Analytical method for predicting the reduced water content of a tuber as a function of size during convective drying: the case of sweet potato.

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ABSTRACT

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|  In this article, the aim was to predict the reduced water content of taro, cassava, sweet potato and yam. The prediction was based on a study of the evolution of the Newton model drying constant as a function of sweet potato sample size at a temperature of 70 ℃. Chi-square and coefficient of determination were used as indicators of predictive 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 .In order to examine the reliability of the prediction method, samples of cubic-shaped sweet potatoes with a 1.75 cm edge were cut; then samples of spherical; cylindrical; parallelepiped-shaped sweet potatoes with a characteristic diameter D=3 cm were cut, and finally samples of cubic-shaped taro yam cassava with a 2 cm edge were cut.The results showed on the one hand that the nature of the product had an influence on the quality of the prediction by the fact that sweet potato, yam, taro have a coefficient of determination and low while for cassava the and the .On the other hand, the results showed that prediction was more accurate with sweet potato samples cut in the spherical shape than those in the cylindrical and parallelepiped shape. |

*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. 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.

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.

The aim of this work is to predict the reduced water content as a function of size by first drying samples of different sizes. Then, after having determined a mathematical model which is in adequacy with the experimental results, to establish a mathematical model of the evolution of the parameters of the chosen model according to the size. Finally, check the reliability of the method according to the rules of analytical method validation (Taylor, 1983) by comparing experimental data from other samples of sweet potato, cassava, Taro and yam with the data predicted by the method from their characteristic radius.

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 fibre (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 one 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 was purchased at the Bobo Dioulasso fruit market (Burkina Faso). The experimental set-up consists of a stainless steel knife for peeling and trimming sweet potato 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 smoothed using Levenberg Marquardt's iteration algorithm.

**2.2 Methodology**

Since the aim of our study is to predict the drying kinetics of a 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 spherical with a radius of 1.5 cm, parallelepipedic with a length of 2 cm, width of 2 cm and thickness of 1.5 cm, and cylindrical with a radius of 1.5 and height of 1.5 cm. As for the cassava, taro and yam test samples, we cut cubic samples with a 2 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, we introduce all samples 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).

We use diffusional theory, which is governed by Fick's laws described by equation (1) in the case of our 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 smooth 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 smoothing 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. 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).

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).

Indeed, when we 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, when we look at the data in Tables 1, 2 and 3, we see 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 attests that these models used describe sweet potato drying kinetics well.



**Figure 2:** **smoothing 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 . We note that 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. So we can 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, we can clearly see that there is no linear correlation between the values taken by the constants , , and the edge of the samples. 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. So we can say that the Logarithm model and the Pabis & Henderson model do not predict drying kinetics, 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.

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

The correlation between the drying constant and the edge of our samples is expressed 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 . The power form is therefore chosen for the prediction of the drying kinetic constant in our case.

**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 prediction quality indices of our homogeneity test carried out on 1.75 cm cubic samples show 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, we note that 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 we find that the points deviate slightly from the bisector.

In view of the quality index values and and the observation in Fig. 4, we can 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.**

With regard to the influence of shape on the quality of reduced water content prediction, the quality indices show that the prediction method is good. 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.

 On the other hand, comparison of the quality indices shows that the prediction method is more accurate with the spherical shape by the fact that its quality index is closer to unity (0.99416) and its values are lower than the other geometric shapes. Graphically, this can be seen in Fig. 5, where the points of the curve for spherical samples are carried by the bisector.



**Figure 5: Influence of the geometric shape of sweet potato samples with a characteristic 2 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. Indeed, the coefficient of determination ( )and chi-square () for cassava are 0.80234 and respectively, which shows that the uncertainty in the estimation of water content is high, and this is visibly reflected in the deviation of the points on the cassava curve from the bisector in figure 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= 2cm) 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 for spherical samples.

Finally, it shows that sweet potato, yam and taro samples have approximately the same drying kinetic constant, while cassava has a lower drying kinetic constant than the tubers in this study.

References

Abdou-Salam, G., Honore, O. K., & François, Z. (2020). Taking into Account the Complex Nature and the Intrinsic Parameters of Agro-Food. *Journal of Biophysical Chemistry*, *11*(1), 1-13.

Ahouannou, C., Jannot, Y., Lips, B., & Lallemand, A. (2000). Caractérisation et modélisation du séchage de trois produits tropicaux: manioc, gingembre et gombo. *Sciences des aliments= Food science: an international journal of food science and technology*, *20*, 413-432.

Aina, A. J., Falade, K. O., Akingbala, J. O., & Titus, P. (2010). Physicochemical Properties of Caribbean Sweet Potato.

AOAC. (1990). Official Methods of Analysis. *Association of official Chemists, Washington,DC 934*, 06.

Belahmidi, E., Belghit, A., Mrani, A., Mir, A., & Kaoua, M. (1993). Approche expérimentale de la cinétique du séchage des produits agro-alimentaires: application aux peaux d'oranges et à la pulpe de betterave. *Revue générale de thermique*, *32*(380-81).

Bruce, D. M. (1985). Exposed-layer barley drying: Three models fitted to new data up to 150 C. *Journal of Agricultural Engineering Research*, *32*(4), 337-348.

Crank, J. (1979). *The mathematics of diffusion*. Oxford university press.

de Gusmão, R. P., Gusmão, T. A. S., Rangel, M. E., Cavalcanti-Mata, M., & Duarte, M. E. M. (2016). Mathematical modeling and determination of effective diffusivity of mesquite during convective drying. *American Journal of Plant Sciences*, *7*(6), 814-823.

Djinet, A. I., Nana, R., Tamini, Z., & Badiel, B. (2014). Mise en évidence des valeurs nutritionnelles de dix (10) variétés de patate douce [Ipomea batatas (L.) Lam.] du Burkina Faso. *International Journal of Biological and Chemical Sciences*, *8*(5), 2062-2070.

Doymaz, I. (2004). Convective air drying characteristics of thin layer carrots. *Journal of food engineering*, *61*(3), 359-364.

FAO. ( 2023). Retrieved 20-03-2024 from <https://www.fao.org/faostat/fr/#data/QCL>

Feinberg, M. (1996). La validation des méthodes d'analyse. Une approche chimiométrique de l'assurance qualité au laboratoire.

Goyal, R., Kingsly, A., Manikantan, M., & Ilyas, S. (2007). Mathematical modelling of thin layer drying kinetics of plum in a tunnel dryer. *Journal of food engineering*, *79*(1), 176-180.

Hassini, L., Azzouz, S., Peczalski, R., & Belghith, A. (2007). Estimation of potato moisture diffusivity from convective drying kinetics with correction for shrinkage. *Journal of food engineering*, *79*(1), 47-56.

Henderson, S. (1974). Progress in developing the thin layer drying equation. *Transactions of the ASAE*, *17*(6), 1167-1168.

Honore, O. K., Abdou-Salam, G., Salam, I. A., Désiré, B., & François, Z. (2023). Validation of a Characteristics Dimensions for Transfers during Convective Drying of Sweet Potato Cubic, Cylindrical and Spherical Shapes. *Open Journal of Applied Sciences*, *13*(10), 1714-1722.

Honoré, O. K., François, Z., Raguilignaba, S., Aboubacar, T., & Hélène, D. (2014). Characterization of okra convective drying, influence of maturity. *Food and Nutrition Sciences*, *2014*.

Kosasih, E. A., Zikri, A., & Dzaky, M. I. (2020). Effects of drying temperature, airflow, and cut segment on drying rate and activation energy of elephant cassava. *Case Studies in Thermal Engineering*, *19*, 100633.

Maroulis, Z., Kiranoudis, C., & Marinos-Kouris, D. (1995). Heat and mass transfer modeling in air drying of foods. *Journal of food engineering*, *26*(1), 113-130.

Murthy, T. P. K., & Manohar, B. (2014). Hot air drying characteristics of mango ginger: Prediction of drying kinetics by mathematical modeling and artificial neural network. *Journal of food science and technology*, *51*, 3712-3721.

Newman, A. (1931). The drying of porous solids: Diffusion calculations. *Trans. Am. Inst. Chem. Eng.*, *27*, 203-220.

Ouoba, H., Zougmore, F., Naon, B., & Desmorieux, H. (2012). Profils des teneurs en eau de la patate douce Durant son Séchage Convectif. *Rev. CAMES-Série A*, *13*(2), 201-205.

Ouoba, K. (2013). *Séchage des produits agroalimentaires: Influence de la taille, de la forme et de la découpe* Thèse de Doctorat. Université de Ouagadougou, Burkina Faso].

Pabis, S., & Henderson, S. (1962). Grain drying theory. III The air grain temperature relationship. *Journal of Agricultural Engineering Research*, *7*(1), 21-26.

Salam, I. A., Honoré, O. K., Dé, B., Karim, Z., & Salifou, O. (2024). Effect of Size and Initial Water Content on the Effective Diffusion Coefficient during Convective Drying of Sweet Potato Cut into Cubic and Cylindrical Shapes. *Journal of Materials Science and Chemical Engineering*, *12*(6), 71-82.

Sherwood, T. (1931). Application of theoretical diffusion equations to the drying of solids. *Trans. Am. Inst. Chem. Engrs*, *27*, 190-202.

Singh, N. J., & Pandey, R. K. (2012). Convective air drying characteristics of sweet potato cube (Ipomoea batatas L.). *Food and Bioproducts Processing*, *90*(2), 317-322.

Sorour, H., & El-Mesery, H. (2014). Effect of microwave and infrared radiation on drying of onion slices. *Int.. J. Res. Appl. Nat. Social Sci*, *2*(5), 119-130.

Taylor, J. K. (1983). Validation of analytical methods. *Analytical Chemistry*, *55*(6), 600A-608A.

Toğrul, İ. T., & Pehlivan, D. (2002). Mathematical modelling of solar drying of apricots in thin layers. *Journal of food engineering*, *55*(3), 209-216.

Velić, D. a., Planinić, M., Tomas, S., & Bilić, M. (2004). Influence of airflow velocity on kinetics of convection apple drying. *Journal of food engineering*, *64*(1), 97-102.

Yaldiz, O., Ertekin, C., & Uzun, H. I. (2001). Mathematical modeling of thin layer solar drying of sultana grapes. *Energy*, *26*(5), 457-465.