

Effect of Size and Initial Water Content on the Effective Diffusion Coefficient during Convective Drying of Sweet Potato Cut into Cubic and Cylindrical Shapes

Ibrango Abdoul Salam, Ouoba Kondia Honoré, Bama Désiré, Traoré Yssa, Zongo Karim, Ouedraogo Salifou

Laboratoire de Matériaux de l'Héliophysique et Environnement (La.M.H.E.), Unité de Formation et de Recherche en Sciences. Exactes et Appliquées (UFR/SEA), Université Nazi BONI de Bobo-Dioulasso, Bobo-Dioulasso, Burkina Faso
Email: ouobakahonore@yahoo.fr

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Abstract

In this article, we investigated the influence of size and initial water content on the effective diffusion coefficient of sweet potatoes samples cut into cubic and cylindrical shapes. The sizes of the cubic samples are 0.5, 1, 1.5, 1.75, 2, 2.5 and 3 cm edge with a respective initial water content of 2.7, 3.76, 3.48, 2.68, 3.28, 2.17 and 2.29 kg/kg_{ms}. For cylindrical samples, the radius is set at 0.5 cm and sample heights are 1, 1.5, 2, 2.5, 3, 3.5 and 4 cm with respective water contents of 2.2, 3.19, 2.85, 2.1, 2.17, 2.39 and 2.03 kg/kg_{ms}. The effective diffusion coefficients of cubic samples are of the order of 10⁻¹⁰ and 10⁻⁹ m²·s⁻¹ grew with sample edge. As for the cylindrical samples, the effective diffusion coefficients were of the order of 10⁻⁹ m²·s⁻¹ and there was no linear correlation between cylinder height and their effective diffusion coefficient. As for the examination of the initial water content on the effective diffusion coefficient, it turned out that the initial water content had no influence on the effective diffusion coefficient of the sweet potato samples.

Keywords

Effective Diffusion Coefficient, Initial Water Content, Sweet Potato, Cubic, Cylindrical

1. Introduction

The sweet potato is a tuberized root plant. Cultivated in tropical and humid temperate zones, it ranks 14th in crops and 3rd in the tuberized root plant family after cassava and yam in West Africa, according to FAO 2022 data [1]. In Bur-

kina Faso, sweet potatoes are the leading tuber crop. Both internationally and locally (Burkina Faso), the value of its agricultural production is increasing [2], so it is necessary to conserve the surplus production. Convective drying is one of the most widely used techniques for preserving agricultural produce, and has been the subject of several research projects.

Thematic models have been established to describe the evolution of drying kinetics for agri-food products [3] [4] [5]. Other researchers have shown that intrinsic parameters such as product composition and maturity [6] [7] or extrinsic parameters such as drying air velocity, temperature, relative humidity, pressure, product thickness and shape [8] [9] [10] [11] [12] influence drying kinetics and the effective diffusion coefficient.

Investigations carried out on sweet potatoes have shown that pre-treatment, sample size, exposure surface and temperature have an influence on drying kinetics [13] [14].

However, the effect of size and initial water content on the effective diffusion coefficient of sweet potatoes is unknown.

Thus, our work is to examine whether variation in sample size or differences in initial water content have an influence on the effective diffusion coefficient by cutting cylindrical and cubic shaped samples.

2. Materials and Methods

2.1. Materials

The sweet potato used in this study was purchased in the fruit market of Bobo Dioulasso (Burkina Faso). We focused on the sweet potato because it occupies first place in terms of root and tuber plant production in Burkina Faso [15]. In addition, unlike other tropical products, it has an almost uniform macrostructure, the initial water content within a sample is uniform and water and heat transfers are symmetrical [16]. In the GERME & TI laboratory (Groupe d'étude et de Recherche en Mécanique Energétique et Techniques Industrielles) at Nazi Boni University, we use a stainless steel knife to peel and cut potato samples into cubic and cylindrical shapes. We used a digital caliper (MITUTOYO, Japan, 2×10^{-5} m precision) as a measuring instrument, an electronic balance (SARTORIUS, 0.001 g precision) for mass measurement and an oven (AIR concept, temperature ranging from 40 to 250°C, digital display) for drying.

2.2. Methods

The aim is to examine whether the size and initial water content of the samples can influence the effective diffusion coefficient. To this end, we extracted cubic shapes from potatoes, with 0.5 cm, 1 cm, 1.5 cm, 1.75 cm, 2 cm, 2.5 cm and 3 cm edges. For cylindrical shapes, we set the radius ($r = 0.5$ cm) and the height at 1 cm, 1.5 cm, 2 cm, 2.5 cm, 3 cm, 3.5 cm and 4 cm. Three (3) samples were cut for each dimension of these geometric shapes for acceptable repeatability. Then, after taking the initial masses of the samples, we introduce them into the oven for

a fixed drying temperature $T = 70^\circ\text{C}$.

Since air velocity and relative humidity influence drying kinetics [17] [18], we place all samples in the same oven. A mass sample is taken at each 15-minute interval, and the dry masses m_s of the samples are determined when the difference between three (03) successive weighings does not exceed the value of 0.001 g [19].

At the end of drying, residual water content was determined using the AOAC method [20].

2.2.1. Establishing Drying Kinetics

The initial water content of the sample, X_0 , is calculated as the quotient of the total mass of water contained in the freshly cut product, divided by the mass of the dry matrix, as shown in the following relationship:

$$X_0 = \frac{m_0 - m_s}{m_s} \quad (1)$$

where X_0 is expressed in kilograms of water per kilogram of dry mass ($\text{kg}/\text{kg}_{\text{ms}}$)

m_0 and m_s are the initial mass and dry mass of the sample respectively, expressed in kilograms (kg).

The water content of the sample at time t is determined by the expression:

$$X(t) = \frac{m(t) - m_s}{m_s} \quad (2)$$

where $X(t)$ is the water content at time t expressed in kilograms of water per kilogram of dry mass ($\text{kg}_e/\text{kg}_{\text{ms}}$)

$m(t)$ is the mass of the sample at time t of drying.

We associate with each time value, the corresponding water content value i.e. the relation $X(t) \rightarrow t$ that gives us the drying kinetics.

Note that for each dimension of a given shape, we have three (3) samples and each point of its drying kinetics represents the arithmetic mean of the water content $X(t)$ of its samples.

In order to have the same basis for comparison, we normalize the water content at time t by the initial water content X_0 of the product determined according to equation (1). This gives us the curves $X/X_0 \rightarrow t$.

2.2.2. Coefficient De Diffusion Effective

The initial water content of the potato being uniform [16] and assuming that the transfer is unidirectional, the effective diffusion coefficient is determined according to the shape of the sample from the solutions of the Fick equation developed by Crank and Hashemi [21] [22]. The solutions are:

$$\text{Cylindrical shape: } MR = \frac{X(t) - X_{eq}}{X_0 - X_{eq}} = \frac{4}{\beta^2} \exp\left(-\frac{\beta^2 D_{eff}}{r_c^2} t\right) \quad (3)$$

$$\text{Spherical shape: } MR = \frac{X(t) - X_{eq}}{X_0 - X_{eq}} = \frac{6}{\pi^2} \exp\left(-\frac{\pi^2 D_{eff}}{r_s^2} t\right) \quad (4)$$

$$\text{Infinite plate: } MR = \frac{X(t) - X_{eq}}{X_0 - X_{eq}} = \frac{8}{\pi^2} \exp\left(-\frac{\pi^2 D_{eff}}{4 L^2} t\right) \quad (5)$$

where MR is the reduced water content, X_{eq} is the equilibrium water content per unit dried mass (kg_d/kg_{ms}).

D_{eff} is the effective diffusion coefficient ($m^2 \cdot s^{-1}$).

r_c is the radius of the cylindrical sample.

r_s is the radius of the spherical sample.

L is the length of the infinite plate sample.

β and π are constants.

From the curve of the function $\ln(MR) \rightarrow t$, which has the form of a straight line, we determine from its slope the effective diffusion coefficients. Indeed, the equations can be put simply into the form [23] [24]:

$$\ln(MR) = A - k.t \quad (6)$$

where A and k are constants.

Thus, by equation (6), we determine the effective diffusion coefficient of the cylindrical shape by member-to-member identification as follows:

$$\ln(MR) = \ln\left(\frac{4}{\beta^2}\right) - \left(\frac{\beta^2 D_{eff}}{r_c^2}\right)t = A - k.t \quad (7)$$

$$\Rightarrow \begin{cases} A = \ln\left(\frac{4}{\beta^2}\right) \\ k = \left(\frac{\beta^2 D_{eff}}{r_c^2}\right) \end{cases} \Rightarrow \begin{cases} \beta^2 = \frac{4}{\exp(A)} \\ D_{eff} = \left(\frac{k.r_c^2}{\beta^2}\right) \end{cases} \quad (8)$$

For the cubic form, we have not found a solution to Fick's equation in the literature. Note that a sphere of radius $a/2$ has the same characteristic radius as a cube of edge a [10]. Thus, we have assimilated the cube to a sphere as shown in **Figure 1**. The values of the effective diffusion coefficient of this approximation are in agreement with the literature, i.e. of order 10^{-11} to $10^{-9} m^2 \cdot s^{-1}$ for food products [25].

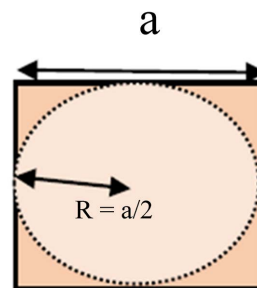


Figure 1. Assimilation of a cube to a sphere.

$$\ln(MR) = \ln\left(\frac{6}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}}{(a/2)^2}\right)t = A - k.t \quad (9)$$

$$\Rightarrow \begin{cases} A = \ln\left(\frac{6}{\pi^2}\right) \\ k = \left(\frac{\pi^2 D_{eff}}{(a/2)^2}\right) \end{cases} \Rightarrow D_{eff} = k \left(\frac{a}{2\pi}\right)^2 \quad (10)$$

3. Results and Discussion

3.1. Drying Kinetics

The drying kinetics of the cubic and cylindrical samples shown in **Figure 2** and **Figure 3** respectively have the same appearance and are similar to the drying kinetics of agri-food products such as sweet potatoes [26], cassava and ginger [9], eggplant [27], okra [6] [28], etc. In addition, we note that, for both cubic and cylindrical samples, the smaller the sample size, the more its drying kinetics decrease.

In addition, we note that for both cylindrical and cubic samples, the smaller the sample size, the more its drying kinetics decrease. This means that smaller samples dry faster than larger ones. Indeed, the drying times for cubic samples with 0.5 to 3 cm edges are 90, 315, 495, 660, 885, 1005 and 1215 minutes (min) respectively. This suggests that the drying time increases as the dimensions (edges) or initial surface area of the cubic samples submitted to our study increase.

As for the cylindrical samples in **Figure 3**, we can see that the curves are closer together and tend to merge, as in the case of cylindrical samples with heights of 1, 1.5 cm and 3.5, 4 cm. This can be explained by the fact that the cylindrical samples have the same radius ($r = 0.5$ cm) and the difference in height between two successive samples is small (0.5 cm). In addition, the drying times for cylindrical samples with heights from 1 to 4 cm are 225, 240, 285, 315, 315, 375, 405 min respectively, which means that for cylindrical samples with the same radius, the drying time increases with cylinder height.

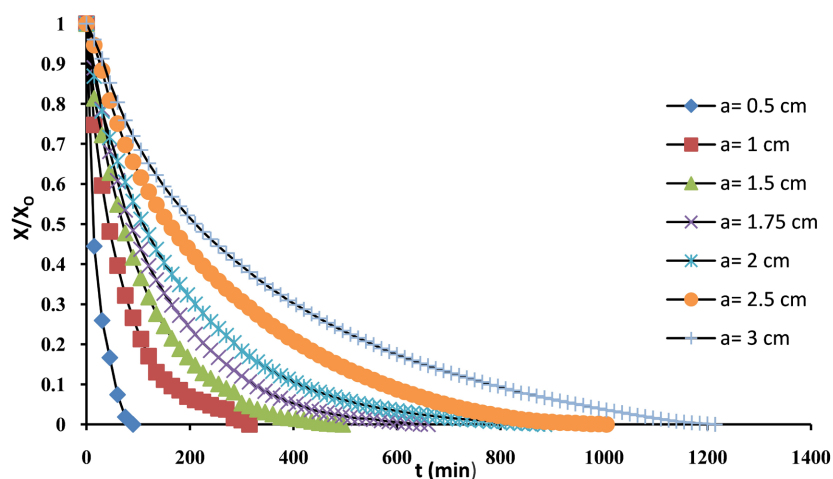


Figure 2. Drying kinetics of cubic samples at $T = 70^\circ\text{C}$.

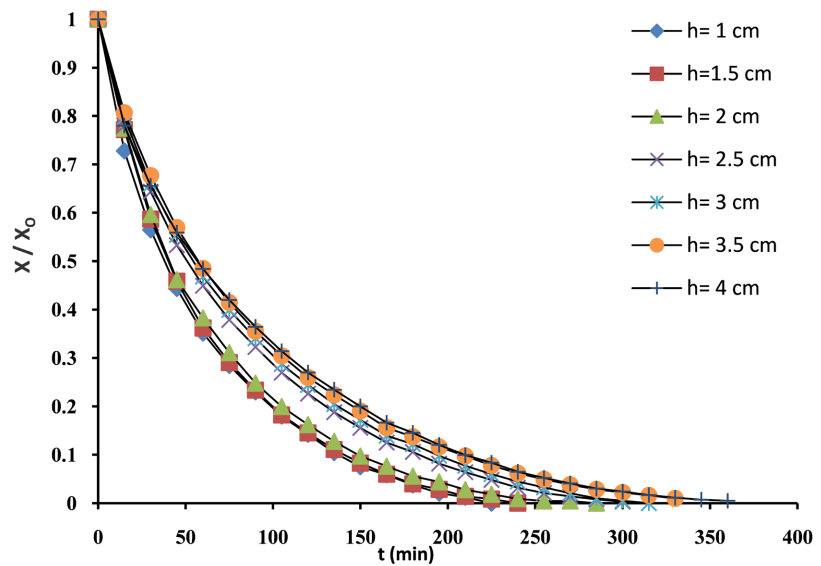


Figure 3. Drying kinetics of cylindrical samples at $T = 70^{\circ}\text{C}$.

3.2. Effective Diffusion Coefficient for Cubic Samples

The curves of $\ln(MR)$ as a function of time t for cubic-shaped samples are grouped together in Figure 4. We note that, with the exception of the curves for samples with 1 and 1.5 cm edges, which are linear, all the curves have a linear part and a hyperbolic branch. This can be explained by the fact that as sample thickness increases, the hyperbolic part, which reflects the phenomenon of diffusion, becomes more distinct from the linear part, where the withdrawal of liquid water by capillarity from the center to the surface of the sample is predominant.

Thus, we determine the linear trend curves corresponding to the hyperbolic part of each curve for the determination of the effective diffusion coefficient. The trend curves of the form $\ln(MR) = A - k.t$ grouped in Figure 5 show a good fit, as their coefficients of determination $R^2 \geq 0.987$. The conditions for determining the effective diffusion coefficients defined above give us the values grouped in Table 1. From Table 1 we note that the values of the effective diffusion coefficients are of the order 10^{-10} or $10^{-9} \text{ m}^2.\text{s}^{-1}$, which is in agreement with the values expected for food products.

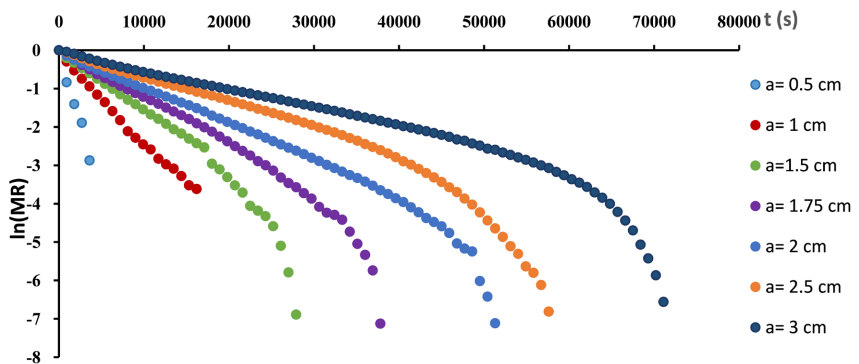


Figure 4. Curve of $\ln(MR)$ of cubic samples as a function of time.

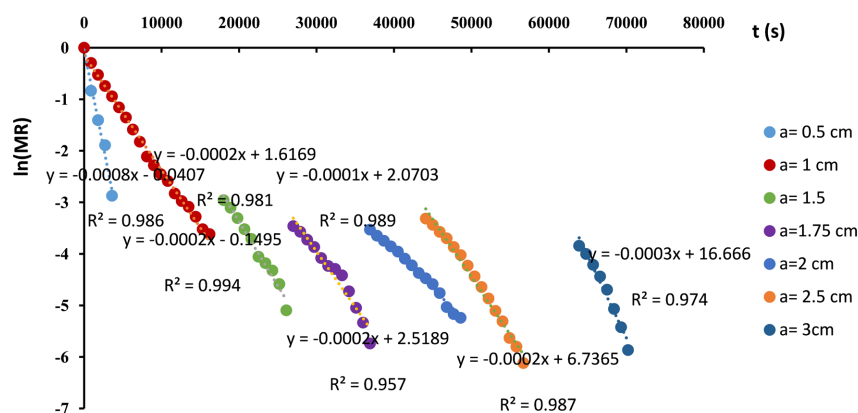


Figure 5. Linear fitting of $\ln(MR)$ curves for cubic samples as a function of time.

Table 1. Data from the $\ln(MR)$ curve and initial water content of cubic samples.

arête (cm)	Equation $\ln(MR) = -k.t + A$	R^2	K	D_{eff} ($m^2 \cdot s^{-1}$)	X_0 (kg_j / kg_{ms})
0.5	$\ln(MR) = -8 \times 10^{-4}t - 0.0407$	0.9865	8E-4	5.07E-10	2.7
1	$\ln(MR) = -2 \times 10^{-4}t - 0.1495$	0.9947	2E-4	5.07E-10	3.76
1.5	$\ln(MR) = -2 \times 10^{-4}t + 1.6169$	0.9812	2E-4	1.14E-9	3.48
1.75	$\ln(MR) = -2 \times 10^{-4}t + 2.5189$	0.9576	2E-4	1.55E-9	2.68
2	$\ln(MR) = -10^{-4}t + 2.0703$	0.9892	1E-4	1.01E-9	3.28
2.5	$\ln(MR) = -2 \times 10^{-4}t + 6.7365$	0.9873	2E-4	3.17E-9	2.17
3	$\ln(MR) = -3 \times 10^{-4}t + 16.666$	0.9743	3E-4	6.85 E-9	2.29

3.3. Effective Diffusion Coefficient and Size

From the analysis of **Table 1**, we can say that there is a linear correlation between the effective diffusion coefficient and the size of the cubic samples. Indeed when we observe the data in **Table 1**, we find that with the exception of the 2 cm edge sample where we observe a drop in the value of the effective diffusion coefficient from 1.55×10^{-9} to $1.01 \times 10^{-9} m^2 \cdot s^{-1}$, the effective diffusion coefficient increases with the edges of our cubic samples.

This drop observed with the 2 cm edge sample can be explained by the fact that in addition to the size of any intrinsic parameters would have an influence on the effective diffusion coefficient. Note that the largest value of the effective diffusion coefficient ($6.84 \times 10^{-9} m^2 \cdot s^{-1}$) is obtained with the 3 cm sample which is the largest edge and the smallest value ($5.07 \times 10^{-9} m^2 \cdot s^{-1}$) is obtained with the smallest 0.5 cm edge sample and the 1 cm edge sample. This shows that the larger the size, the greater the effective diffusion coefficient.

So, in addition to the influence of temperature on the effective diffusion coefficient described by the Arrhenius law [29] [30], we can say that size, which is an extrinsic parameter, has an influence on the effective diffusion coefficient for sweet potato samples cut in cubic form.

3.4. Effective Diffusion Coefficient for Cylindrical Samples

Figure 6 shows the $\ln(MR)$ curves for the various cylindrical samples. We can see that the curves decrease linearly, as the diffusional phase is not distinguished from the phase of water withdrawal by capillarity inside the sample. This observation, which was made with the 0.5 and 1 cm cubic samples, is repeated with our cylindrical samples with a radius of 0.5 cm. Therefore, we can say that for thin samples, the $\ln(MR)$ curve is linear. The linear trend curve associated with the entire $\ln(MR)$ curve for each sample shown in **Figure 6** has a coefficient of determination $R^2 \geq 0.99$ and therefore exhibits good regression. The values of the effective diffusion coefficients of the cylindrical samples grouped in **Table 2** are of the order of $10^{-9} \text{ m}^2 \cdot \text{s}^{-1}$ and are within the range predicted by the literature.

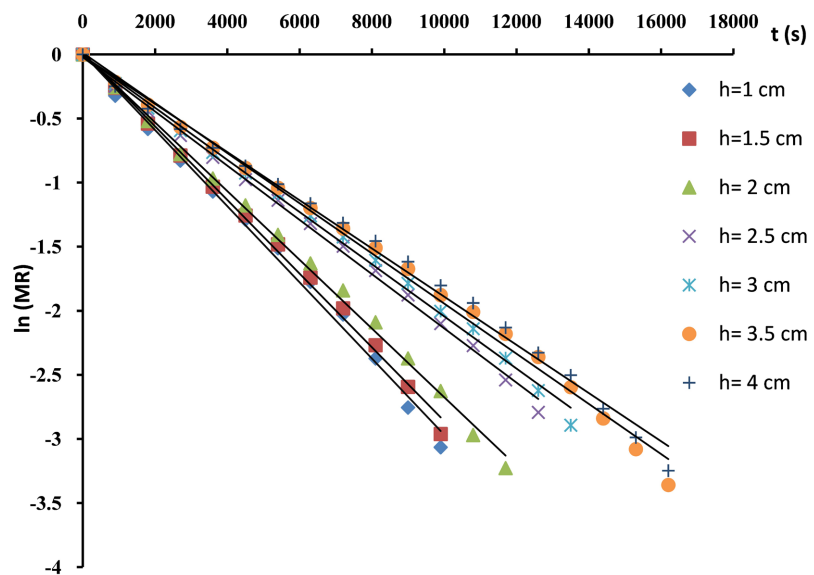


Figure 6. Linear fitting of $\ln(MR)$ curves for cylindrical samples as a function of time.

Table 2. Data from the $\ln(MR)$ curve and initial water content of cylindrical samples.

hauteur (cm)	Equation $\ln(MR) = -k \cdot t + A$	R^2	β^2	k	D_{eff} ($\text{m}^2 \cdot \text{s}^{-1}$)	X_0 ($\text{kg}_v / \text{kg}_{ms}$)
1	$\ln(MR) = -3 \times 10^{-4} t + 0.0045$	0.9941	3.982	3E-4	1.88E-9	2.2
1.5	$\ln(MR) = -3 \times 10^{-4} t + 0.0139$	0.996	3.944	3E-4	1.9E-9	3.19
2	$\ln(MR) = -3 \times 10^{-4} t + 0.006$	0.997	3.976	3E-4	1.89E-9	2.85
2.5	$\ln(MR) = -2 \times 10^{-4} t - 0.0221$	0.997	4.089	2E-4	1.22E-9	2.1
3	$\ln(MR) = -2 \times 10^{-4} t - 0.0087$	0.996	4.363	2E-4	1.15E-9	2.17
3.5	$\ln(MR) = -2 \times 10^{-4} t + 0.0129$	0.994	3.948	2E-4	1.27E-9	2.39
4	$\ln(MR) = -2 \times 10^{-4} t - 0.0098$	0.993	4.039	2E-4	1.24E-9	2.03

3.5. Effective Diffusion Coefficient and Size

In contrast to cubic samples, we can see from **Table 2** that there is no linear correlation between the height of cylindrical samples and the effective diffusion

coefficient.

Indeed, when we consider cylindrical samples with heights of 1, 1.5 and 2 cm, we find that their effective diffusion coefficients have almost the same value, despite the increase in height.

Then we see a drop in the effective diffusion coefficient from 1.89×10^{-9} to $1.22 \times 10^{-9} \text{ m}^2\cdot\text{s}^{-1}$, values associated with samples 2 and 2.5 cm respectively, followed by an oscillation around $1.22 \times 10^{-9} \text{ m}^2\cdot\text{s}^{-1}$ for samples 2.5 to 4 cm high. From these analyses, we can say that size (height) alone as an external parameter has no influence on the effective diffusion coefficient of cylindrical samples of the same radius.

Moreover, according to Fick's law, all cylindrical samples of the same radius should have approximately the same effective diffusion coefficient, as in the case of samples 1, 1.5 and 2 cm, but this is not the case. Therefore, we can say that there are one or more parameters intrinsic to the sweet potato that influence its effective diffusion coefficient.

3.6. Effective Diffusion Coefficient and Initial Water Content

The initial water contents of our cubic and cylindrical samples range from 2.03 to $3.76 \text{ kg}_d/\text{kg}_{ms}$ and **Figure 7** shows the variation of the effective diffusion coefficient as a function of initial water content.

From observation of **Figure 7** we note that the curve is not monotonic, showing the absence of linear correlation between the effective diffusion coefficient and initial water content. Indeed the largest value of the effective diffusion coefficient is obtained with the sample of water content $2.29 \text{ kg}_d/\text{kg}_{ms}$ that is neither the largest nor the smallest initial water content of our samples. The lowest effective diffusion coefficient value ($5.07 \times 10^{-10} \text{ m}^2\cdot\text{s}^{-1}$) was obtained with two samples (2.7 and $3.76 \text{ kg}_d/\text{kg}_{ms}$), one of which is the sample with the highest initial water content. This proves that the amount of initial water content does not determine the value of the sample's effective diffusion coefficient.

In addition, we noted large differences in effective diffusion coefficient for samples with almost the same initial water content. These are sample 2.7 and $2.68 \text{ kg}_d/\text{kg}_{ms}$ where the difference in effective diffusion coefficient is of the order of 3.06; the two samples of $2.17 \text{ kg}_d/\text{kg}_{ms}$ with an effective diffusion coefficient difference of order 2.75; the samples of 2.2 and $2.29 \text{ kg}_d/\text{kg}_{ms}$ that have an effective diffusion coefficient difference of order 3.61.

On the other hand, we find that samples have almost the same effective diffusion coefficient with very large initial water content differences. The observation is made with samples of 2.17 and $3.48 \text{ kg}_d/\text{kg}_{ms}$, which respectively have an effective diffusion coefficient of $1.15 \times 10^{-9} \text{ m}^2\cdot\text{s}^{-1}$, and $1.14 \times 10^{-9} \text{ m}^2\cdot\text{s}^{-1}$; samples 2.7 and $3.76 \text{ kg}_d/\text{kg}_{ms}$ with an effective diffusion coefficient of $5.07 \times 10^{-10} \text{ m}^2\cdot\text{s}^{-1}$, the samples 2.2 and $3.19 \text{ kg}_d/\text{kg}_{ms}$ with respective coefficients of 1.88×10^{-9} and $1.9 \times 10^{-9} \text{ m}^2\cdot\text{s}^{-1}$.

In view of the results of the curve analysis, we can say that the initial water content, which is an intrinsic parameter characterizing porosity on the one

hand, has no influence on the effective diffusion coefficient for sweet potato.

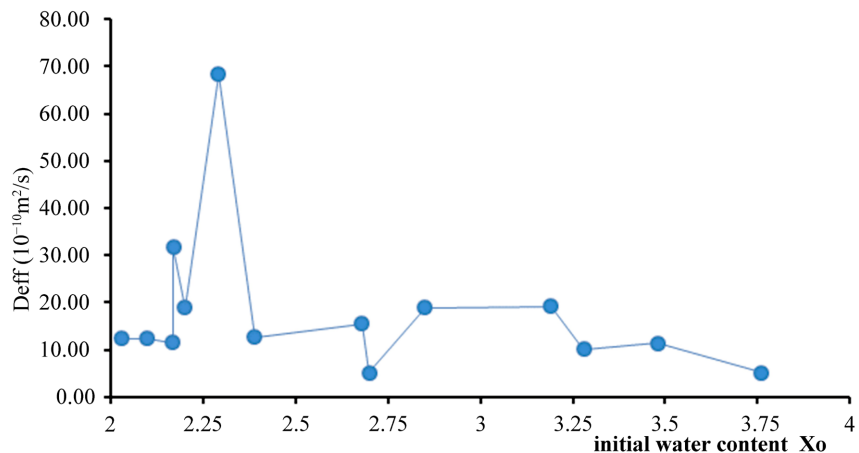


Figure 7. Effective diffusion coefficient curves as a function of initial water content.

4. Conclusions

From this study of sweet potato samples, we know that the drying time of cubic samples increases with edge, and their drying kinetics are clearly distinguishable from each other with increasing edge in 0.5 cm steps. For cylindrical samples of the same radius ($r = 0.5$ cm), the drying time increases slightly with height in 0.5 cm steps, and the drying kinetics tend to merge for two samples whose height difference does not exceed 0.5 cm.

In addition, the curve of $\ln(MR)$ is linear for sweet potato samples whose thickness is less than 1 cm and has a hyperbolic shape for samples whose thickness exceeds 1 cm.

Furthermore we retain that the effective diffusion coefficient of our samples, which is of the order of $10^{-10} m^2 \cdot s^{-1}$, and $10^{-9} m^2 \cdot s^{-1}$, increases with the edge of cubic samples, while for the case of cylindrical samples of the same radius ($r = 0.5$ cm), height has no influence on the effective diffusion coefficient.

Finally, we found that the initial water content of all our samples ranging from 2.03 to 3.76 kg_e/kg_{ms} has no influence on the effective diffusion coefficient of sweet potato samples.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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