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Determination of moisture adsorption isotherms of rice flour using a dynamic vapor sorption technique

Aleida J. Sandoval, José A. Barreiro and Alejandro J. Müller

SUMMARY

Moisture adsorption isotherms for rice flour were determined in a temperature range of 5 to 45°C using a dynamic vapor sorption technique. A water activity range from 0 to 0.945 was studied. Typical type-II isotherms were obtained. The equilibrium moisture content (EMC) decreased with increasing temperature over the whole water activity range studied. The EMC did not exhibit isotherm cross-over with temperature as previously reported for rice flour using thymol as an antimicrobial agent. The adsorption data obtained was fitted to various isotherm models. It was found that EMC data was better described by the modified GAB model. Moisture sorption data obtained in this study can be considered more reliable and accurate than those previously reported for this product using static gravimetric techniques since no antimicrobial agents were used during experimentation.

Introduction

Dynamic vapor sorption (DVS) techniques are currently used to determine the sorption characteristics of food products. When compared with the static gravimetric technique (SGT), extensively used as a classical method in the existing scientific literature, DVS techniques have shown many advantages, including shorter equilibration time. As a consequence, no antimicrobial agents are needed at elevated water activities to prevent microbial growth and sample deterioration during experimentation. The use of antimicrobial agents could alter isotherm performance and the reliability of the results obtained (Yu et al., 2008; Sandoval et al., 2011). Among others, DVS techniques have the advantage of allowing determination of adsorption rates under constant or varying hydration conditions with the same sample, and further calculation of apparent water diffusion coefficients, as illustrated by Román-Gutiérrez et al. (2003).

A large number of moisture sorption isotherm models have been proposed in the literature for different food products. They include those derived theoretically and based on thermodynamic considerations such as the BET (Brunauer, Emmett and Teller; Brunauer et al., 1938) and the GAB (Guggenheim-Anderson-De Boer; Van den Berg and Brüin, 1981) models; and additional semi-empirical and empirical models (Peleg, 1993; Viollaz and Rovedo, 1999). Many other empirical two-parameter isotherm models have also been proposed for different a_w ranges. Although at present there is not a unique model to accurately represent moisture sorption data in the whole range of water activity, due mainly to the complex sorption mechanisms involved, the GAB equation has been recognized as the most versatile sorption model. Quiríjns et al. (2005) underlined the GAB sorption isotherm ability to deduce the thermodynamic state of the different types of water (bound and free) in a food system, as well as the transition among them. However, it has been claimed that the GAB model does not hold on rough or irregular surfaces such as those of grains and other starchy powders, and that it is more appropriate for homogeneous planer surfaces. An isotherm describing the multilayer adsorption on fractal surfaces, based on BET theory, was presented by Aguerre et al. (1996) and successfully applied to amaranth starch by Calzetta-Resio et al. (1999). On the other hand, Viollaz and Rovedo (1999) proposed an extension of the GAB model to correlate sorption data for a_w values that include the range above 0.9, not considered in the original GAB model. This model has also been successfully applied to starchy and powdery products in our previous work (Perdomo et al., 2009; Brett et al., 2009; Barreiro et al., 2010).

Rice flour is frequently used as an ingredient in many starchy processed food products. Knowledge of the sorption characteristics of rice flour is important to establish the packaging requirements and stability of products containing this ingredient, but few papers have been found in the reviewed literature. Durakova and Menkov (2004) studied the sorption characteristics of rice flour in a temperature range of 10 to 30°C, in a water activity range of 0.11 to 0.85 that excluded elevated water activities. Sigmoidal type-II isotherms were found. Brett et al. (2009) presented...
Las isotermas de adsorción de humedad en la harina de arroz fueron determinadas en un intervalo de temperatura entre 5 y 45°C usando una técnica de sorción de humedad dinámica. Estudió un intervalo de actividad de agua entre 0 y 0,945 y se obtuvieron isotermas tipo II. En toda la extensión de actividades de agua estudada, el teor de humedad de equilibrio (CHE) disminuyó con incrementos de temperatura. Al contrario de lo reportado en estudios previos para la harina de arroz, usando timol como agente antimicrobiano, el CHE no exhibió cruze de isoterms con la temperatura. Los datos de adsorción obtenidos fueron ajustados a varios modelos de isotermas. Se encontró que los datos de CHE fueron mejor descritos por el modelo modificado de GAB. Los datos de sorción de humedad obtenidos en este trabajo pueden ser considerados más confiables y exactos que los reportados previamente para este producto usando una técnica gravimétrica estática, ya que no se usaron agentes antimicrobianos durante las determinaciones.

**Materials and Methods**

**Raw material**

Native rice flour with initial moisture content of 14.39% (w.b.), manufactured by Kel Industries (Venezuela), was provided by Alfonzo Rivas y Cia., Caracas, Venezuela. Proximate composition of this lot of rice flour (g per 100g, wet basis ±standard deviation) was determined in a previous study (Sandoval et al., 2009) and shown to be: moisture 14.39 ±0.09; protein 8.64 ±0.21; fat 0.31 ±0.00; ash 0.92 ±0.02; carbohydrates (from difference) 75.74 ±0.15.

**Adsorption isotherms**

Moisture adsorption isotherms of native rice flour were determined in a dynamic vapor sorption (DVS) apparatus. The experiments were carried out using an IGASorp moisture sorption analyzer (Hiden Isochema Ltd., UK), consisting on a controlled atmosphere microbalance, in which the relative humidity and the change in sample weight were continuously monitored. The equipment has a real time processor using IGASorp System Software V6.50.42 (Hiden Analytical Ltd.). Equilibrium relative humidity (ERH) values used to build the isotherm were defined by the user. The software determined the mixing ratio of water vapor and dry ultra high purity nitrogen required to obtain each of the desired ERH values. In this process, sample weight data were analyzed to determine kinetic parameters for the prediction of equilibrium uptake in real-time. In order to determine the whole isotherm, this process was repeated for all ERH values set. The maximum operational water activity that can be obtained in this equipment is 0.95. The equipment is able to regulate sample temperature. Results obtained were exported to an MS Excel file and plotted.

Adsorptions were obtained by adsorption by setting thirteen RH-level set (timeout) was used if the equilibrium criterion was not already reached. The equilibrium criterion for stability was defined by the time the weight had relaxed to within 1% of the equilibrium uptake. The isotherms were obtained in triplicate at temperatures of 5, 23 and 45°C.

**Adsorption data analysis**

Adsorption data obtained were adjusted to various sorp-
tion models used for starchy products: BET, Peleg, GAB and modified GAB (see Table I). The goodness of fit was evaluated by determining the correlation coefficient \( R^2 \) and the root mean square error (RMSE). For this purpose, non linear regression was carried out using Matlab™ version 6.5. The monolayer water content was estimated from the BET and GAB models.

The Clausius-Clapeyron equation (Eq. 5) was used to determine the effect of temperature on the sorption data and to calculate the net isosteric heat of sorption. Its expression is

\[
\frac{\partial \ln(a_w)}{\partial (1/T)} = \frac{q_{u}}{R}
\]

where \( T \): absolute temperature (K), \( q_{u} \): net isosteric heat of sorption (J·mol\(^{-1}\)), and \( R \): universal gas constant (8.314 J·mol\(^{-1}\)·K\(^{-1}\)).

**Results and Discussion**

The adsorption isotherms for rice flour and the error bars (± one standard deviation) for the EMC values obtained are shown in Figure 1. A sigmoidal shape characteristic of type II isotherms, based on Brunauer's classification (Brunauer et al., 1940; Al-Muhtaseb et al., 2002) was obtained. The isotherms for rice flour presented similar behavior to those of other starch-rich foods (McMinn and Magee, 1999; Al-Muhtaseb et al., 2004; Dura kova and Menkov, 2004; Brett et al., 2009; Perdomo et al., 2009).

The effect of temperature on moisture adsorption isotherms can be appreciated in Figure 1. As expected, for a given water activity, the corresponding EMC decreases with increasing temperature. This behavior has been attributed to the higher energy levels and lower stability of water molecules at higher temperatures, favoring their separation from the binding sites present in the food matrix (Palipane and Driscoll, 1992).

No cross-over was observed due to the effect of temperature, as reported by Brett et al. (2009) for this product using the SGT. These authors used thymol as an antimicrobial agent for water activities >0.80. The presence of isotherm cross-over due to the effect of temperature was attributed to the use of thymol at elevated water activities (Sandoval et al., 2011). The moisture sorption data obtained in the present work using a DVS technique can be considered more reliable and accurate than those determined by means of SGT requiring the use of antimicrobial additives at elevated water activities.

Adsorption data obtained using the DVS technique for rice flour at temperatures of 5, 23 and 45°C were fitted to the isotherm models presented in Table I. The results for the constants of the various isotherms tested, as well as the corresponding \( R^2 \) and RMSE values, are shown in Table II. Excellent fitting to the experimental data was obtained for all the models tested. However, Peleg and modified GAB models showed the best results. The modified GAB model was selected because it is able to describe the whole isotherm. This model exhibited elevated \( R^2 \) values (0.999) and low RMSE values (0.001-0.002). The modified GAB model was used to draw the isotherms shown in Figure 1. The value of constants A, B, C and D presented in Table II for the different temperatures studied were substituted in Eq. 4.

The monolayer water content calculated using the BET and GAB models is represented by constants A in Table II. The rice flour monolayer water content values in a temperature range of 5 to 45°C were lower for the BET model (0.069 to 0.055 g

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**TABLE I**

<table>
<thead>
<tr>
<th>Model</th>
<th>Mathematical expression</th>
<th>( a_w ) range of applicability</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>BET (Brunauer, Emmett and Teller, 1938)</td>
<td>( M = A \cdot B \cdot a_w/(1-a_w) \cdot (1+(B-1) \cdot a_w) )</td>
<td>&lt;0.50</td>
<td>(1)</td>
</tr>
<tr>
<td>Peleg (Peleg, 1993)</td>
<td>( M = A \cdot a_w^C + B \cdot a_w^D )</td>
<td>&lt;~0.9</td>
<td>(2)</td>
</tr>
<tr>
<td>GAB (Van den Berg and Bruin, 1981)</td>
<td>( M = \frac{A \cdot B \cdot C \cdot a_w}{(1-C \cdot a_w) \cdot (1-C \cdot a_w + B \cdot C \cdot a_w)} )</td>
<td>&lt;0.95</td>
<td>(3)</td>
</tr>
<tr>
<td>Modified GAB (Viollaz and Rovedo, 1999)</td>
<td>( M = \frac{A \cdot B \cdot C \cdot a_w^2}{(1-C \cdot a_w) \cdot (1-C \cdot a_w + B \cdot C \cdot a_w)} + \frac{A \cdot B \cdot C \cdot D \cdot a_w^2}{(1-C \cdot a_w) \cdot (1-a_w)} )</td>
<td>&lt;0.98</td>
<td>(4)</td>
</tr>
</tbody>
</table>

\( a_w \): water activity

In Eqs. 1, 3 and 4, A represents the monolayer moisture content of the BET and GAB models, respectively. B in Eqs. 1, 3 and 4, and C in Eqs. 3 and 4 are energy constants related to the temperature effect.
water/g dry solids) than for the GAB model (0.079 to 0.066g water/g dry solids). Values reported by Rahman (1995) for cereal products ranged from 0.051 to 0.086g water/g dry solids. These values are similar to those determined herein for rice flour. The value of the monolayer water content decreased with increasing temperatures regardless of the model used (Table II).

Values for the monolayer water content of rice flour have been reported by Durakova and Menkov (2004) as 0.0714-0.0680g water/g dry solids in a temperature range of 10-40°C using the BET equation. These values are in agreement with those reported in the present work (Table II). Toğrul and Arslan (2006), working with Baldo type rice, reported abnormally high monolayer water content values using the GAB model, and from 0.0937 to 0.0968kg water/kg dry solids (25-45°C) using the adsorption data with the BET model. These values are higher than those obtained in this study. Brett et al. (2009) presented monolayer water contents (5-45°C) ranging from 0.064 to 0.080g water/g dry solids when the BET equations were used. These values are of the same order of magnitude as those obtained in this work.

Monolayer water content values reported by Brett et al. (2009) using the GAB model were higher than those obtained in this study. This was probably due to EMC deviations at elevated water activities reported by these authors showing isotherm cross-over with temperature. These abnormal data were taken into account when fitting the GAB model in order to obtain the monolayer water content.

Figure 2 shows the variation of the net isosteric heat of sorption with moisture content. As expected, net isosteric heat of sorption decreased with increasing moisture content; being this relationship described by

\[ q_a = 23.38e^{-0.137MC} \quad R^2 = 0.996 \]  

with the moisture content value (MC in Eq. 6) in g/100g of dry solids.

As shown in Figure 2, the net isosteric heat of sorption varied from 0.5 to 10kJ·mol\(^{-1}\) in a moisture content range of 6 to 24% (d.b.). Durakova and Menkov (2004) reported values for rice flour (2.3-22.3kJ·mol\(^{-1}\)) in an MC range of 10-22% (d.b.); while Stripatrawan and Jantawat (2006) found values for Jasmine rice crackers of 0.1-24.9kJ·mol\(^{-1}\) in a range of moisture content of 1 to 28% (d.b.) for the isosteric heat of sorption.

**Conclusions**

Adsorption isotherms of rice flour were determined at temperatures of 5, 23 and 45°C using a dynamic sorption vapor technique. Typical type II isotherms were obtained. No isotherm cross-over with temperature was evidenced for these products as reported by other authors using thymol as antimicrobial agent. Adsorption data were better described by the modified GAB model in the whole temperature range studied, evidenced by elevated \( R^2 \) values and low RMSE values for both products. The water monolayer contents determined using BET model \((a_w<0.5)\) were similar to previous data obtained with a static technique; while those obtained from the GAB model \((a_w<0.95)\) were different, a fact attributed to the variation of moisture content values obtained when thymol is used as an antimicrobial agent at elevated water activity and particularly high temperatures. In general, moisture adsorption data of rice flour determined by the dynamic technique used in this work can be considered more accurate than those obtained in a previously reported work, where thymol was used at elevated water activities.

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