Analytical Approach for Predicting Water Loss in Tubers During Convective Drying: A Case Study on Sweet Potato

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ABSTRACT

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|  In this article, the aim was to develop a method using an analytical approach to determine the reduced water content of sweet potato samples during convective drying. The prediction was made based on a study of the evolution of the drying constant of Newton's model as a function of the size of sweet potato samples at a temperature of 70 ℃.  Chi-square and coefficient of determination were used as indicators of prediction and modeling quality.The study carried out on sweet potato samples cut into cubic shapes with 0.5, 1, 1.5, 2, 2.5 and 3 cm edges showed that the evolution of the drying kinetic constant is best expressed mathematically as a power with .  Examination of the reliability of the prediction method carried out on samples of cubic-shaped sweet potatoes with an edge of 1.75 cm showed good results and accuracy . The one carried out on spherical; cylindrical; parallelepiped sweet potato samples of characteristic diameter showed that the prediction was more accurate with sweet potato samples cut in the spherical form. To check whether the results obtained from the analytical approach applied to sweet potato samples could be transposed to other tubers, cassava, yam and taro samples with a 3 cm cube were cut. The comparative study between the experimental and predicted reduced water contents showed that the results obtained by the method on sweet potato were transposable to yam and taro, with good quality indices. On the other hand, for cassava, the predicted results needed adjustment with regard to quality indices. |

***Keywords:*** *prediction method, taro, cassava, sweet potato, yam, drying kinetic constant.*

1. INTRODUCTION

 Achieving food security is one of the greatest challenges facing sub-Saharan and developing countries. This security cannot be achieved without industrializing the mechanisms for preserving and processing agricultural products during periods of overproduction.

Convective drying, like other drying techniques, reduces post-harvest losses, facilitates product transport and preserves the nutritional qualities of products over long periods.

 In Burkina Faso, however, industry in the agricultural sector is still in its infancy, particularly in the drying sector. In local markets, products from the same batch are not of the same quality. This difference in quality is explained by the difference in the final reduced water content of the products.

Based on experimental results, many researchers have proposed mathematical models and methods to describe or predict the drying kinetics of various agricultural products (Henderson, 1974) (Toğrul & Pehlivan, 2002) (Maroulis et al., 1995; Murthy & Manohar, 2014). Other researchers have shown that parameters such as temperature, relative humidity, drying air velocity, product composition and size have an influence on the drying kinetics of agri-food products (Abdou-Salam et al., 2020; de Gusmão et al., 2016; Honoré et al., 2014; Ouoba, 2013; Salam et al., 2024).

This means that mastery of the extrinsic and intrinsic parameters involved in drying agricultural produce is a prerequisite for industrialization.

This work uses an analytical approach to predict the reduced water content of sweet potato (Ipomoea batatas) samples during drying. Sweet potato samples are cut into cubic, cylindrical, spherical and parallelepiped shapes, and their water content is predicted from their characteristic diameters.

On the other hand, it was necessary to verify, according to the rules of analytical method validation (Taylor, 1983), whether the results obtained from the sweet potato analytical approach could be applied to other tubers such as cassava (manihot esculenta),), Taro (colocasia esculenta) and yam (Dioscorea esculenta)).

2. material and methods

2.1 equipment

 The choice of sweet potato as a study sample is due to the fact that it occupies 1st place in Burkina Faso and 3rd place in West Africa in terms of tuber cultivation (FAO, 2023). Moreover, in nutritional terms, it is a source of energy, protein, mineral salts and is rich in dietary fiber (Djinet et al., 2014) (Aina et al., 2010). Its macrostructure and initial water content within a sample are uniform, and internal transfers are symmetrical (Ouoba et al., 2012), making sweet potatoes a preferred sample for a study of convective drying plant parameters for agri-food products. The choice of transposing the sweet potato results to cassava, taro and yam is because they are tubers and their drying kinetics are similar. They occupy an important place in the local and international economy (FAO, 2023; Nainggolan et al., 2024) and their nutritional value and contribution are not negligible(Parmar et al., 2017) (Attaie et al., 1998; Soudy, 2011).

 . The tubers used for the experimental study in the GERME&TI laboratory (Groupe d'étude et de Recherche en Mécanique Energétique et Techniques Industrielles) at Nazi Boni University were purchased at the Bobo Dioulasso fruit market (Burkina Faso). The experimental device consists of a stainless steel knife for peeling and cutting the samples to the desired shape and size. A digital caliper that serves as a measuring instrument (MITUTOYO, Japan,m precision ). An electronic balance (SARTORIUS, 0.001 g precision) for taking masses and an oven (AIR concept, temperature ranging from 40 to 250°C, digital display) with which we carry out drying. The results of the experimental study are processed on a computer using Origine pro 2019 software, and the data are modelled using Levenberg Marquardt's iteration algorithm.

**2.2 Study Protocol**

Since the aim of our study is to predict the drying kinetics of a sweet potato sample as a function of size, we cut cubic samples with edges of 0.5 cm; 1 cm; 1.5 cm; 2 cm; 2.5 cm and 3 cm, which serve as study samples.

We also cut samples of sweet potato, cassava, taro and yam to serve as test samples for the prediction method. The sweet potato test samples are cubic with an edge of 1.75 cm, spherical with a diameter of 1.5 cm, parallelepipedic with a length of 2 cm, a width of 2 cm and a thickness of 1.5 cm, cylindrical with a diameter of 1.5 cm and a height of 1.5 cm. As for the cassava, taro and yam test samples, we cut cubic samples with a 3 cm edge.

For reliable results, three samples were extracted for each dimension of a given shape. Once the initial masses had been taken, drying began and weighing was carried out at time intervals of 15 minutes (min) for the sweet potato study samples, 10 minutes for the test sweet potato samples and 20 minutes for the other tubers.

Size being the only variable parameter, while extrinsic parameters such as air velocity, relative humidity and temperature have influences on drying kinetics, all samples have been introduced into the same oven for a fixed drying temperature T=70°C. Equilibrium water contents are determined when three (03) weighings are identical to within (Belahmidi et al., 1993) and dry masses are obtained according to the AOAC method (AOAC, 1990).

Diffusion theory, which is governed by Fick's laws described by equation (1), is the theory used in this work. Note that this theory, which is widely used by several researchers, has shown good results in drying continuous-structure agri-food products such as cassava, sweet potatoes, carrots, apples (Singh & Pandey, 2012) (Kosasih et al., 2020) (Doymaz, 2004) (Velić et al., 2004)...

 (1)

**2.2.1** **Choice of empirical models**

As all sweet potato samples can be assimilated to spherical shapes (Honore et al., 2023), the reduced water content of our samples at each instant is described by relationship (2), which is the solution of the Fick equation proposed by Newman and Sherwood (Newman, 1931) (Sherwood, 1931) and developed by crank (Crank, 1979) for the spherical shape.

 (2)

Where denotes the water content per kilogram of dry mass at time t,

 the equilibrium water content

 initial water content per kilogram of dry mass

 the reduced water content.

 is the effective diffusion coefficient

 is the radius of the spherical sample.

To fit the experimental data, we use three mathematical models derived from the first set of Fick's equation solutions.

For we have:

 (3)

by posing relationship (3) becomes:

 (4)

Considering the initial condition at t = 0, we drop the constant and write equation (5).

 (5)

from which we obtain Newton's empirical model (Bruce, 1985) with being the drying kinetic constant which depends on temperature, relative humidity, air velocity and the diameter of the product used.

On the other hand, if we replace the value by an empirical constant we obtain equation (6), which is the Henderson and Pabis model (Pabis & Henderson, 1962).

 (6)

Where is a dimensionless empirical constant and is the drying kinetics constant.

In the literature, the empirical constant of the Henderson and Pabis model Sometimes has values strictly less than 1. This has been observed in mathematical modelling of the drying of grapes, mesquite, onions, etc (Yaldiz et al., 2001) (de Gusmão et al., 2016) (Sorour & El-Mesery, 2014).

It is therefore necessary to add a second constant , from which we obtain the equation of the logarithmic model (Yaldiz et al., 2001) given by the equation below:

 (7)

With and being the drying kinetics constant.

We will use the three semi-theoretical models described for fitting the drying kinetics of the sweet potato study samples. Then we determine a function that describes the evolution of the parameters of the best smoothing model as a function of size. Finally, a reliability test is performed by comparing the predicted data with experimental data from control samples.

**2.2.2 Assessment criteria**

The coefficient of determination is the first statistical criterion that measures the fit between a mathematical model derived from linear or non-linear regression and experimental data. Translated by equation (8), a model is reliable and shows a good translation of experimental data when its coefficient of determination is very close to or equal to 1.

 (8)

Where Represents the i th experimentally obtained water content of the sample,

 Represents the i th water content predicted by the mathematical model

and the arithmetic mean of the experimental water content of the sample.

The Chi-square measures the difference between experimental values and those predicted by mathematical models. A low value of ensures the repeatability of the method. It is determined by the following equations:

 (9)

Where is the number of constants in the mathematical model and is the number of measurements.

A model is consistent with experimental results only if, in addition to its coefficient of determination being close to unity, the value of the mean square error is low (Sorour & El-Mesery, 2014) (Feinberg, 1996) (Goyal et al., 2007) (Saeed & Abidin).

3. results and discussion

3.1. Drying kinetics

The drying kinetics for a reduction in initial moisture content to 0.02% for the various sweet potato samples are shown in Fig.1. The drying kinetics of our samples show a decreasing exponential trend compared with those obtained by Hassini et al for potatoes (Hassini et al., 2007) and by Clément et al for cassava (Ahouannou et al., 2000).

In addition, the results shown in Fig. 1 corroborate Ouoba's and Singh's findings concerning the effect of sweet potato sample size on drying kinetics (Ouoba, 2013) (Singh & Pandey, 2012).

In fact, let's consider the drying kinetics of our samples, at time t= 3600 s (1Hour), samples with edges *a* = 0.5 cm; 1cm; 1.5 cm; 2cm; 2.5cm and 3 cm were at 07%; 39.62%; 54.88%; 65.73%; 75.05%; 80.38% of their initial water content, respectively. So we can say that resistance to heat and mass transfer increases with sample size, and the consequence is that for large-scale drying, samples of small thickness should not be mixed with those of large thickness. The risk is that mechanical properties may differ greatly within the same batch, and that moisture may rise from the product's interior to its surface, leading to storage problems.

 In addition, the drying times for our a = 0.5 cm; 1cm; 1.5 cm; 2cm; 2.5cm and 3cm ridge samples are 4500 s; 18000 s; 28800 s; 52200 s; 58500 s; 72000 s, respectively, which means that the drying time for sweet potato samples increases with size (thickness).



**Figure 1: Influence of size on drying kinetics**

**2.2 Selection of the empirical drying kinetics model**

The Newton, Pabis & Henderson and Logarithm models used to describe the drying kinetics of our samples are in good agreement with the experimental results. Indeed, when we look at Fig. 2, we see that the trend curves according to each empirical model tend to merge with the experimental curves.

 Furthermore, observation in Tables 1, 2 and 3, show that the coefficient of determination of the fit of each curve is greater than 0.9 and the reduced chi-square of the samples present low values . This shows that the models used describe sweet potato drying kinetics just as well as they do for cassava (Koua et al., 2009), taro (Olalusi et al., 2014), yam (Amedor et al., 2024), potato (Masud et al., 2021)...



**Figure 2:** **Fitting of experimental data: a) logarithm model, b) Newton model, c) Pabis & Henderson model**

As for the Newton model whose data are contained in Table 1, the varies from 0.99217 to 0.99702 and the varies from to . In addition the drying constant, which varies from to , decreases with increasing sample size. This observation is also made with the drying constants of the Logarithm model and the Pabis & Henderson model grouped in Table 2 and Table 3 respectively. Therefore, it allow to say that the drying constant decreases with the thickness of the sweet potato samples.

**Table 1: Drying kinetics constant and Newton model quality index**

|  |  |  |  |
| --- | --- | --- | --- |
| **Edges (cm)** |  |  |  |
| a = 0.5 |  |  |  |
| a= 1 |  |  |  |
| a= 1.5 |  |  |  |
| a= 2 |  |  |  |
| a= 2.5 |  |  |  |
| a= 3 |   |  |  |

As for the Pabis & Henderson and Logarithm models, the varies respectively from 0.99252 to 0.99823; from 0.99358 to 0.99836 and the varies from to and from to .

From analysis of the data in Table 2 and Table 3, it is clearly appear that there is no linear correlation between the values taken by the constants , , and the edge of the samples of sweet potato. The absence of linear correlation shows that these constants take random values and are used as a correction to adjust the smoothing of the experimental data. This reveals that the Logarithm model and the Pabis & Henderson model do not predict drying kinetics as a function of size, but rather describe them more accurately than the Newton model.

 **Table 2: Quality index and parameters of the Pabis & Henderson model**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Edges (cm)** |  |  |  |  |
| 0.5 |  |  |  |  |
| 1 |  |  |  |  |
| 1.5 |  |  |  |  |
| 2 |  |  |  |  |
| 2.5 |  |  |  |  |
| 3 |  |  |  |  |

**Table 3: Quality index and model parameters Logarithm**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Edges (cm)** |  |  |  |  |  |
| 0.5 |  |  |  |  |  |
| 1 |  |  |  |  |  |
| 1.5 |  |  |  |  |  |
| 2 |  |  |  |  |  |
| 2.5 |  |  |  |  |  |
| 3 |  |  |  |  |  |

Given that there is no linear correlation between thickness and the parameter constants of the Logarithm and Pabis & Henderson models, and the fact that the Newton model would describe drying kinetics better than the other two models without their constants, the Newton model is chosen to predict the drying kinetics of our test samples from their initial size.

**2.3 Establishing a mathematical model for the evolution of the drying constant**

The correlation between the drying constant of the Lewis model and the **a-**edge of our samples is reflected by non-linear regressions in exponential, 4th-order polynomial and power forms, as shown in Fig. 3. Table 4 shows that all the mathematical expressions for the evolution of the drying constant have good coefficients of determination . Comparison of these mathematical forms reveals that the power form better reflects this correlation, with a coefficient of determination closer to unity . Thus, the mathematical expression of the power form is used to obtain the predicted drying kinetics constant as a function of our test sample size.



**Figure 3: Modeling the evolution of drying kinetics as a function of the edge of cubic samples**

***Table 4: Quality index and equation for mathematical models of drying kinetics constant evolution***

|  |  |  |
| --- | --- | --- |
| ***mathematical models*** | **Equation** |  |
| Polynomial |  |  |
| Exponential |  |  |
| Power |  |  |

**2.4. Model reliability test**

The homogeneity test performed on the three 1.75 cm edge cubic samples whose value corresponds to shows that the results of this prediction method are in line with the experimental results. Indeed, the close to unity of our three (03) 1.75 cm edge samples are 0.98992, 0.99175, 0.99257 and the low values of their are , , and .

 Furthermore, the prediction is more accurate from the first instants and towards the end of drying . This is visibly reflected in Fig. 4 by the fact that from the first instants and towards the end of drying the points of each sample are carried by the bisector while in mid-dryings , the points deviate slightly from the bisector.

In view of the quality index values and and the observation in Fig. 4, it is allow to say that this prediction method is good and more accurate from the beginning and towards the end of drying for all sweet potato samples with a characteristic diameter of between 0.5 and 3 cm.



**Figure 4: Comparison of the evolution of the reduced water content of cubic samples and that predicted for 1.75 cm sweet potato.**

Examination of a possible influence of the shape of our samples on prediction quality was carried out by predicting the drying constant from their characteristic diameters . The results reveal that sample shape has no significant influence on prediction quality if is determined from characteristic diameters. Indeed, the quality indices close to unity for spherical, cylindrical and parallelepipedic samples are 0.99416, 0.97084, 0.95346 respectively, and their low values are , , respectively. This result is in agreement with Ouoba's work regarding the characteristic diameter that can be a parameter guiding the drying of sweet potato samples of different shapes (Honore et al., 2023).

 On the other hand, comparison of the quality indices shows that the prediction method is more accurate with the spherical shape, despite having the same value. In fact, its quality index is closer to unity (0.99416) and its is weaker () than the other geometric shapes. Graphically, this is shown in Fig .5 by the observation that the points of the curve for spherical-shaped samples are carried by the bisector.



**Figure 5: Influence of the geometric shape of sweet potato samples with a characteristic 1,5 cm diameter on prediction**.

However, as the prediction method is based on sweet potatoes, the compliance tests extended to other tubers, notably cassava, taro and yam, showed good results, with the exception of cassava, although they have the same . Indeed, the coefficient of determination ( )and chi-square () for cassava are 0.80234 and respectively. The low value of shows that the uncertainty in the estimation of water content during drying is high, and this is visibly reflected in the deviation of the points on the cassava curve from the bisector in Fig. 6. It also suggests that the drying kinetic constant of cassava is lower than that of sweet potato and other tubers, notably taro and yam.

 For taro and yam, the was 0.98146, 0.97608 and the and respectively. These values being close to unity and the being low shows that yam and taro have approximately the same drying kinetics constant as sweet potato, as evidenced by the small deviation between the yam and taro curve points and the bisector in Fig. 6.



**Figure 6: Influence of the nature of cubic samples (a= 3cm) on prediction**

**Conclusion**

From the study of sweet potato samples, we retain that the Logarithm, Newton, Pabis & Henderson model describe well the drying kinetics of sweet potato samples with close to unity and low values.The evolution of the Newton model drying kinetics constant of sweet potato samples as a function of size can be described in exponential, power and 4th-order polynomial form.

The comparative study between experimental and predicted values shows firstly that the prediction method is good for sweet potato samples. Secondly, it shows that for different geometric shapes with the same characteristic diameter, the prediction is more accurate with spherical samples. Finally, it shows that the results of the prediction of reduced water content using the analytical approach for sweet potatoes can be transposed to yam and taro. On the other hand, the transposition of the results of the prediction of the analytical approach made on sweet potato requires prior adjustment for the case of cassava.

**Disclaimer (Artificial intelligence)**

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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