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Modeling of the adsorption isotherm of *Pleurotus ostreatus* using Guggenheim-Anderson-de Boer (GAB) equation

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Moisture sorption isotherms of *Pleurotus ostreatus* were determined at three different temperatures (10, 30 and 40) and relative humidity (6 to 88%), using standard static gravimetric method. The samples were used to determine the equilibrium moisture content and the data fitted to the Guggenheim-Anderson-de Boer (GAB) equation to describe the moisture adsorption characteristics within the water activity used for this study. Model parameters c, k and M_o were derived. The GAB monolayer moisture values (M_o) were 0.179, 0.163 and 0.123 at 10, 30 and 40°C respectively. The c and k value decreased from 0.729 to 0.613 at 10°C and 19.455 to 18.551 at 30°C, and increased to 0.712 and 24.737 when the temperature was further increased to 40°C. The mean relative percent modulus (%E) were 1.318, 5.393 and 3.224% at 10, 30 and 40°C respectively. The r^2 values obtained varied between 0.980 and 0.997, indicating strong correlations between the experimental and predicted data; whereas the error values ranged from 0.007 to 0.017, showing very good fitness between the experimental moisture sorption and the modeled sorption. Thus, GAB model could be used to predict the moisture sorption behavior of *P. ostreatus* mushroom at the range of water activity used in this study.

Key words: *Pleurotus ostreatus,* mushroom, Guggenheim-Anderson-de Boer (GAB) model, adsorption, isotherm, monolayer.

INTRODUCTION

Moisture sorption isotherms are useful thermodynamic tools in the determination of interactions of water and food substances, to provide information on food processing operations such as drying, packaging and storage (Rizvi, 1995). The oyster mushroom (*Pleurotus ostreatus)* is a *Basidiomycete* fungus belonging to the *Polyporaceae* family. This edible mushroom is widely used as a culinary ingredient and dietary supplement in Asia because of its enticing flavor and nutritional value (Hong et al., 2013; Tsao et al., 2013). Fresh mushrooms easily deteriorate because of their high moisture content and nutrient density. In terms of preservation, studies have increasingly focused on various processes for the drying of mushrooms (Cui et al., 2003). In order to

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increase the use of *P. ostreatus* and promote the development of the mushroom industry, the mushrooms can also be supplied as dried, which will ensure longetivity.

In nature, among more than 2,000 species of mushrooms, only less than 25 species are widely accepted as edible fungi of commercial importance (Cuptapun et al., 2010). Besides being known as a good source of protein, vitamins and minerals (Cuptapun et al., 2010; Kakon et al., 2012; Kalač, 2009), mushroom contains nutraceuticals (Cuptapun et al., 2010; Elmastas et al., 2007; Ribeiro et al., 2007) responsible for their antioxidant, antitumor (Cuptapun et al., 2010; Wasser and Weis, 1999), and antimicrobial properties (Cuptapun et al., 2010; Hatvani, 2001; Barros et al., 2007; Turkoglu et al., 2007). As a result, consumption of mushrooms has increased substantially not only due to their nutritional value, but also due to their delicacy and favor (Shivhare et al., 2004). However, fresh mushrooms have a short shelf life because of high moisture content in the range of 87 to 95% (wet basis) (Rhim and Lee, 2011; Walde et al., 2006; Arumuganathan et al., 2009). Therefore, they are needed either to be marketed soon after harvest or to be preserved using specific processes such as drying and storing under suitable conditions (Tulek, 2011).

Due to the practical significance in both drying and storage of foods, the relationship between total moisture content and water activity of food, over a range of value, and at constant temperature, namely a moisture sorption isotherm, plays important role as it is important in the design of drying process and microbiological safety (Shivhare et al., 2004). The moisture sorption isotherm is a plot of equilibrium moisture content (EMC), defined as the moisture content when vapor pressure of water present in the food material has reached equilibrium with its surroundings, as a function of water activity (Shivhare et al., 2004; Lee and Lee, 2008).

Under ideal climatic conditions, shelf life of these mushrooms is about 10 days, with their quality being predominantly affected by storage temperature. The shelf life can be reduced from 9 days at 2°C to 3 days at 18°C (Lukasse and Polderdijk, 2003). Therefore, cooling the fresh mushrooms can be an alternative regarding their distribution and sale, thus increasing their shelf life (Villaescusa and Gil, 2003). For long periods of conservation, the traditionally used method for *Pleurotus* genus mushrooms is the convective drying at 45 to 65ºC (Pal and Chakraverty, 1997; Arora et al., 2003). Drying is a classical method of food conservation, based on the principle that the reduction of the water activity of the product must be conducted until defined levels that guarantee the microbiological and physicochemical stability (Cao et al., 2003; Krokida et al., 2002; Lewicki and Jakubczyk, 2004).

The objective of this study was to determine sorption isotherm of *P. ostreatus* at three temperatures and calibration of Guggenheim-Anderson-de Boer (GAB) model at the various water activities used.

MATERIALS AND METHODS

In this work, freshly cultivated *P. ostreatus* mushroom were sorted according to uniform maturity, size and cleaning. The average initial moisture content (dry basis) of the mushroom samples was determined using the standard method (AOAC, 2002).

The adsorption isotherms of the mushroom samples were determined using a standard static gravimetric method at air temperature of 10, 30, and 40°C with five saturated salt solutions of known water activity. The prepared fresh samples were put into a container saturated with saturated salt solutions. About 3 g bone dried sample was placed in a Petri dish inside five dessicators containing saturated salt solutions of KOH, $MgCl_2$, $(MgNO_3)_2$, $NaCl_2$, $Na_2C_7H_5O_2$ with relative humidity 6, 33, 52, 75 and 88% respectively. At high relative humidity ($a_w > 0.7$), toluene (1.5 ml) was placed in the desiccators to prevent microbial growth. The dessicators were placed inside incubators maintained at three different temperatures of 10, 30, and 40°C. The sample weight was measured periodically until constant value was reached, where the samples were assumed to be at equilibrium and subsequently the moisture content of the sample was determined by means of hot-air oven (AOAC, 1990). The equilibrium moisture content (EMC) of the mushroom sample was subsequently plotted against the water activity to obtain sorption isotherm curves. The data for the water adsorption were fitted to the GAB equation (Van de Berg and Bruin, 1981) to describe the moisture adsorption process.

Theory of Guggenheim-Anderson-de Boer (GAB) equation

The GAB equation can be expressed as shown in Equation 1.

$$M_e = \frac{cKMoaw}{(1-Kaw)(1-Kaw+cKaw)} \quad (1)$$

The three parameters of GAB values of c, k and M_o were derived from the second order polynomial form (Equation 2) which was solved by multi-linear regression analysis to obtain α, β, γ, r^2 and E% (Xiong, 2002):

$$\frac{aw}{Me} = \alpha a_w^2 + \beta a_w + \gamma \quad (2)$$

Where

$$\alpha = K/M_o\,(1/c - 1) \quad (3)$$

$$\beta = 1/M_o\,(1-2/c) \quad (4)$$

$$\gamma = 1/M_o\,Kc \quad (5)$$

The values of parameters α, β and γ were obtained for each temperature through the following relations:

$$M_o = \frac{1}{\sqrt{\beta^2-4\alpha\gamma}} \quad (6)$$

$$c = \frac{2\sqrt{\beta^2-4\alpha\gamma}}{-\beta+\sqrt{\beta^2-4\alpha\gamma}} \quad (7)$$

$$k = \frac{-\beta+\sqrt{\beta^2-4\alpha\gamma}}{2\alpha\gamma} \quad (8)$$

$$\%E = \frac{100}{\mathrm{N}}\sum\frac{\mathrm{Mexp}-\mathrm{Mcal}}{\mathrm{Mexp}} \quad (9)$$

$$r^2 = \frac{RSS}{TSS} = \frac{\sum(Mcal-Mave)^2}{\sum(Mexp-Mave)^2} \quad (10)$$

Table 1. Experimental [$M_{e(exp)}$] and GAB equilibrium moisture content [$M_{e(cal)}$] (% db) of the *Pleurotus ostreatus* stored at 10, 30 and 40°C.

Water activity a(aw)	Equilibrium moisture content [M_e %]					
	10°C		30°C		40°C	
	$Me_{(exp)}$	$Me_{(cal)}$	$Me_{(exp)}$	$Me_{(cal)}$	$Me_{(exp)}$	$Me_{(cal)}$
0.06	0.095	0.094	0.083	0.0761	0.056	0.056
0.32	0.194	0.196	0.143	0.157	0.127	0.125
0.51	0.255	0.256	0.213	0.198	0.156	0.164
0.75	0.383	0.375	0.269	0.267	0.255	0.237
0.88	0.482	0.489	0.319	0.323	0.294	0.305

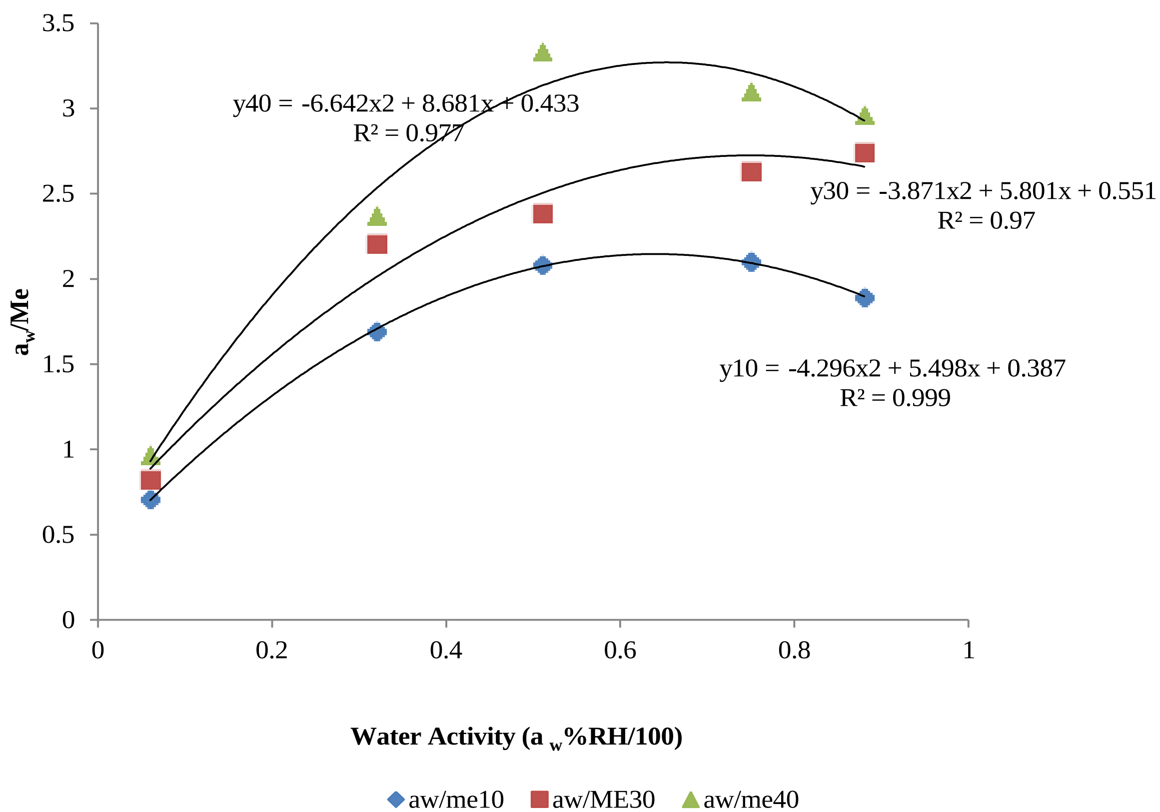

Figure 1. GAB model isotherm curve for *Pleurotus ostreatus* stored at 10, 30 and 40°C at water activities of 0.05 to 0.9.

RESULTS AND DISCUSSION

Table 1 shows the results of the determinations of the equilibrium moisture content at three temperatures of 10, 30 and 40°C. The data obtained were fitted to the GAB equation to describe their moisture adsorption.

Fitting of GAB sorption model to the experimental sorption data

The result of the multi-regression analysis of fitting the GAB sorption equations to the experimental data and the GAB model isotherm curves are shown in Figure 1, from where the values of α, β, γ and r^2 were obtained. These were used to calculate the three model parameters of c, k and M_o as shown in (Table 2). The values of the GAB constants c, k and M_o were calculated using linear regression Equations 3, 4 and 5 (Abramovic and Klofutar, 2002). The resulting parameters were fixed into Equation 2, and $M_{e(cal)}$ were obtained over a wide range of water activity (0.06 to 0.88) used for this study. The calculated equilibrium moisture content, $Me_{(cal)}$ were compared to the experimental sorption data, $M_{e(exp)}$ (Figure 2) to

Table 2. GAB model calibration statistics for *P. ostreatus* stored at 10, 30 and 40°C.

Temperature of storage (°C)	k	c	M_o	SEE	E%	r^2
10	0.729	19.455	0.179	0.007	1.318	0.997
30	0.613	18.551	0.163	0.017	5.393	0.967
40	0.712	24.737	0.123	0.012	3.224	0.980

k, c, M_o are model constants; E% is mean relative percentage deviations modulus, SEE is standard error of estimate and r^2 is coefficient of determination.

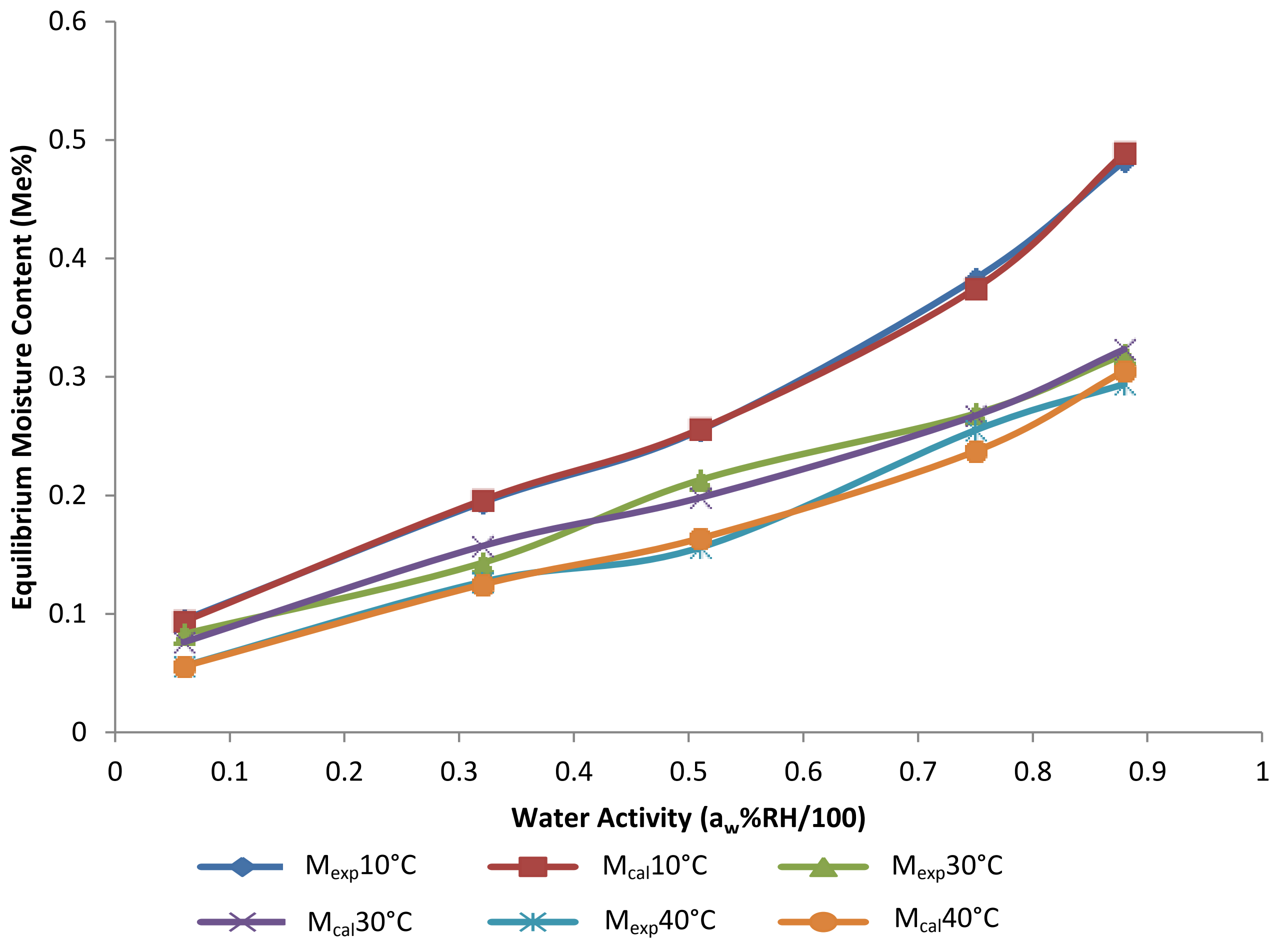

Figure 2. Experimental and GAB fitted data for *P. ostreatus* stored at 10, 30 and 40°C AT water activities of 0.05 to 0.9.

determine if GAB model can be used to describe the sorption behaviour of *P. ostreatus* over the entire range of water activity.

The monolayer (M_o) value of GAB obtained were temperature dependent (Table 2). The monolayer values were 0.179, 0.163 and 0.123 at 10, 30 and 40°C respectively. Increase in temperature leads to decrease of M_o from 0.179 to 0.123. The decrease in GAB monolayer moisture content (M_o) is an indication that the absorbed molecules gained kinetics energy thereby loosening the attractive forces and allowing some water molecules to break away from their sorption sites leading to decrease in equilibrium moisture values (Arevalo-Pinedo et al*.,* 2004).

The monolayer moisture contents were contrary to the values obtained by Giannini et al*. (*2010), in which 13 and 33% were obtained at 30 and 40°C respectively. This difference may be due to the substrate used in cultivation, time of harvest etc. The parameter c and k values initially decreased from 0.729 at 10°C to 0. 613 at 30°C and then increased to 0.712 at 40°C; while the parameter c follows the same trend, c values initially decreased from 19.455 at 10°C to 18.551 at 30°C and then increased to 24.737 at 40°C. This shows a slight variation from the general trend which is supposed to be temperature dependent. This usual behaviour is similar to the result of Giannin et al. (2010) in *P. ostreatus*, Oluwamukomi et al. (2008) in soy-melon "gari" and Diosady et al. (1996) for canola oil where there is equally a decrease in both k and c. However, the increase obtained in c and k at 40°C shows that at higher temperatures, the multilayer molecules become more entropic while the decrease in M_o is an indication that the adsorbed molecules gain kinetic energy loosening the attractive forces and thus allowing some molecules to break away from their sorption sites therefore reducing their equilibrium moisture values (Oluwamukomi et al., 2008). The rate of quality loss due to chemical changes is high above M_o of dried product. When the experimental and predicted isotherm values were compared, good fit were obtained at the range of water activity used. The mean relative percentage deviations modulus (%E) values of the experimental and predicted were less than 10%, which was an indication of goodness of fit for GAB. The %E values were 1.32, 5.39 and 3.22% at 10, 20 and 30°C and were all below 10%. The r^2 ranged from 0.980 to 0.997, showing strong correlations between the calculated and expected values.

Conclusion

From the data obtained for the mean relative percent modulus (%E) of 1.318 to 3.318, r^2 values of 0.997 to 0.998 and the SEE values of 0.07 to 0.09, there was a very good fit between the experimental moisture sorption and the predicted GAB sorption. Hence GAB model could be used to predict the sorption behavior of *P. ostreatus* mushroom at the range of water activity used in this study.

Nomenclature

a_w, water activity; **M_{exp},** the experimental moisture content; **M_{cal},** the calculated moisture content; **M_e,** equilibrium moisture content of sample (g/g db); **M_o,** monolayer moisture value in g H_20/100 g dry matter; **α,** k/M_o (1/c - 1); **β,** $1/M_o$ (1 - 2/c); **γ,** $1/M_o$ k c; **c and k,** sorption constants; **c,** constant related to thermal effects; **k,** the constant related to the properties of multilayer water molecules with respect to the bulk liquid; **r^2,** coefficient of determination; **%E,** mean relative percent deviation modulus; **SEE,** standard error of estimate.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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