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Vacuum Drying Characteristics of *Salicornia herbacea* L.

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ABSTRACT

Vacuum drying of *Salicornia herbacea* L. was performed at different drying temperatures (50, 60, 70, and 80°C) to evaluate the drying characteristics and the effect of drying temperatures on the quality of *Salicornia*. As the drying temperature increased, the drying time decreased significantly (P< 0.05). The drying rate decreased with decrease in moisture content and increase in drying time. On the other hand, the drying rate increased with increase in drying temperature. The logarithmic model exhibited the best fit to the experimental drying data among the tested models. The drying constants estimated using the logarithmic model were found to be affected by the drying temperature. The activation energy for drying was 15.02 kJ mol^{-1}. The surface color of the *Salicornia herbacea* samples was significantly affected by the drying temperature (P< 0.05). CIE *L-, *b**-, and Chroma (*C**)-values increased significantly, while *a**- and hue angle (*h**)-values decreased significantly after drying at all of the drying temperatures (P< 0.05).**

Keywords: Modeling, *Salicornia herbacea*, Thin layer drying, Vacuum drying kinetics.

INTRODUCTION

Salicornia herbacea L., known as 'Tungtungmadi' or 'Hamcho' in Korea, is one of the most salt-tolerant (halophyte) land plant shrubs and grows in salt marshes on the southern and western seashore of the Korea peninsula (Kim and Song, 1983; Jang *et al*., 2007). *Salicornia herbacea* is rich in natural minerals and dietary fibers (Min *et al*., 2002) and is currently receiving renewed interest because of its nutritional benefits and functional properties (Lee *et al*., 2002; Jeong *et al*., 2004) such as antidiabetic (Bang *et al*., 2002), antioxidant (Lee *et al*., 2007), hypocholesterolemic (Cha *et al*., 2004), and antiaging (Lee and An, 2002) effects. Generally, it is dried and used as a dry powder, tablet, and as a liquid extract, but is also used as an additive in the production of various food products like soy sauce, fermented soybean paste, red pepper paste, bread, rice cakes, etc.

Drying is a commonly used pre-processing method for the production of *Salicornia herbacea* powder. It is considered not only as a preservation process, but also as a way to add values to foods (Singh *et al*., 2008). Drying is one of the most important industrial unit operations as it accounts for 10-25% of the total energy used in the food manufacturing processes worldwide (Mujumdar and Passos, 2000).

Knowledge of the drying kinetics of *Salicornia herbacea* is required to design, optimize, and control the drying process. It is also necessary to investigate the vacuum drying characteristics of plant to evaluate the practicality of vacuum drying for improving the quality of dried *Salicornia herbacea*. Although several studies have been carried

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out to investigate the vacuum drying characteristics of various food materials (Jaya and Das, 2003; Cui *et al*., 2004; Methakhup *et al*., 2005; Arevalo-Pinedo and Murr, 2006; Arevalo-Pinedo and Murr, 2007; Wu *et al*., 2007; Amellal and Benamara, 2008; Sahari *et al*., 2008; Lee and Kim, 2009), no data on the vacuum drying behavior of *Salicornia herbacea* are available in the literature.

The objectives of this study were to determine the effect of drying temperature on the drying kinetics of *Salicornia herbacea*, to select the suitable drying model for describing the vacuum drying process, and to investigate the effects of different drying temperatures on the color quality of the powder.

MATERIALS AND METHODS

Material

Fresh *Salicornia herbacea* plants, which were harvested in June, 2008 at closed salt farms in Shinan, Jeollanam-do Province, Korea, were purchased from Dasarang Co., Ltd. (Jeollnam-do, Korea) and kept in a refrigerator before use. Prior to drying, the plants were cut into small pieces (cylindrical shape with about 10 cm long and 0.4 cm thick) and washed with running water to remove contaminants from the surface. Excess surface moisture was first removed using a salad spinner (WD23-210, Myeongmoon LC Corp., Gyeonggi, Korea) and, then, the samples were dried at room temperature for 30 minutes.

The samples were immediately weighed and placed into a vacuum dryer (VOS-301SD, Tokyo Rikakikai Co., Tokyo, Japan; temperature variation: ±1.5°C at 240°C setting) without any pre-treatments. The average weight of the used sample was 50.01±0.04 g. The initial moisture contents of the *Salicornia herbacea* samples were determined by vacuum drying at 70°C for 24 hours (AOAC, 1999). The initial average moisture content of the slices was 10.40±0.28 kg of water per kg of dry matter.

Drying Experiment

Shredded *Salicornia herbacea* samples about 50 g (*ca*. 10 cm long) were dried at air temperatures of 50, 60, 70, and 80°C by using a vacuum dryer (VOS-301SD, Tokyo Rikakikai Co., Tokyo, Japan). Samples were spread in a single layer on the tray and the absolute vacuum pressure in the dryer was 0.1 MPa. The moisture losses of the samples were recorded at 30 minutes intervals using a digital balance of 0.001 g accuracy (CP423S, Sartorius AG, Goettingen, Germany; repeatability: ±0.001 g, linearity: ±0.002 g, stabilization time: 1 s). The vacuum was broken and restored before and after the weight measurements and each process took less than 20 s. It was considered that the dry product reached an equilibrium condition with the atmosphere inside the drying chamber when the constant weight was attained with three consecutive measurements. The moisture content at that time was considered to be the equilibrium moisture content. Each experiment was replicated three times and the average values were used for analysis.

Mathematical Modeling of Moisture Ratios

The moisture ratios (*MR*) and drying rates of the *Salicornia herbacea* samples during the thin layer drying experiments were calculated using the following equations:

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

Since the M_e value is relatively small compared to M_o and M values, the M_e value can be neglected and the moisture ratio can be expressed as follows (Doymaz and Pala, 2003; Goyal *et al.,* 2007):

$$MR=\frac{M}{M_o} \quad (2)$$

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Drying rate was calculated using a forward finite difference method as follows:

$$Drying\ rate = \frac{M_t - M_{t+\Delta t}}{\Delta t} \quad (3)$$

where, M, M_o, M_e, $M_{t+\Delta t}$ and M_t are the moisture content at any time, initial moisture content, equilibrium moisture content, moisture content at time $t+\Delta t$ and t (kg water kg^{-1} dry matter), respectively, and Δt is the time interval for reading weight of sample (5 minutes).

Seven well-known thin layer drying models shown in Table 1 were tested to select the best model for describing the drying characteristics of the *Salicornia herbacea*. Non-linear least square regression analysis was performed by using the Levenberg-Marquardt procedure in the SigmaPlot computer program (SigmaPlot®, SPSS Inc., Chicago, IL, USA). The coefficient of determination (R^2) was the primary criterion for selecting the best model to describe the drying curve. In addition, mean relative percent deviation (*EMD*), root mean square error (*RMSE*), and the reduced chi-square (χ^2) were used to determine the goodness of fit (Erenturk *et al*., 2004; Goyal *et al*., 2007). These parameters can be calculated as follows:

$$EMD = \frac{100}{N}\sum_{i=1}^{N}\frac{|MR_{pre,i} - MR_{\exp,i}|}{MR_{\exp,i}} \quad (4)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(MR_{pre,i} - MR_{\exp,i})^2\right]^{1/2} \quad (5)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}(MR_{pre,i} - MR_{\exp,i})^2}{N - z} \quad (6)$$

Where, $MR_{exp,i}$ is the i^{th} experimentally observed moisture ratio, $MR_{pre,i}$ the i^{th} predicted moisture ratio, N the number of observations, and z is the number of constants in the model. The model was considered best when *EMD*, *RMSE*, and χ^2 were at minimum values and R^2 at a maximum value.

Color Measurement

Surface color of the dried *Salicornia herbacea* samples were determined in terms of CIE (Commission International de I'Eclairage) color characteristics (L^*, a^*, and b^*), using a Minolta CM-600d Spectrophotometer (Minolta Co., Osaka, Japan; spectral reflectance: standard deviation within 0.1%). The color measurements were replicated 20 times and the average and standard deviation values were reported. Because of the roughness on the dried samples, powdered samples were used to measure the color characteristics with the exception of the fresh samples.

The total color change (ΔE^*) was calculated as follows:

$$\Delta E^* = [(L_0^* - L^*)^2 + (a_0^* - a^*)^2 + (b_0^* - b^*)^2]^{\frac{1}{2}} \quad (7)$$

The L^*, a^*, and b^* values correspond to the values of *Salicornia herbacea* samples at different drying conditions, whereas the values of L^*_0, a^*_0, and b^*_0 are related to the fresh *Salicornia herbacea*. Chroma or strength of color (C^*) and hue angle (h^*) were also calculated as follows:

$$C^* = \sqrt{(a^*)^2 + (b^*)^2} \quad (8)$$

Table 1. Thin layer drying models used for mathematical calculation of the drying of *Salicornia herbacea.*

No.	Model name	Model	References
1	Newton	$MR = \exp(-kt)$	O'Callaghan *et al.* (1971)
2	Page	$MR = \exp(-kt^n)$	Page (1949)
3	Modified Page	$MR = \exp((-kt)^n)$	Overhults *et al.* (1973)
4	Henderson and Pabis	$MR = a\exp(-kt)$	Henderson and Pabis (1961)
5	Logarithmic	$MR = a\exp(-kt)+c$	Yagcioglu *et al.* (1999)
6	Two term	$MR = a\exp(-kt)+b\exp(-ft)$	Henderson (1974)
7	Modified Henderson and Pabis	$MR = a\exp(-kt)+b\exp(-gt)+c\exp(-ht)$	Karathanos (1999)

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$$h^* = \tan^{-1}\left(\frac{b^*}{a^*}\right) \quad (9)$$

Duncan's multiple range tests (P= 0.05) were performed to determine any significant differences among the various treatments (SAS Version 9.1, SAS Institute, Cary, NC).

Scanning Electron Microscopy (SEM)

The structures of the *Salicornia herbacea* samples dried at different air temperatures were examined using a low vacuum scanning electron microscope (Hitachi S-4300, 5.0 kV, Hitachi Ltd., Tokyo, Japan) operated at 5.0 kV and, WD 15 mm using the high vacuum mode. The samples were fixed on the SEM stub, which were subsequently coated with lead/platinum in order to provide a reflective surface for the electron beam. The coated samples were subsequently viewed under the microscope.

RESULTS AND DISCUSSION

Effect of Drying Temperature on Moisture Content

Salicornia herbacea samples were dried in a single layer at drying temperatures of 50, 60, 70, and 80°C from initial moisture content of 10.40±0.28 kg of water per kg of dry matter to the final moisture content of about 0.12±0.03 kg of water per kg of dry matter. Figure 1 shows the results of moisture ratios as a function of drying time at various drying temperatures. Moisture ratio decreased continuously with increase in drying time. The drying at the higher temperatures resulted in higher rate of removal of water and, consequently, resulted in shorter drying times. The drying times required to reduce the moisture content from 10 to 0.2 kg water kg^{-1} of dry matter were 922.4, 607.9, 474.6, and 345.7 minutes at the drying temperatures of 50, 60, 70, and 80°C, respectively. As the drying temperature increased from 50 to 60, 70 and

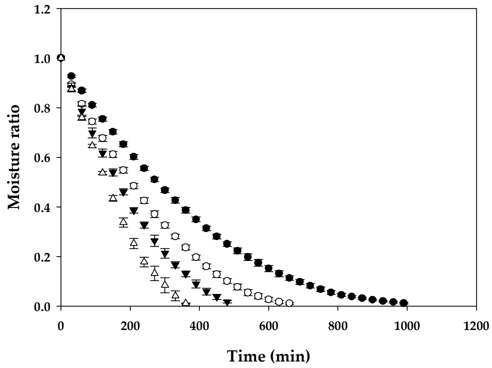

Figure 1. Drying curves of *Salicornia herbacea* samples undergoing vacuum drying: ● (T= 50°C), ○ (T= 60°C), ▼ (T= 70°C), △ (T= 80°C).

80°C, drying time decreased significantly (P< 0.05). Such phenomena has been frequently observed with many food stuffs such as red pepper (Akpinar *et al*., 2003), rosehip (Erenturk *et al*., 2004), figs (Babalis and Belessiotis, 2004; Babalis *et al*., 2006), green beans (Doymaz, 2005), mint leaves (Doymaz, 2006), raw mango slices (Goyal *et al*., 2006), organic apple slices (Sacilik and Elicin, 2006), red chillies (Kaleemullah and Kailappan, 2006), apple pomace (Wang *et al*., 2007), pistachio nuts (Kashaninejad *et al*., 2007), and Asian white radish slices (Lee and Kim, 2009).

Effect of Drying Temperature on Drying Rate

The variation of moisture content with drying time was obtained at each drying temperature as shown in Figure 2. From these results, the drying rates were calculated using Eq. (3) and plotted against moisture content. As expected, drying rate decreased continuously with decreasing moisture content or increasing drying time. It was also noted that the drying rate increased with the increase in drying temperature. The drying rate was greater for the *Salicornia herbacea* samples dried at higher temperature than for those dried at

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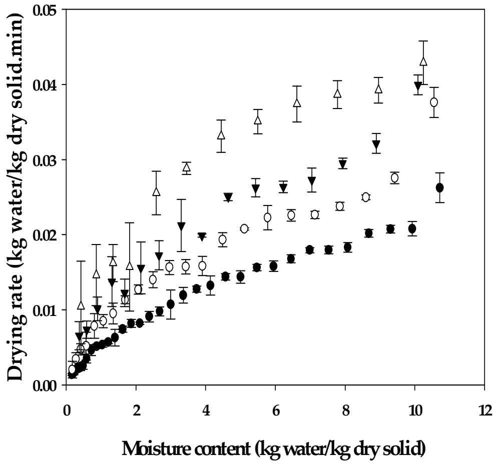

Figure 2. Drying rate of *Salicornia herbacea* samples undergoing vacuum drying: ● (T= 50°C), ○ (T= 60°C), ▼ (T= 70°C), △ (= 80°C).

lower temperature for the same average moisture content of the samples. Consequently, the drying time decreased at higher drying temperature condition. A higher moisture transfer rate with the higher drying temperature was due to the fact that the relative humidity of the drying air at higher temperature was less as compared to that at lower temperature, i.e. the difference of the partial vapor pressure between the *Salicornia herbacea* samples and their surroundings was greater in the environment of higher drying temperature (Kaleemullah and Kailappan, 2007). Similar results of the influence of drying temperature on the drying rate have been reported for parboiled wheat (Mohapatra and Rao, 2005), mint leaves (Doymaz, 2006), organic apple slices (Sacilik and Elicin, 2006), red chillies (Kaleemullah and Kailappan, 2006), pistachio nuts (Kashaninejad *et al*., 2007), and Asian white radish slices (Lee and Kim, 2009).

A constant-rate drying period was not observed and all the drying operations were seen to occur in the falling rate period. This is due to the quick removal of moisture from the surface of *Salicornia herbacea* (Kaleemullah and Kailappan, 2007), which indicates the diffusion-dominant drying phenomena. At the beginning of the drying process, the drying rate was very high, but decreased as the moisture content approached the equilibrium. These findings are in good agreement with the results for red pepper (Akpinar *et al*., 2003), green beans (Doymaz, 2005), mint leaves (Doymaz, 2006), organic apple slices (Sacilik and Elicin, 2006), red chillies (Kaleemullah and Kailappan, 2006), pistachio nuts (Kashaninejad *et al*., 2007), and Asian white radish slices (Lee and Kim, 2009).

Selection of the Drying Model

Selected thin layer drying models, listed in Table 1, were fitted to the drying curves (*MR* versus time) obtained at different drying temperatures. Table 2 presents the estimated values of model constants and the statistical results of the different models. The goodness of fit of the model was tested using parameters such as the coefficient of determination (R^2), mean relative percent deviation (*EMD*), root mean square error (*RMSE*), and the reduced chi-square (χ^2). Based on the criteria of the highest R^2 and the lowest *EMD, RMSE*, and χ^2, the best model describing the thin layer drying characteristics of *Salicornia herbacea* was selected. For all experiments, the R^2, *EMD, RMSE*, and χ^2 values of the models varied between 0.9775 and 0.9997, 8.42 and 143.20, 0.00004 and 0.00291, and 0.00009 and 0.00632, respectively (Table 2). Among the tested thin layer drying models, the logarithmic model exhibited the highest R^2 value and the lowest values of *EMD, RMSE,* and χ^2. The R^2, *EMD, RMSE*, and χ^2 values varied between 0.9993-0.9997, 8.42-22.15, 0.00004-0.00010, and 0.00009-0.00022, respectively. Based on these results, the logarithmic model was selected as the most suitable model to represent the thin layer drying behavior of *Salicornia herbacea*.

Figure 3 shows the result of the experimental and the predicted moisture ratios calculated using the logarithmic model versus the drying time for the dried *Salicornia herbacea* samples at 50, 60, 70, and 80°C. The proposed model provided conformity between the experimental

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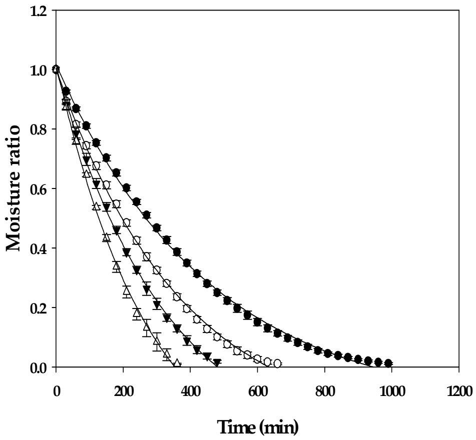

Figure 3. Comparison of drying curves of *Salicornia herbacea* samples undergoing vacuum drying: ● (T= 50°C), ○ (T= 60°C), ▼ (T= 70°C), △ (T= 80°C). Solid line (—) represents curve fitting using logarithmic model.

and predicted moisture ratios. Figure 4 shows the comparison between the predicted and the experimental moisture ratio values determined at various drying temperatures. There was very good agreement between the experimental and the calculated moisture ratio values, which are closely banding around a 45° straight line. This indicates the suitability of the logarithmic model in describing the drying behavior of *Salicornia herbacea*. The logarithmic model has been frequently used to describe the drying characteristics of various plant materials such as rosehip (Erenturk *et al.*, 2004), white mulberry (Doymaz, 2004), olive cake (Akgun and Doymaz, 2005), mint leaves (Doymaz, 2006), plum (Goyal *et al.*, 2007), peach slices (Kingsly *et al.*, 2007), whole figs (Xanthopoulos *et al.*, 2007), hull-less seed pumpkin (Sacilik, 2007), and Asian white radish slices (Lee and Kim, 2009).

Effect of Temperature on Drying Characteristics

The drying constant (k) in the logarithmic model increased (0.0022-0.0036 min^{-1}) significantly with the increase in the drying temperature ($P< 0.05$) (Table 2). The temperature dependency of the drying constant (k) was tested using a simple Arrhenius-type relationship:

$$k = k_0 \exp\left(-\frac{E_a}{RT}\right) \quad (10)$$

Where, k_0 is the pre-exponential factor of the Arrhenius equation (m^2 s^{-1}), E_a the activation energy (kJ mol^{-1}), R the universal gas constant (8.314 J mol^{-1} K^{-1}), and T the absolute temperature (K). The activation energy was calculated by plotting the natural logarithm of k versus the reciprocal of the absolute temperature. A straight line was obtained with coefficient of determination (R^2) of 0.987 and the activation energy was determined to be 15.02 kJ mol^{-1} (Figure 5). The value obtained in this study was within a close range of 15-40

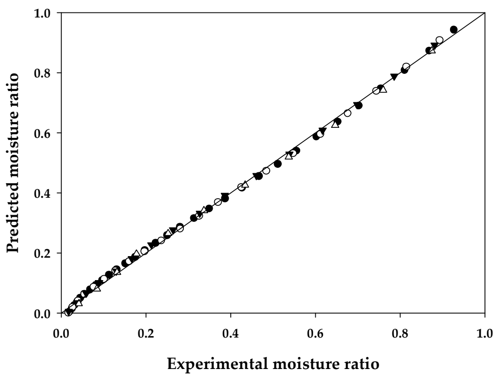

Figure 4. Comparison of experimental and predicted moisture ratio by the logarithmic model: ● (T= 50°C), ○ (T= 60°C), ▼ (T= 70°C), △ (T= 80°C)

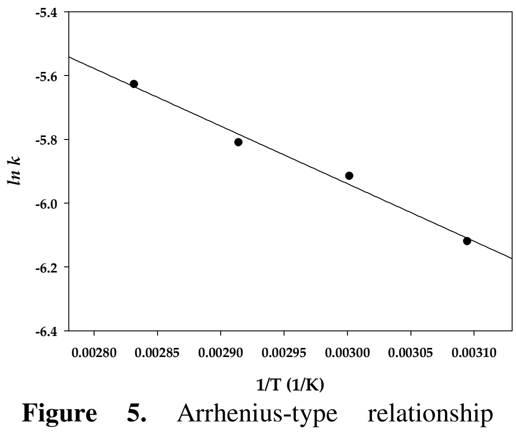

Figure 5. Arrhenius-type relationship between the drying constant and absolute temperature.

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Table 2. Statistical results obtained from various thin layer drying models.

Model No.	Temp. (°C)	Model constants	R^2	*EMD* (%)	*RMSE*	χ^2
1	50	*k*= 0.0029	0.9921	57.57	0.00080	0.00164
	60	*k*= 0.0040	0.9907	74.11	0.00102	0.00213
	70	*k*= 0.0049	0.9909	55.57	0.00113	0.00239
	80	*k*= 0.0063	0.9869	97.54	0.00175	0.00378
2	50	*k*= 0.0006, *n*= 1.2510	0.9988	30.44	0.00022	0.00045
	60	*k*= 0.0009, *n*= 1.2702	0.9977	26.71	0.00035	0.00073
	70	*k*= 0.0010, *n*= 1.2925	0.9980	23.67	0.00025	0.00052
	80	*k*=0.0008, *n*= 1.4048	0.9985	31.88	0.00024	0.00051
3	50	*k*= 0.0025, *n*= 1.0000	0.9855	97.41	0.00162	0.00335
	60	*k*= 0.0035, *n*= 1.0000	0.9830	111.36	0.00175	0.00366
	70	*k*= 0.0043, *n*= 1.0000	0.9842	81.59	0.00193	0.00410
	80	*k*= 0.0054, *n*= 1.0000	0.9775	143.20	0.00291	0.00632
4	50	*k*= 0.0030, *a*= 1.0623	0.9941	54.42	0.00060	0.00124
	60	*k*= 0.0042, *a*= 1.0553	0.9923	67.22	0.00084	0.00176
	70	*k*= 0.0052, *a*= 1.0563	0.9925	49.12	0.00092	0.00196
	80	*k*= 0.0068, *a*= 1.0723	0.9897	85.03	0.00138	0.00298
5	50	*k*= 0.0022, *a*= 1.1626, *c*= -0.1457	0.9993	18.67	0.00007	0.00015
	60	*k*= 0.0027, *a*= 1.2264, *c*= -0.2228	0.9994	19.60	0.00006	0.00013
	70	*k*= 0.0030, *a*= 1.3091, *c*= -0.3053	0.9997	8.42	0.00004	0.00009
	80	*k*= 0.0036, *a*= 1.4201, *c*= -0.4021	0.9993	22.15	0.00010	0.00022
6	50	*k*= 0.0030, *f*=0.0030, *a*= 0.5541, *b*= 0.5082	0.9941	54.42	0.00060	0.00124
	60	*k*= 0.0042, *f*= 0.0042, *a*= 0.5482, *b*= 0.5072	0.9923	67.23	0.00084	0.00176
	70	*k*= 0.0052, *f*=0.0052, *a*= 0.5473, *b*= 0.5090	0.9925	49.12	0.00092	0.00196
	80	*k*= 0.0068, *f*=0.0068, *a*= 0.5595, *b*= 0.5128	0.9897	85.03	0.00138	0.00298
7	50	*k*= 0.0030, *a*= 0.3673, *b*= 0.3582, *c*= 0.3369, *g*= 0.0030, *h*= 0.0030	0.9941	54.43	0.00060	0.00124
	60	*k*= 0.0042, *a*= 0.3634, *b*= 0.3557, *c*= 0.3362, *g*= 0.0042, *h*= 0.0042	0.9923	67.22	0.00084	0.00176
	70	*k*= 0.0052, *a*= 0.3630, *b*= 0.3557, *c*= 0.3376, *g*= 0.0052, *h*= 0.0052	0.9925	49.12	0.00092	0.00196
	80	*k*= 0.0068, *a*= 0.3718, *b*= 0.3600, *c*= 0.3405, *g*= 0.0068, *h*= 0.0068	0.9897	85.03	0.00138	0.00298

kJ mol^{-1} for various foods as reported by Rizvi (1986). The E_a of *Salicornia herbacea* is close to that of Asian white radish slices (16.49-20.26 kJ mol^{-1}) (Lee and Kim, 2009), olive cake (17.97 kJ mol^{-1}) (Akgun and Doymaz, 2005), *Agaricus bisporus* mushroom (19.79 kJ mol^{-1}) (Arora *et al*., 2003), lettuce and cauliflower leaves (19.82 kJ mol^{-1}) (Lopez *et al*., 2000), and red delicious apple (19.96-22.62 kJ mol^{-1}) (Kaya *et al*., 2007).

Effect of Temperature on Color Characteristics

The influence of the drying temperatures on the color of *Salicornia herbacea* is presented in Table 3. The *Salicornia herbacea* initially possessed a dark green color as interpreted by *L**-values ranging from 30.56 to 39.12, *a**-values ranging from -6.64 to -8.00, and *b**-values ranging from 14.83 to 17.42. The

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Table 3. Color characteristics of fresh and dried *Salicornia herbacea* as affected by drying temperature.

Drying temperature (°C)	Color functions					
	*L**-value	*a**-value	*b**-value	*C**-value	*h**-value	Δ*E**
Fresh	34.68±2.65[b]	-6.91±0.53[a]	15.60±1.63[c]	17.07±0.23[c]	114.00±1.54[a]	-
50	57.52±0.41[a]	-7.99±0.05[b]	28.92±0.23[b]	30.00±0.23[b]	105.44±0.08[b]	26.48
60	57.39±0.29[a]	-8.17±0.04[c]	28.98±0.25[b]	30.11±0.25[b]	105.75±0.09[b]	26.40
70	57.40±0.26[a]	-7.96±0.08[b]	29.05±0.13[b]	29.96±0.75[b]	105.37±0.10[b]	26.44
80	57.51±0.25[a]	-8.46±0.06[d]	29.95±0.23[a]	31.12±0.22[a]	105.78±0.14[b]	27.03

[a-c] Different letters within the same column indicate significant difference (P< 0.05).

drying of *Salicornia herbacea* produced a considerable change in color, regardless of the drying temperature. The vacuum drying process influenced the color parameters in dissimilar ways, in which the *L**-, *b**-, and *C**-values increased significantly while *a**- and *h**-values decreased significantly after drying at any temperature (P< 0.05), implying the color change of *Salicornia herbacea* to light green.

Increasing the drying temperature from 50 to 80°C did not have a significant effect (P > 0.05) on either the lightness (*L**) or hue angle (*h**) of the dried *Salicornia herbacea*. Interestingly, the *a**-value was significantly influenced by the drying temperature (P<0.05) but no direct relationship was found, whereas the *b**- and *C**-values for the samples dried at 80°C were significantly higher than the others (P< 0.05). Total color difference, Δ*E**, ranged from 26.40 to 27.03. The highest Δ*E** value was observed for the sample dried at 80°C; however, the difference in Δ*E** values from the other temperatures was small and the drying time taken was much shorter than for the other drying temperatures. Thus, drying *Salicornia herbacea* at 80°C could be considered to be optimum for obtaining a high quality product while reducing the drying time.

Morphology of Dried *Salicornia herbacea*

Different drying conditions can produce diverse surface structures of materials. The effect of drying temperature on the structure of the dried *Salicornia herbacea* was observed under a scanning electron microscope. Figure 6 shows modifications in the *Salicornia herbacea* tissue in the course of drying at temperatures of 50, 60, 70, and 80°C. Noticeable open structures or pores were not found, in contrast to other studies (Prachayawarakorn *et al*., 2006; Giri and Prasad, 2007), but it appeared that a relatively higher amount of wrinkles and more disrupted structure were found as drying temperature increased. Such wrinkle formation was possibly induced by moisture stresses, which increased as the drying rate was accelerated, and developed during drying. Nowak and Lewicki (2005) also suggested that the drying rate can be responsible for the structural changes occurring in the material. Larger shrinkage stresses at high drying rates causes more severe damage in the tissue structure than at low drying rates (Nowak and Lewicki, 2005).

CONCLUSIONS

The vacuum drying of *Salicornia herbacea* samples took place in the falling rate period. The moisture content and drying rate were significantly influenced by the drying temperature. Increasing the drying temperature caused a decrease in the drying time with an increase in the drying rate. The logarithmic model showed the best fit to the experimental results among the tested drying models, and it

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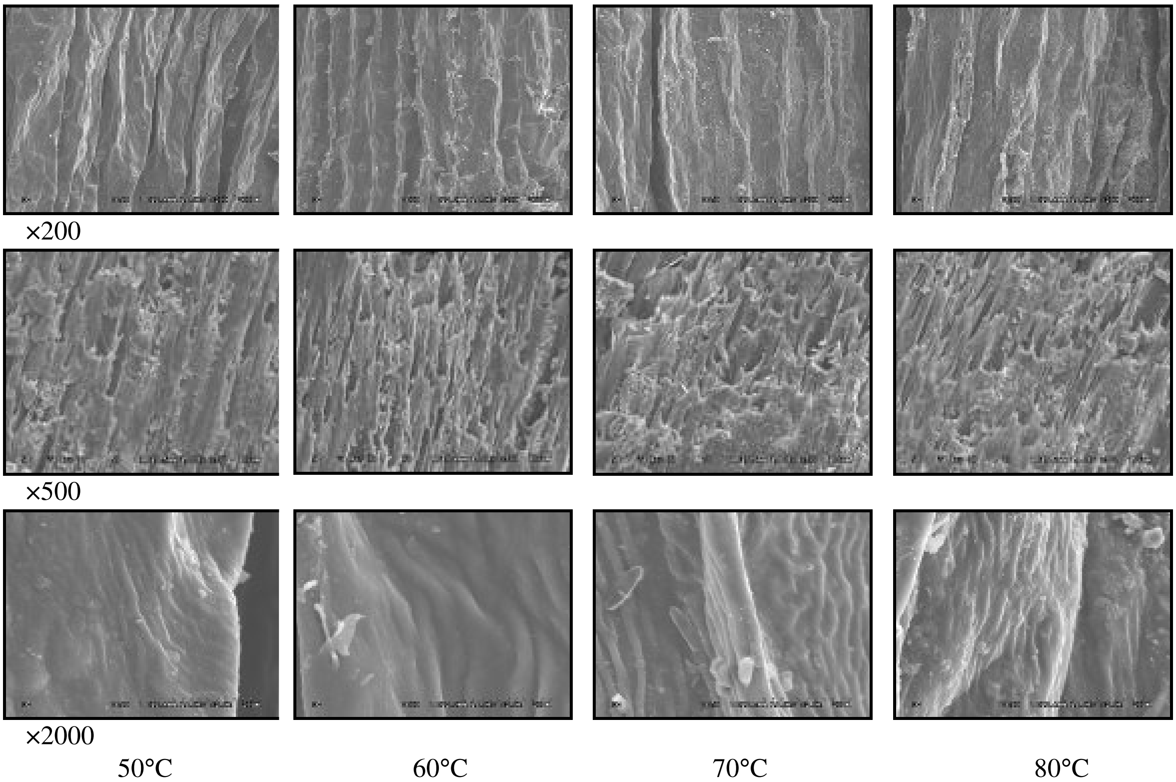

Figure 6. Scanning electron microscope photographs (5.0 kV ×200, ×500, and ×2000) of dried *Salicornia herbacea* samples as influenced by drying temperature.

could be used to describe the thin layer vacuum drying behavior of the *Salicornia herbacea* samples. The activation energy for moisture diffusion was found to be 15.02 kJ mol^{-1}. The drying of *Salicornia herbacea* produced considerable change in color, regardless of drying temperature. SEM analysis indicated no noticeable open structures or pores, however, relatively higher amount of wrinkles and more disrupted structure were observed as drying temperature increased.

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ویژگی های خشک کردن خلایی سالیکورنیا .*Salicornia herbacea* L

ج. ه. لی، ه. ج. کیم، و ج. و. ریم

چکیده

این بررسی به منظور ارزیابی ویژگی های خشک کردن خلایی سالیکورنیا ***Salicornia herbacea*** Lدر درجه حرارت های مختلف (۵۰، ۶۰، ۷۰، و ۸۰ درجه سانتی گراد) و تعیین اثر درجه حرارت خشک کردن روی کیفیت سالیکورنیا انجام شد. با افزایش درجه حرارت خشک کردن، زمان خشک شدن به طور معنی داری($P<0.05$) کاهش یافت. نرخ خشک شدن با کاهش رطوبت موجود در نمونه ها و افزایش زمان خشکاندن کم شد. از سوی دیگر، نرخ خشک شدن با افزایش درجه حرارت زیاد شد. در میان مدلهای مختلف آزمون شده، مدل لگاریتمی برازش بهتری با داده های آزمایش نشان داد. ضرایب خشک شدن که با کاربرد مدل لگاریتمی برآورد شده بودند تحت تاثیر درجه حرارت خشک کردن قرار داشتند. انرژی فعال ساز برای خشک کردن برابر15.02 kJ mol^{-1} بود. رنگ سطح نمونه های سالیکورنیا به گونه ای معنی دار($P<0.05$) تحت تاثیر درجه حرارت خشکاندن قرار داشت. در کلیه درجه حرارت های به کار رفته در فرایند خشک کردن، مقادیر-CIE L* و-b* و کروما -(C*)به طور معنی داری افزایش یافت در حالی که مقادیر-a* و زاویه هیو-(h*) به طور معنی دار ($P<0.05$)کم شدند.

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