

ADSORPTION ISOTHERMS IN WHOLE MUÑA FLOUR (MINTHSTACHYS MOLLIS): A MATHEMATICAL MODELING APPROACH

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ABSTRACT

The moisture content of whole muña flour (*Minthostachis mollis*) is associated with diuretic properties, which reduce the elimination of uric acid, benefiting people who have arthritis problems, and its high levels of potassium and magnesium help regulate blood pressure and strengthen the functions of nutrients in flours. The objective was to determine the moisture content of the product in the monomolecular layer “X_m”, determining values of 8.40 y 11.02 g of water/100g of dry solid using the BET and GAB models, respectively, and to statistically validate these models; considering that the sample data follow a normal distribution, the Pearson correlation coefficient for the BET and GAB models is highly significant; the methodology was based on obtaining the equilibrium moisture content and water activity and determining the sorption isotherms, representing the equilibrium moisture of whole muña flour (*Minthostachis mollis*) χ (kilograms of water/kilogram of dry matter) as a function of a_w ; according to the mathematical models, the interest of a mathematical expression that expresses the relationship $\chi = f(a_w)$ is evident; the validation of the models, which follow a normal distribution and applying the Pearson correlation coefficient test, shows that both models are highly significant, and the water percentages are 7.75 and 9.93 for the BET and GAB models, respectively, in a water activity interval from 0.047 to 0.843; obtaining that both models showed the best fit with Pearson correlation coefficients of 0.970 and 0.972.

KEYWORDS: Whole muña flour, monomolecular layer moisture, sorption isotherms, BET and GAB models.

1. INTRODUCTION

The moisture content of whole muña flour (*Minthostachis mollis*) confers diuretic properties, helping to eliminate uric acid, being favorable for people who have arthritis problems, and its high levels of potassium and magnesium help regulate blood pressure and strengthen the functions of nutrients, Collazo-Abreu et al. [1]. Vázquez et al. [2] mention that the drying curves for a wide variety of vegetables were obtained in a batch-operated fluidized-bed dryer at different temperatures (40, 60, 70, 80, and 100 °C) and two levels of initial moisture content (15 and 20% dry basis); for the analysis of these curves, a linear semi-empirical mathematical model for wheat drying is proposed, analogous to a first-order reaction kinetics, and the values of the drying constant as a function of temperature are treated according to an Arrhenius-type exponential law, in which the values of the activation energy of the drying process are calculated, finding that there is no defined influence of the wheat variety on the value of the activation energy; however, it can be noted that it decreases with an increase in the initial moisture content.

Ocampo [3] indicates that hot-air drying is an operation that tends to reduce the moisture content of a product. Drying kinetics curves provide an idea of the required drying time, energy consumption, the mass transfer mechanism, the prevailing conditions in heat and mass transfer, and the influence that process variables such as temperature, inlet humidity, air velocity, etc., have on the drying rate; allowing for a more efficient design or selection of dryers, as well as of the process variables, García et al. [4].

Matos-Chamorro and Rajo-Angulo [5] mention that the stability of foods during storage depends on moisture content and control; since the main and most important constituent in them is water, its availability is expressed as water activity, which directly influences drying, mixing, storage, packaging, and other

processing operations; bearing in mind that for each food there is an optimal water activity at which stability against deterioration is greatest.

Coffee is a widely consumed product worldwide due to its stimulating and energizing properties. In addition, the drying process is an essential factor that influences the final quality of the product; in this sense, the objective of the present article was to estimate the moisture content of parchment coffee by using an automated solar dryer through mathematical models. The models used were of the multiple linear regression and nonlinear regression types, which were determined using the software R and Curve Expert Professional, respectively, as indicated by Barzola-Cárdenas et al. [6].

Mathematical models constitute a fundamental tool for understanding the complexity that characterizes various systems; they allow for the analysis of technological, economic, and environmental impacts, the evaluation of productive strategies, and forecasts of crop yields; where their use is generally focused on better understanding problems and anticipating the reality under investigation [6].

Iriarte and Bistoni [7] mention that the characteristic drying curve is usually divided into three periods: the preheating period, the constant drying rate period, and the falling drying rate period; however, the first two are usually very short compared to the entire drying period in dry pasta production; therefore, the models reported in the literature are focused on the falling drying rate period. These studies consider theoretical, semi-theoretical, and empirical models to describe water transfer and the kinetics of the drying process. Most of the theoretical models used in food science are based on Fick's diffusion laws and their derived equations.

Drying is the oldest method for food preservation and is also a widely used method for the preservation of fruits and vegetables; it works by removing water from foods, thereby preventing the growth of microorganisms and decomposition. Water is removed until a final concentration that ensures the stability and microbial safety of the product and minimizes chemical and physical changes in the material during storage. In most drying processes, water is removed by evaporation through the supply of hot air [7]. Lema et al. [8] mention that nonlinear regression analysis was used to determine the constants of the models evaluated in the thin-layer drying process of parsley (*Petroselinum crispum*). Although at each temperature there was a different model that optimized the fit, the Midilli-Kucuk model more adequately described the drying kinetics within the studied temperature range, and the effective diffusivity showed an Arrhenius-type dependence on temperature, thus allowing the obtainment of an acceptable value for the activation energy.

For the purpose of carrying out an efficient design of a food dryer, it is advantageous to have a thorough study of the operating conditions, taking into account the desired characteristics of the final product, and the models used to simulate drying kinetics can also be used to design new units as well as to control and optimize existing units; for this reason, drying kinetics must be well defined, otherwise it is necessary to have reliable models [8].

The drying process is generally carried out by forced convection of hot air; therefore, the rate of the process, and thus the drying kinetics, depend both on food-related factors (density, porosity, composition, initial moisture content, geometry) and on operational factors that include temperature, humidity, and air circulation velocity, Larrosa et al. [9]. Collazo-Abreu et al. [1] state that drying is an operation that is difficult to describe due to the complexity of the internal and external phenomena that occur during it; therefore, mathematical models are used to represent the drying kinetics of foods and to help predict processing times and thus optimize drying efficiency; currently, several methods have been proposed to analyze the drying of food products: theoretical, semi-empirical, and empirical models, among which the most commonly used are drying kinetics models based on semi-empirical thin-layer relationships, involving a simplification of the equations that describe the process. Solar drying of agricultural products is a decisive factor in improving efficiency in the industrial, residential, and rural sectors; and given its significant importance, researchers have proposed and developed a large number of theoretical and experimental models, seeking to generally predict the drying kinetics of the process, including the machine and the product; and with the use of solar thermal dryers, significant advances have been achieved in the development of models, which, when unified, allow the prediction of temperature and moisture profiles for various types of seeds, being supported by the wide diversity of products and the large differences among existing processes [1]. Prieto et al. [10] mention that an isotherm is simply a curve that relates the equilibrium moisture content in a product to the relative humidity of the air or the water activity of the product, and that the moisture content of a hygroscopic material, under certain conditions of temperature and equilibrium relative humidity, depends on the path it follows to reach it; and that for the same relative humidity there may be two isotherms, called adsorption and desorption isotherms, depending on the initial experimental conditions, where the isotherms have a sigmoidal shape and sorption isotherms provide the data necessary to calculate the enthalpy of vaporization, which mainly depends on temperature and the moisture content of a product; the higher the moisture content of a product, the lower the amount of energy required to evaporate a unit mass of water contained in the product, and vice versa.

Soria [11] mentions that liquid milk is subjected to dehydration, with the removal of water until the product reaches a solid state, obtaining characteristics that help the formation of homogeneous droplets during atomization for drying, facilitating a more uniform evaporation in the particles and improving the solubility of the powder at the time of reconstitution; therefore, two processes are used: a dehydrator that reduces the amount of liquid by 50%, followed by spray drying or drying using the technique known as roller drying,

a technology by which a percentage of free fat in the powder much higher than the chemical composition of milk can be obtained, which is based on proteins, lipids, vitamins, and minerals.

Ramírez-Miranda et al. [12] mention that knowledge of the thermodynamic properties related to the behavior of water sorption is important for dehydration in several aspects: first, food properties relate the concentration of water in the food to its partial pressure, which is crucial for the analysis of mass and heat transfer phenomena during dehydration; second, they determine the final point at which foods can be dehydrated to obtain a stable product with an optimal moisture content; and third, the sorption enthalpy provides an approximation of the minimum amount of energy (theoretical) required to remove a certain amount of water from foods.

Sorption isotherms were constructed at three temperatures (24, 30, and 35 °C), within a water activity range from 0.074 to 0.970, using the equilibrium cell method (PEC), obtaining type II isotherms; and the prediction of the curves using the B.E.T., G.A.B., and Henderson models was carried out by means of nonlinear regression analysis, where the G.A.B. and Henderson models showed the best fit (mean relative error < 4.4%) [12].

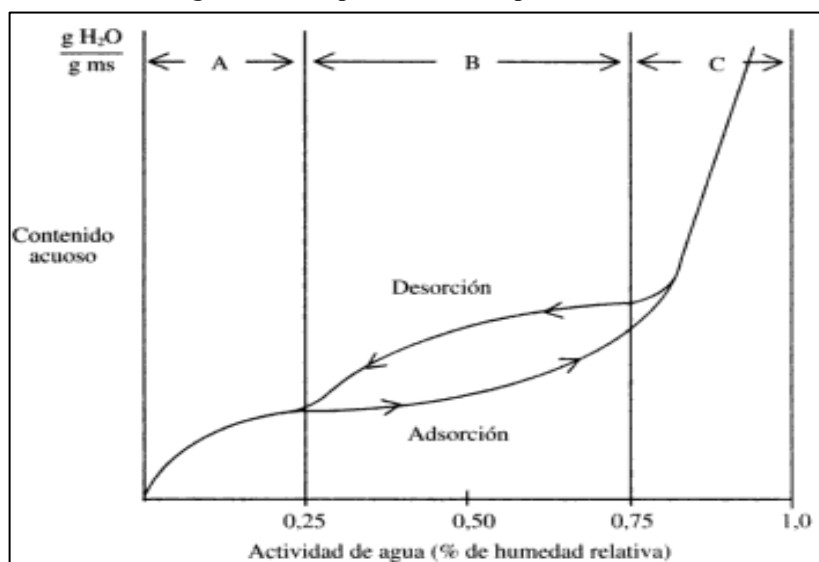
Water sorption isotherms, microstructural properties (starch), and thermal properties (specific heat and enthalpy) of cañihua grains (*Chenopodium pallidicaule* Aellen) of the Cupi and Illpa varieties, with and without perigonium, were determined in order to demonstrate the roasting potential of these two varieties, evaluating water activity with nonlinear regression fitting to the GAB, OSWIN, HENDERSON, and HALSEY mathematical models; where the best model was GAB, which better represents the experimental values of the sorption isotherms of both varieties, determining that the Cupi variety, with and without perigonium, presents greater water absorption [13]. It is also stated that the determination of thermal properties in foods is of vital importance in industrial processes, since these properties determine the rate of heat transfer of a product, and that specific heat is representative of each material; the higher the specific heat, the more thermal energy is required to increase the temperature. When foods are subjected to processes and operations, they undergo microstructural and macrostructural changes that in some cases are irreversible, also implying changes in their characteristics and properties (nutritional value, odor, flavor), appearance (shape, size, and color), and texture [13]. The determination of thermal properties in foods is of vital importance in industrial processes, since these properties determine the rate of heat transfer of a product and specific heat is representative of each material; the higher the specific heat, the more thermal energy is required to increase the temperature [13]. Water activity (A_w) is one of the most important tools in predicting food stability. The rate of many deterioration changes has been related to this parameter, since it determines the water that at a given moment is available for microbial growth and the progress of different chemical and biochemical reactions, providing detailed information on microorganism development, moisture migration, chemical stability, biochemical stability, physical properties, and shelf life. One of the techniques for measuring a_w is the hygrometric method [13].

Water activity values strongly affect the tendency of a food to undergo microbial, enzymatic, and chemical spoilage; and the levels of A_w that contribute to food deterioration depend on solute concentration, temperature, pH, the presence of additives, humectants, and many other factors [13].

Water is the major component of foods, reaching up to 90% in foods such as milk, fruits, and vegetables, whose content in foods influences both their organoleptic and textural properties, as well as food stability; and consequently, it is largely responsible for chemical, enzymatic, and microbiological reactions, which are the three main causes of food deterioration [6]. In animal and plant tissues, water is not uniformly distributed due to the hydrated complexes established with proteins, carbohydrates, lipids, and other constituents, in which the moisture content of a food refers to all the water in a global manner, without considering that in most products there are microscopic zones or regions that, due to a high accumulation of lipids, do not allow its presence and force it to be distributed heterogeneously [6]. Water activity (a_w) is considered the most important property of water in a food system, demonstrating that foods with the same water content deteriorate differently; therefore, it is deduced that the amount of water alone is not an indicative tool of food deterioration; thus, the concept of a_w , arises, which indicates the fraction of the total moisture content of a product that is free and, consequently, available for the growth of microorganisms and for the occurrence of various chemical reactions that affect food stability, according to López-Mejía et al. [14]. When the a_w of these products decreases, undesirable textural attributes appear, such as hardness, dryness, and hardening; therefore, foods with low a_w are crisp and brittle, and if their a_w increases, texture changes occur, producing product softening, in which a_w also affects other properties such as the agglomeration of powdered and granular products [14].

An increase in a_w is generally accompanied by an increase in water content, but not in a linear manner; in which the relationship between a_w and water content at a given temperature is graphically illustrated in the so-called sorption isotherms (Figure 1), which are determined experimentally [11].

Figure 1 Adsorption and desorption isotherms



The first section, in which a_w ranges from 0-0.35, corresponds to strongly bound water; in this region there is a BET monomolecular layer of water fixed to the polar groups of certain compounds. In the section where a_w ranges from 0.35-0.75, water molecules have restricted mobility and a reduced freezing point. In the section where a_w ranges from 0.75 to 0.99, free water is found, which represents most of the water in fresh foods; it is easy to freeze and evaporate. Water activity describes the continuity of energy states of water in a system, in which the water in a product is “bound” by forces of varying intensity, which is indicative of a continuity of energy states rather than a static binding or bond.

Water activity (a_w) is defined by the decrease in the partial pressure of water vapor of a solution or a food relative to the partial pressure of pure water at a given temperature. The chosen reference state is pure water, whose activity is set by convention as equal to unity; therefore, the water activity of a solution or a food is always less than one.

The sorption isotherm of a hygroscopic food is defined as the representation of the moisture content of that food χ (kilograms of water/kilogram of dry matter) as a function of a_w , or equivalently, as a function of the relative humidity of the air surrounding the food once equilibrium has been reached, at a constant temperature.

According to what has been stated previously, with regard to mathematical models, the interest in having a mathematical expression that expresses, for each food, the relationship $\chi = f(a_w)$, is evident; due to the difficulty of experimentally determining the critical point, several researchers have proposed different mathematical models that allow, in addition to reproducing the relationship $\chi = f(a_w)$ with a greater or lesser degree of approximation, the calculation of the values of certain parameters that provide information about the conditions of maximum stability of the food during its storage.

All proposed models, whether empirical, semi-empirical, or theoretical, are capable of reproducing equilibrium moisture data with a certain degree of success; however, none has been able to provide precise results over the entire de a_w range and for the different types of foods.

2 MATERIALS AND METHODS

Methodology: In this research, Conway plates made of sterilized glass material, Sibata PAT brand, were used, consisting of a circular base with two concentric chambers separated by a circular partition and an octagonal lid; in which the base and lid are hermetically sealed and secured by means of a pressure device. Each plate has a diameter of 85 mm and a height of 20 mm. For each Conway plate, 2 g of muña flour (*Minthostachis mollis*) were placed in a container covered with aluminum foil and installed in the central chamber of the Conway plates. In the outer part of a plate, 4 mL of saturated solution with an A_w lower than the A_w of the muña flour (*Minthostachis mollis*) was placed. The plates were then hermetically sealed and incubated at 25 °C for 10 h. After the elapsed time, mass differences were plotted as a function of the relative humidity of water (RHW) in the chamber, and the RHW was obtained by interpolation at the point where there was neither loss nor gain of mass.

2.1. The BET and GAB Models

Brunauer, Emmett, and Teller (B.E.T.) Model

$$\frac{\chi}{Xm} = \frac{C \times a_w}{(1 - a_w)(1 + (c - 1) \times a_w)} \quad (1)$$

Where: χ = equilibrium moisture constant in *grams of water/100grams of dry solid (ga/100gds)*

Xm = product moisture corresponding to the monomolecular layer of absorbed water; expressed in the same units as χ .

a_w = water activity.

C = constant = $K \times e^{Q_s/RT}$

Q_s = heat of adsorption

R = universal gas constant (1.9872 cal/molg°K)

T = absolute temperature (K)

K = (accommodation coefficient / frequency factor) = 1.0

Rearranging equation (1); we have:

$$\frac{a_w}{\chi \times (1 - a_w)} = \frac{1}{Xm \times C} + \frac{a_w \times (c - 1)}{Xm \times C}$$

Whose linear regression analysis is of the form: $Y = A + Bx$; whose purpose is to calculate Xm .

Guggenheim, Anderson, and de Boer (G.A.B.) Model

$$\frac{\chi}{Xm} = \frac{C \times K \times a_w}{(1 - K \times a_w)(1 - K \times a_w + C \times K \times a_w)}$$

Which, by rearranging terms, yields:

$$\frac{a_w}{\chi} = \frac{1}{Xm \times C \times K} + \frac{c-2}{Xm \times C} \times a_w + \frac{K \times (1-c)}{Xm \times C} \times a_w^2$$

Where: χ = equilibrium moisture content (% dry basis);

Xm = moisture content of the monolayer

a_w = water activity; C = Guggenheim constant;

$$C = C_0 \times e^{\frac{H_1 - H_m}{RT}}$$

K = correction factor for the properties of molecules in the multilayers: $K = K_0 \times e^{\frac{H_1 - H_q}{RT}}$

H_1 = heat of condensation of pure water vapor.

H_q = total sorption heat of the water multilayers.

H_m = sorption heat of the monolayer.

R = universal gas constant (1.9872 cal/molg°K)

T = absolute temperature (°K).

The nonlinear regression analysis has the form: $Y = A + Bx + Cx^2$; whose purpose is to calculate Xm .

Where: $A = \frac{1}{Xm \times C \times K}$; $C = \frac{K \times (1-c)}{Xm \times C}$ y $B = \frac{c-2}{Xm \times C}$

The value of the monomolecular layer is described by Xm , corresponding to the bound water fixed to polar groups. The property of this amount of water is that it does not act as a solvent, is not available for microorganisms, and is not reactive.

2. RESULTS

Having the sorption isotherms at two temperatures (25 and 33 °C), within a water activity range from 0.047 to 0.843, the equilibrium moisture content (X_{eq}) and water activity (A_w) of whole muña flour (Minthostachis mollis) were analyzed, determined under constant working conditions and in triplicate, as shown in Table 1.

Table 1. Triplicate data of equilibrium moisture content (X_{eq}) and water activity (A_w) for whole muña flour (Minthostachis mollis).

A_{w1}	X_{eq1}	A_{w2}	X_{eq2}	A_{w3}	X_{eq3}
0.08	5.02	0.082	5.00	0.07	5.07
0.15	8.25	0.14	8.30	0.15	8.40
0.25	10.30	0.27	10.32	0.24	10.35
0.32	11.15	0.33	11.25	0.34	11.30
0.40	11.35	0.39	11.40	0.42	11.41
0.48	11.60	0.49	11.58	0.51	11.65
0.57	12.70	0.56	12.75	0.61	12.80
0.65	13.75	0.66	13.80	0.67	13.82
0.73	14.72	0.74	14.70	0.72	14.81
0.84	17.08	0.82	17.12	0.87	17.15

The average values of equilibrium moisture content (X_{eq}) and water activity (A_w) for whole muña flour (Minthostachis mollis), as well as the values for the B.E.T. and G.A.B. models, are presented in Table 2.

Table 2. Average data of equilibrium moisture content (X_{eq}) and water activity (A_w) for whole muña flour (Minthostachis mollis).

$\overline{A_w}$	$\overline{X_{eq}}$
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0.047±0.005	5.030±0.029
0.147±0.005	8.317±0.062
0.253±0.012	10.323±0.021
0.330±0.165	11.233±0.062
0.403±0.012	11.387±0.026
0.493±0.012	11.610±0.029
0.580±0.022	12.750±0.041
0.660±0.088	13.790±0.029
0.730±0.088	14.743±0.048
0.843±0.021	17.117±0.029

Table 3. Equilibrium moisture content data (X_{eq}) and water activity (A_w) for whole muña flour (*Minthostachis mollis*), and the values for the B.E.T. and G.A.B. models.

A_w	X_{eq}	$A_w/[X_{eq}[(1 - A_w)]]$	A_w/X_{eq}
0.047	5.030	0.0166	0.0153
0.147	8.317	0.0207	0.0177
0.253	10.323	0.0328	0.0247
0.330	11.233	0.0438	0.0294
0.403	11.387	0.0593	0.0354
0.493	11.610	-	0.0425
0.580	12.750	-	0.0455
0.660	13.790	-	0.0479
0.730	14.743	-	0.0495
0.843	17.117	-	0.0492

Application of the B.E.T. Model

$$\frac{a_w}{\chi \times (1 - a_w)} = \frac{1}{Xm \times C} + \frac{a_w \times (c - 1)}{Xm \times C}$$

According to the linear regression analysis carried out on the first five data points in Table 3, the corresponding data are obtained:

$$\frac{a_w}{\chi \times (1 - a_w)} = 0.006555602 + 0.119001686 \times a_w$$

With a Pearson correlation coefficient $r = 0.97$.

Obtaining: $\frac{1}{Xm \times C} = 0.006555602$ and $\frac{(c-1)}{Xm \times C} = 0.119001686$

Where: $C = 19.1527$; $Xm = 8.4032ga/100gds$ and $\% \text{ moisture} = \frac{8,4032}{100+8,4032} \times 100 = 7.7518 \% \text{ moisture}$.

Application of the G.A.B. model

$$\frac{a_w}{\chi} = \frac{1}{Xm \times C \times K} + \frac{c-2}{Xm \times C} \times a_w + \frac{K \times (1-c)}{Xm \times C} \times a_w^2$$

According to the nonlinear regression analysis carried out on the ten data points in Table 3, the corresponding data are obtained:

$$\frac{a_w}{\chi} = 0.0083268 + 0.0833828 \times a_w - 0.03828623 \times a_w^2$$

Obtaining:

$$\frac{1}{Xm \times C \times K} = 0.0083268 ; \frac{c-2}{Xm \times C} = 0.0833828 \text{ and } \frac{K \times (1-c)}{Xm \times C} = -0.03828623$$

Where: $C = 24.7667$; $Xm = 11.0244128$ and $K = 0.439844$

and $\% \text{ moisture} = \frac{11.0244128}{100+11.0244128} \times 100 = 9.93 \% \text{ moisture}$.

Validation of the BET model

Considering that the sample data follow a normal distribution and applying the Pearson Correlation Coefficient test, the following results are obtained.

Table 4. Pearson Correlation Coefficient test for the BET model

Component	Result
Main assumption	The correlation under the BET model is not significant

Pearson correlation coefficient	0.970**
Significance level	0.05
P-value	0.006
Decision	The correlation under the BET model is highly significant

Note. (**) the correlation is significant at the 0.01 level.

Validation of the GAB model

Considering that the sample data follow a normal distribution and applying the Pearson Correlation Coefficient test, the following results are obtained.

Table 5. Pearson Correlation Coefficient test for the GAB model.

Component	Result
Main assumption	The correlation under the model is not significant
Pearson correlation coefficient	0.972**
Significance level	0.05
P-value	0.000
Decision	The correlation under the GAB model is highly significant

Nota. (**) the correlation is significant at the 0.01 level.

4. DISCUSSION

The behavior of sorption isotherms at two temperatures (25 and 33 °C) was determined over a water activity range from 0.047 to 0.843, obtaining sorption isotherms and curve predictions using the B.E.T. and G.A.B. models. These were carried out using linear and nonlinear regression analyses, where both models—within the constraints shown by each—exhibited the best fit, with Pearson correlation coefficients of 0.970 and 0.972, respectively, closely matching those reported by Ramírez-Miranda [12]. Water activity (a_w) in whole muña flour (*Minthostachis mollis*) is considered the most important water property in this type of flour, corroborating those foods with similar water contents deteriorate differently. Therefore, it is affirmed that water content alone is not an indicative tool of food deterioration, giving rise to the concept of a_w , which indicates the fraction of total moisture content that is available for microbial growth and for carrying out various biological reactions that affect food stability, in agreement with López-Mejía et al. [14]. The mathematical models B.E.T., G.A.B., and others constitute tools of great importance for understanding the complexity that characterizes different values in any process of food engineering, technology, and science, allowing estimations and predictions, technological impacts, and applications in many other fields of human knowledge. Their use is generally focused on better understanding problems and anticipating the reality under investigation, corroborating what was stated by Barzola-Cárdenas et al. [6]. Likewise, water activity values emphasize the tendency of a food to undergo different types of deterioration and that the levels of water activity favoring food alteration are related to a series of compositional and physicochemical properties of foods, in agreement with Huiche-Mamani [13].

From this study, it is concluded that the moisture content of the product corresponding to the monomolecular layer of absorbed water " X_m " is 8.4032 g of water/100g of dry solid and 11.0244 g of water/100g of dry solid according to the BET and GAB models, respectively. The validation of the BET and GAB models, considering that the sample data follow a normal distribution and applying the Pearson correlation coefficient test to both models, is highly significant. The corresponding water percentages are 7.75 and 9.93 for the BET and GAB models, respectively.

Based on the experience obtained, it is recommended that water activity tests be carried out on other types of flours with physicochemical properties similar to those of muña flour (*Minthostachis mollis*); that decimal approximation for equilibrium moisture and for water activity itself be taken to four decimal places in order to achieve greater precision in all calculations; and that other models used to analyze sorption isotherms of foods and other hygroscopic materials also be applied.

REFERENCES

1. P.L. Collazo-Abreu, Y. Morejón-Mesa, L. Fernández-Chuairey, y Y. Vázquez-Alfonso "Modelos matemáticos y experimentales para el análisis del secado solar de semillas". Revista Ciencias Técnicas Agropecuarias, vol. 27, no. 1, pp. 89-98, 2018.
2. Ch. L. Vázquez, M. M. Vizcarra y M. A. Villagómez, "Modelo matemático semi empírico de la cinética de secado de trigo (*Triticum aestivum*). Universidad Autónoma Metropolitana Iztapalapa, México D.F. Departamento. de Biotecnología y Departamento. de Ingeniería. de Procesos e Hidráulica, vol. 1, no. 2, pp. 89- 94, 2016.
3. Ocampo. "Modelo cinético del secado de la pulpa de Mango". Disponibilidad Libre en: <http://revista.eia.edu.co/articulos5/art105.pdf>. 2006.
4. S. García, M. Schmalko, y A. Tanzariello, "Isotermas de Adsorción y Cinética de Secado de Ciertas Hortalizas y Aromáticas Cultivadas en Misiones".2007. Formato pdf. Disponibilidad Libre en: http://www.inta.gov.ar/ediciones/ria/36_1/07_.pdf.

5. A. Matos-Chamorro, y R. Rajo-Angulo, “Influencia del Tamaño de Partículas en las Isotermas de Adsorción del Harina de Haba (Vicia faba L.)”. Universidad Peruana Unión. Lima, Perú Rev. Investigación en Ciencia y Tecnología. Alimentaria, vol. 1. no. 1, 2010.
6. A. Barzola-Cárdenas, L. Quiñones-Huatangari, B. Vásquez-Ochoa, I. Pérez-Guevara y M. Díaz-Torres, “Estimación de humedad de café pergamino utilizando un secador solar automatizado, mediante modelos matemáticos en Jaén-Perú”, 2020. DOI: <https://doi.org/10.21754/tecnia.v30i1.824>.
7. A. Iriarte y S. Bistoni (2018). “Secado de manzana en secadero túnel de laboratorio y en secadero solar en convección natural. Modelización de la cinética de secado”. Avances en Energías Renovables y Medio Ambiente, vol. 22, pp. 02.01-02.11, 2018.
8. [A. Lema, M. Pontin, A. Sanmartino, M. Ziletti y M. Martinello , (2007). “Características del proceso de secado en capa delgada del perejil (*Petroselinum crispum*)”. Rev. Avances en Energías Renovables y Medio Ambiente, vol. 11, 2007.
9. V. Larrosa, G. Lorenzo, N. Zaritzky, y A. Califano, “Modelado matemático del secado de pastas libres de gluten en relación con la temperatura y humedad relativa del aire”. Revista del Laboratorio Tecnológico del Uruguay (INNOTEC), vol. 11, pp. 54-58, 2016.
10. J. Prieto, F. Prieto, A. D. Román, E. M. Otazo y M. A. Méndez, “Correlación de modelos matemáticos de adsorción de humedad en cereales para desayuno”Universidad Autónoma del Estado de Hidalgo. Centro de investigaciones químicas, Pachuca de soto, Hidalgo – México. Aci, vol. 3, no. 1, pp. 137-150, 2012.
11. M. A. Soria “Modelamiento matemático del proceso industrial de producción de leche en polvo”. Tesis de pregrado, Universidad Estatal de Milagro, Facultad Ciencias de la Ingeniería. Milagro. Ecuador. 2017.
12. R. Ramírez-Miranda, M. T. Cruz-Victoria, M. G. Vizcarra-Mendoza y I. Anaya-Sosa “Determinación de las isotermas de sorción y las propiedades termodinámicas de harina de maíz nixtamalizada”. Revista mexicana de Ingeniería Química, vol. 13, no. 1, pp. 165-178, 2014.
https://www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S1665-27382014000100013
13. A. L. G. Huiche-Mamani, “Determinación de las isotermas de sorción de agua, propiedades microestructurales y térmicas de dos variedades de granos de cañihua (*Chenopodium pallidicaule aellen*) con y sin perigonio”. Tesis para optar el título profesional de ingeniero agroindustrial. Puno. Perú, 2018.
14. N. López-Mejía, M. M. Andrade-Mahecha, H. A. Martínez-Correa, “Modelamiento matemático de la cinética de secado de espagueti enriquecido con pulpa de zapallo deshidratada (*Cucurbita moschata*)”. Revista U.D.C.A Actualidad & Divulgación Científica, vol. 22, no. 1 ,2019.
<https://doi.org/10.31910/rudca.v22.n1.2019.1151>