JMBFS
Journal of Microbiology, Biotechnology and Food Sciences
International peer-reviewed scientific online journal
Published by Faculty of Biotechnology and Food Sciences

OSMOTIC DEHYDRATION OF WHITE RADISH (*Raphanus Sativus* L.) SLICES: MASS TRANSFER CHARACTERISTICS AND MODELING

*NGUYEN MINH THUY[1], DINH THI NHI[1], VO QUANG MINH[2], NGO VAN TAI[*1,3]*

Address(es): NGO VAN TAI,
[1]Department of Food Technology, College of Agriculture, Can Tho University, Can Tho city, 900000, Vietnam.
[2]Department of Land Resources, College of Environment and Natural Resources, Can Tho University, Can Tho city, 900000, Vietnam.
[3]School of Food Industry, King Mongkut's Institute of Technology Ladkrabang, Bangkok 10520, Thailand.

*Corresponding author: ngovantai1509@gmail.com

https://doi.org/10.55251/jmbfs.4940

ARTICLE INFO

Received 23. 6. 2021
Revised 20. 5. 2022
Accepted 27. 9. 2022
Published 1. 12. 2022

Regular article

OPEN ACCESS

ABSTRACT

White radish sliced at 4 mm thickness was dehydrated by traditional osmotic dehydration (TOD) with nine types of osmotic solutions prepared by a randomized combining three levels concentration of sucrose and sodium chloride. The mass transfer characteristics were evaluated through the moisture diffusivity (D_m) and solid diffusivity (D_s), the fit of model was also estimated based on three popular models, including Newton, Henderson, and Pabis and Weibull. The results showed that white radish had the highest D_m and D_s value in the 4% salt and 15% sucrose solution, which presented that the fastest transfer process occurred in this solution. In addition, the Weibull model was the best model due to the highest R^2 and the lowest root mean square error and chi-square, which means this model could fully describe the mass transfer (moisture/solid transfer) behavior of white radish.

Keywords: mass transfer behavior, osmotic dehydration, solid gain, water loss, white radish

INTRODUCTION

Around the world, radishes are widely grown and consumed and are also considered part of the human diet. Recent studies have shown that radish contains unique bioactive components and has been recognized as having potential health benefits for humans (**Banihani, 2017**). The mild spicy substance in white radish helps antibacterial, relieves pain, helps support the liver, and prevents cardiovascular disease because it contains the betaine - a biological substance. In Vietnam, white radish is produced in a very large area in both the South and the North; however, it still struggles to "output". Not many products are made from white radish, so this precious raw material has not been used effectively. Therefore, processing products from white radish is also a way to reduce post-harvest losses and improve the value of this commodity. Due to high moisture content, white radishes were quickly spoilage by microorganisms (**Rawat, 2005**). Food preservation to extend shelf life while ensuring safety and quality is a primary concern of the food industry. Osmotic dehydration is one of the most common pretreatment processes that can effectively enhance the shelf life of fruits and vegetables. Osmotic dehydration is widely used in food preservation because it reduces water activity in fruits and vegetables (**Yadav and Singh, 2014**). Osmotic dehydration is preferred over other methods thanks to the retention ability of their color, aroma, and nutritional components (**Chavan and Amarowicz, 2012**). Sugar and salt (sodium chloride) or brine with vegetables are commonly used as solutes in osmotic dehydration. Mass transfer kinetics is an important characteristic to consider while researching osmotic dehydration. Solid/water diffusion was discovered to follow Fick's second law of diffusion over a wide range of temperatures. These figures differ depending on the type of fruit or vegetable as well as the osmotic agents used (**Yadav and Singh, 2014**). The mass transfer process is strongly influenced by the mass media, including the type and concentration of the mass media (**Tortoe, 2010**). One of the issues that should be considered is the quality of the mass media, the solution used must not only have a good taste but also can improve the nutritional and sensory value of the product (**Chandra and Kumari, 2015**). Salt, sugar or a combination of these two solutions are often used to infiltrate vegetables.
To describe the osmosis process, osmotic kinetics is often constructed to analyze the transfer between the material and the osmotic medium. However, this process depends on many external and internal factors. In recent studies, kinetic models often describe the osmotic dehydration process (**Corrêa *et al.*, 2016**; **Corzo *et al.*, 2008; Thuy *et al.*, 2022**). However, at present, the mass transfer kinetics of sliced radish has been not yet thoroughly studied, including the influence of medium and osmotic agents on mass transfer. Therefore, the study was carried out to apply different mass transfer media to determine the mass transfer rate (water loss and solid gain) and to apply three mass transfer models to describe the transfer kinetics. Simultaneously, parameters describing the transfer process are also calculated and discussed.

MATERIAL AND METHODS

Sample preparation

The white radish was harvested and purchased from a local market in Can Tho city, Vietnam. The initial moisture content of the material was 94.71±0.06% (fresh weight). After being collected, it was washed under running tap water, peeled and sliced to 4 mm in thickness with 4±0.2 cm of the diameter.

Osmotic treatment procedure

Nine different solutions were prepared by a random combination of three different concentrations of sucrose (10; 12.5; 15% w/v) and sodium chloride (NaCl) (2; 3; 4% w/v) in combination with distilled water. To ensure that the concentration of the solution is not affected by the input material, the ratio of material and medium is fixed at 1:10 (w/w). 25 g sample was weighed, soaked and emerged in osmotic solutions (sucrose and NaCl) at ambient temperature for 420 min. During treatment, samples were randomly taken out at 30, 60, 90, 120, 150, 180, 210, 240, 270, 300, 330, 360, 390 and 420 min for measurement. The material is washed off the penetrant agents and used a paper towel to remove the moisture at the surface to achieve the most accurate results.

Osmotic dehydration behaviors

The change of water loss (WL) and solids gain (SG) describe the osmotic transfer kinetics. WL and SG of the samples were calculated by **Equations 1&2**, respectively.

$$WL = \frac{M_o X_o - M_t X_t}{M_o} \times 100\% \qquad (1)$$

$$SG = \frac{M_t S_t - M_o S_o}{M_o} \times 100\% \qquad (2)$$

Where M_o and M_t are the weight of the sample at initial and time t, respectively (g); X_o and X_t are moisture content (%) of sample at initial and time t, respectively; S_o and S_t are the solid content of the sample at initial and time t, respectively (%)

Determination of diffusion coefficients

Doymaz and İsmail (2011) described two formulas to calculate the ratio of moisture and solid as following **Equation 3&4**, respectively.

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

$$SG = \frac{SG - SG_e}{SG_e} \quad (4)$$

Where WL_e and SG_e are the WL and SG at an equilibrium point.
In addition to calculating WL_e and SG_e, **Equation 5&6** were used, respectively **(Azuara *et al.*, 1998).** The WL_e and SG_e could be obtained by linear regression using the correlation between $\frac{1}{WL}$ or $\frac{1}{SG}$ and $\frac{1}{t}$.

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

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

where S_1 and S_2 are constant rate, and t is the measurement time.

Fick's second law of diffusion was used to describe the osmosis process, however, due to the long duration of osmosis, the model was simplified as shown in **Equation 7&8** (**Chenlo *et al*., 2006**).

$$MR = \frac{8}{\pi^2} \exp\left(-\frac{\pi^2 D_m t}{4L^2}\right) \quad (7)$$

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

where D_m is the effective moisture (m^2s^{-1})and and D_s is solid diffusivity (m^2s^{-1}), t is the osmotic dehydration time (s) and L is the half-thickness of the samples (m).

Mathematical modeling

Three common mathematical models were selected to fit the experimental data from the osmotic dehydration process (**İspir and Toğrul, 2009**; **Nuñez-Mancilla *et al*., 2001**), including Newton (**Equation 9**), Henderson and Pabis (**Equation 10**), and Weibull (**Equation 11**).

$$MR = \exp(-k_1 t) \quad (9)$$

$$MR = a\exp(-k_2 t) \quad (10)$$

$$MR = \exp\left(-\left(\frac{t}{\beta}\right)^{\alpha}\right) \quad (11)$$

where the kinetic parameter of Newton and Henderson and Pabic model are k_1 and k_2, respectively. The Henderson and Pabis model constant is a, while the Weibul model is described by the shape (α) and the scale (β) parameter.
A non-linear regression analysis was conducted by using Statgraphic Centurions XV.I application. To evaluate the best fit of model, coefficient of determination (R^2), reduced Chi square (χ^2) and root mean square error (RMSE) analyses were used and calculated by using the following **Equation 12**, **13**, **14**.

$$R^2 = 1 - \left[\frac{\sum_{i=1}^{N}(MR_{exp,i} - MR_{pre,i})^2}{\sum_{i=1}^{N}(MR_{exp,i} - \overline{MR}_{pre,i})^2}\right] \quad (12)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}(MR_{exp,i} - MR_{pre,i})^2}{N - z} \quad (13)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^{1/2}\right] \quad (14)$$

where $MR_{exp,i}$ and $MR_{pre,i}$ are the actual and predicted MR at the time (i) during omostic treatment.

Average density determination

The average densities were calculated using **Equation 15** (**Pei *et al.*, 2019**).

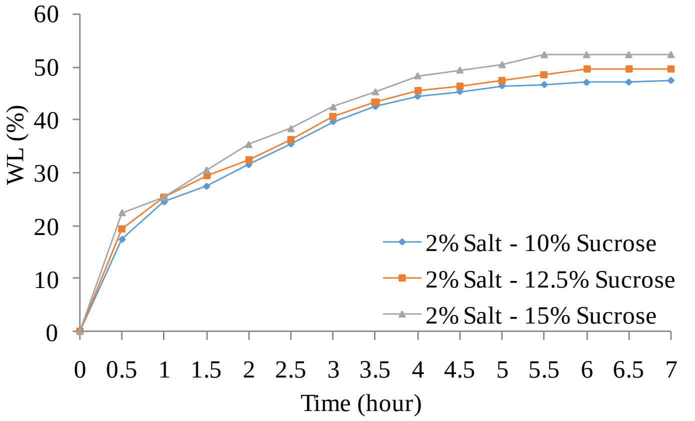
$$\rho = \frac{m}{V} \quad (15)$$

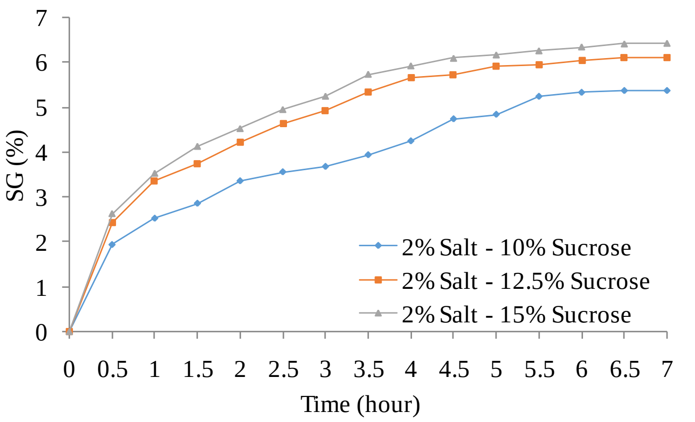
Where ρ is the average density (g/cm^3), m and V are the sample weight (g) and volume (cm^3) after treatment, respectively.

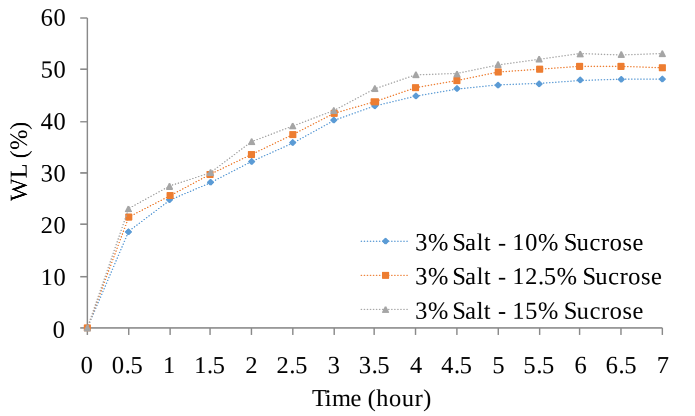
RESULTS AND DISCUSSION

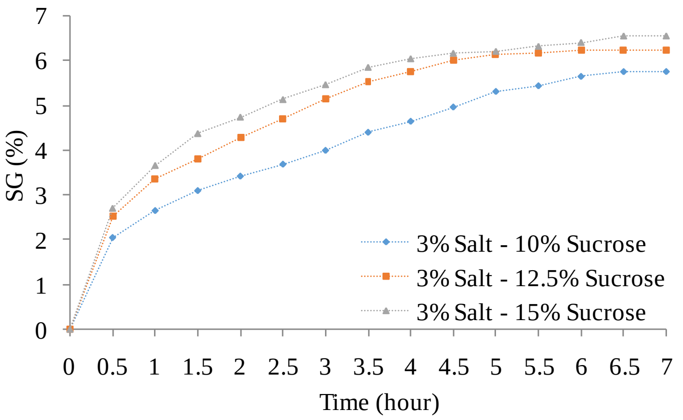
Osmotic dehydration behaviors of sliced white radish

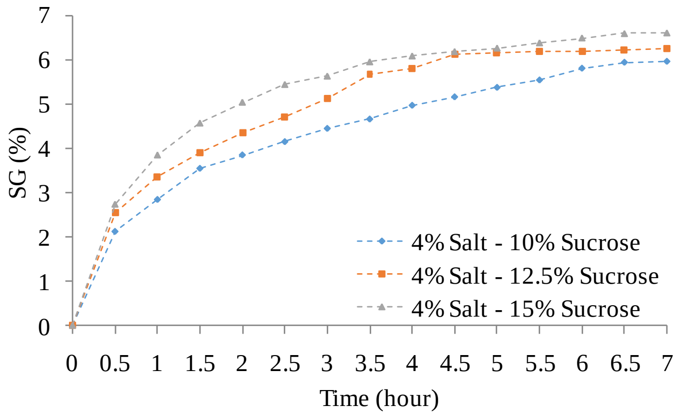
There are many factors affecting the osmosis process. The use of solutions with different concentrations could be one of the critical influencing factors that changed the mass transfer characteristics. The changes in WL and SG of sliced radish during osmotic in other solutions are shown in figure 1. In this study, the treatment solutions were a hypertonic medium. They had a higher osmotic pressure than inside the matrix cell of sample, thus leading to water and solid movement between solution and cells through the cell membrane. With time, a general increase in water loss and solid gain of white radish slices was observed. It could be seen clearly that both the process of WL and SG occurs rapidly in the beginning stages of osmotic dehydration (OD), after 2.5 hours of soaking, these process were slowed down. A similar trend was found in some previous studies (**Park *et al*., 2002**). **Rastogi *et al.* (2002)** explained that the difference between the osmotic pressure in the solution and the cell leads to mass transfer. However, depending on the type of osmotic solution or the concentration of the solution used, the rate of dehydration and increase in solids might also vary. A higher concentration of solution used causes a more significant osmotic pressure differential, leading to a faster WL/SG increase (**Jokic *et al.*, 2007**). Similar results were also found in the study of **Sareban and Souraki (2016)**. The water loss/mass gain did not increase appreciably in the final stages of the experiment (after 4 hours), indicating that the osmotic pressure gradient difference between the hypertonic environment and the material cells had nearly reached equilibrium. The change in osmotic pressure increased the concentration of NaCl used, while simultaneously causing the dehydration content to increase more rapidly. Besides, sodium chloride solution reduces water activity and easily penetrates into cells due to low molecular weight, which leads to more dehydration (**Islam and Flink, 1982**; **Lenart and Flink, 1984**). However, the use concentration of NaCl salt is often limited due to the salty taste of the product.











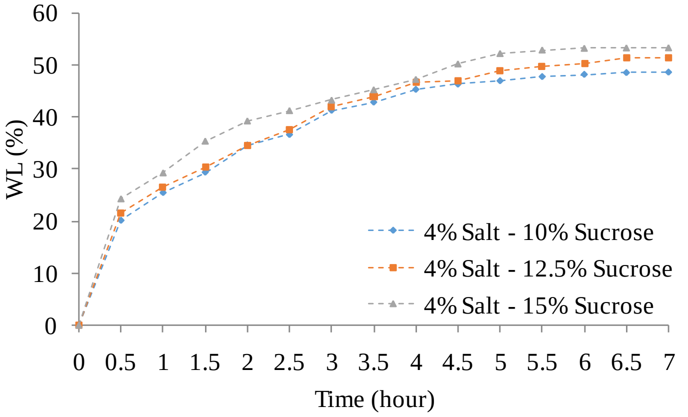


Figure 1 Water loss (WL, %) and solid gain (SG, %) during OD treatment

The non-linear regression analysis was performed in Statgraphics centurion XV.I. The value of rate of constants (S_1, S_2) and water loss/solid gain (WL_e and SG_e) of samples were also obtained and shown in table 1. When the solution concentration increases, an increase of S1, S2, WLe, and SGe means more efficient OD processing thanks to a high concentration in the treatment solution. Specifically, the highest S_1 value obtained was 1.3858 when using a combination of 4% salt and 15% sugar so,lution and the lowest S_1 value (0.9012) was achieved when using 2% salt and 10% sugar in the soaking solution. However, the different trend was found at the change of S_2 value. The lowest and highest S_2 were achieved when using a solution of 4% salt plus 10% sucrose and 4% salt combined with 15% sucrose, respectively. The ionization of sodium chloride and high concentration of sucrose leads to not only the fastest water loss but also solid gain thanks to an increase of the osmotic pressure (**Zhao *et al.*, 2003**). Sample shrinkage occurred in a solution with high salt content causing a high rate of dehydration, but in some cases could reduce the rate of solids gain (**Rastogi *et al.*, 2000**).

Table 1 Osmotic dehydration characteristics of sliced white radish

Salt (%)	Sucrose (%)	S_1	WL_e	D_mx10^{-8}(m^2/s)	S_2	SG_e	D_s x10^{-8}(m^2/s)
	10	0.9012	0.5365	1.3874	1.0018	0.0543	2.8318
2	12.5	1.0387	0.5372	1.6769	1.0760	0.0668	1.5684
	15	1.1745	0.5522	2.0141	1.1335	0.0702	1.5603
	10	0.9864	0.5332	1.5183	0.9747	0.0582	2.6484
3	12.5	1.1766	0.5348	1.9379	1.1014	0.0681	1.6163
	15	1.2447	0.5511	2.1374	1.1586	0.0715	1.4934
	10	1.1230	0.5277	1.6221	0.9555	0.0625	1.8009
4	12.5	1.1890	0.5389	1.9421	1.0988	0.0687	1.5741
	15	1.3858	0.5609	1.9893	1.1690	0.0732	1.3617

The water and solute diffusion coefficient (D_m and D_s) are the most critical parameter to determine the eefficiencyof the OD process (**Yadav and Singh, 2014**). When using osmotic solutions with different concentrations, the values of D_m and D_s were changed. The moisture content of the material, the temperature of the solution, the shrinkage of the material, and the osmotic environment are factors affecting the effective moisture and solid diffusivities (**Seth and Sarkar, 2004**). As seen in Table 1, the D_m and D_s values ranged from 1.3874-2.1374x10^{-8} m^2/s and 1.3617-2.8318x10^{-8} m^2/s, respectively. When the concentration of the osmotic substance is increased in the solution, the concentration gradient is different and leads to the osmotic process. When this difference is ore significant the osmosis rate will occur faster to reach the equilibrium value (**Jokic *et al.*, 2007**). A similar trend of D_s and D_m value was found to correspond with the above-results. Mass transfer of water and dissolved solids oco-occurred during mass transfer between osmotic water into the cell. The higher the obtained mass transfer rate coefficient value presents the more efficient the transfer process (**Yadav and Singh, 2014**).

Model fitting

Three kinetic models were selected to describe the process of the transfer process, including moisture and solid transfer during OD process, using the changes of MR/SR versus time of treatment. The actual data (MR/SR) were measured through non-linear regression analysis, the rate of constant as well as coefficient determination; RMSE and chi-square were obtained and shown in table 2 and 3.

Table 2 Model fitting for moisture transfer in sliced white radish during osmotic dehydration

Model	Salt (%)	Sucrose (%)	Model constants		RSME	R^2 (%)	χ^2
		10	k = 0.4438		0.0545	95.52	0.0032
	2	12.5	k = 0.4882		0.0514	96.20	0.0028
		15	k = 0.5331		0.0516	96.38	0.0029
		10	k = 0.4734		0.5269	95.93	0.0030
Newton	3	12.5	k = 0.5326		0.0526	96.19	0.0030
		15	k = 0.5518		0.0552	95.86	0.0033
		10	k = 0.5191		0.0550	95.56	0.0032
	4	12.5	k = 0.5349		0.0538	95.92	0.0031
		15	k = 0.5968		0.0632	94.16	0.0043
		10	a = 0.9071	k = 0.3974	0.0461	97.03	0.0024
	2	12.5	a = 0.9074	k = 0.4388	0.0426	97.58	0.0021
		15	a = 0.9131	k = 0.4841	0.0446	97.49	0.0023
Henderson		10	a = 0.9082	k = 0.4253	0.0443	97.33	0.0023
and Pabis	3	12.5	a = 0.9095	k = 0.4811	0.0450	97.41	0.0023
		15	a = 0.9076	k = 0.4977	0.0480	97.10	0.0023
	4	10	a = 0.9020	k = 0.4625	0.0464	97.06	0.0025
		12.5	a = 0.9038	k = 0.4791	0.0454	97.31	0.0024

		15	a = 0.8883	k = 0.5216	0.0546	95.95	0.0034
Weibull	2	10	α = 0.7217	β = 2.0952	0.0230	99.26	0.0006
		12.5	α = 0.7384	β = 1.8856	0.0238	99.25	0.0007
		15	α = 0.7684	β = 1.7287	0.0346	98.49	0.0014
	3	10	α = 0.7306	β = 1.9520	0.0236	99.24	0.0006
		12.5	α = 0.7538	β = 1.7201	0.0325	98.65	0.0012
		15	α = 0.7532	β = 1.6506	0.0369	98.28	0.0016
	4	10	α = 0.7068	β = 1.7461	0.0210	99.40	0.0005
		12.5	α = 0.7325	β = 1.6985	0.0280	98.97	0.0009
		15	α = 0.6715	β = 1.4563	0.0260	99.08	0.0008

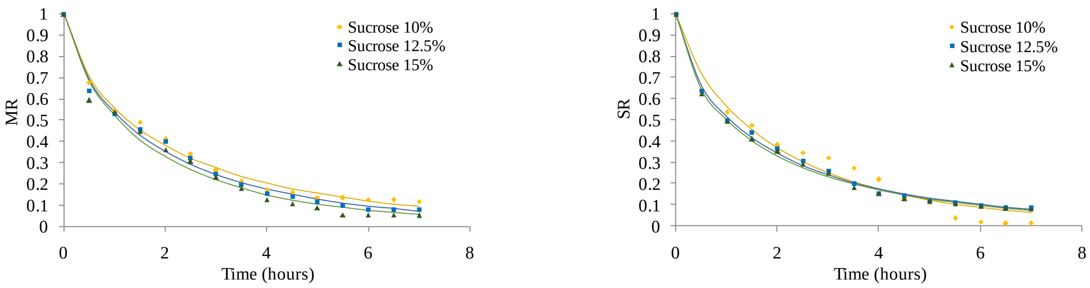
Table 3 Model fitting for solid transfer in sliced white radish during osmotic dehydration

Model	Salt (%)	Sucrose (%)	Model constants		RSME	R^2 (%)	χ^2
Newton	2	10	k = 0.4682		0.0621	95.05	0.0041
		12.5	k = 0.4994		0.0580	94.94	0.0036
		15	k = 0.5201		0.0602	94.49	0.0039
	3	10	k = 0.4607		0.0563	95.92	0.0034
		12.5	k = 0.5092		0.0559	95.40	0.0034
		15	k = 0.5310		0.0647	93.46	0.0045
	4	10	k = 0.4535		0.0554	95.54	0.0033
		12.5	k = 0.5097		0.0571	95.17	0.0035
		15	k = 0.5402		0.0727	91.38	0.0057
Henderson and Pabis	2	10	a = 0.9154	k = 0.4271	0.0569	96.14	0.0037
		12.5	a = 0.9753	k = 0.4403	0.0483	96.74	0.0027
		15	a = 0.8913	k = 0.4558	0.0506	96.39	0.0030
	3	10	a = 0.9196	k = 0.4224	0.0508	96.92	0.0030
		12.5	a = 0.8999	k = 0.4525	0.0469	96.99	0.0025
		15	a = 0.8849	k = 0.4598	0.0551	95.58	0.0035
	4	10	a = 0.9005	k = 0.4037	0.0454	97.23	0.0024
		12.5	a = 0.8996	k = 0.4525	0.0484	96.78	0.0027
		15	a = 0.8757	k = 0.4591	0.0636	93.87	0.0047
Weibull	2	10	α = 0.8090	β = 2.0029	0.0540	96.52	0.0034
		12.5	α = 0.6920	β = 1.8055	0.0179	99.55	0.0004
		15	α = 0.6748	β = 1.7145	0.0147	99.69	0.0002
	3	10	α = 0.8210	β = 2.0490	0.0485	97.19	0.0027
		12.5	α = 0.7075	β = 1.7789	0.0219	99.34	0.0006
		15	α = 0.6473	β = 1.6578	0.0092	99.88	0.0001
	4	10	α = 0.7308	β = 2.0291	0.0262	99.07	0.0008
		12.5	α = 0.7025	β = 1.7759	0.0230	99.27	0.0006
		15	α = 0.6084	β = 1.6030	0.0089	99.88	0.0001

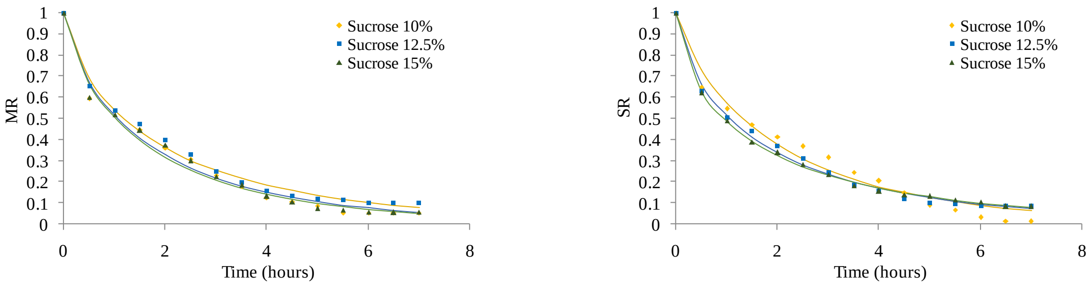
The determination of coefficient, RMSE, and chi-square are the most critical standards in choosing the best model (**Wang *et al*., 2013**). It was observed that the Weibull model gave the highest R^2 and lowest RMSE, chi-square, in both moisture and solid transfer. Similar results were also found in some previous studies, which were performed OD on mushrooms (**Fei *et al*., 2019**); strawberries (**Nuñez-Mancilla *et al*., 2011**).

The parameters of the Weibull model as the shape (α) and scale (β) parameters are used to evaluate and analyze the efficiency of the osmosis process. Value of α parameter lower than 1 is related to a decreasing Weibull distribution function which was observed by concentration effects (**Corzo and Bracho, 2008**). **Moreria *et at.* (2008)** defined the parameter β, which is mass uptake rate and give the time required to complete the mass uptake or dehydration and also depends on the mechanism of process. In the study of **Fei *et al.* (2019)**, sucrose solution gave the highest β value, which means the lowest rate of WL/SG, beside, sodium chloride mediums gave the lowest β value. Combining two kinds of solution helps provide an osmotic balance process.

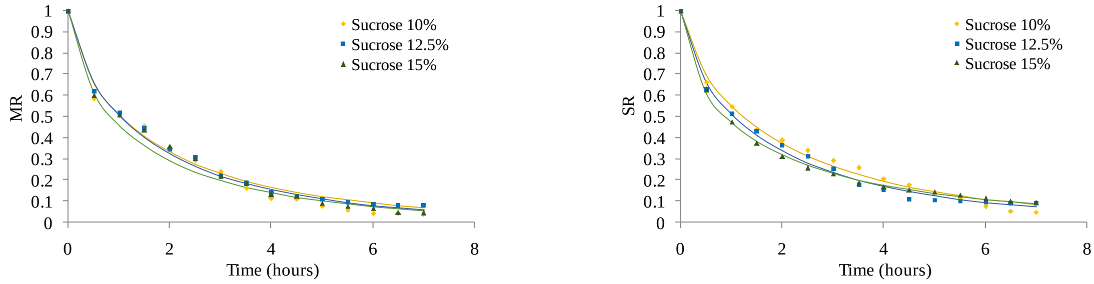
The comparison between the calculated values from Weibull model and experimental values was observed (Figs. 2 & 3). It could be seen that both values were very similar with a high correlation (R^2>98%).



a. 2% Salt



b. 3% Salt



c. 4% Salt

Figure 2 Moisture and solid ratio (*MR* and *SR*, respectively) of white radish during OD with different solutions using Weibull model

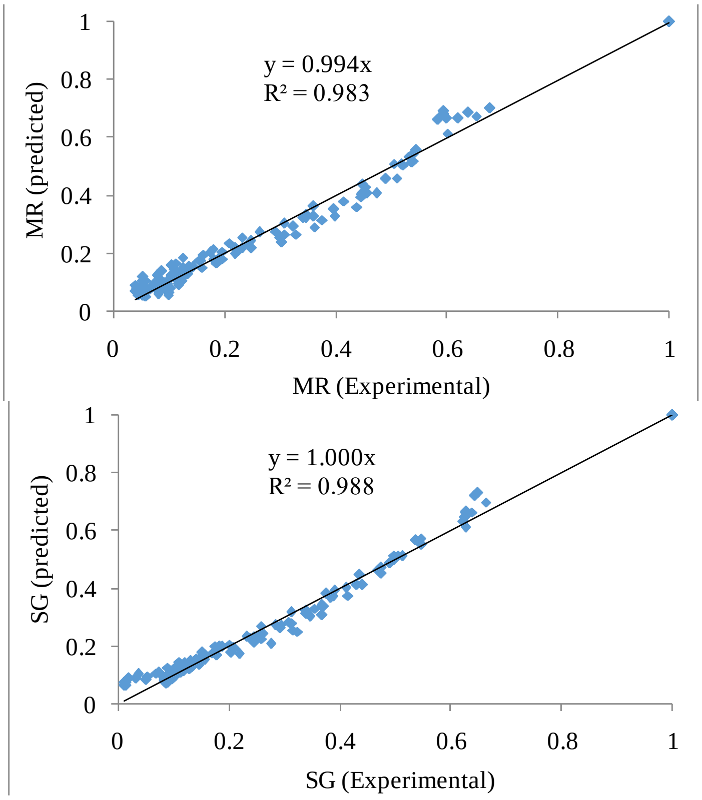


Figure 3 Graphs of MR and SG actual data against calculated data from Weibull model

Average density

After osmotic dehydration, the average density of the samples was calculated and shown in figure 4. With the increase in the treatment concentration, the mean density of white radish was also increased. The mean density of white radish in 4% sodium chloride solution was significantly ($P<0.05$) higher than the lower salt concentrations used. This phenomenon might be due to the more significant difference in the concentration of osmotic ntagent in the soaking medium, making it easier for the solute to infiltrate the tissue (**Fei *et al*., 2019**).

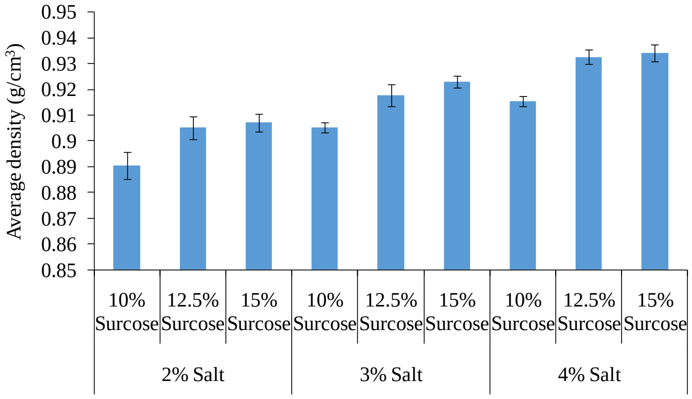


Figure 4 The average density of white radish after osmotic treatment

CONCLUSION

The variation of the mass transfer of the product is strongly influenced by the concentration of salt and sugar used. It can be seen that, in the experimental process, when increasing the concentration of salt and sugar in the osmotic solution, the rate of dehydration and solid gain also increased. Fick's second law equation described the mass transfer of sliced white radish. Among the three models applied to describe the mass transfer process, the Weibull model showed a high agreement between the experimental and estimated data with a high correlation coefficient of determination ($R^2>0.98$).

REFERENCES

Azuara, E., Beristain, C. I., & Gutiérrez, G. F. (1998). A method for continuous kinetic evaluation of osmotic dehydration. *LWT-Food Science and Technology*, *31*(4), 317-321. **https://doi.org/10.1006/fstl.1997.0364**

Banihani, S. A. (2017). Radish (*Raphanus sativus*) and diabetes. *Nutrients*, *9*(9), 1014. **https://doi.org/10.3390/nu9091014**

Corrêa, J. L. G., Ernesto, D. B., & de Mendonça, K. S. (2016). Pulsed vacuum osmotic dehydration of tomatoes: Sodium incorporation reduction and kinetics modeling. *LWT-Food Science and Technology*, *71*, 17-24. **https://doi.org/10.1016/j.lwt.2016.01.046**

Corzo, O., & Bracho, N. (2008). Application of Weibull distribution model to describe the vacuum pulse osmotic dehydration of sardine sheets. *LWT-Food Science and Technology*, *41*(6), 1108-1115.**https://doi.org/10.1016/j.lwt.2007.06.018**

Corzo, O., Bracho, N., Pereira, A., & Vásquez, A. (2008). Weibull distribution for modeling air drying of coroba slices. *LWT-Food Science and Technology*, *41*(10), 2023-2028. **https://doi.org/10.1016/j.lwt.2008.01.002**

Doymaz, İ., & İsmail, O. (2011). Drying characteristics of sweet cherry. *Food and bioproducts processing*, *89*(1), 31-38. **https://doi.org/10.1016/j.fbp.2010.03.006**

Chandra, S., & Kumari, D. (2015). Recent development in osmotic dehydration of fruit and vegetables: a review. *Critical Reviews in Food Science and Nutrition*, *55*(4), 552-561. **https://doi.org/10.1080/10408398.2012.664830**

Chavan, U. D., & Amarowicz, R. (2012). Osmotic dehydration process for preservation of fruits and vegetables. *Journal of Food Research*, *1*(2), 202. **https://doi.org/10.5539/jfr.v1n2p202**

Chenlo, F., Moreira, R., Fernández-Herrero, C., & Vázquez, G. (2006). Mass transfer during osmotic dehydration of chestnut using sodium chloride solutions. *Journal of Food Engineering*, *73*(2), 164-173. **https://doi.org/10.1016/j.jfoodeng.2005.01.017**

Islam, M. N., & Flink, J. N. (1982). Dehydration of potato: II. Osmotic concentration and its effect on air drying behaviour. *International Journal of Food Science & Technology*, *17*(3), 387-403. **https://doi.org/10.1111/j.1365-2621.1982.tb00194.x**

İspir, A., & Toğrul, İ. T. (2009). Osmotic dehydration of apricot: Kinetics and the effect of process parameters. *Chemical Engineering Research and Design*, *87*(2), 166-180. **https://doi.org/10.1016/j.cherd.2008.07.011**

Jokić, A., Gyura, J., Lević, L., & Zavargó, Z. (2007). Osmotic dehydration of sugar beet in combined aqueous solutions of sucrose and sodium chloride. *Journal of Food Engineering*, *78*(1), 47-51. **https://doi.org/10.1016/j.jfoodeng.2005.09.003**

Lenart, A., & Flink, J. M. (1984). Osmotic concentration of potato. I. Criteria for the end-point of the osmosis process. *International Journal of Food Science & Technology*, *19*(1), 45-63.**https://doi.org/10.1111/j.1365-2621.1984.tb00326.x**

Moreira, R., Chenlo, F., Chaguri, L., & Fernandes, C. (2008). Water absorption, texture, and color kinetics of air-dried chestnuts during rehydration. *Journal of Food Engineering*, *86*(4), 584-594. **https://doi.org/10.1016/j.jfoodeng.2007.11.012**

Nuñez-Mancilla, Y., Perez-Won, M., Vega-Gálvez, A., Arias, V., Tabilo-Munizaga, G., Briones-Labarca, V., & Di Scala, K. (2011). Modeling mass transfer during osmotic dehydration of strawberries under high hydrostatic pressure conditions. *Innovative Food Science & Emerging Technologies*, *12*(3), 338-343. **https://doi.org/10.1016/j.ifset.2011.03.005**

Park, K. J., Bin, A., Brod, F. P. R., & Park, T. H. K. B. (2002). Osmotic dehydration kinetics of pear D'anjou (*Pyrus communis* L.). *Journal of Food Engineering*, *52*(3), 293-298. **https://doi.org/10.1016/S0260-8774(01)00118-2**

Pei, F., Xiao, K., Chen, L., Yang, W., Zhao, L., Fang, Y., & Hu, Q. (2019). Mass transfer characteristics during ultrasound-assisted osmotic dehydration of button mushroom (*Agaricus bisporus*). *Journal of Food Science and Technology*, *56*(4), 2213-2223. **https://doi.org/10.1007/s13197-019-03707-8**

Rastogi, N. K., Angersbach, A., & Knorr, D. (2000). Synergistic effect of high hydrostatic pressure pretreatment and osmotic stress on mass transfer during osmotic dehydration. *Journal of Food Engineering*, *45*(1), 25-31. **https://doi.org/10.1016/S0260-8774(00)00037-6**

Rawat, S. (2015). Food Spoilage: Microorganisms and their prevention. *Asian Journal of Plant Science and Research*, *5*(4), 47-56.

Sareban, M., & Souraki, B. A. (2016). Anisotropic diffusion during osmotic dehydration of celery stalks in salt solution. *Food and Bioproducts Processing*, *98*, 161-172.**https://doi.org/10.1016/j.fbp.2016.01.005**

Seth, D., & Sarkar, A. (2004). A lumped parameter model for effective moisture diffusivity in air drying of foods. *Food and Bioproducts Processing*, *82*(3), 183-192. **https://doi.org/10.1205/fbio.82.3.183.44181**

Thuy, N. M., Tham, N. T. N., Minh, V. Q., Vu, P. T., & Tai, N. V. (2022). Evaluation of water loss and solute uptake during osmotic treatment of white radishes (*Raphanus sativus* L.) in salt-sucrose solution. Plant Science Today, *9*(1), 191-197. **https://doi.org/10.14719/pst.1422**

Tortoe, C. (2010). A review of osmodehydration for the food industry. *African Journal of Food Science*, *4*(6), 303-324.

Wang, L., Wang, Z., & Li, X. (2013). Optimization of ultrasonic-assisted extraction of phenolic antioxidants from Malus baccata (Linn.) Borkh. using response surface methodology. *Journal of Separation Science*, *36*(9-10), 1652-1658. **https://doi.org/10.1002/jssc.201300062**

Yadav, A. K., & Singh, S. V. (2014). Osmotic dehydration of fruits and vegetables: a review. *Journal of Food Science and Technology*, *51*(9), 1654-1673. **https://doi.org/10.1007/s13197-012-0659-2**

Zhao, S. L., Liu, Q. H., & Ou-Yang, Z. C. (2003). Apex shift of circular biconcave vesicles. *International Journal of Modern Physics B*, *17*(26), 4661-4665**.** **https://doi.org/10.1142/S0217979203022969**