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Kinetics of Initial Water Vapor Adsorption by *Inonotus obliquus* Mushroom Powders

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Abstract

Water vapor adsorption kinetics of *Inonotus* mushroom powders were investigated in temperature and water activity ranges of 20 to 40°C and 0.30 to 0.81, respectively. Initial water vapor adsorption rate of mushroom powders increased with increases in temperature and water activity. The temperature dependency of water activity followed the Clausius-Clapeyron equation. The net isosteric heat of sorption increased with an increase in water activity. Water vapor adsorption kinetics of the mushroom powders can be well described by a simple empirical model. Temperature dependency of the reaction rate constant followed the Arrhenius relationship. The activation energy ranged from 56.86 to 91.35 kJ/mol depending on water activity. Kinetic compensation relationship was observed between k_0 and E_a with the isokinetic temperature of 790.27 K.

Key words: water vapor adsorption, kinetics, *Inonotus obliquus*, mushroom powder

INTRODUCTION

Inonotus obliquus mushroom is a black parasite fungus that grows on birch trees in colder northern climates, at latitudes of 45°N~50°N (1,2). *Inonotus* has been commonly used as a treatment for cancers and digestive system diseases without any observed side effects (3-5), and has been widely used as a folk remedy in Russia without toxicity (6). Despite its substantial increase in consumption and process applications, studies on mushroom dehydration are still scarce in the literature, and mainly focus on drying techniques (7,8) and functional properties (9-13).

Evaluation of adsorption behavior of mushroom powders is important for the development of various types of stable functional foods such as dietary supplement tablets, herbal tea blends, or powdered ingredients for formulating immune system boosting dietary supplements and natural cosmetics. Former studies on the isotherms (14) only explain the final equilibrium condition but do not explain sorption of water vapor during the process. To understand the initial adsorption behavior of the mushroom powder, adsorption curves (which are plots of weight against time at a constant relative humidity and temperature) are obtained and the rate of water adsorption is characterized.

The objectives of the present study were to provide reliable experimental data regarding initial water vapor adsorption behavior of *Inonotus* mushroom powder and to identify and test simple relationships to characterize the initial water vapor adsorption kinetics of the mushroom powder at different temperatures and water activity levels.

MATERIALS AND METHODS

Materials

Fresh *Inonotus* mushroom was obtained from the Korean Ginseng Corp. (Imported from Baikal Herb Ltd.; harvested in March 2006) and stored at room temperature before use. Samples were frozen at -45°C for 24 h in a freezer (VLT 1450-3-D-14, Thermo Electron Corp., Asheville, NC, USA) and then lyophilized using a freeze-dryer (Eyela FDU-1100, Tokyo Rikakikai Co., Tokyo, Japan) at a vacuum pressure of 8.5 Pa to a final moisture content of 3.84% (w.b.).

Lyophilized mushrooms were broken into small pieces and milled using an analytical mill (DA-282, Daesung Artron Co., Ltd., Paju, Korea) and screened through different particle size sieves (D-55743, FRITSCH, Idar-Oberstein, Germany) to yield particle sizes of 150~250 μm. Powdered samples were placed in a polyethylene bag prior to measurements. Moisture contents of fresh and dehydrated *Inonotus* mushrooms were determined by drying in a convectional oven at 105°C for overnight (15).

Water vapor adsorption behavior

Accurately weighed samples of mushroom powder

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were stored in individual desiccators maintained at three water activity levels ranging from 0.30 to 0.81 and three temperature levels (20, 30, and 40°C). The relative humidities were prepared by using saturated-salt aqueous solutions of $MgCl_2$, NaBr, and NaCl, respectively. The weight changes of the samples were monitored at 10 min intervals for first 60 min and at 20 min intervals thereafter for up to 120 min. All measurements were done in triplicate.

Water activity measurement

Water activity inside each desiccator after attaining equilibrium with each saturated salt solution at each temperature was determined using a Thermo Recorder (TR-72U, T&D Corp., Matsumoto city, Nagano, Japan). Temperature dependency of water activity was tested using the Clausius-Clapeyron equation as follows:

$$\frac{d\ln a_w}{d(1/T)} = \frac{-\Delta H}{R} \tag{1}$$

where a_w is the water activity, T is the absolute temperature (K), ΔH is net isosteric heat of sorption (kJ/mol), and R is the universal gas constant (8.314 J/mol K).

Data analysis

Water vapor adsorption curves of each sample were obtained by plotting moisture increase (M, g H_2O/g dry solid) against adsorption time (min). Plotting the inverse of M against inverse of time gave a straight line and the reaction rate constant was calculated by taking inverse of the slope value.

Temperature dependency of water vapor adsorption rate was tested using the following Arrhenius equation:

$$k = k_0 \exp(-E_a/RT) \tag{2}$$

where k_0 is a pre-exponential factor and E_a is the activation energy.

Table 1. Water activity values of saturated salt solutions at different temperatures

Saturated salt solution	Water activity			ΔH[1]
	20°C	30°C	40°C	(kJ/mol)
$MgCl_2$	0.33	0.31	0.30	3.65
NaBr	0.59	0.55	0.52	4.82
NaCl	0.81	0.73	0.70	5.59

[1]Net isosteric heat of sorption.

RESULTS AND DISCUSSION

Water activity of saturated salt solutions

Water activity values and net isosteric heat of sorptions for the saturated salt solutions are summarized in Table 1. The water activity values of saturated salt solutions decreased with an increase in temperature. The temperature dependency of water activity followed the Clausius-Clapeyron equation. The net isosteric heat of sorption increased with an increase in water activity. The values for saturated salt solutions of $MgCl_2$, NaBr, and NaCl were 3.65, 4.82, and 5.59 kJ/mol, respectively.

Water vapor sorption curves

Water vapor adsorption behaviors of *Inonutus* mushroom powder at different temperatures and water activities are shown in Fig. 1. The rapid initial moisture sorptions, due to the filling capillaries of the surface of the mushroom powder (16,17), were observed from the curves. The maximum attainable water vapor adsorption of mushroom powder is influenced by species of the mushroom and water activities tested. The maximum increases in weight due to water vapor adsorption by the mushroom powder were 0.027, 0.042, and 0.048 g at water activities attained by $MgCl_2$, NaBr, and NaCl, respectively. The sorption curves also indicated that the amount of water vapor adsorbed increased with the increases in temperature and water activity. Similar findings were reported for soybeans (17), chitosan films (18), soy protein films (19), and sweet potato starch-based edible films (20).

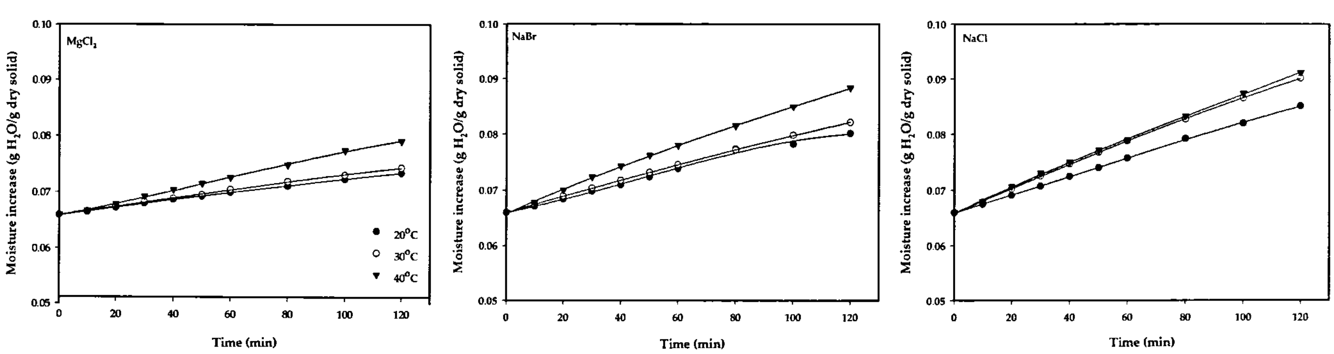

Fig. 1. Water vapor adsorption behaviors of *Inonotus* mushroom powders at different temperatures and water activities.

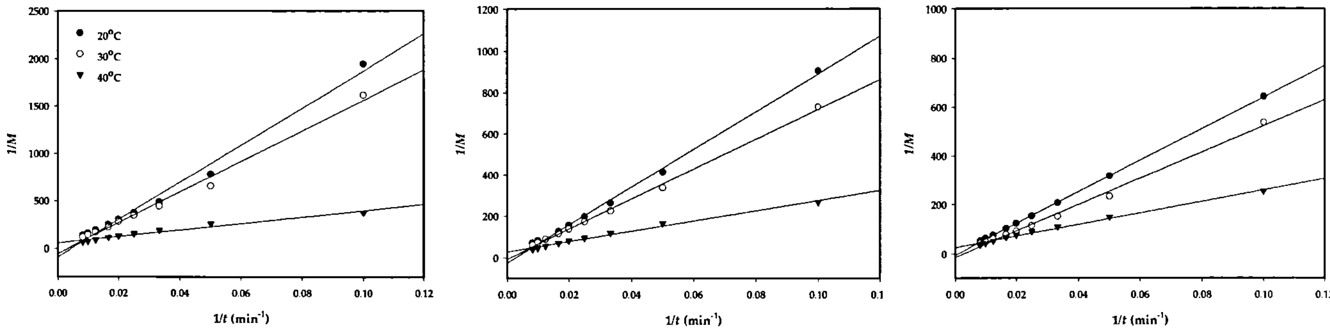

Fig. 2. Adsorption kinetics of *Inonotus* mushroom powders determined at different temperatures and water activities.

Table 2. Reaction rate constants for water vapor adsorption of *Inonotus* mushroom powders

Saturated salt solutions	Temp (°C)	k ($\times10^{-3}$ g H_2O/g dry solid/min)	R^2
	20	0.051	0.988
$MgCl_2$	30	0.062	0.990
	40	0.295	0.963
	20	0.109	0.998
NaBr	30	0.138	0.998
	40	0.408	0.997
	20	0.155	1.000
NaCl	30	0.186	0.995
	40	0.427	0.993

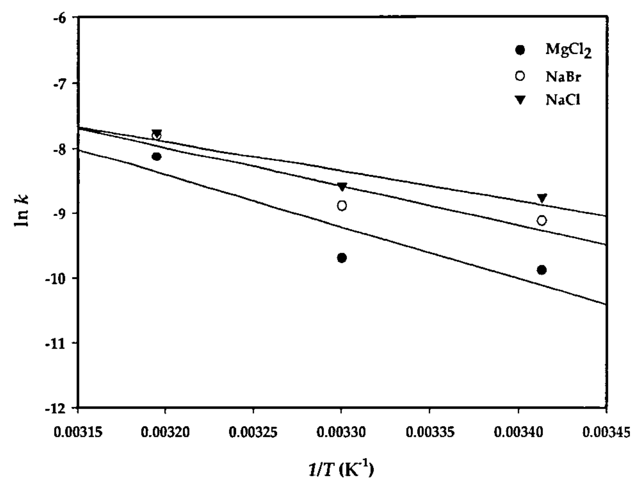

Fig. 3. Temperature dependency of water vapor adsorption of *Inonotus* mushroom powders at different water activities.

Table 3. Kinetic parameters for water vapor adsorption of *Inonotus* mushroom powders

Saturated salt solutions	k_o (g H_2O/g dry solid/min)	E_a (kJ/mol)	R^2
$MgCl_2$	5.915×10^4	91.35	0.831
NaBr	7.089×10^4	92.86	0.865
NaCl	3.031×10^2	56.86	0.866

Water vapor adsorption rate

The inverse of M against inverse of t was plotted for each condition and presented in Fig. 2. Good straight lines were obtained as indicated by high R^2-values. Water vapor adsorption rates were determined by taking the inverse of the slope value of the straight lines and summarized in Table 2. Reaction rate constant increased with an increase in temperature and water activity, which is in good agreement with the findings of Kim and Rhim (20).

Fig. 2 shows the temperature dependency of water vapor adsorption rate of *Inonutus* mushroom powders. Good linear relationships were observed, indicating that the Arrhenius model is appropriate to describe the temperature dependency of the water vapor adsorption rate of mushroom powders. Simple linear regression analysis was further conducted using the Arrhenius plot (Fig. 3) to calculate the kinetic parameters and the results are presented in Table 3. The activation energy ranged from 56.86 to 91.35 kJ/mol depending on water activity. The values are within the range of those reported for the hydration of food stuffs (16,17,21). The activation energy in the middle range of water activity [NaBr] was higher than those of lower and higher ranges of water activity. This indicates that the rate of water vapor sorption by the mushroom powder is more temperature sensitive at the middle range of water activity. Similar observation was made in sweet potato starch-based edible films (20).

Numerical values of kinetic parameters are affected by reaction conditions and those two parameters (k_0 and E_a) are generally related linearly, which is known as a kinetic compensation effect (22). Fig. 4 shows the linear relationship between k_0 and E_a for water vapor adsorption rates of mushroom powder. The following linear relationship was obtained from linear regression analysis:

$$\ln k_0 = 0.1522E_a - 2.9366 \quad (R^2 = 0.99) \tag{3}$$

The isokinetic temperature for water vapor adsorption was found to be 790.27 K which is bit higher than values reported for some selected protein and starch foods (23). Nevertheless, the high degree of linear correlation verified the validity of compensation theory.

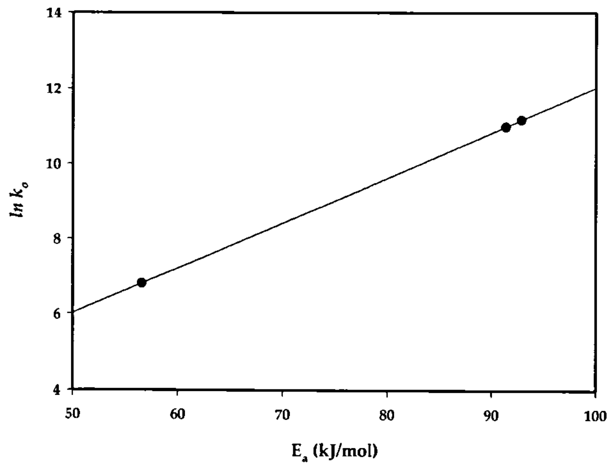

Fig. 4. Kinetic compensation effect of water vapor adsorption of *Inonotus* mushroom powders.

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