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Mathematical Modeling of Hot Air Drying Kinetics of *Momordica charantia* Slices and Its Color Change

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Abstract: This study presented the drying characteristics of fresh *Momordica charantia* slices at different drying temperatures (50, 60, 70 and 80°C) and different thicknesses (0.5, 0.75 and 1.0 cm). Three mathematical models including Page, Henderson and Pabis and Wang and Singh equations were compared and discussed. The results showed that the Page model provided the best correlation capacity with the decision coefficient R^2 of 0.998. The color change of *Momordica charantia* slices during hot air drying at different temperatures were also studied by the measuring of color parameters such as the values of Hunter L^* (whiteness/darkness), a^* (redness/greenness) and b^* (yellowness/blueness). The total color change (ΔE) of the samples was observed to increase as drying temperature increased. The results show that the color of *Momordica charantia* slices changed sharply when temperature was higher than about 70°C. The study could provide theoretical bases of the equipment design and process optimization for hot air drying of *Momordica charantia*.

Keywords: Color change, hot air drying, mathematical modeling, *Momordica charantia*

INTRODUCTION

Momordica charantia (bitter melon) is a subtropical vine in cucurbitaceous species that widely distributed in south Asia, Africa and Latin America (Ahmed *et al*., 2001). It is well-known that seeds, aerial parts and unripe fruits of *Momordica charantia* contain biologically active compounds that have been used to treat diabetes in various parts of the world (Alam *et al*., 2009; Joseph and Jini, 2013). Other use of this plant can be seen from the recently review (Krishna *et al*., 2011; Tuan *et al*., 2011). Like other traditional fruits, fresh *Momordica charantia* is prone to perish because of its high moisture content (Shih *et al*., 2009). To reduce the water and microbiological activity of the material, hot air drying method might be the most important method of food preservation, improving the food stability and reducing transportation and storage costs (Ratti, 2001).

Hot air drying is a complicated process containing simultaneous mass and heat transfer where water is transferred by diffusion from inside the food material to the air stream by forced convection (Kumar *et al*., 2011). The high temperature in the hot air drying process may have a disadvantageous impact on product quality, such as browning reactions and oxidation of chlorophyll (Lewicki, 2006). On the other hand, the amount of energy required to dry a product depends on many factors, such as drying air temperature, time and velocity (Ertekin and Yaldiz, 2004). Thin layer drying equations describing the drying characteristics of different fruits and vegetables can be used to design efficient dryers and optimize the drying process (Sacilik and Elicin, 2006). In the past decade, there are many studies on the drying characteristic of fruits and agricultural products such as apricots (Ihns *et al*., 2011), bananas (Karim and Hawlader, 2005), carrots (Doymaz, 2004), figs (Babalis *et al*., 2006), pineapples (Ramallo and Mascheroni, 2012), pumpkins (Yaldız and Ertekin, 2001) and mushrooms (Wei *et al*., 2013). For example, Ding *et al*. (2012) have compared the mathematical models of hot air drying kinetics for *Spratelloides gracilis* and found the Wang and Singh model gave best fit to experimental drying data with the highest coefficient of determination (R^2). For *Momordica charantia*, many new drying technologies have been applied such as microwave drying (Cheng *et al*., 2006), solar cabinet drying (Akpinar and Bicer, 2008). The effects of hot air drying temperature on the *Momordica charantia* slices have also been reported by Lidhoo and Khar (2007). However, the mathematical modeling and color change of fresh *Momordica charantia* in thin-layer convection drying at both parameters of temperature and thickness of slice have not been reported.

The objectives of the present study are:

- To study the effect of temperature and thickness on the drying of *Momordica charantia*
- To choose the best equation among several thin layer drying models for predicting the drying characteristics of convection drying of *Momordica charantia* at different drying conditions. These

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models include the Page, Henderson and Pabis and Wang and Singh equations

- To study the effect of temperature on the color change of *Momordica charantia* slices during hot air drying process.

MATERIALS AND METHODS

Materials: The fresh *Momordica charantia* was procured from local market, Hangzhou, China. They were washed by running tap water and stored in a refrigerator at about 5°C until they were taken for studies. The average initial moisture content of the *Momordica charantia* samples was about 94.4±0.2% in wet basis, as determined by vacuum drying at 70°C for about two days. Prior to experiments the *Momordica charantia* tubers were cut into slices with certain thickness using a kitchen cutter. At least 8 slices were measured for the thickness and used for the hot air drying study in each batch.

Equipments and apparatus: All drying experiments were performed on a continuous convective (hot air) dryer that the same as used before by Meng *et al*. (2011). The air temperature can be automatically controlled by regulating the required voltage to the heaters inside the air channel. The accuracy of the temperature was ±1°C by carefully control. In this study, the drying experiments were carried out by using temperatures of 50±1.5, 60±1, 70±1 and 80±1°C with a constant perpendicular air velocity of about 1.2 m/s. A digital electronic balance (Model BS124S, Beijing Sartorius instrument system Co., LTD., China) in the measurement range of 0-210 g and an accuracy of 0.01 g was used for the moisture loss of samples. The weighing interval of the drying samples as 2 min during the drying process.

Theoretical and mathematical modeling: The dimensionless Moisture Ratio (MR) number of *Momordica charantia* slices during hot air drying can be calculated by the equation below:

$$\mathrm{MR} = \frac{M - M_e}{M_0 - M_e} \quad (1)$$

where,

M = The mean *Momordica charantia* slices moisture content

M_0 = The initial value

M_e = The equilibrium moisture content

Convection drying phenomenon of fruits are always took place in the falling rate period after a short heating period (Ozbek and Dadali, 2007). It is generally accepted that liquid diffusion is the only physical mechanism to transfer water to surface to be evaporated. Fick's second law can be used to describe the drying process. And many models have been proposed based on the Fick's second law by different assumptions. These models always assume that the dried material contains same initial moisture content; drying air humidity, internal temperature gradient and heat transfer between materials and volume contraction rate during drying are negligible. To select a suitable model for describing the drying process of *Momordica charantia* slices, drying curves were fitted with three well known thin-layer drying moisture ratio models as shown in Table 1.

Table 1: Mathematical models applied to the moisture ratio values

Model no.	Model	Model name
1	$\mathrm{MR} = \exp(-A \times t^B)$	Page
2	$\mathrm{MR} = A \times \exp(-B \times t)$	Henderson and pabis
3	$\mathrm{MR} = 1 + A \times t + B \times t^2$	Wang and singh

Nonlinear least square method based on the Levenberg-Marquardt method was used to fit the experimental data to selected equations. The values of coefficient of determination R^2 can be used to test the linear relationship between experimental and model calculated values (Gunhan *et al*., 2005) and are one of the primary criteria for the selection of best model. Statistical parameter R^2 may be computed from the following mathematical equation:

$$R^2 = 1 - \frac{\sum_{1}^{N} (\mathrm{MR}_{\exp,i} - \mathrm{MR}_{\mathrm{pre},i})^2}{\sum_{1}^{N} (\overline{\mathrm{MR}_{\exp}} - \mathrm{MR}_{\mathrm{pre},i})^2} \quad (2)$$

where, N is the total number of observations, $\mathrm{MR}_{\exp,i}$ and $\mathrm{MR}_{\mathrm{pre},i}$ are the experimental and predicted moisture ratio at any observation i. High R^2 value which closer to 1 represents the best fit of the model.

Determination of color: The color change of *Momordica charantia* slice during hot air drying at different temperatures are also studied by the measuring of color parameters using a Reflectance Chroma Meter CR 210 (Minolta Co. Ltd., Osaka, Japan). Three replicates of each sample were measured to determine the average values of Hunter L^* (whiteness/darkness), a^* (redness/greenness) and b^* (yellowness/blueness). The total color change (ΔE) are then calculated from the L^*, a^* and b^* values (Dadali *et al*., 2007), as shown in Eq. (3):

$$\Delta E = \sqrt{(L_0^* - L^*)^2 + (a_0^* - a^*)^2 + (b_0^* - b^*)^2} \quad (3)$$

where, L_0^*, a_0^*, b_0^* are the initial color values of fresh samples and the L^*, a^*, b^* are the final color values of the dried samples.

RESULTS AND DISCUSSION

Drying characteristics of *Momordica charantia* slices under different conditions: Drying curves (moisture ratio versus time) of *Momordica charantia* slices at different drying temperatures were given in Fig. 1. As

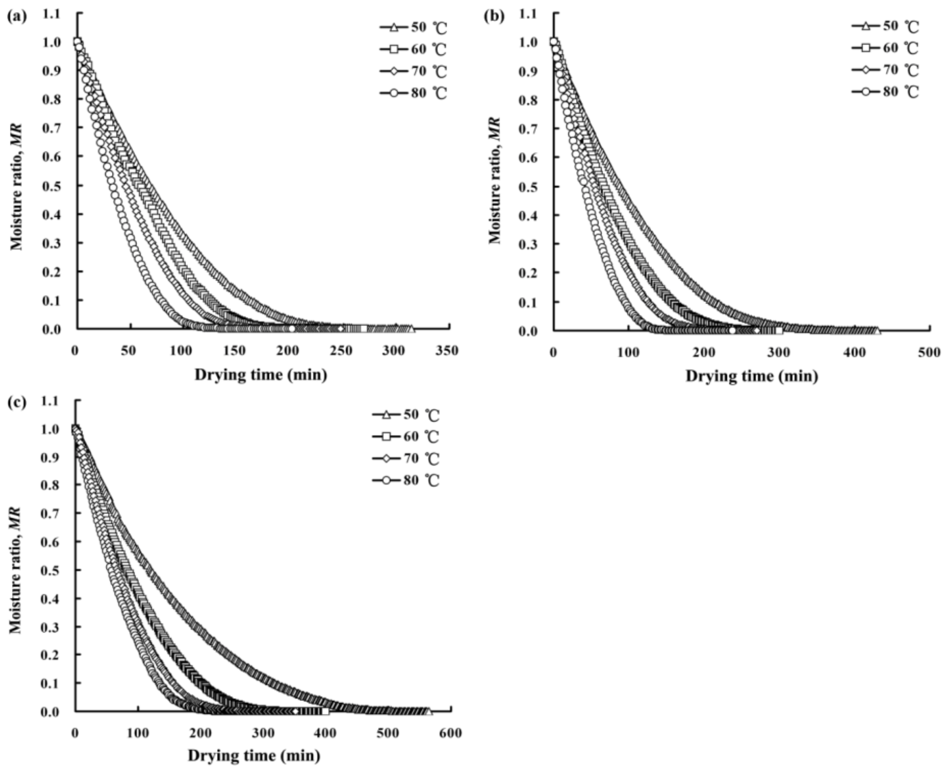

Fig. 1: The change of water content MR for momordica charantia with drying time t at different temperature and thickness: (a) 0.5cm; (b) 0.75cm; (c) 1.0cm

clearly seen from Fig. 1, there's an adverse relationship between drying temperature and drying time. The higher the temperature was, the shorter it would take for *Momordica charantia* slices to reach the equilibrium moisture content. On the other hand, the thickness of slices has an important effect on the drying of *Momordica charantia, too*. *Momordica charantia* slices dried under the 50°C forced air with the thickness of 0.5 cm, for example, took an average of about 162 min to reach *MR* = 0.1. When drying air temperature was increased from 50 to 80°C, only 78 min was needed decreased by 100% to achieve the same moisture ratio. It was found that the constant drying rate period wasn't detected at the 4 temperatures and only the falling rate period showed up in the drying procedure, which indicated that the drying of *Momordica charantia* slices was controlled by inner water diffusion. Similar results can also be found in several studies for different agri-products, such as apple (Wang *et al*., 2007), orange (Diaz *et al*., 2003).

As expected, the thicker of the slice provided longer drying times to achieve the same moisture ratio. *Momordica charantia* slices with a slice thickness of 0.5 cm got a much higher drying rate than the others' during the whole drying course. The causation of this phenomenon can be concluded that the moisture traveling distance was greatly reduced and the surface area exposed to the hot air for a given volume of the product was increased significantly compared to that of 0.75 and 1.0 cm *Momordica charantia* slices.

For the effect of drying temperature, as it is well known that the higher drying temperature made the relative humidity of air around *Momordica charantia* slices become lower. As a result, the heat transfer and evaporation of the water from the slices was greatly enhanced. On the other hand, the drying rate increased as the temperature increases, but the increase became gradually smaller. It was found that the *Momordica charantia* slice dried at 80°C got the highest drying rate in all the drying temperature concerned. However, the extent of surface hardening and shrinkage effect was intensified on the slice surface at 80°C. This could be explained that the migration rate to surface of moisture was further lower than the moisture evaporation rate from surface to air at the drying temperature of 80°C. Hence, allows the presence of phenomena such as hardening and shrinkage of *Momordica charantia* slices. Besides, high temperature would lead to color changes greatly. Lot's of nutrition might be destroyed and *Momordica charantia* slices were getting darker sharply during the drying process at 80°C. Considered of the energy conservation and product quality, drying temperature at about 60~70°C was the suitable temperature for *Momordica charantia* slices by forced air drying method.

Modeling of drying process: As shown in Table 1, the experimental drying curves of *Momordica charantia* slices dried at 4 different drying temperatures (50, 60, 70 and 80°C) and 3 different thicknesses (0.5, 0.75 and

Table 2: Results for models to correlate drying character for *momordica charantia* at different temperature and thickness

		Page model			Henderson and pabis model			Wang and singh model		
Thickness (cm)	*t* (°C)	$A \times 10^2$	*B*	R^2	*A*	$B \times 10^2$	R^2	$A \times 10^5$	$B \times 10^2$	R^2
0.50	50	0.2678	1.323	0.997	1.099	1.3090	0.986	0.831	-0.6091	0.838
	60	0.2930	1.400	0.998	1.119	1.8286	0.985	0.925	-0.6526	0.555
	70	0.3908	1.364	0.998	1.107	1.9949	0.986	0.943	-0.6610	0.425
	80	0.6984	1.322	0.998	1.097	2.6886	0.989	0.986	-0.6808	0.413
0.75	50	0.2235	1.286	0.998	1.092	0.9903	0.987	0.708	-0.5513	0.955
	60	0.2784	1.322	0.998	1.104	1.3486	0.988	0.840	-0.6130	0.821
	70	0.5458	1.270	0.999	1.091	1.8777	0.992	0.929	-0.5860	0.486
	80	0.5089	1.337	0.997	1.098	2.2204	0.987	0.962	-0.6698	0.243
1.00	50	0.2075	1.215	0.998	1.076	0.6908	0.991	0.495	-0.4467	0.993
	60	0.2336	1.295	0.997	1.091	1.0575	0.988	0.743	-0.5680	0.937
	70	0.2504	1.344	0.998	1.113	1.3533	0.988	0.840	-0.6135	0.829
	80	0.2947	1.351	0.998	1.107	1.5562	0.986	0.884	-0.6341	0.714
				0.998			0.988			0.684

Table 3: Effect of drying temperature on the color change of *momordica charantia*

Temperature (°C)	*L**	*a**	*b**	Δ*E*
50	40.70±0.28	-7.61±0.28	30.42±0.58	51.29
60	44.24±0.21	-9.61±0.26	31.69±1.46	54.32
70	47.08±0.12	-0.91±0.73	31.64±0.47	56.57
80	47.62±1.41	-2.51±0.12	36.80±1.16	62.63

1.0 cm) were also fitted to three frequently used models (Page, Henderson and Pabis and Wang and Singh) to describe the drying characteristics. The drying constants (A) and (B) for three model in Table 1 and also statistical parameters R^2 were given in Table 2 for different experimental conditions. Generally, the R^2 values changed between 0.997-0.998, 0.985-0.992 and 0.413-0.955 for the Page, Henderson and Pabis and Wang and Singh equation, respectively. It could be found that although the first two models adequately described the drying characteristics of *Momordica charantia* slices under the forced air method, it was the Page equation that gave the closest fit to the experimental data.

The established model was validated by comparing experimental and predicted moisture content at any drying conditions. Plots of experimental and predicted (straight line) moisture ratios against drying time have also been represented in Fig. 1. As can be observed in the figure, the Page model provided a good agreement between experimental and predicted moisture ratios. Hence, the Page model could be selected as the most suitable model to represent the thin-layer hot air drying behavior of the *Momordica charantia* slices. Similar findings were reported by Madamba *et al*. (1996) for garlic slices and (Akpinar and Bicer, 2005) for eggplant drying.

Colors change: The effects of hot air drying parameters on color change of the *Momordica charantia* slice was also evaluated in this study. The color was measured and expressed as the *L**, *a** and *b** system. It is known that the parameter *a** represents the hue range of the colors red and green, *b** represents the hue range of colors yellow and blue, while *L** represents the brightness of the color. Table 3 showed the Effect of drying temperature on the color change of *Momordica charantia*.

With the increase of the temperature, *Momordica charantia* got higher *L** value and higher *b** value. The *L** , *a**, *b** values of dried *Momordica charantia* color at the examined drying conditions ranging from 40.70 to 47.62, -7.61 to -0.91 and 30.42 to 36.80, respectively, rapidly changing at a drying air temperature of 70°C. Increasing the drying air temperature also raised the total color change (Δ*E*), ranging from 51.29 to 62.63.

The change of color could be attributed to the browning reactions and the decomposing of chlorophyll or carotenoid compounds that took place during the drying process. It has been demonstrated that the fresh *Momordica charantia* contain a high level of chlorophyll. During the hot air drying process, chlorophyll could be easily oxidized and decompose thermally. Moreover, the high temperature could help promote Maillard condensation and Caramel reaction happening. As observed, the variable with most effect on color was the air temperature during drying process. So considering the energy and quality, 70°C was chosen as the suitable temperature for *Momordica charantia* slices drying experiment.

CONCLUSION

The hot air drying characteristics of *Momordica charantia* slices were examined under different temperatures (50, 60, 70 and 80°C) and slice thickness (0.5, 0.75 and 1.0 cm), respectively. Increasing drying temperature could reduce the drying time, while increasing slice thickness prolonged it. The drying data were fitted to different semi-theoretical models, including Page, Henderson and Pabis and Wang and Singh equations. Among the three mathematical models compared, the Page model gave the highest decision coefficient (R^2) value of 0.998 for the hot air drying of *Momordica charantia* slices. The color change of *Momordica charantia* slices during hot air drying at different temperatures were also studied by the measurement of color parameters. The total color change (Δ*E*) of the *Momordica charantia* slices was observed to increase as drying temperature increased. The results show that the color of *Momordica charantia* slices changed sharply when temperature was higher than about 70°C.

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