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RESEARCH NOTE

Rehydration Kinetics of Vacuum-dried *Salicornia herbacea*

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Abstract Rehydration kinetics of *Salicornia herbacea* prepared by vacuum drying at 70 or 80°C was studied at water temperature of 30, 60, and 90°C, respectively. A 2-term 5-parameter exponential decay model was used to describe the rehydration process. The rehydration times for the *S. herbacea* to reach maximum water absorption (t_M) at each rehydration condition varied depending on the rehydration temperature and the drying air temperature. The inverse of the time ($1/t_M$) showed linear temperature dependency as described by the Arrhenius-type relationship. The activation energy values for the *S. herbacea* dried at 70 and 80°C were 17.66 and 21.06 kJ/mol, respectively.

Keywords: *Salicornia herbacea*, rehydration, kinetics, Arrhenius relationship

Introduction

Drying is one of the most important preservation methods to prepare shelf-stable foods for the long-term preservation of products (1). Moisture removal through drying prevents the growth of spoilage microorganisms, slows the action of enzymes, and minimizes many moisture mediated reactions (2). Drying provides not only a longer shelf-life to food but also results in lighter weight for transportation and less required storage space. Drying is also used as a pretreatment for further processes, such as milling to make powdered products. Currently, a wide variety of dehydrated foods are available to consumers and such foods are typically rehydrated before use.

Rehydration cannot be regarded as a simple reverse process of dehydration (3). Rehydration is a complex process and should be considered as a measure of the injury to the material caused by drying (4). A thorough understanding of the operation and problems related to the design of the rehydration process is essential to meet quality specifications and conserve energy (1,2). From a processing and engineering point of view, it is important to know how fast the absorption of water takes place, how it is affected by the processing variables, and how the rehydration time under given conditions is predicted (5).

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 seashores of the Korea peninsula (6,7). *S. herbacea* is rich in natural minerals and dietary fibers (8), and is currently receiving renewed interest because of its nutritional benefits and functional properties (9,10). It is mainly processed into dry powder, pill, or liquid extract forms, and is used as additive in the production of soy sauce, fermented soybean paste, red pepper paste, bread, rice cakes, etc.

Knowledge of the rehydration kinetics of dried *S. herbacea* is required to understand the mechanisms and the influence that certain process variables exert on moisture transfer (11,12). Although several studies have been reported on the rehydration kinetics of various foods including broccoli (13), banana (14), shrimp (15), mushroom (16), and avocado (17), data on the rehydration kinetics of *S. herbacea* are not available in the literature.

The objective of this work was to study the rehydration kinetics of vacuum-dried *S. herbacea* dried at different drying air temperatures as well as the effects of rehydration temperatures and the drying air temperatures on the rehydration kinetics of the plant.

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Materials and Methods

Materials Fresh *Salicornia herbacea* was purchased from Dasarang Co., Ltd. (Jeonnam, Korea), which was harvested during June at closed salt farms in Shinan, Jeonnam, Korea, and was kept in a 4°C refrigerator before use. Prior to dehydration, the plants were cut into small pieces of approximately 10 cm in length and washed with running water to remove any surface dirt. Excess surface moisture was first removed using a salad spinner (Myeongmoon LC Corp., Seoul, Korea) and then any extra surface water was dried at room temperature for 30 min.

Sample preparation The fresh *S. herbacea* samples were immediately weighed and dried without any pre-treatments. About 60 g of a shredded sample (about 10 cm long) was dried in a vacuum dryer (VOS-301SD; Tokyo Rikakikai Co., Tokyo, Japan) at different air temperatures of 70 and 80°C and an absolute pressure of 0.1 mPa. Drying was completed when the sample reached a constant weight, which was determined by 3 consecutive measurements without a significant change in weight.

Rehydration The dehydrated samples (about 2 g) were rehydrated by immersing in distilled water at temperatures of 30, 60, and 90°C with a ratio of sample to water of 1:50 (w/w). The water was drained at different time intervals for 60 sec using a tea drainer and surface water was removed with blotting paper. The samples were then weighed using an electronic balance (BP221S; Sartorius AG, Göettingen, Germany) with an accuracy of 0.0001 g. Each experimental run was performed in triplicate and mean values were used for further analysis.

Data analysis The rehydration ratio (*RR*) was determined as the ratio of the difference between the weight measured at a given time (m_t) and the initial weight to the initial dry matter (m_o) of a sample according to Eq. (1):

$$RR = \frac{m_t}{m_o} \quad (1)$$

Non-linear least square regression analysis was performed using the Levenberg-Marquardt procedure in the SigmaPlot computer program (SigmaPlot®, SPSS Inc., Chicago, IL, USA) to fit the following 2-term 5-parameter exponential decay model to the experimental *RR* data:

$$RR = y_0 + a\ \exp(-bt) + c\ \exp(-dt) \quad (2)$$

The predicted *RR* data determined using the exponential decay model were compared with the experimental data and the maximum water absorption time (t_M) was determined at each rehydration temperature. The inverse of t_M was used as the rate constant (k) of each *S. herbacea* sample to reach the maximum imbibitions of water as suggested by Rhim (18). The temperature dependency of the rate constant (k) was tested using a simple Arrhenius-type relationship:

$$k = k_0 \exp\left(-\frac{E_a}{RT}\right) \quad (3)$$

where, k_0 is the pre-exponential factor (1/min), E_a the activation energy (kJ/mol), R the universal gas constant (8.314 J/mol·K), and T the absolute temperature (K). The activation energy was determined by plotting the natural logarithm of k versus the reciprocal of the absolute temperature.

Results and Discussion

Rehydration characteristics Figure 1A and 1B present the results of the water absorption characteristics of *S. herbacea* in terms of *RR* at different soaking temperatures and times for the rehydration of test samples dehydrated at 70 and 80°C, respectively. The dehydrated *S. herbacea* absorbed water rapidly at the early stage of the rehydration process, which then slowed at the later stage and ceased after reaching the maximum imbibition. Water absorption ultimately stopped at the point of maximum water imbibition, indicating that the water absorption approached an equilibrium condition. This trend was similar at all soaking temperatures regardless of the sample drying temperature. However, samples rehydrated at 90°C exhibited lower rehydration capacity than the samples rehydrated at 60°C after reaching the equilibrium. This may be possibly due to changes in the structure/texture of samples rehydrated at such high temperature. Maskan (19) reported lower rehydration capacity of microwave dried kiwifruit slices as compared with the samples dried using hot air or hot air-microwave combined for similar reasons. The rapid water uptake at the early stage was probably due to the filling of capillaries on the surface (18,23,24). The decreased rehydration rate in the later stage was likely attributable to the filling of free capillary and intermicellar spaces with water as the rehydration process progressed (18). Similar hydration phenomena have been observed with various food materials such as soybeans (18), osmotically pretreated apples (20), lupin seeds (21), rice kernels (22), microwave dried spinach (3), and potato (1).

Figure 1A and 1B also indicate that the rehydration rate was significantly affected by the drying temperatures. The rehydration rate increased as the drying temperature increased from 70 to 80°C. This is probably due to the development of more surface wrinkles by vacuum drying the *S. herbacea* at higher temperature, which in turn would increase the amount of surface area for moisture diffusion.

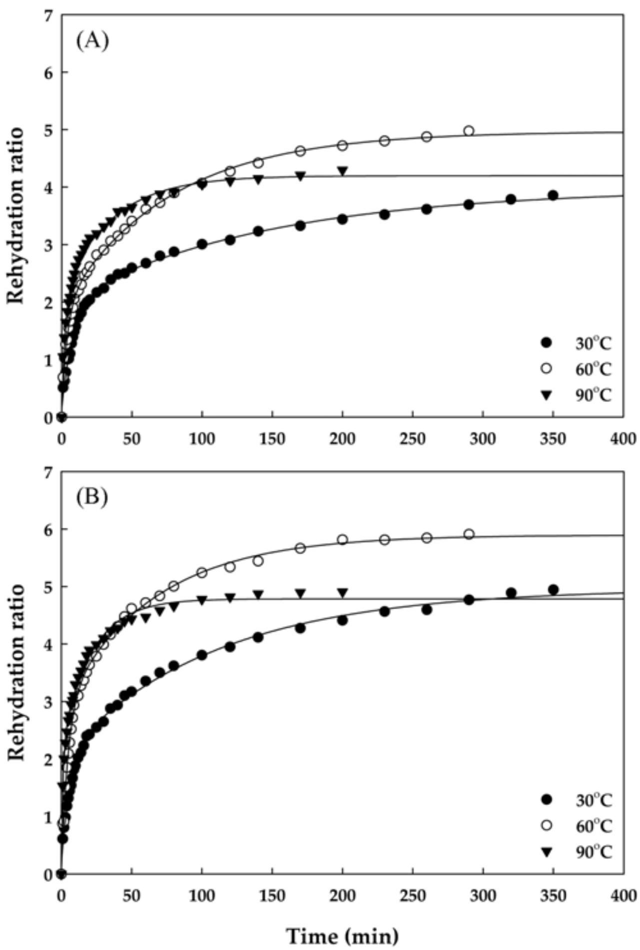

Fig. 1. Experimental and estimated rehydration curves at different rehydration temperatures for *S. herbacea* samples vacuum-dried at (A) 70 and (B) 80°C, respectively. Solid line (—) represents curve fitting using 2-term 5-parameter exponential decay model and given temperature.

Improved quality after rehydration has been reported for carrots that were fluidized-bed dried at higher temperature due to a higher rehydration rate and causing less shrinkage of the dried carrots (25).

The rehydration ratios at 90°C were higher than those at 60°C followed by 30°C in the early stage of rehydration for samples dried at the same drying temperature. This indicates that the higher the temperature of the steeping water, the faster the diffusion of the water into the material. A similar effect of rehydration temperature on rehydration was observed for various dehydrated agricultural products such as banana, corn, potato, and leek (2), as well as carrot (26), spinach (3), and water chestnut (27).

Rehydration kinetics Equation 2 was used to fit the experimental data with the curves. The parameters estimated using non-linear regression analysis are shown in Table 1. The high coefficient of determination (R^2) indicates a very good fit of the model to the experimental data. This implies that the 2-term 5-parameter exponential decay model reasonably described the absorption kinetics of *S. herbacea*, as shown in Fig. 1A and 1B, respectively.

The rehydration times for the *S. herbacea* samples to reach maximum absorption (t_M) at each rehydration condition were evaluated using the 2-term 5-parameter exponential decay model. The results are shown in Table 1. The t_M varied depending on the rehydration temperature as well as the drying air temperature. It was indicated that samples rehydrated at lower temperature required more time to reach an equilibrium condition. In addition, t_M decreased exponentially with an increase in rehydration temperature. This time period represents the time required or elapsed to reach a certain degree of reaction (18), and the inverse of the time can be considered the reaction rate constant (k) of the *S. herbacea* samples to absorb the maximum moisture (28).

Interestingly, the inverse of the time ($1/t_M$) showed linear temperature dependency as described by the Arrhenius-type relationship shown in Fig. 2 with the following:

$$ln(1/t_M) = -2124(1/T) + 0.260 \qquad (R^2=0.97)$$
for samples dried at 70°C

$$ln(1/t_M) = -2533(1/T) + 1.718 \qquad (R^2=0.93)$$
for samples dried at 80°C

The relatively high coefficient of determination suggests that the rate constants determined by this method fit adequately to the Arrhenius kinetic model. The activation energy and pre-exponential factor values determined using the above relationships for *S. herbacea* dried at 70 and

Table 1. Parameters estimated using Eq. 2 for rehydration process of *S. herbacea*

Rehydration temp. (°C)	Drying air temp. (°C)	t_M (min)	Parameter					R^2
			y_0	a	b	c	d	
30	70	840	3.9685	-1.8190	0.1205	-1.9883	0.0070	0.9996
	80	695	4.9632	-1.8644	0.1504	-2.9085	0.0091	0.9995
60	70	520	4.9676	-1.7587	0.2434	-3.0600	0.0130	0.9993
	80	440	5.8953	-2.8305	0.2040	-2.9907	0.0153	0.9997
90	70	260	4.1968	-1.9471	0.3702	-2.0913	0.0286	0.9994
	80	175	4.7850	-2.1968	0.8156	-2.5439	0.0463	0.9995

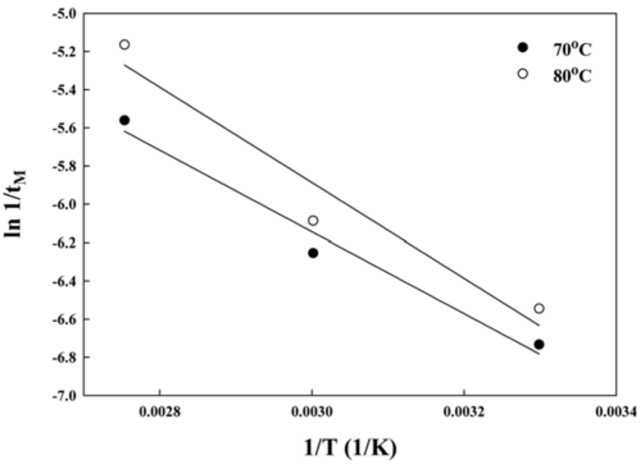

Fig. 2. Temperature dependency of the rehydration time to reach the equilibrium condition for *S. herbacea* samples vacuum-dried at 70 and 80°C.

80°C were 17.66 kJ/mol and 1.30/min, and 21.06 kJ/mol and 5.57/min, respectively. The activation energy values for the rehydration of *S. herbacea* determined using the proposed method in this study agree well with reported values of other agricultural products. Abu-Ghannam and McKenna (24) reported an activation energy value of 27.22 kJ/mol for the hydration of blanched red kidney beans while Dadali *et al.* (3) reported a value of 23.84 kJ/mol for the rehydration of microwave dried spinach. The present results are also comparable with activation energy values reported for dried Asian white radish slices (16.49-20.26 kJ/mol) (29), olive cake (17.97 kJ/mol) (30), *Agaricus bisporus* mushrooms (19.79 kJ/mol) (31), lettuce and cauliflower leaves (19.82 kJ/mol) (32), and red delicious apples (19.957-22.624 kJ/mol) (33). This indicates that the simple kinetic method proposed in the present study can be conveniently used to determine of kinetic parameters in the rehydration of plant materials. Modeling the kinetics of moisture uptake depending on the sample prepared by drying at different temperatures could lead to a better understanding and control over the mechanisms underlying the sorption process and the ability of the product to rehydrate. Such information is vital in process and quality optimization.

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References

1. Cunningham SE, McMinn WAM, Magee TRA, Richardson PS. Experimental study of rehydration kinetics of potato cylinders. Food Bioprod. Process. 86: 15-24 (2008)
2. Krokida MK, Marinos-Kouris D. Rehydration kinetics of dehydrated products. J. Food Eng. 57: 1-7 (2003)
3. Dadali G, Demirhan E, Özbek B. Effect of drying conditions on rehydration kinetics of microwave dried spinach. Food Bioprod. Process. 86: 235-241 (2008)
4. McMinn WAM, Magee TRA. Physical characteristics of dehydrated potatoes-Part II. J. Food Eng. 33: 49-55 (1997)
5. Krokida MK, Philippopoulos C. Rehydration of dehydrated foods. Dry. Technol. 23: 799-830 (2005)
6. Kim CS, Song TG. Ecological studies on the halophyte communities at western and southern coasts in Korea. Korean J. Ecol. 6: 167-176 (1983)
7. Jang HS, Kim KR, Choi SW, Woo MH, Choi JH. Antioxidant and antithrombus activities of enzyme-treated *Salicornia herbacea* extracts. Ann. Nutr. Metab. 51: 119-125 (2007)
8. Min JG, Lee DS, Kim TJ, Park JH, Cho TY, Park DI. Chemical composition of *Salicornia herbacea* L. J. Food Sci. Nutr. 7: 105-107 (2002)
9. Lee JT, Jeong YS, An BJ. Physiological activity of *Salicornia herbacea* and its application for cosmetic materials. Korean J. Herbol. 17: 61-69 (2002)
10. Jeong CY, Rhy JS, Choi CK, Jeon BS, Park JW, Shin GG, Kim BK, Bae DW, Cha JY. Supplemented effect of *Salicornia herbacea* extract powder on preparation and quality characteristics of fermented milk product. J. Life Sci. 14: 788-793 (2004)
11. Tong CH, Lund DB. Effective moisture diffusivity in porous materials as a function of temperature and moisture content. Biotechnol. Progr. 6: 67-75 (1990)
12. Gekas V, Lamberg I. Determination of diffusion coefficients in volume changing systems-application in the case of potato drying. J. Food Eng. 13: 317-326 (1991)
13. Sanjuan N, Simal S, Bon J, Mulet A. Modelling of broccoli stems rehydration process. J. Food Eng. 42: 27-31 (1999)
14. Maskan M. Microwave/air and microwave finish drying of banana. J. Food Eng. 44: 71-78 (2000)
15. Namsanguan Y, Tia W, Devahastin S, Soponronnarit S. Drying kinetics and quality of shrimp undergoing different two-stage drying processes. Dry. Technol. 22: 759-778 (2004)
16. Garcia-Pascual P, Sanjuan N, Bon J, Carreres J, Mulet A. Rehydration process of *Boletus edulis* mushroom: Characteristics and modeling. J. Sci. Food Agr. 85: 1397-1404 (2005)
17. Lee KT, Farid M, Nguang SK. The mathematical modelling of the rehydration characteristics of fruits. J. Food Eng. 72: 16-23 (2006)
18. Rhim JW. Hydration kinetics of soybeans. Food Sci. Biotechnol. 12: 303-306 (2003)
19. Maskan M. Drying, shrinkage, and rehydration characteristics of kiwifruits during hot air and microwave drying. J. Food Eng. 48: 177-182 (2001)
20. Bakalis S, Karathanos VT. Study of rehydration of osmotically pretreated dried fruit samples. Dry. Technol. 23: 533-549 (2005)
21. Solomon WK. Hydration kinetics of lupin (*Lupinus albus*) seeds. J. Food Process Eng. 30: 119-130 (2007)
22. Bello MO, Tolaba MP, Suárez C. Hydration kinetics of rice kernels under vacuum and pressure. Int. J. Food Eng. 4: 1-21 (2008)
23. Hsu KH, Kim CJ, Wilson LA. Factors affecting water uptake of soybeans during soaking. Cereal Chem. 60: 208-211 (1983)
24. Abu-Ghannam N, McKenna B. The application of Peleg's equation to model water absorption during the soaking of red kidney beans (*Phaseolus vulgaris* L.). J. Food Eng. 32: 391-401 (1997)
25. Prakash S, Jha SK, Datta N. Performance evaluation of blanched carrots dried by three different driers. J. Food Eng. 62: 305-313 (2004)
26. Planinić M, Velić D, Tomas S, Bilić M, Bucić A. Modelling of drying and rehydration of carrots using Peleg's model. Eur. Food Res. Technol. 221: 446-451 (2005)
27. Singh GD, Sharma R, Bawa AS, Saxena DC. Drying and rehydration characteristics of water chestnut (*Trapa natans*) as a function of drying air temperature. J. Food Eng. 87: 213-221 (2008)
28. Rhim JW, Jones VA, Swartzel RS. Texture degradation kinetics of sweet potatoes during heat treatment. Food Sci. Biotechnol. 11: 24-28 (2002)
29. Lee JH, Kim HJ. Vacuum drying kinetics of Asian white radish

(*Raphanus sativus* L.) slices. Lebensm. -Wiss. Technol. 42: 180-186 (2009)
30. Akgun NA, Doymaz Ý. Modeling of olive cake thin-layer drying process. J. Food Eng. 68: 455-461 (2005)
31. Arora S, Shivhare US, Ahmed J, Raghavan GSV. Drying kinetics of *Agaricus bisporus* and *Pleurotus florida* mushrooms. T. ASAE 46: 721-724 (2003)
32. Lopez A, Iguaz A, Esnoz A, Virseda P. Thin-layer drying behavior of vegetable wastes from wholesale market. Dry. Technol. 18: 995-1006 (2000)
33. Kaya A, Aydin O, Demirtas C. Drying kinetics of red delicious apple. Biosyst. Eng. 96: 517-524 (2007)