the refractance window drying of banana puree where the influence temperature results could be attributed to the faster rate the heat and mass transfer between the heating medium and banana slices, leading to a higher drying capability of the banana (Rajoriya et al., 2021). Golpour et al. (2021) carried out the convective drying process of paddy at 30–80°C air temperatures with air velocities between 0.54 and 3.27 m s^{-1} where the drying coefficient of paddy was higher at 80°C regardless of the air velocity used (Golpour et al., 2021). Hai et al. (2022) reported same results in term of the infrared power on infrared drying coefficient of dragon fruit slices. The largest drying coefficient could be observed at the highest value of radiation intensity used in infrared drying (Hai et al., 2022). Furthermore, it is can be seen from **Table 1** that at almost all air temperatures, reducing the sweet potato diameters caused an increased drying coefficient. This was due to a short distance of the water diffusion path within the sweet potatoes and then lead to faster moisture evaporation of water from the surface from these wet product samples. This observation on diameter effect is consistent generally with influences on drying parameters of characteristic dimensions of other products dried such as banana slices (Rajoriya et al., 2021), mushroom slices (Ghanbarian et al., 2016) and eggplant slices (Liu et al., 2013).

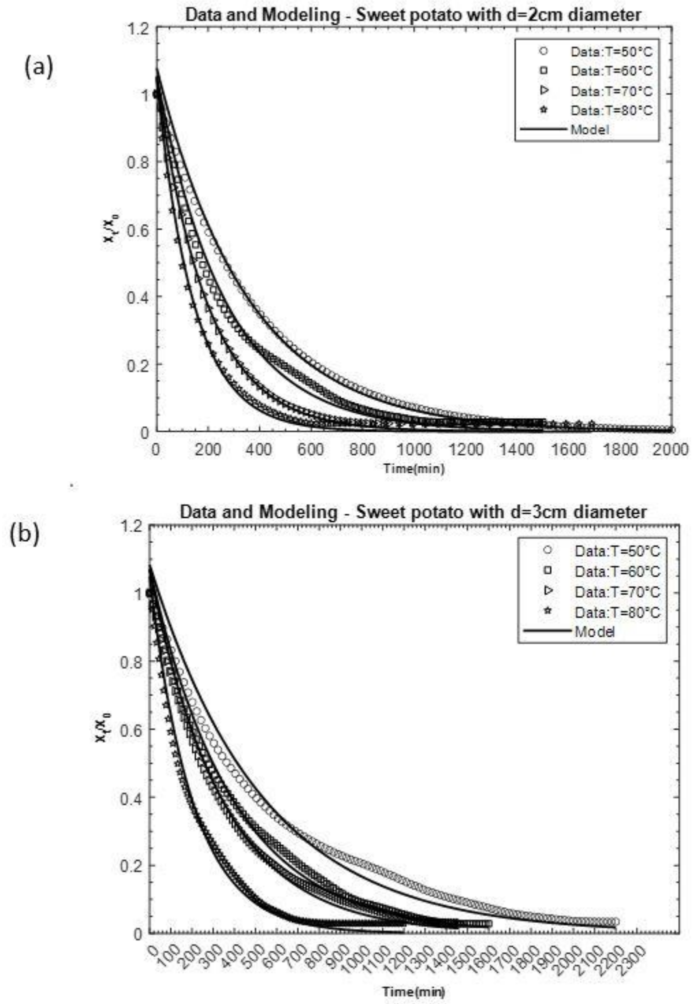

Figure 1. Variation of effective moisture diffusivity of sweet potatoes versus air temperature for 2-3 cm sample diameter.

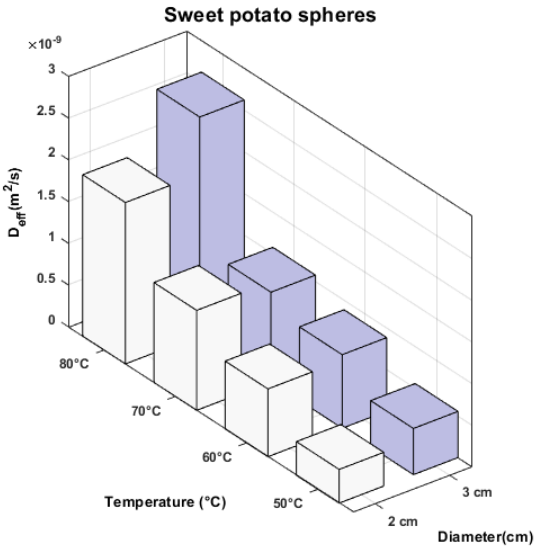

Figure 2. Variation of effective moisture diffusivity of sweet potatoes versus air temperature for 2-3 cm sample diameter.

The lag factor of spherical samples was an indicator of magnitude of both internal and external resistance of sweet potatoes to the heat and/or moisture transfer during convective drying process. Table 1 shows the hot air-drying process of sweet potato spherical samples and the lag factor (G) of sweet potatoes which varied from 1.043 to 1.083. Its lag factor values were in range from 1 to 2 for the drying spherical objects and this led to the moisture Biot numbers in the range between 0.1 and 100. This range was known as the most common case for the drying applications (Polatoğlu and Aral, 2022). Our

Table 1. Drying coefficient (S) and lag factor (G), MR = G exp(−St), for hot air drying of spherical sweet potato samples drying at different temperatures and for two sample diameters.

Diameter (cm)	Temperature (°C)	Model coefficients		Statistical parametres		
		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

Table 2. Mass transfer parameters calculated for the 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}

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-d} (kJ/mol)	R^2	RMSE	SSE	E_{a-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

lag factors indicated that moisture diffusion within the sweet potato samples was controlled by both internal and external resistance (all more 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. It is evident from **Table 1** , that the increase in drying air temperature and decrease in sweet potato diameter decreased the lag factor (G) values. This trend can imply that at high drying air temperature and small sweet potato diameter, moisture evaporation from the samples was less delayed at the beginning of the process and the drying period at decreasing rate started from this beginning of the process. However, at low air temperature and large sweet potato diameter, moisture evaporation was more delayed by the heating period of wet samples leading to a relatively long lag period. A similar observation was made by Bezerra et al., (2015) for passion fruit peel drying (Bezerra et al., 2015), by Rajoriya et al. (2021) for drying of banana (Rajoriya et al., 2021) and by Nguyen et al. (2023) for drying of burdock root (Nguyen et al., 2023). Agbede et al. (2024) investigated convective drying of *Jatropha curcas* L. seeds and found lag factor values of 1.101, 1.098, 1.095 and 1.093 at respective temperatures of 80,100,120 and 140° C (Agbede et al., 2024). The values of lag factor of 1.111, 1.124, 1.137 and 1.156 at air temperatures of 40, 50, 60 and 70 °C, respectively were obtained for drying chili pepper showing temperature effect on lag factor (Enahoro et al., 2022).

Influence of temperature and diameter on mass transfer Biot numbers

The Mass Biot number (Bi_m) is an important dimensionless parameter in food drying such as sweet potato. It explains the ratio of the internal moisture diffusion resistance inside the sweet potato samples to the external moisture convective resistance at its surfaces. It can also be used to calculate the rate of internal mass diffusion in the sweet potatoes. In this study, 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 calculated Biot number values for sweet potatoes were in the range of 0.1232 - 0.2462. This range was in the case where $0.1<Bi_m<100$ for common case of drying application (Rajoriya et al., 2021). It indicates the presence of both external and internal resistances to the moisture diffusion of sweet potatoes. 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 results in **Table 2** showed that the Biot numbers were influenced by the drying air temperature and the sweet potato sample diameters. It was observed that the Bi values decrease with increase in the drying air temperature for all sample diameter. When sweet potato diameter increases, the Bim values increased also regardless of drying air temperature of samples. It was due to increased internal resistance within sweet potatoes when sample diameters increase. Similar trend of results under the drying conditions of air temperature and product diameter have been reported for burdock root slices (Nguyen et al., 2023), for cornelian cherry slices (Polatoğlu & Aral, 2022), for banana slices

(Rajoriya et al., 2021) and for cumbeba waste (Ferreira et al., 2020). Subsequently, the Bim values for spherical sweet potatoes were used for obtaining the root $\mu 1$ for moisture transfer of the transcendental characteristic equation, as show in **Table 2.** These values were in range from 0.6354 to 0.9187 for our drying conditions. Those decreased with increasing air temperature and decreasing sample diameter. Similar results were obtained in cornelian cherry drying (Polatoğlu & Aral, 2022), in banana drying (Rajoriya et al., 2021) and in chili pepper drying (Enahoro et al., 2022).

Influence of temperature and diameter on moisture transfer parameters

Moisture effective diffusivity values of sweet potatoes which refers to the area diffusion ability of spherical samples in per second from internal to external, were calculated at 50-80°C air temperatures for 2-3 samples diameter and the results are listed in **Table 2.** In this table, 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. These results lie in the range of 10^{-12}– 10^{-8} m^2/s for drying foodstuff (Rajoriya et al., 2021).

Moreover, moisture diffusivity value depends on drying temperature, variety and composition of the drying samples. For hot air drying of spherical sweet potatoes, moisture diffusivity values increased with increased air temperature from 50°C to 80°C and increased sweet potato sample diameter from 2 cm to 3 cm (**Figure 1** and **Table 2**). This can be explained by the fact that the surface temperature of sweet potato spherical samples was increased when the drying temperature was raised, which enhanced the molecular motion and surface suction within the spherical sweet potatoes. As an outcome, water molecules migrate outwards (vaporize) with a larger energy content. This improves the moisture-removal-to-time ratio, which means that the drying samples lose moisture faster, and the moisture diffusivity is increased. Furthermore, an increase in air temperature causes a decrease in water viscosity and increases the activity of water molecules of drying samples. These phenomena facilitate diffusion of water molecules in different sweet potatoes pores and consequently, increase also the moisture diffusivity (Rajoriya et al., 2021). The same trend results of air temperature have been reported in the literature by researchers in term of hot air drying of foods notably the date fruits (Metwally et al., 2024), the corn (Jibril et al., 2024), the walnuts (Man et al., 2024) and the Chinese medicine residues (Feng et al., 2024). Meanwhile, Yamchi et al. (2024) had reported that by changing the air temperature from 50-70°C in the infrared drying of ripe and unripe bitter melon slices the D_{eff} amounts for ripe and unripe bitter melon samples varied from 1.75×10^{-8} to 3.98×10^{-8} and 1.37×10^{-8} to 2.84×10^{-8} m^2/s, respectively (Yamchi et al., 2024). Also, Moura et al. (2023) reported an increasing D_{eff} values of 5.75×10^{-10} -1.516×10^{-9} m^2/s and 3.47×10^{-10} - 8.59×10^{-10} m^2/s for convective drying of smelling and pout peppers at an air temperature range of 50 to 80°C (Moura et al., 2023). Then, Rajoriya et al. (2021) reported an increasing D_{eff} values of 2.89 $\times 10^{-9}$ - 3.32×10^{-9} m^2/s for the refractance window drying of banana puree at a slice thickness range of 2-3 mm and constant temperature of 70°C (Rajoriya et al., 2021). Meanwhile, Maamar et al. (2023) observed that in the vacuum drying of olive pomace at a slice thickness range from 5 mm to 15 mm and gauge pressure of −130 mbar, the D_{eff} values generally increased from 1.1324×10^{-8} - 4.0306×10^{-6} m^2/s (Maamar et al., 2023).

The convective moisture transfer coefficient (h_m) of the spherical sweet potatoes was calculated at 50-80 °C air temperature for 2-3 cm sample diameters on the basis of the D_{eff}, Bi_m and R values. The h_m values for spherical sweet potato samples were obtained to be in the range of 7.490×10^{-8} – 7.844×10^{-7} m s^{-1} (**Table 2**). The convective moisture transfer coefficient (h_m) in the boundary layer on the surface of foods such as sweet potatoes depend on the properties of the airflow, drying conditions, and the geometry of the dried material. For sweet potato spherical samples, the h_m values increased with increasing air temperature and decreasing sample diameter, as shown in **Table 2**. In fact, as the results show, as the air temperature increased from 50°C to 80°C for 2 cm sample diameter, the h_m values increased from 8.89×10^{-8} to 7.844×10^{-7} m/s. Contrary, for a 70°C air temperature, as the sample diameter increased from 2 cm to 3 cm, these values decreased from 4.153×10^{-7} to 1.797×10^{-7} m/s. This variation in hm values can be explained through higher diffusivity, which increases the moisture transfer rate from the inside to the surface of the sweet potatoes being dried. Subsequently, this increases the gradient of moisture concentration between the surface of spherical sweet potatoes and the surrounding air, thus increasing the rate of absorption of water vapor by the air. Besides, heat and mass transfer also occurs in the sweet potatoes due to the circulation of air surrounding the samples that increases the convection mechanism resulting in a higher mass transfer coefficient (Rajoriya et al., 2021). Also, the moisture transfer rate from the surface of spherical samples depends on the thickness of the thermal and concentration boundary layers along the surfaces of these samples. The thickness of the thermal and the concentration boundary layers originate from difference of temperature and concentration between the sweet potato samples surfaces and free stream drying air. Higher drying temperatures increase evaporation capability of the free stream drying air and lead to higher mass transfer rates (Beigi, 2017). In the literature, similar reports of the influence of air and samples parameters on h_m has been presented for burdock root (Nguyen et al., 2023), jatropha seeds (Agbede et al., 2024), chili peppers (Enahoro et al., 2022), and beetroot slices (Malakar et al., 2022). Meanwhile, Golpour et al. (2021) also determined the convective mass transfer coefficients (h_m) for paddy in cylindrical shapes, and their results lead to the highest h_m value of 4.807×10^{-6} m/s is obtained at 80°C and an air velocity of 3.27 m s^{-1}, while the lowest h_m amount is 5.118×10^{-8} m/s at 30°C and an air velocity of 0.54 m s^{-1}(Golpour et al., 2021). Agarry et al. (2021) have reported an increasing hm values from 1.61×10^{-7} to 1.83×10^{-6} m/s for drying of okra slices due to increasing air temperature from 40°C to 70°C (Agarry et al., 2021).

Influence of temperature and diameter on activation energy

For practical engineering applications, it is useful for obtaining Arrhenius functions that describe the effect of air temperature on moisture diffusivity (D_{eff}) or on convective mass transfer coefficient (h_m). The Arrhenius functions expressing the variations of moisture diffusion and mass transfer coefficients for spherical sweet potatoes according to air temperature are determined by least-square fits of the experimental sets of data from **Table 2** in the form of pairs ln (D_{eff}) or ln(h_m) versus 1/ (T (°C) + 273.15) using equation (15) and equation (17), respectively. The natural logarithm of D_{eff} and h_m for 2-3 cm diameter sweet potato samples was plotted against the reciprocal of absolute temperature in **Figure S1**. In this figure, the values of activation energy for moisture diffusion (E_{a-d}) and convective mass transfer (E_{a-c}) are got from the different curve slopes which are equivalent to the ratio of activation energy to the general of perfect gas constant (Ea/R). The energy of activation (E_a) for moisture diffusion reflects 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-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-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 are in the range of 12.70–110.00 kJ/ mol for most agricultural materials (Jibril et al., 2024). The activation energy (E_{a-d}) calculated for moisture diffusion in the present study was comparatively close activation energies of other works i.e. 45.94 kJ/mol for the drying of paneer cubes (Arulkumar et al., 2023), 36.74 - 41.43 kJ/mol and 37.49 - 42.91 kJ/mol for drying of ripe and unripe bitter melon slices(Yamchi et al., 2024) , 50.538 and 61.825 kJ mol^{-1} were the lowest and highest values of moisture diffusion activation energy for drying of paddy (Golpour et al., 2021), 46.71 kJ/mol for drying of cumbeba waste (Ferreira et al., 2020). Also, our activation energy (E_{a-c}) for convective mass transfer are similar aux E_{a-c} values in literature such as 72.325-87.386 kJ mol-1 for drying of paddy (Golpour et al., 2021) , 50.8 and 48.5 kJ/mol for kiwi and eggplant drying (Guine et al., 2017). The magnitudes of E_{a-d} and E_{a-c} are decreased with increasing sample diameter for all drying conditions applied. The variability for activation energy could be attributed to a different temperature range and also to different elements shape and characteristic dimension. Besides, these variabilities can also be due to the chemical composition of the food, which is related to its structure and water activity, among others (Guine et al., 2017). In general, high activation energy values are associated with foods in which the water is more strongly bound to the food structure and, consequently, in which water removal is driven by the food's structure. In the case of sweet potatoes, the activation energy values for moisture diffusion and convective mass transfer found was slightly high (Compaoré et al., 2022).

Materials and Methods

Raw material and processing

Sweet potato of the 'BF 13' local variety (Djinet et al., 2014) was used as drying material in this study. Samples of this 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) for 24 h before the drying process at the laboratory of materials of Helio physics and environment of the Nazi BONI University from Nazi Boni University. Before drying, sweet potato samples were placed in laboratory to reach room temperature (25 ± 1 °C). Sweet potato tubers with (35±0.01 g) average weights were selected, washed, peeled, cut into spheres with diameters from 1 ± 0.002 cm to 3 ± 0.002 cm, measured manually using a digital calliper. 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 (Petković et al., 2024). Triplicate samples were used for determination of moisture content and the average values were 2.259 $kg_{water}/kg_{dry\ matter}$.

Drying procedure

Drying experiments were carried out in an air circulated 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 Helio physics and environment of the Nazi BONI University from Nazi Boni University, Bobo-Dioulasso, Burkina Faso, previously described by Ouoba et al. (2021) (Ouoba et al., 2021). 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 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 digital electronic balance (model 2102, SARTORIUS, France, range 0–2,100 g with an accuracy of ±0.01 g) was kept very close to dryer (less than 1 m) (Wang et al., 2022). Convective drying was continued until there was no significant variation in change in masses of the sweet potatoes. Drying tests were terminated when masses of samples were stabilized, which assumes that thermodynamic equilibrium is reached. Dried samples were cooled under laboratory conditions after each drying experiment and stored in airtight jars. Mass loss of sample 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 (Compaoré et al., 2022). The moisture content was calculated as follows (Wang et al., 2024):

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

Where X(t) is dry-based moisture content (d.b.) expressed in kg $_{water}$/kg $_{dry\ matter}$; m (t), mass of the wet product, expressed in kg at time t and m_s, dry matter mass of sample (kg).

Drying theory

Moisture ratio

The moisture ratio (MR) was calculated from the mass loss data of samples during drying. Equation (2) was used to calculate the moisture ratio (Jibril et al., 2024):

$$\mathrm{MR} = \frac{\overline{X}(t) - X_e}{X_0 - X_e} \qquad (2)$$

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

As Xe is much lower than X_0 and X, it is negligible in this study. Then moisture ratio becomes:

$$\mathrm{MR} = \frac{\overline{X}}{X_0} \qquad (3)$$

Moisture transport analysis

Moisture transport during drying of most foods is accomplished by moisture diffusion (liquid and/or vapor). The moisture diffusion process observed during food drying is similar to the transient heat conduction process in these wet solid objects. 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 (Torki-Harchegani et al., 2017):

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

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 (e.g., drying coefficient and lag factor) and determine the mass transfer parameters (e.g., effective moisture diffusivity and convective mass transfer coefficient) of spherical sweet potato samples during hot air convection drying at different diameter and air temperature levels, Equation (4) is used under certain assumptions. These assumptions include: (a) the primary moisture content is uniform; (b) the solid maintains its shape and volume; (c) the thermophysical properties of the solid and the drying medium 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) in axially symmetric spherical coordinates and in dimensionless form can be written as a function of the radial direction (*r*) as follows (Man et al., 2024):

$$\frac{\partial \phi}{\partial t} = \frac{\mathrm{D_{eff}}}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial \phi}{\partial r}\right) \qquad (5a)$$

$$\phi(r,t) = \frac{X(r,t) - X_e}{X_0 - X_e} \qquad (5b)$$

The initial and boundary conditions for solving equation (5) are (Golpour et al., 2021):

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

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

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

Where h_m is convective moisture transfer coefficient of wet product *(m /s)*, *r* and R are respectively the distance from the centre 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 (Polatoğlu & Aral, 2022):

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

where A_n and B_n are defined as follows (Torki-Harchegani et al., 2015):

$$\begin{cases} A_n = \dfrac{2Bi \sin\mu_n}{\mu_n - \sin\mu_n\cos\mu_n} & \text{for } 0.1 < \mathrm{Bi}_m < 100 \qquad (7b) \\ B_n = exp(-\mu_n^2 Fo) \end{cases}$$

Where μ_n is the nth root of the transcendental (dimensionless) characteristic equation; Bi_m and *Fo* are respectively the Biot number and the Fourier number for moisture transport which, for a sphere of radius R, are defined as:

$$\mathrm{Bi}_m = \frac{h_m R}{\mathrm{D_{eff}}} \qquad (8a)$$

$$Fo = \frac{\mathrm{D_{eff}} t}{R^2} \qquad (8b)$$

The above form of the series solutions can be simplified if the values of Fo > 0.2 are negligible. Thus, the infinite sum of equation (7) is well approximated by the first term only, that is (Polatoğlu & Aral, 2022):

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

The root μ_1 of the transcendental characteristic equation is given for the spherical product as follows (Hai et al., 2022):

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

In equation (9), G represents the lag factor (dimensionless) and is obtained by regressing the dimensionless values of moisture ratio (MR) and drying time in the exponential form of the equation below using the least squares curve fitting method (Golpour et al., 2021):

$$MR = G\exp(-St) \qquad (11)$$

Where S represents the drying coefficient (s^{-1}). The drying coefficient S shows the drying capacity of sweet potato per unit time and the lag factor G is an indication of the internal resistance of spherical sweet potato samples to moisture transfer during convection drying. These parameters are useful for evaluating the drying process of sweet potato samples. Those parameters were obtained using the curve fitting tool of MATLAB R2023b (MathWorks, Inc., Natick, MA) and nonlinear regression technique were applied to fit the moisture ratio data with the Equation (11).

Both equations (9) and (11) are in the same form and can be equated. Therefore, having $A_1 = G$ and replacing the Fourier number (Fo) and B_1 with their expressions in equations (8) and (11), the moisture diffusivity for spherical sweet potato samples is given in the following form:

$$\mathrm{D_{eff}} = \frac{SR^2}{\mu_1^2} \qquad (12)$$

The expression of the moisture transfer coefficient (h_m) for drying of spherical sweet potato samples is obtained using the mass transfer Biot number (Bi_m) as defined by the following equation (Kaya et al., 2010):

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

To determine the mass transport parameters for drying sweet potato samples, the following procedure was applied (Golpour et al., 2021):

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

Activation energy

Effective moisture diffusivity can be linked to air temperature by Arrhenius type expression (Feng et al., 2024), such as:

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

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:

$$\ln(\mathrm{D_{eff}}) = \ln(\mathrm{D_0}) - \frac{\mathrm{E_{a-d}}}{\mathcal{R}(\mathrm{T} + 273.15)} \qquad (15)$$

Also, a similar procedure can be adopted to describe the convective mass transfer coefficient (h_m) depending on the temperature following an Arrhenius type equation (Golpour et al., 2021):

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

So,

$$\ln(\mathrm{h_m}) = \ln(\mathrm{h_{m0}}) - \frac{\mathrm{E_{a-c}}}{\mathcal{R}(\mathrm{T} + 273.15)} \qquad (17)$$

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

Statistical analysis

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):

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

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

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(P_{exp,i} - p_{pre,i}\right)^2}{N - z} \quad (20)$$

$$SSE = \sum_{i=1}^{N}\left(P_{exp,i} - P_{pre,i}\right)^2 \quad (21)$$

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 (Compaoré et al., 2022).

Conclusion

The influence of drying parameters such as air temperature and sample diameter on 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. Using the drying data, the aim of this study is to determine the influence of air temperature and sample diameter on the mass and moisture transport parameters such as lag factor, drying constants, moisture diffusivities, and moisture transfer coefficient for spherical sweet potatoes subjected to convective drying. In experiments, sweet potato spheres were dried at different drying air temperature conditions and moisture ratio changes were recorded during the drying time. As results, the drying coefficient of sweet potato increased up to 1.950×10^{-6} s^{-1} with increasing drying temperature regardless of the employed sample diameters. At almost all air temperatures, reducing the sweet potato diameters caused the drying coefficient to increase. The increase in air temperature from 50 to 80 °C and decrease in sample diameter from 3 to 2 cm decreased the lag factor from 1.083 to 1.043. The Biot number values decrease from 0.2462 to 0.1232 with increase in the air temperature for all sample diameters. When sweet potato diameter increases, the mass Biot number values increased also at any drying air temperature of samples. For hot air drying of spherical sweet potatoes, moisture diffusivity values increased with increased air temperature from 50°C to 80°C and increased sweet potato sample diameter from 2 cm to 3 cm. The moisture diffusion and convective mass transfer activation energy values are decreased with increasing samples diameter for all drying conditions applied. The results of this study are useful to optimize drying process parameters for commercial scale production of dried sweet potato using convective oven dryer and to achieve superior quality of the dried products.

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