Mass transfer characteristics during ultrasound-assisted osmotic dehydration of button mushroom (*Agaricus bisporus*)

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Abstract Button mushroom (*Agaricus bisporus*) slices were dehydrated using ultrasound-assisted osmotic dehydration (UOD), and three osmotic agents including sucrose, glucose and sodium chloride were investigated for their effects on the mass transfer characteristics, average density and microstructure. Different mathematical models were selected to describe the osmotic behaviours, and the effective moisture (D_m) as well as solid diffusivities (D_s) during UOD were also calculated. The results showed that, during UOD, button mushrooms had the highest D_m values in the sodium chloride solutions, and they had the highest D_s values in the glucose solutions, which indicated that faster moisture and solid transfers could occur in these two osmotic solutions, respectively. Moreover, the Weibull model provided the best fit for the UOD curves of button mushrooms under the study's operating conditions, which showed good predictability for the moisture and solid contents of the button mushrooms during UOD. In addition, sucrose agents were suggested for use in the UOD of button mushrooms due to the better microstructure of the products as well as the appropriate rates of effective

moisture and solid diffusivities during UOD. This study provides a theoretical basis for the deep processing of mushrooms and other food products.

Keywords Button mushrooms · Ultrasound-assisted osmotic dehydration · Mass transfer · Water loss · Solid gain · Microstructure

Introduction

Button mushroom (*Agaricus Bisporus*) is one of the most popular edible mushrooms around the world due to its high nutritional value (Mattila et al. 2001; Walton et al. 1998). However, the button mushroom has only a short shelf-life of just a few days due to its high moisture content and high respiration rate (Fito et al. 2001; Jiang et al. 2011). Ultrasound-assisted osmotic dehydration (UOD) is one of the most common pretreatment processes that can effectively enhance the shelf life of fruits and vegetables. Osmosis depends upon the phenomenon of moisture diffusion from food materials by immersion in a hypertonic solution (Ahmed et al. 2016). Meanwhile, the sponge-like effect (Kapturowska et al. 2011) and cavitation effect (Fan et al. 2008; Fernandes et al. 2009), which are caused by ultrasound, can improve the mass transfer efficiency during the osmotic dehydration.

The type of osmotic agent and the concentration of the osmotic solution are two main variables that influence the mass transfer characteristics during UOD (Ertekin and Cakaloğlu 1996). The osmotic agent should be harmless and have a good taste which could not only reduce the moisture load but also enhance the nutritional value and sensory characteristics after osmotic treatment (Chandra and Kumari 2015). Sucrose, glucose and sodium chloride are

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the three most commonly used osmotic agents for fruits and vegetables during osmotic treatment. Lenart and Flink (2010) studied the osmosis spatial distribution curves of sucrose and sodium chloride solutions during osmotic treatment, and they found that sucrose accumulated around the surface of the tissue, which hindered the mass transfer during osmotic treatment, but sodium chloride penetrated the tissue to a much greater depth and had less impact on the mass transfer. In general, the rates of water loss and solid gain increased with an increase in the osmotic solution concentration (Ahmed et al. 2016). Nevertheless, an exorbitant concentration of the osmotic solution decreased the rate of mass transfer due to its high viscosity (Ganjloo et al. 2012). According to van't Hoff's law, the osmotic pressure difference is proportional to the ion concentrations between the hypertonic solution and cells during osmotic treatment (Zhao et al. 2003). Therefore, the concentration of the solution was usually no more than 60% (sugar) or 25% (salt). For example, Deng and Zhao (2008) and Herman-Lara et al. (2013) studied apple and radish osmotic processes, respectively, and 60% high-fructose corn syrup and 25% sodium chloride solutions, respectively, were applied in their studies.

Osmotic kinetics is typically accustomed to analyzing the microscopic mechanisms of mass transfer during OD. However, many factors might influence osmotic kinetics such as the osmotic methods, conditions and agents. More recently, studies have focused on empirical models to define the proper conditions in osmotic treatment. Corrêa et al. (2016) studied the mass transfer characteristics of tomatoes and demonstrated that the Fito and Chiralt (1997) model provided a better fit to the experimental data of the OD processes, and the mass exchange rate of tomatoes was also improved due to the OD process in a ternary solution. Corzo and Bracho (2008) also investigated the Weibull frequency distribution model for predicting the moisture and salt contents of sardine sheets during vacuum pulse osmotic dehydration using brine at different concentrations. However, there is no information available about the differences among the osmotic agents, which could significantly influence the mass transfer efficiency and quality of food products.

The overall purpose of the study was to investigate and compare the differences among the three most commonly used osmotic agents (sucrose, glucose and sodium chloride) on the mass transfer characteristics, average density and microstructure of button mushrooms during UOD. Several empirical models were selected to describe and predict the water loss (WL) and solid gain (SG) of samples, and the effective diffusivities of samples during UOD were also calculated and compared.

Materials and methods

Sample preparation

Fresh button mushrooms were obtained from a local market (Nanjing, China) with an initial moisture content of $92.93 \pm 0.12\%$ (w.b.). Prior to UOD, the button mushrooms were washed, stems removed and sliced to a thickness of 5 mm with a mushroom slicer (MSC International Co., Montreal, Canada).

Osmotic processing

The osmotic solutions were prepared using different concentrations of glucose (40%, 50% and 60% w/w), sucrose (40%, 50%, 60% w/w) and sodium chloride (10%, 15%, 20% w/w) with distilled water, respectively. UOD pretreatments were carried out in an ultrasound generator (SB 25-12 DTDN, Ningbo Xinzhi Ningbo Bio-Technique Co. Ltd., China). For each pretreatment, a 10 g mushroom sample was weighed and placed in osmotic solution at 30 °C for 75 min. The ultrasound frequency was 40 kHz and the ultrasound power was 200 W to avoid increases in the solution temperature. The ratio of mushrooms to osmotic solution was 1:10 (w/w) in order to avoid the influence of the changes in the solution concentration during osmotic treatment. During UOD, samples were randomly removed at 15, 30, 45, 60 and 75 min for analysis after washing the osmotic agents and removing the moisture from the surface with absorbent paper. The water loss (WL) and solid gain (SG) of the samples were evaluated using the following equations:

$$WL = \frac{M_0 X_0 - M_t X_t}{M_0} \times 100\% \quad (1)$$

$$SG = \frac{M_t S_t - M_0 S_0}{M_0} \times 100\% \quad (2)$$

where M_0 and M_t are the initial weight of the sample (g) and the weight of the sample at time t (g), respectively, X_0 and X_t are the initial moisture content (g/100 g) and the moisture content at time t (g/100 g), respectively, and S_0 and S_t are initial solid content (g/100 g) and the solid content at time t (g/100 g), respectively.

Determination of diffusion coefficients

The moisture ratio (MR) and solid ratio (SR) of the button mushroom slices were calculated using Eqs. (3) and (4), respectively (Doymaz and İsmail 2011):

$$MR = \frac{M_t - M_e}{M_0 - M_e} = \frac{WL - WL_e}{WL_e} \quad (3)$$

$$SR = \frac{S_t - S_e}{S_0 - S_e} = \frac{SG - SG_e}{SG_e} \quad (4)$$

where M_e and S_e are the equilibrium moisture and solid content and WL_e and SG_e are the WL and SG when the UOD processes are in equilibrium.

Azuara et al. (1998) had put forward models for calculating the WL_e and SG_e , as follows:

$$WL = \frac{S_1 \cdot t \cdot WL_e}{1 + S_1 \cdot t} \quad (5)$$

$$SG = \frac{S_2 \cdot t \cdot SG_e}{1 + S_2 \cdot t} \quad (6)$$

where S_1 and S_2 are rate constants of Eqs. (5) and (6), respectively, and t is the time of UOD. When taking the reciprocal of both sides, Eqs. (5) and (6) could be expressed as Eqs. (7) and (8), respectively:

$$\frac{1}{WL} = \frac{1}{S_1 \cdot t \cdot WL_e} + \frac{1}{WL_e} \quad (7)$$

$$\frac{1}{SG} = \frac{1}{S_2 \cdot t \cdot SG_e} + \frac{1}{SG_e} \quad (8)$$

It can be seen that the relationship between $1/WL$ and $1/t$ is linear and the same as $1/SG$ and $1/t$. This observation indicates that WL_e and SG_e could be obtained by linear regression.

Mass transfer kinetics during the OD treatment have been successfully and widely modelled using Fick's second law of diffusion (Chenlo et al. 2006):

$$MR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(-\frac{(2n+1)^2 \pi^2 D_m t}{4L^2}\right) \quad (9)$$

$$SR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(-\frac{(2n+1)^2 \pi^2 D_s t}{4L^2}\right) \quad (10)$$

where D_m and D_s are the effective moisture and solid diffusivity ($\text{m}^2 \text{s}^{-1}$), respectively, n is a positive integer, t is the UOD time (s) and L is the half-thickness of the slab in samples (m). For long osmotic periods, Eqs. (9) and (10) can be written in more simplified forms as Eqs. (11) and (12), respectively:

$$MR = \frac{8}{\pi^2} \exp\left(-\frac{\pi^2 D_m t}{4L^2}\right) \quad (11)$$

$$SR = \frac{8}{\pi^2} \exp\left(-\frac{\pi^2 D_s t}{4L^2}\right) \quad (12)$$

Mathematical modelling

The OD curves were fitted with three well-known mathematical models based on previous studies (İspir and Toğrul

2009; Nuñez-Mancilla et al. 2011), namely, Newton [Eq. (13)], Henderson and Pabis [Eq. (14)], and Weibull [Eq. (15)], respectively:

$$MR = \exp(-k_1 \cdot t) \quad (13)$$

$$MR = a \cdot \exp(-k_2 \cdot t) \quad (14)$$

$$MR = \exp\left(-\left(\frac{t}{\beta}\right)^\alpha\right) \quad (15)$$

where k_1 and k_2 are the kinetics parameters, a is the constant parameter of the Henderson and Pabis model, and α and β are the shape and scale parameters of the Weibull model, respectively.

The statistical software, 1stOpt V1.5, was used to conduct a non-linear regression analysis. The coefficient of determination (R^2), reduced Chi square (χ^2) and root mean square error (RMSE) analyses were used to evaluate the goodness of fit and were calculated in this study by using the following equations:

$$R^2 = 1 - \frac{\sum_{i=1}^N (MR_{\text{exp},i} - MR_{\text{pre},i})^2}{\sum_{i=1}^N (MR_{\text{exp},i} - \overline{MR_{\text{pre},i}})^2} \quad (16)$$

$$\chi^2 = \frac{\sum_{i=1}^N (MR_{\text{exp},i} - MR_{\text{pre},i})^2}{N - z} \quad (17)$$

$$\text{RMSE} = \left[\frac{1}{N} \sum_{i=1}^N (MR_{\text{pre},i} - MR_{\text{exp},i})^2 \right]^{\frac{1}{2}} \quad (18)$$

Average density determination

The average density could reflect the degree of shrinkage of the sample during osmotic processes, and it was determined by means of quartz replacement. The diameters of quartz sand were 0.3–0.7 mm, and the average densities were calculated using Eq. (19).

$$\rho = \frac{m}{V} \quad (19)$$

where ρ is the average density (g/cm^3), m is the mass of the sample after osmotic pretreatment (g), and V is the volume of sample after osmotic pretreatment (cm^3).

Microstructure

To evaluate the interior structure of the sample during different osmotic processes, the mushroom slices were frozen at -30°C after the osmotic treatments and freeze-dried by a freeze dryer (Labconco Equipment Co.). Then the dried samples were cut into $5 \times 1 \times 1$ mm and observed by a scanning electron microscope (TM3000, Hitachi Co, Ltd., Tokyo, Japan).

Data analysis

The experimental data were analysed using the statistical software, PASW statistic 18. Comparison between the indices relative to different treatments were conducted by ANOVA, and a significance difference was defined when $p < 0.05$. The least significant difference was used for multiple range tests and to compare means. All analyses were conducted in triplicate.

Results and discussion

Kinetic characteristics of mass transfer

The OD processes could be influenced by many factors, and different osmotic solutions might play important roles in the kinetic characteristics of mass transfer during the OD processes. Figure 1 shows the changes in water loss and solid gain with different osmotic solutions during UOD. It seems clear that the water loss and solid gain of the

Fig. 1 Water loss (WL) and solid gain (SG) curves of *Agaricus bisporus* during ultrasound-assisted osmotic dehydration with different solution concentrations of sucrose (a and d, respectively), glucose (b and e, respectively), and sodium chloride (c and f, respectively)

Table 1 S_1 , S_2 , WL_e , SG_e and effective diffusion coefficients of *Agaricus bisporus* during ultrasound-assisted osmotic dehydration

Solution	Concentration (%)	$S_1 (\times 10^{-3})$	WL_e	$S_2 (\times 10^{-3})$	SG_e	$D_m \times 10^{-10} (m^2/s)$	$D_s \times 10^{-10} (m^2/s)$
Sucrose	40	0.588	0.708	0.425	0.056	6.41	4.91
	50	0.700	0.716	0.463	0.060	7.17	5.11
	60	0.802	0.728	0.508	0.061	7.76	5.51
Glucose	40	0.671	0.652	1.299	0.045	7.03	10.38
	50	0.739	0.696	1.303	0.052	7.42	10.41
	60	0.997	0.704	1.449	0.054	9.08	11.11
Sodium chloride	10	1.864	0.591	0.599	0.043	12.91	6.11
	15	2.677	0.633	0.625	0.051	15.46	6.45
	20	4.680	0.649	0.644	0.058	19.48	6.67

mushrooms first significantly increased ($p < 0.05$) and then levelled out during the OD processes. This finding could be due to the high osmotic pressure between the hypertonic solution and cell, which caused the water and solid to diffuse through the cell (Rastogi et al. 2002). Moreover, for a certain kind of osmotic solution, the rates of water loss and solid gain increased with increasing concentrations of the osmotic solution. Comparable results were also reported by Sareban and Souraki (2016) when working with celery stalks in salt solution during OD. This result was because the higher solution concentration caused higher concentration gradients between, into and out of cells, which might have led to the rates of water loss and solid gain increasing (Jokic et al. 2007). In addition, there were no significant differences ($p > 0.05$) in the water loss and solid gain of the mushroom during osmotic dehydration between 60 and 75 min. This result showed that the osmotic pressure between the hypertonic solution and cells reached equilibrium at this time.

The statistical software, 1stOpt V1.5, was used to perform the non-linear regression analysis, and the values of S_1 , S_2 , WL_e , and SG_e of samples during UOD with different solutions were obtained, as shown in Table 1. It appears that the values of S_1 , S_2 , WL_e , and SG_e increased when the solution concentration increased which means that a high solution concentration led to faster spreading velocity and more efficient OD processing. It should be noted that higher values of S_1 and WL_e did not correspond with higher values of S_2 and SG_e . Specifically, the S_1 values of the sodium chloride solutions ($1.864\text{--}4.680 \times 10^{-3}$) were highest, followed by the glucose solutions ($0.671\text{--}0.997 \times 10^{-3}$), and the lowest S_1 values were sucrose ($0.588\text{--}0.802 \times 10^{-3}$). This finding meant that the fastest rate of water loss occurred in the sodium chloride solutions, and the slowest rate occurred in the sucrose solution. This phenomenon might likely be due to the ionization of sodium chloride to increase the osmotic pressure between the hypertonic solution and cells (Zhao et al. 2003). However, the S_2 values of the glucose

solutions ($1.299\text{--}1.449 \times 10^{-3}$) were highest, followed by the sodium chloride ($0.599\text{--}0.644 \times 10^{-3}$) and sucrose solutions ($0.425\text{--}0.508 \times 10^{-3}$), which indicated that the solid gain rates of sucrose and sodium chloride solutions were slower than those of the glucose solutions. This result also indicated that the sample shrinkage that occurred in sodium chloride solutions, caused by a high rate of water loss, might decrease the rate of solid gain (Rastogi et al. 2000). Moreover, it was expected that the microscopic channels in cells, created by the ultrasound treatment would make glucose diffusion into cells easier due to its lower molecular weight (Panagiotou et al. 1999).

Effects of different osmotic solutions on the effective moisture and solid diffusivities

The effective moisture and solid diffusivities (D_m and D_s , respectively) are dependent on several factors such as the moisture content, temperature, degree of shrinkage of food materials and osmotic environment (Seth and Sarkar 2004). The values of D_m and D_s under different osmotic conditions, obtained by Eqs. (11) and (12), respectively, are presented in Table 1. It can be seen that the D_m and D_s values ranged from 7.03 to $19.48 \times 10^{-10} m^2/s$ and 4.91 to $11.11 \times 10^{-10} m^2/s$ during UOD. These values of diffusivities corresponded with the results of literatures on apples (D_s and D_m were $0.31\text{--}0.69 \times 10^{-9} m^2/s$ and $0.35\text{--}0.50 \times 10^{-9} m^2/s$, respectively) (Parniakov et al. 2016) and tomatoes (D_s and D_m were $1.21 \times 10^{-10} m^2/s$ and $4.08 \times 10^{-10} m^2/s$, respectively) (Corrêa et al. 2016) during OD. As expected, the D_m and D_s values of mushrooms increased as the solution concentration increased, which again seemed to suggest that the higher solution concentration of the UOD had a faster mass transfer efficiency. This phenomenon could be due to an increase in the osmotic pressure gradient, which improved the rate of mass transfer during UOD and changed the porosity and cell permeabilization (İspir and Toğrul 2009; Rastogi and Ksms 1997).

Table 2 Coefficients of different models for moisture transfer and solid transfer of *Agaricus bisporus* during ultrasound-assisted osmotic dehydration

Mass transfer	Models	Coefficients	Sucrose			Glucose			Sodium chloride		
			40%	50%	60%	40%	50%	60%	10%	15%	20%
Moisture transfer	Lewis (Newton)	k	0.0003496	0.0003969	0.0004398	0.000385	0.0004129	0.000516	0.0008334	0.001099	0.001642
		R ²	0.9875	0.9771	0.9523	0.9833	0.9693	0.9829	0.9986	0.9826	0.9493
		RMSE	0.0545	0.06519	0.0756	0.06062	0.06927	0.07259	0.07435	0.06791	0.05058
		χ^2	0.02024	0.03363	0.0518	0.02801	0.03898	0.05734	0.1202	0.1492	0.1561
		α	0.8011	0.7515	0.7057	0.7697	0.7328	0.6718	0.5091	0.4177	0.2836
	Henderson and Pabis	k	0.0002557	0.0002696	0.0002771	0.0002699	0.0002722	0.000316	0.0003909	0.0004318	0.0004815
		R ²	0.9752	0.9542	0.913	0.9659	0.9433	0.9491	0.9567	0.9713	0.9571
		RMSE	0.02143	0.02793	0.03687	0.02467	0.03049	0.02768	0.02015	0.01359	0.01129
		χ^2	0.00337	0.005901	0.01055	0.004833	0.006696	0.007709	0.006178	0.004420	0.004892
		α	0.6839	0.6372	0.5960	0.6578	0.6204	0.5944	0.5138	0.4719	0.4052
Solid transfer	Weibull	β	2989	2547	2221	2646	2417	1784	892	573	255
		R ²	0.9902	0.9806	0.9553	0.9856	0.9738	0.9789	0.988	0.9921	0.9833
		RMSE	0.01336	0.018	0.02616	0.01589	0.02055	0.01757	0.01041	0.006973	0.006887
		χ^2	0.001328	0.002429	0.005148	0.002034	0.002928	0.003122	0.001559	0.001271	0.00189
		k	0.0002778	0.0002895	0.0003142	0.0006473	0.0006468	0.0006936	0.000353	0.0003665	0.0003752
	Lewis (Newton)	R ²	0.9458	0.9483	0.9613	0.9346	0.953	0.9699	0.8667	0.9156	0.9448
		RMSE	0.05463	0.05817	0.06912	0.08468	0.816	0.08016	0.08492	0.07617	0.07133
		χ^2	0.01812	0.02092	0.0313	0.1106	0.104	0.1101	0.0515	0.04403	0.03908
		α	0.8487	0.8284	0.7899	0.5781	0.5868	0.5634	0.7344	0.7486	0.7516
		k	0.0002131	0.0002144	0.0002196	0.0003342	0.0003422	0.0003534	0.0002212	0.000241	0.0002505
	Henderson and Pabis	R ²	0.9317	0.9313	0.896	0.8525	0.8776	0.8967	0.8201	0.8781	0.9129
		RMSE	0.03519	0.03459	0.04128	0.04217	0.03881	0.03425	0.05249	0.04454	0.03791
		χ^2	0.007487	0.00732	0.01021	0.01851	0.01738	0.01457	0.01654	0.01337	0.009954
		α	0.7047	0.6784	0.6314	0.5293	0.5395	0.5297	0.5751	0.6070	0.6194
		β	4011	3851	3527	1284	1293	1166	3057	2867	2763
	Weibull	R ²	0.9534	0.9576	0.9387	0.9147	0.9323	0.9477	0.8855	0.9265	0.9529
		RMSE	0.02901	0.02705	0.03153	0.03163	0.02840	0.02397	0.04165	0.03434	0.02766
		χ^2	0.004971	0.004418	0.005843	0.009962	0.009084	0.00695	0.01011	0.007808	0.005182

Fig. 2 Comparison of experimental data and predicted data for moisture and solid ratio (*MR* and *SR*, respectively) of *Agaricus bisporus* during ultrasound-assisted osmotic dehydration with

different solution concentrations of sucrose (**a** and **d**, respectively), glucose (**b** and **e**, respectively), and sodium chloride (**c** and **f**, respectively)

Moreover, the sodium chloride solutions showed the best moisture transfer efficiency during the UOD ($12.91\text{--}19.48 \times 10^{-10} \text{ m}^2/\text{s}$ for D_m), followed by the glucose solutions ($7.03\text{--}9.08 \times 10^{-10} \text{ m}^2/\text{s}$ for D_m) and sucrose solutions ($6.41\text{--}7.76 \times 10^{-10} \text{ m}^2/\text{s}$ for D_m). Thus, the sodium chloride showed a faster rate for decreasing moisture compared to the other osmotic agents. However, the glucose solutions demonstrated the best solid transfer efficiency, and the D_s values ($10.38\text{--}11.11 \times 10^{-10} \text{ m}^2/\text{s}$) were much higher than for sodium chloride ($6.11\text{--}6.67 \times 10^{-10} \text{ m}^2/\text{s}$) and sucrose solutions

($4.91\text{--}5.51 \times 10^{-10} \text{ m}^2/\text{s}$), which indicated that the solid gain rates of the button mushrooms were highest during UOD in the glucose solutions. The trends of D_s and D_m values corresponded with the S_1 , S_2 , WL_e , and SG_e coefficients during UOD with the different solutions.

Statistical analysis of the models

The moisture loss and solid gain data under different UOD conditions were converted to the moisture ratio (*MR*), and then curves of the *MR* verses-drying time (*t*) were fitted

with Lewis (Newton), Henderson and Pabis, and Weibull models, respectively, as shown in Table 2. It appears that the Weibull model gave the highest R^2 (0.9553–0.9902) as well as lowest RMSE (0.006887–0.02616) and χ^2 values (0.001271–0.005148) among these models (Table 2). These results indicated that the Weibull model gave the best fit for describing the water loss of the mushrooms during UOD. Likewise, the Weibull model also provided the best fit for the solid gain changes of the mushrooms during UOD as indicated in Table 2. Figure 2 shows the comparison between the predicted values from Eq. (15) and actual values for the UOD products under the experimental conditions. It could be seen that the actual values were very similar to the predicted values based on the Weibull model. Comparable studies were also reported by Corzo and Bracho (2008) and Nuñez-Mancilla et al. (2011) when the OD processes were performed on sardine sheets and strawberries, respectively, and the Weibull models were found to fit for describing the mass transfer during the OD processes.

The parameters α and β which could be considered to be the shape and scale parameters of the Weibull model would be helpful to further analyse different UOD processes. The scale parameter β could be defined as the rate of the mass uptake process, and it represents the time required to accomplish approximately 63% of the mass uptake/water loss process and depends on the process mechanism (Moreira et al. 2008). For water loss processes of osmotic solutions, the sucrose solutions gave the highest β values (2221–2989 s), followed by the glucose solutions (1784–2646 s), and the sodium chloride solutions provided the lowest values (255–892 s). This finding implied that the rate of water loss in the sodium chloride was faster than those in the sucrose and glucose solutions. By the same token, compared to sodium chloride and sucrose solutions, the glucose solutions yielded the lowest β values (1166–1293 s) for the solid gain of the osmotic solutions, indicating that a higher velocity of solid gain in the mushrooms could be operated in glucose solutions.

Average density and microstructure

The average densities of samples after the ultrasound-assisted osmotic dehydration are shown in Fig. 3. With the increase in the osmotic concentration, the average densities of mushrooms increased as well. The average densities of mushrooms in 10% sodium chloride solution, 40% sucrose solution and 40% glucose solution were significantly lower ($p < 0.05$) than the mushrooms in higher osmotic concentrations. This phenomenon could be due to the higher concentration of osmotic solution causing the solute to easily infiltrate into the tissue during UOD. Moreover, there was no significant difference ($p > 0.05$) in the

Fig. 3 The average density of mushrooms after the ultrasound-assisted osmotic dehydration. Values not sharing the same superscript are significant ($p < 0.05$)

average density of mushrooms between 15 and 20% sodium chloride solution, 50% and 60% sucrose solution, 50% and 60% glucose solution, respectively. This finding means that the effect of the average density of mushrooms with a high osmotic concentration showed no difference.

Figure 4 shows the microstructures of the fresh samples and the different osmotic samples. Compared to the fresh samples, the micrographs of samples with osmotic treatments (Fig. 4b–d) showed different degrees of damage in their tissues. This observation could be due to the water loss and solid gain occurring through the cells during UOD (Khin et al. 2007). The samples undergoing osmosis in sodium chloride solutions presented the worst damage. This result conformed to the earlier work performed in this study, which means that the higher rate of water loss that occurred in osmotic treatments with sodium chloride could lead to severe shrinkage and higher average densities. Moreover, there were similar internal pore structures between the glucose (Fig. 4e–g) and sucrose (Fig. 4h–j) treatments, and this further proved that similar deformation happened in these osmotic treatments and resulted in no differences in the average densities among these samples (Fig. 3).

Taken together, the sucrose agents were recommended for use in the UOD of button mushrooms, although glucose and sodium chloride displayed better capacities for increasing the solid gain and water loss, respectively, based on the data. The results demonstrated that the samples undergoing osmosis in sodium chloride solutions presented more shrinkage compared to those in the other solutions which might be due to the higher rate of water loss. Meanwhile, the solid gain in sucrose was lower than those in glucose (Fig. 1) which indicated that the solid contents

Fig. 4 The microstructure of mushrooms after the ultrasound-assisted osmotic dehydration. **a** non-osmotic treatment; **b–d** 10%, 15%, 20% w/w concentrations of sodium chloride, respectively; **e–**

g 40%, 50% and 60% w/w concentrations of sucrose, respectively; **h–j** 40%, 50% and 60% w/w concentrations of sucrose, respectively

of the final products during UOD in sucrose solutions were lower.

Conclusion

In this study, three osmotic solutions, including sucrose, glucose and sodium chloride, were applied for the button mushroom UOD process, and the mass transfer characteristics, average density and microstructure of the samples were measured and compared. Based on the findings of this experiment, all three osmotic agents (sucrose, glucose and

sodium chloride) had a significant effect on the mass transfer of button mushrooms during UOD. According to the statistical tests, the button mushrooms had the highest effective moisture and solid diffusivities in the sodium chloride and glucose solutions during UOD, respectively. Meanwhile, the Weibull model provided the best fit for the button mushroom dehydration during UOD due to its higher coefficient of determination (R^2), lower reduced Chi square (χ^2) and root mean square error (RMSE) values. Moreover, due to appropriate rates of effective moisture and solid diffusivities, better microstructure and relatively lower solid gain, the sucrose agents were considered and

recommended for use in the UOD of button mushrooms, which can be widely applied industrially.

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