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Desorption Isotherms of Dioscorea Schimperiana (Hairy Yam): An Experimental and Modeling Approach

Fabien Akana Tsopmo [1]*,Yvan ArmelKom[2],Jean Claude Damfeu[1], Yimen Nacer[1], Brillant Djomsi W.[2], AbrahamKanmogne [1,2], J.R. Lucien Meva'a [1,2], B. GAGA Dadi[1]
[1]Energy, Water and Environmental Laboratory, National Advanced School ofEngineering; Yaoundé, Cameroon
[2]Civil and Mechanical Engineering Laboratory, National Advanced School ofEngineering; Yaoundé, Cameroon

Abstract:- Several scientific types of research have already been carried out on yam tuber varieties of the Dioscorea family such as Dioscorea Retundata, and Dioscorea Alata. We can mention among others: the determination of sorption isotherms, their isosteric heat, and the drying kinetics. Dioscorea Schimperiana is also a tuber belonging to the same family and is currently a very popular foodstuff in the West Cameroon region. This plant, considered a nutritional element, also has several therapeutic virtues. However, the lack of knowledge of some of its thermophysical properties, especially the water content at equilibrium, is a hindrance to its optimal use. The present study, therefore, focuses on the determination of desorption isotherms, which could be useful for the modeling of a suitable dryer for the drying of Dioscorea Schimperiana. These desorption isotherms are obtained by the static gravimetric method, in the range of relative humidity from 11 to 97% and temperatures of 30°C, 40°C, and 50°C. The Henderson, Harkings and Jura, Halsey, modified Oswin, and GAB models were used for smoothing the experimental points. The isotherms obtained are of type II and characterized by a sigmoidal shape. The best fits were obtained for the GAB and Henderson equations.

These data obtained by the GAB and Henderson models are of great use as it allows us to model the isosteric heat of desorption of Dioscorea Schimperiana.

Keywords:- *Dioscorea Schimperiana, water content, the isotherm of desorption, relative humidity, GAB, Henderson.*

I. INTRODUCTION

Plants are a vital component of the world's biological diversity and an essential resource for human well-being. Worldwide, there are approximately 600 to 800 species of yam plants which represent an immensely important, largely unvalued natural resource (Miège, 1968; Medoua, 2005). Among these species is the Dioscorea Schimperiana belonging to theDioscoreaceae family. It is a highly prized commodity in the West Cameroon region. Its conservation is done in several ways by the populations of this region. Conservation by burying, conservation above ground, and conservation in the form of cossettes, which is widely practiced and is obtained in the following way: harvesting tubers from the field or in the home gardens, washing with plenty of water, cooking with steaming the yams in the field, peeling, dicing then drying the dice in the sun or the attic (Tchiègang & Ngueto, 2009). At the end of drying, cossettes are obtained. In addition, their marketing provides income to rural populations through an important informal social trade.

Despite this importance, producers are confronted with the problems of post-harvest losses linked to the quantity of water in the product during storage. To reduce losses, extend the durability of the product, and add value to the product, conventional storage is adopted. It is an operation widely used both in the food industry and in the cottage industry by farmers. This process then makes it possible to stabilize the product in such a way as to ensure its physicochemical and microbiological stability. Despite all this, a better knowledge of these thermophysical properties could contribute to further improving its valorization. In particular, knowledge of desorption isotherms is one of the essential elements of this valorization. Indeed, the study of sorption isotherms is a privileged means of knowing the distribution of the intensity of water bonds, as well as its functional availability in poorly or moderately hydrated agri-food products. These isotherms are curves that provide valuable information on the hygroscopic balance of a product because they allow us to know its stability range after drying by determining the final water content (Wang, N., Brennan, J.G, 1991; Kouhila & al., 2001; Talla A. , Jannot, Kapseu, & Nganhou, 2001; Aviara NA, Ajibola OO, 2002; McMinn, W.A.M., Magee, T.R.A., 2003; Belghith A, Azzouz S, ElCafsi A, 2016; La Choviya Hawa, Ubaidillah Ubaidillah, Retno Damayanti , Yusuf Hendrawan, 2020).

During the last two decades, a significant amount of work has been done on the study of sorption isotherms of food products(Charles Taiwo Akanbi, Remi Sikiru A., Ademola Ojo, 2006; O.J. Oyelade, T.Y. Tunde-Akintunde and al., 2008; Tom Ahmat, Denis Bruneau et al., 2014; Lankouande & al, 2021; Salah & al, 2022), the influence of temperature on isotherms and the study of mathematical models describing sorption isotherms.Tchongouang, Tchiègang, and Leng (Tchongouang, 2007; Tchiègang & Ngueto, 2009; Leng & al, 2018; Leng & al, 2019), in their work on Dioscorea Schimperiana, the subject of this present study, have shown that it is a food product very rich in nutrients, which also has therapeutic virtues such as numeral salts, vitamins, and carotenoids which represent provitamins A. Moreover, Dioscorea Schimperiana has not yet been the subject of thermophysical studies. This research, therefore, aims to determine the desorption isotherms of Dioscorea Schimperiana, to optimize the hygroscopic equilibrium

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conditions to improve the quality of the product and better conservation during its drying and storage process.

II. MATERIALS AND EXPERIMENTAL DEVICE

A. Material

The material for this study is Dioscorea Schimperiana (hairy yam) (Figures 1a and 1b). It is a yam with yellow-zebra flesh that can be oval or long-limbed.

a) Origin and processing of samples

The samples tested were fresh tubers harvested in PETE, a village in the commune of Bandjoun (West region of Cameroon). These hairy yam tubers underwent several treatments before their use and are of two types (raw and boiled).

(a) (b)

Fig. 1: Yam sample: a) Underground Tuber stalk b) Harvested tuber

b) Conditioning and dry extract

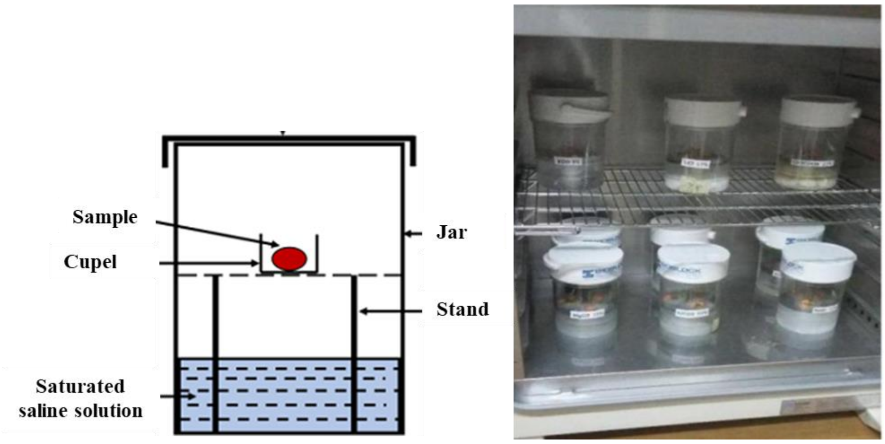
For packaging and dry extract, two pieces of equipment were used:

- A SARTORIUS brand electronic scale. The maximum load is 3000 g, The reading accuracy on the measurements is ± 0.01g and has a stabilization time of the order of two seconds.
- **Ventilated oven**: This is a 900W power desiccation chamber (figure 2) which can operate in a temperature range of 30-250°C. It is equipped with a mechanical set point regulation system and a mercury thermometer for reading the interior temperature. The set temperature, fixed using a potentiometer, is 103±2°C. The system works in natural convection. The oven is equipped with stainless steel shelves on which the samples of the product to be tested are placed. The overheating safety is class 1. This oven makes it possible to obtain the dry extract and to measure the anhydrous mass of the sample.

Fig. 2: Ventilated oven (L3E, ENSP UY1)

B. Experimental apparatus

The device used is an enclosure regulated by temperature and humidity (Figure 3b). It is regulated in temperature and relative humidity using a control microprocessor incorporated into the device. A Pt100 probe and a humidity sensor transmit information to the temperature and relative humidity control systems. The accuracies of the measurements are respectively ± 0.1°C and ± 1%. The samples were placed in hermetically sealed jars containing saline solutions (Figure 3a, Table 1). The jars were 11 cm high and 10 cm in diameter, as recommended by Spiess and Wolf (Spiess & Wolf, 1987). The samples were placed on a 10 mm grid above the surface of the solution to prevent them from getting wet.



(a) (b)

Fig. 3: Experimental device: (a) sample in a jar, (b) enclosure regulated in temperature and humidity

III. METHODS FOR DETERMINING DESORPTION ISOTHERMS

The determination of desorption isotherms is a privileged means of knowing the water content at equilibrium, as well as its functional availability in low or moderately hydrated food products.

A. Determination of desorption equilibrium water content

The desorption isotherms were determined by the static gravimetric method. Weused saturated saline solutions covering a relative humidity interval between 11 and 97% (Table 1)(Multon & Bizot, 1978). These solutions were prepared in hermetically sealed jars and kept in the thermostatically controlledenclosure. Two samples for each type of yam were placed in each jar above the saline solutions, in an atmosphere stabilized in temperature and relative humidity. The tests were carried out at three temperature values: 30°C, 40°C, and 50°C.

	Relative Humidity		
Salts	30°C	40°C	50°C
LiCl	11.3	11.2	11.1
$MgCl_2$	32.4	31.6	30.5
$Mg(NO_3)_2$	51.4	48.4	45.4
NaBr	56	53.2	50.9
IK	67.89	66.09	64.49
NaCl	75.1	74.7	74.4
KCl	83.6	82.3	81.2
K2SO4	97	96.4	95.8

Table 1: Saturated saline solutions: relative humidity as a function of temperature (Multon & Bizot, 1978)

The determination of the water content (Xeq) required the knowledge of the equilibrium wet mass (mheq) of the sample, and the anhydrous mass (m_s). The phenomenon materialized the equilibrium condition (15 days at 30°C, 10 days at 40°C, and 7 days at 50°C) when a mass difference of the order of 0.01g between three consecutive measurements was observed. After obtaining mheq for each sample, this led to the determination of the anhydrous mass. In this case, the sample was conditioned for 48h in the ventilated oven regulated at 103±2°C. The equilibrium water content is then evaluated by the relationship:

$$Xeq = 100\left(\frac{mh_{eq}}{m_s} - 1\right) \quad (1)$$

Where:mheq: Represents the wet mass of the sample in equilibrium and m_s the anhydrous mass in g, Xeq: The equilibrium water content of the product on a dry basis (Kg water/Kg ms).

The calculated equilibrium water contents are the averages of two experimental values (for each raw and boiled hair yam).

B. Modeling of desorption isotherms

The theoretical reproducibility of the desorption curves obtained experimentally was made according to five (5) models described in the literature and commonly used for an optimal adjustment, presented as follows.

a) Henderson model (1952

It is an empirical equation developed by Henderson and which is written as follows:

$$Xeq = \left[\frac{-1}{TK_1}\ln(1 - a_w)\right]^{1/K_2} \quad (2)$$

A linearization of the function $\ln(-\ln(1-a_w)) = f(Xeq)$ by the method of least squares makes it possible to determine the constants K_1 and K_2 of this model.

b) Harkings and Jura model (1944)

$$Xeq = \left[\frac{-K_2}{\ln(a_w) - K_1}\right]^{1/2} \quad (3)$$

c) Halsey model (Rahman, 1995)

$$Xeq = \left[\frac{K_1}{\ln(1/a_w)}\right]^{1/K_2} \quad (4)$$

d) Modified Oswin model (1946)

$$Xeq = (K_1 + K_2 T)\left[\frac{a_w}{1-a_w}\right]^{K_3} \quad (5)$$

Where: K_1, K_2, and K_3 are correlation parameters (constants); Xeq: water content of the product in % on a dry basis (Kgwater/Kgms); a_w: water activity; T: equilibrium temperature of the system (in K);

Among the four (4) models mentioned above, Henderson and modified Oswin integrates the test temperature, which turns out to be a significant parameter of the hygroscopic behavior of biological products (Talla, Jannot, Nkeng, & Puigalli, 2005).

e) GAB model (1985)
This model not only calculates the moisture content of the monolayer, but also the heat sorption of the monolayer and the multilayer. It is applicable for water activities between 0.05 and 0.95 and this model is given by the following equation (Mohammad Shafiur Rahman, Rashid Hamed Al-Belushi, 2006; Djedro & al, 2015; C. Madhusudan Nayak, C. T. Ramachandra and al., 2022):

$$Xeq = \frac{X_m C K a_w}{(1-Ka_w)(1-Ka_w+CKa_w)} \quad (6)$$

Where: Xeq: moisture content at equilibrium (gH2O/gms); Xm: Moisture content of GAB monolayer (gH2O/gms); C: constant related to the heat of monolayer sorption; K: factor linked to the heat of sorption of the multilayer. The parameters of GAB were determined using the method of the transformed form of the isotherm of GAB (Timmerman, 2003). The GAB model can be rearranged into a polynomial equation as shown in equation (8).

$$\frac{a_w}{X_{eq}} = \frac{K}{X_m\left(\frac{C}{1-C}\right)} a_w^2 + \frac{C-2}{X_m C} a_w + \frac{1}{X_m K C} \quad (7)$$

Its reduced form is:

$$\frac{a_w}{X_{eq}} = \alpha a_w^2 + \beta a_w + \gamma \quad (8)$$

Where:

$$\alpha = \frac{K(1-C)}{X_m C};\quad \beta = \frac{K(C-2)}{X_m C};\quad \gamma = \frac{1}{X_m C K}$$

The validation of the experimental and predicted data is obtained when their correlation coefficients (R) tend toward 1, their average relative error (P(%)), and their residual error (e_i) are very low (Simbarashe Samapundo, Frank Devlieghere and al., 2007). These magnitudes are obtained from relations (12; 13 and 14).

$$\boldsymbol{R}^2 = \frac{\sum_{i=1}^{N}\left(\boldsymbol{X}_{eqi,pre} - \overline{\boldsymbol{X}_{eqi,exp}}\right)^2}{\sum_{i=1}^{N}\left(\boldsymbol{X}_{eqi,exp} - \overline{\boldsymbol{X}_{eqi,exp}}\right)^2} \quad (12)$$

$$\boldsymbol{P}(\%) = \frac{100}{\boldsymbol{N}}\sum_{i=1}^{N}\left|\frac{\boldsymbol{X}_{eqi,expi} - \boldsymbol{X}_{eqi,pre}}{\boldsymbol{X}_{eqi,exp}}\right| \quad (13)$$

$$\boldsymbol{e}_i = \boldsymbol{X}_{eqi,exp} - \boldsymbol{X}_{eqi,pre} \quad (14)$$

Where:

$X_{eqi,exp}$: water content at the balance obtained experimentally; $X_{eqi,pre}$: water content at the predicted balance; N: number of experimental points.

IV. RESULTS AND DISCUSSION

A. *Determination of the parameters of each model*

From the experimental data, we used some empirical or semi-empirical models mentioned in paragraph 3.2, to find the values of the parameters which will be used to reproduce the hygroscopic character of the products. The experimental results are then presented in the form of n pairs of values defined by the expression:

$$\left\{(X^e_{eqi}, H^e_{ri})\right\} = \left\{(X^e_{eq1}, H^e_{r1}), (X^e_{eq2}, H^e_{r2}), (X^e_{eq3}, H^e_{r3}), \ldots\ldots, (X^e_{eq(n-1)}, H^e_{r(n-1)}), (X^e_{eqn}, H^e_{rn})\right\} \quad (15)$$

The resolution of the linear equation system by the numerical method of Correlation by the least Squares made it possible to determine the parameters of each model. For the four models, namely, GAB, modified Oswin, Harkings, and Henderson, the percentage of deviation is less than or equal to 10% whatever the temperature considered (table2).

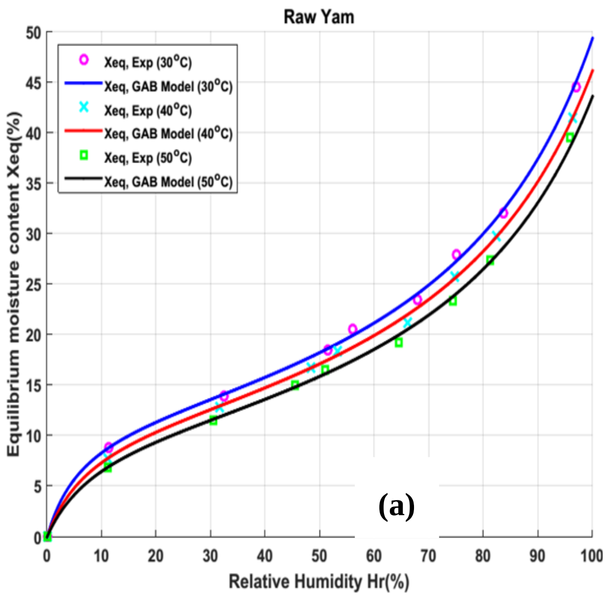
MODELS	PARAMETERS	DESORPTION TEMPERATURE 30 °C RAW	30 °C BOILED	40 °C RAW	40 °C BOILED	50 °C RAW	50 °C BOILED
GAB	M_O	12.42	10.02	11.76	10.01	10.81	9.02
	K	0.75	0.79	0.75	0.77	0.76	0.79
	C	19.42	20.7189	16.78	13.68	15.48	11.44
	P(%)	0.1761	0.1356	0.1324	0.1803	0.2134	0.1586
	R^2	0.9993	0.9996	0.9995	0.999	0.9992	0.9994
H and JURA	K1	0.0755	0.0564	0.065	0.044	0.05	0.026
	K2	243.93	170.75	206.88	146.39	171.08	113.31
	P(%)	6.15	7.25	7.19	8.68	7.85	10.01
	R^2	0.9893	0.9915	0.987	0.9886	0.988	0.9834
HENDERSON	K_1	$6.42X10^{-6}$	$1.07X10^{-6}$	$7.8\ X10^{-6}$	$1.87X10^{-5}$	$1.25X10^{-5}$	$2.62X10^{-5}$
	K_2	2.026	1.9098	1.955	1.789	1.872	1.676
	P(%)	4.47	5.83	3.87	3.38	3.85	3.86
	R^2	0.9966	0.9946	0.9971	0.997	0.9963	0.9968
Modified OSWIN	K_1	1	1	1	1	1	1
	K_2	0.56	0.48	0.39	0.33	0.28	0.23
	K_3	3.31	3.11	3.12	2.85	2.93	2.62
	P(%)	7.17	6.11	6.83	6.61	5.98	6.53
	R^2	0.9754	0.9836	0.9784	0.9862	0.9858	0.9865

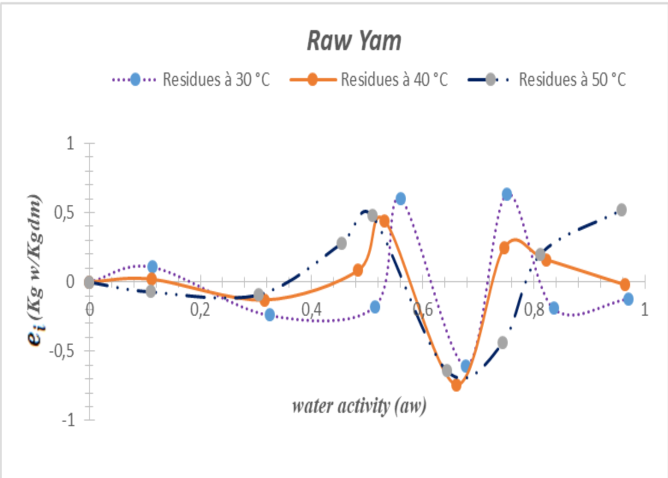
Table 2: Parameters of selected models at 30°C, 40°C, and 50°C

These four models can therefore be used to model the desorption isotherms of Dioscorea Schimperiana. The models best suited to the description of our experimental desorption curves are those of GAB and Henderson, for which the values of P and e_i for boiled and raw yam at 30°C,40°Cand 50°C are the smallest (ie less than or equal to 5%) and their R^2 tend towards 1 (table 2).

B. Experimental and modeled curves obtained at 30°C, 40°C, and 50°C.

The desorption isotherms of Dioscorea Schimpériana measured and calculated for the chosen models and the temperatures of 30°C, 40°C, and 50°C are represented respectively byfigures 1and 2. These isotherms are in agreement with the analysis of the values of R^2, e_i, and P(%).





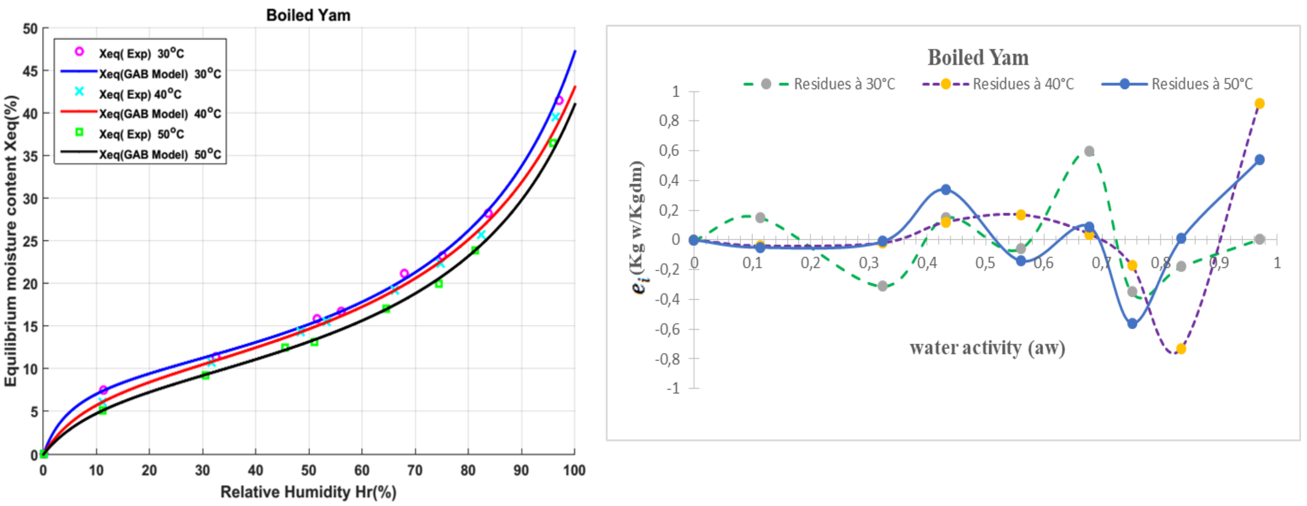


Figure 4: Desorption isotherm of raw (a) and boiled (c) Dioscorea Schimperiana (Hairy Yam); with desorption residues (b) and (d) at 30°C, 40°C, and 50°C: Experimental and theoretical curve (GAB model)

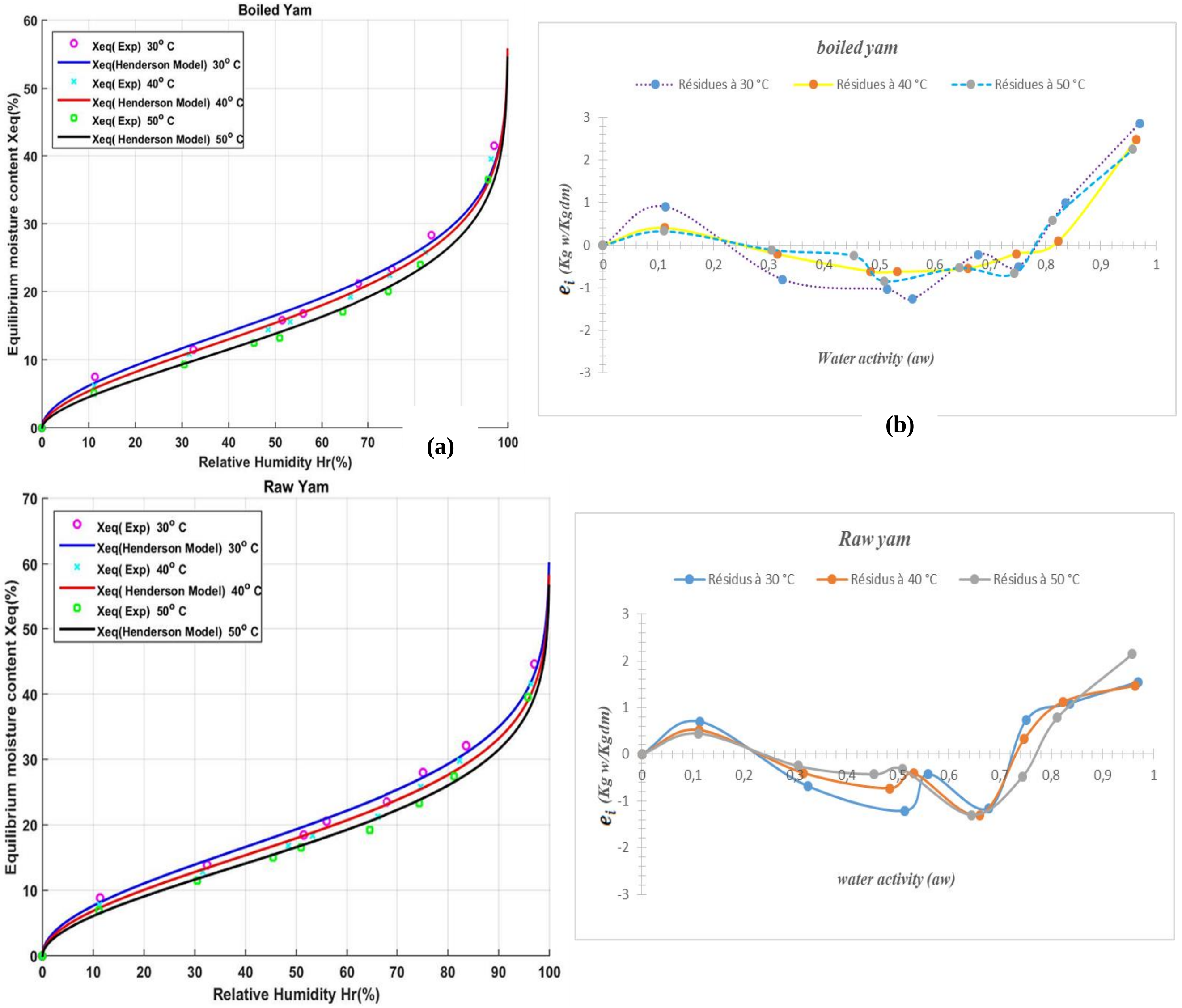


Fig. 5: Desorption isotherm of boiled (a) and raw (c) Dioscorea Schimperiana (Hairy Yam); with desorption residues (b) and (d) at 30°C, 40°C, and 50°C: Experimental and theoretical curve (Henderson model)

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Figures 4 and 5 present the experimental results for 30°C, 40°C, and 50°C in desorption as well as the smoothing curves of the GAB and Henderson models.These isotherms are type II (sigmoid shape), like most organic products, especially products with a high water content(McMinn, W.A.M., Magee, T.R.A., 2003; Talla, Jannot, Nkeng, & Puigalli, 2005; Charles Taiwo Akanbi, Remi Sikiru A., Ademola Ojo, 2006; Wang, N., Brennan, J.G, 1991; Kanmogne & al, 2012; Akil & al, 2020; Benseddik & al, 2021). It is generally noted that the isotherms obtained at higher temperatures are below those obtained at lower temperatures. In other words, for given water activity, the equilibrium water content of Dioscorea Schimperiana decreases when the temperature increases, which corroborates the results obtained by many authors for tropical agri-food products with high water content(Talla, André; Jannot; Kapseu; Nganhou, 2001; Tom Ahmat, Denis Bruneau et al., 2014; Nyangena & al, 2021; Ahouannou & al, 2017).On the other hand, the increase in thermal agitation (Multon et al, 1982) would explain why water content decreases with increasing temperature.

The table2 presents the parameters of the models, therefore, the correlation coefficients are the highest, and the percentage of deviation P<10%, for the three working temperatures (30°C, 40°C, and 50°C). GAB monolayer moisture content (X_m) is an important parameter in food spoilage studies. Its value as well as that of C decreases with increasing temperature. These results are in good agreement with those of (Talla, Jannot, Nkeng, & Puigalli, 2005; Nyangena & al, 2021);

The positive value of the parameter K of GAB, whatever the temperature, indicates that the heat of sorption of the multilayer is lower than the latent heat of condensation of pure water. The three zones of isotherms observed (figure 4) easily prove that the medium is non-porous or macroporous and that the desorption isotherm of Dioscorea Schimperiana is characteristic of multimolecular absorption: the progressive thickening of the absorbent layer.The statistical analysis of the four chosen models, as well as their desorption residuals, show that the modelmost suited to the description of our experimental desorption curves is the GAB model, for which the values of P and e_i for boiled and raw yam at30°C,40°C,and 50°C are very small and have an R^2 which tends towards 1.

V. CONCLUSION

The objective of the present study was to determine the desorption isotherms of raw and boiled Dioscorea Schimperiana. For the latter, the experimental results showed that they were of type II with a sigmoidal shape. The most suitable models for the study are those of GAB and Henderson. A good coincidence of the experimental points was observed with the curves obtained.

The experimental and theoretical determination of desorption isotherms appeared to be a privileged means of knowledge of the drying of Dioscorea Schimperiana. In addition to the studies carried out here, it would be wise to consider other studies on the drying of this yam, to model a suitable dryer for the drying of Dioscorea Schimperiana.

- **NOMENCLATURE**

Notation	Designation	Unit
Ms	Anhydrous mass	**g**
Mh	Wet mass	**g**
aw	Water activity	
HR	Equilibrium relative humidity	**%**
Xeq	Equilibrium water content	**(kg.water/kg.Ms)**
P	Relative average value	**%**
R^2	Correlation coefficient	
Xeq	Water content of the product on a dry basis	**$Kg._{water}/Kg._{ms}$**
X_{ei}	Experimental water content	**$Kg_{.water}/Kg_{ms}$**
X_{pi}	Theoretical water content	**$Kg_{.water}/Kg_{ms}$**
N	Number of experimental data	
T	Absolute air temperature	**K**
R	Perfect gas constant	**J/mol.K**
Q_{stn}	Net isosteric heat of desorption	**KJ/mol**
Q_{st}	Isosteric heat of desorption	**KJ/mol**

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