

# Appropriate coating pretreatment enhancing osmotic dehydration efficiency of scallop adductors

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**Abstract:** During osmotic dehydration, extensive solute uptake induces undesirable side effects (such as counteracts water removal, modifies nutritional and/or organoleptic properties in a negative mode, damages the product profile, etc.). In order to explore a novel approach to monitoring solute uptake during osmotic dehydration, effect of 3 coating pretreatments (viz., chitosan, low methoxyl pectinate and sodium alginate) on mass transfer process during osmotic dehydration of scallop adductors was investigated. Peleg's equation was employed to model the mass diffusion and its kinetics. Crank's analytical solution to Fick's second law was also adopted to evaluate the diffusivity of water ( $D_{ew}$ ), solute ( $D_{es}$ ) and osmotic dehydration efficiency ( $D_{ew}/D_{es}$ ). Osmotic dehydration process was significantly ( $P<0.05$ ) influenced by the type of coating materials, temperatures and salt concentrations. Generally, the initial rates of water loss and salt uptake, and the amounts of water loss and salt uptake at equilibrium in coated samples were lower than that in non-coated ones. Effective diffusivity coefficients increased with increasing temperature and were found to be ranged from  $1.224\times10^{-9}$  m<sup>2</sup>/s to  $2.466\times10^{-9}$  m<sup>2</sup>/s, and  $1.152\times10^{-9}$  m<sup>2</sup>/s to  $1.894\times10^{-9}$  m<sup>2</sup>/s for water and salt, respectively. Coating treatments prior to osmotic dehydration could effectively monitor the solute uptake at high temperatures, while maintaining the amount of water loss. Coating with sodium alginate and low methoxyl pectinate prior to osmotic dehydration led to higher ( $P<0.05$ ) osmotic dehydration efficiency  $D_{ew}/D_{es}$  than that of non-coated ones. However, coating with chitosan resulted in higher ( $P<0.05$ ) osmotic dehydration efficiency  $D_{ew}/D_{es}$  than non-coated ones as salt concentration of 30% irrespective of temperature or 20% with temperature of 35 °C. Coating is promising in monitoring solute uptake and promoting dehydration efficiency during osmotic dehydration of scallop adductors.

**Keywords:** coating; dehydration; mass transfer; scallop adductors

doi: 10.11975/j.issn.1002-6819.2016.17.035

CLC number: TS254.4

Document code: A

Article ID: 1002-6819(2016)-17-0266-08

Tian Yuan, Zhao Ya, Shi Qilong. Appropriate coating pretreatment enhancing osmotic dehydration efficiency of scallop adductors[J]. Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE), 2016, 32(17): 266—273. (in English with Chinese abstract) doi: 10.11975/j.issn.1002-6819.2016.17.035 http://www.tcsae.org

田媛, 赵亚, 石启龙. 适宜涂膜预处理提高扇贝柱渗透脱水效率[J]. 农业工程学报, 2016, 32(17): 266—273.

doi: 10.11975/j.issn.1002-6819.2016.17.035 http://www.tcsae.org

## 0 Introduction

Scallop has developed into a vast aquaculture industry in China and its production has also increased sharply in recent years. The scallop adductor muscle contains abundant nutrients and biological active substances, including protein, carbohydrate, fatty acid, essential amino acids, minerals and vitamins<sup>[1]</sup>. However, the high water content in fresh scallop makes it easy rotten, resulting in greatly reduced shelf life<sup>[2]</sup>. Therefore, it is imperative to find a way to reduce the moisture content/water activity of scallop adductors below its safest value. Osmotic dehydration generally can be defined as hypertonic aqueous solution applied for partial

removal of water through the semi-permeable membrane of the food materials by immersing the products in it<sup>[3-4]</sup>. However, due to the extensive salt uptake during osmotic dehydration of aquatic products, the elasticity of protein especially myofibril protein in meat will be significantly decreased and the nutrition and flavor of the final products will be significantly reduced<sup>[5-6]</sup>. Nowadays, a few investigations have focused on the ways to monitor solute uptake<sup>[7-9]</sup>. An alternative way to monitor the penetration of solute inside foodstuffs during osmotic dehydration is employing a thin layer of edible coating before osmotic dehydration<sup>[7]</sup>. The application of edible coating can effectively extend the shelf life of fresh-cut fruit and vegetables. Pastor et al.<sup>[10]</sup> investigated the effects of edible coatings (hydroxypropylmethylcellulose, HPMC) on the quality and shelf life during storage of grapes and found that HPMC coatings can prevent browning of grapes, improve their gloss and microbial safety and control the increase in oxygen consumption during cold storage. Sánchez et al.<sup>[11]</sup> found that chitosan coating can reduce surface browning and keep the nutritional and sensorial quality of fresh-cut 'Rocha' pear during storage. In addition,

Received date: 2016-04-21 Revised date: 2016-06-03

Foundation item: the National Natural Science Foundation of China (31171708)

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edible coatings have been used to maintain the quality of other fruits and vegetables such as mango<sup>[12-13]</sup>, strawberries<sup>[14]</sup>, and carrots<sup>[15]</sup>, among others.

The edible coating was not only applied on fresh-keeping of fruits and vegetables but also on the osmotic dehydration process. A few investigations have pointed out that edible coating can be served as a fundamental process step prior to osmotic dehydration process. García et al.<sup>[16]</sup> studied the effects of chitosan coating on mass transfer during osmotic dehydration of papaya and found that chitosan coating process can increase the amount of water seepage of papaya and reduce the amount of infiltration of solute during osmotic dehydration. Khin et al.<sup>[17]</sup> applied maltodextrin coating on apple cubes during osmotic dehydration and indicated that maltodextrin coating provided a good barrier against solute uptake. Jalaei et al.<sup>[18]</sup> investigated the mass transfer coefficient and the characteristics of coated apples in osmotic dehydrating and pointed that edible coatings can prevent the solute intake and reduce color changes and browning reactions during osmotic dehydration. Furthermore, edible coatings using carrageenan, sodium alginate and chitosan as pretreatments for osmotic dehydration process of strawberries, potato and papaya were also investigated<sup>[16,19-21]</sup>. Most relevant researches concerning edible coating have been carried out on the osmotic dehydration process of fruits and vegetables using sugar as osmotic agent. However, no data are available for edible coating as a pretreatment of osmotic dehydration process either for aquatic products in general or for scallop adductors in specific. The objectives of present study were to investigate 3 different coating pretreatments on the mass transfer in scallop adductors during osmotic dehydration, model the mass transfer kinetics of water and osmotic solute over a range of osmotic solution concentrations and temperatures.

## 1 Materials and methods

### 1.1 Materials

Fresh scallops (*Argopecten irradians*) were purchased from a local market in Zibo City, China. All the scallops were washed using tap water and the adductors were cut off and cleaned. The average values of diameter and weight for 20 random samples were  $(1.686 \pm 0.263)$  cm and  $(2.792 \pm 0.752)$  g, respectively. The moisture content, protein, fat and ash content of scallop were  $82.23\% \pm 0.62\%$ ,  $12.23\% \pm 1.15\%$ ,  $2.13\% \pm 0.18\%$  and  $1.38\% \pm 0.12\%$ , respectively.

### 1.2 Preparing of solutions

Preliminary experiments revealed that sodium chloride solution at concentration of 10% led to water absorption of scallops. Similar tendency was observed by Duan et al.<sup>[22]</sup> for osmotic dehydration of tilapia fillet. Therefore, sodium chloride solution at concentration of 20% and 30% was employed as the osmosis solution. Calcium chloride solution was used as a cross-linking agent. In addition, the following 3 coating solutions were prepared:

1) Low methoxyl pectin (LMP) (degree of esterification: 31.5%), with the concentration of 2% as the coating material,

with calcium chloride solution of 2% as gelata<sup>[4]</sup>.

2) Sodium alginate (SA), as the coating material with concentration of 2%, with calcium chloride solution of 2% as gelata<sup>[23]</sup>.

3) Chitosan (CHI) as the coating material with the concentration of 1% (g/mL)<sup>[16]</sup>. Chitosan was dispersed in an aqueous solution of acetic acid (1%, v/v). Then, Tween 80 at 1% (v/v) was added for improving wettability. The resulting mixture was then stirred vigorously with gentle heating using a magnetic stirrer until chitosan was dissolved.

### 1.3 Coating treatments

Coating treatments were carried out prior to osmotic dehydration process. The scallop adductors were washed with distilled water and dipped into 2% SA and 2% LMP for 5 min, respectively. The scallop adductors were then taken out from the coating solutions and dipped into 2%  $\text{CaCl}_2$  for 30 min to have a good cross-linking between calcium and the coating material. The scallop adductors were taken out from  $\text{CaCl}_2$  solution and placed at room temperature (approximately 25 °C) for 5 min to undergo further cross-linking. Finally, the scallop adductors were washed with distilled water to remove the excessive  $\text{CaCl}_2$  and blotted with filter paper. Chitosan coating was prepared by immersing scallop adductors into chitosan-Tween 80 solutions for 30 s and then the coated samples were taken out and placed on a stainless sieve and held at room temperature for 30 min. The sieve allowed sufficient air-flow around the coated samples with the use of a blower to solidify the coating.

### 1.4 Osmotic dehydration process

Scallop adductors with and without coatings were dehydrated osmotically in 20% and 30% NaCl solutions under different temperatures (15, 25 and 35 °C) for 5 h. The ratio of sample to solution was 1:10 (w/w) in order to avoid excessive dilution of the osmotic solution during processing<sup>[24]</sup>. The dehydrated samples were then taken out from the osmotic solution at each given time (i.e., 0, 1, 2, 3, 4 and 5 h). Once the samples were removed from the osmotic medium, they were rinsed with distilled water for 3 s and then smoothly blotted with tissue paper to remove the surface solution and weighed. All the experiments were performed in triplicates and the average values were taken.

### 1.5 Measurement of water loss and solid gain

Moisture content of the samples was determined oven drying method<sup>[25]</sup>. Briefly, the samples were weighted and placed in oven (DHG-9140A, Shanghai Yiheng Scientific Instrument Co. Ltd., Shanghai, China) at 105 °C until constant weight (24 h). The samples were cooled down to room temperature in desiccators and weighted. The moisture content of the samples was then calculated from the weight of the sample before and after drying.

Salt content of the samples was measured according to Khin et al.<sup>[4]</sup> with slight modification. Briefly, the samples were minced and weighed for 1–2 g and then put in 50 mL deionized water. The mixture was homogenized by using a laboratory homogenizer (IKA T18 basic, Ultra-Turrax, Germany) and then heated in a digital thermostat water bath

pot (HH-6, Longkou Xianke Instrument Co. Ltd., Longkou, China) at 40 °C for 30 min. The mixture was then centrifuged by using a centrifuge (DL-5-B, Shanghai Anting Scientific Instrument Factory, Shanghai, China) at 5 000 r/min for 15 min. The solution was then cooled down and the supernatant was taken out to measure the conductivity by using a conductivity meter (DDS-307, Shanghai Leici Instrument Factory, Shanghai, China). The salt content of the solution was read against a standard curve of salt solutions and their corresponding conductivity values. The standard curve ( $y=8\times10^{-5}x-0.086$ ,  $R^2=0.998$ ) was made by using six standard salt solutions in the range of 0.05 – 1.50 g/100 mL and their corresponding values of conductivity<sup>[4]</sup>.

Water loss (WL) and solids gain (SG) were calculated by the following equations<sup>[26-27]</sup>

$$WL = \frac{M_0 \cdot x_{w,0} - M_t \cdot x_{w,t}}{M_0}, \quad (1)$$

$$SG = \frac{M_t \cdot x_{s,t} - M_0 \cdot x_{s,0}}{M_0}. \quad (2)$$

Where  $M_0$  and  $M_t$  are the weight of sample at initial and time  $t$ , g, respectively;  $x_{w,0}$  and  $x_{w,t}$  are the water content at initial and time  $t$ , g/g, respectively;  $x_{s,0}$  and  $x_{s,t}$  are the solute solids content at initial and time  $t$ , g/g, respectively.

## 1.6 Mathematical modeling and statistical analysis

Peleg<sup>[28]</sup> proposed an equation to describe moisture and solute contents when the equilibrium states were asymptotically achieved. This equation was adopted by many researchers to investigate mass transfer kinetics during osmotic dehydration process. In present study, the mass transfer kinetics of water and salt during osmotic dehydration of coated and non-coated scallop adductors were modeled by applying Peleg's equation

$$x_{w,t} - x_{w,0} = -\frac{t}{k_1^w + k_2^w t}, \quad (3)$$

$$x_{s,t} - x_{s,0} = \frac{t}{k_1^s + k_2^s t}. \quad (4)$$

Where  $k_1$  ( $k_1^w$  and  $k_1^s$ ) and  $k_2$  ( $k_2^w$  and  $k_2^s$ ) are model parameters. Values of  $1/k_1$  and  $1/k_2$  are the rates of mass transfer at beginning and equilibrium, respectively. The values of  $k_1$  and  $k_2$  were obtained by linear regression from the experimental data using Matlab 7.1 software (MathWorks Corp., Natick, MA, USA). The constant  $k_2$  is related to water and solute concentrations at equilibrium conditions, according to Eq. (5)

$$x_e = x_0 - \frac{1}{k_2}. \quad (5)$$

Where  $x_0$  and  $x_e$  are the moisture or the solute content of a sample at initial and equilibrium, g/g, respectively.

In addition, Crank<sup>[29]</sup> developed Fick's second law, which can be used to model the rates of water loss and salt uptake for infinite cylinders

$$W_r = \frac{x_t - x_0}{x_e - x_0} = 1 - \sum_{n=1}^{\infty} \frac{4}{r_0 a_n} \exp[-F_0(r_0 a_n)^2]. \quad (6)$$

Where  $W_r$  is the dimensionless values of water loss ( $M_t/M_\infty$ ) or NaCl uptake ( $S_t/S_\infty$ ), dimensionless unit;  $x_t$  is the moisture or salt content of samples at time  $t$ , g/g;  $r_0 a_n$  are the roots of the equation  $J_0(r_0 a_n)=0$ ;  $J_0$  is the current density of diffusion, A/m<sup>2</sup>;  $F_0$  is the Fourier number for diffusion and was defined as

$$F_0 = \frac{D_e t}{r_0^2}. \quad (7)$$

Where  $D_e$  is the effective diffusivity, m<sup>2</sup>/s;  $r_0$  is the radius of the sample, m; and  $t$  is the dehydration time, s. This solution is valid for the following initial condition and boundary conditions: for  $t=0$ ,  $x=x_0$ ,  $0 < r < r_0$  for  $t>0$ ,  $x=x_e$ ,  $r=r_0$  for  $t>0$ ,  $dx/dt=0$ ,  $r=0$ . Values of the Fourier number ( $F_0$ ) were obtained by non-linear regression analysis using Matlab 7.1 software based on Eq.(6), according to the methodology adopted by Rastogi and Raghavarao<sup>[30]</sup>. The values of the Fourier number were plotted (according to Eq.(7)) versus values of immersion time, and then the effective diffusivity values were taken from the slope.

## 1.7 Statistical analysis

Matlab software and SPSS software (Version 18.0, SPSS Inc., Chicago, USA) was used to analyze the resulting data. All the experiments conducted with triplicates and their mean values were used for statistical analysis. One-way analyses of variance (ANOVA) were performed and significant difference ( $P<0.05$ ) between each mean value was determined with the Duncan's multiple ranges tests using SPSS software.

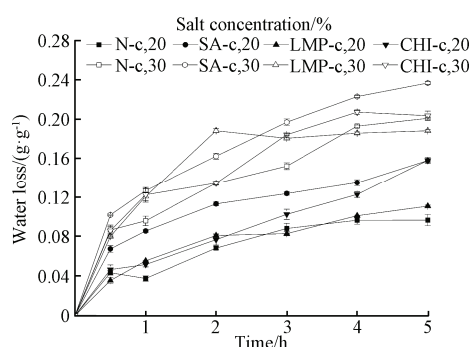
## 2 Results and analysis

### 2.1 Effect of salt concentrations on water loss and solids gain

WL and SG during osmotic dehydration of SA, LMP, chitosan coated and non-coated scallop adductors in different concentrations of salt solution at 25 °C are shown in Figure 1 and Figure 2. WL and SG increased with the increase of salt concentration, which is due to high differences in the chemical potential of water and solute between the sample and osmotic solution<sup>[17]</sup>. As can be seen from Figure 1, coated samples generally showed higher ( $P<0.05$ ) values of WL than non-coated ones at the corresponding concentrations. McHugh et al.<sup>[31]</sup> pointed out that this finding can be related to the chemical nature of polysaccharides. The 3 kinds of coating materials are all polysaccharide. Polysaccharide presents low moisture barrier properties due to its high polarity, which leading to high rates of moisture transportation. In addition, it was observed that SA-coated scallop adductors generally showed a higher ( $P<0.05$ ) WL than other coated and non-coated ones. The reason may be due to SA was high hydrophilic polymer which containing hydrophilic group (i.e., carboxyl). This group is beneficial to accelerate the diffusion of water from the food tissue to the coating solutions.

It can be seen from Figure 2 that coated samples showed a similar behavior for SG to non-coated samples. At fixed temperature of 25 °C, SG increased ( $P<0.05$ ) with the

increase of salt concentration. It was also observed that the coating pretreatments showed lower ( $P<0.05$ ) values of SG during osmotic dehydration process, which might be due to the fact that coatings provide a good barrier property that preventing the salts from permeating inside the samples<sup>[4]</sup>. This circumstance did not occur in samples without coating, where a great amount of soluble penetrated inside the scallop adductor muscle. Furthermore, it can be observed that a sharp increase of WL and SG in the early stages followed by a smooth increase in the later stages. This trend was apparently due to the large differences between the chemical potential of the scallop adductor muscle and the hypertonic osmotic solution at the beginning. Similar findings have been reported by Palou et al.<sup>[32]</sup>, Kowalska and Lenart<sup>[33]</sup> and Park et al.<sup>[34]</sup> for osmotic dehydration behaviors of papaya, vegetables (pumpkin and carrot) and pear D'anjou, respectively.



Note: N-c, CHI-c, LMP-c and SA-c indicate non-coated, chitosan coated, low methoxyl pectinate coated and sodium alginate coated, respectively. The same below.

Fig.1 Effect of salt concentration on water loss during osmotic dehydration of scallop adductors (temperature of 25 °C)

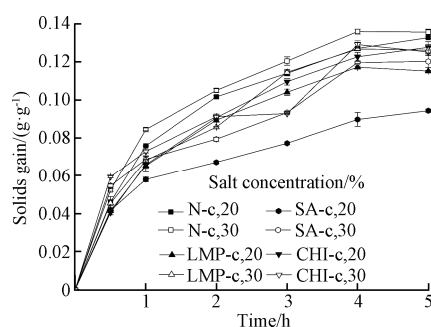


Fig.2 Effect of salt concentration on solids gain during osmotic dehydration of scallop adductors (temperature of 25 °C)

## 2.2 Effect of osmotic temperatures on water loss and solids gain

The effect of temperatures on the WL and SG during osmotic dehydration of coated and non-coated scallop adductors at sodium chloride concentration of 30% is shown in Figure 3 and Figure 4. WL and SG increased with the increase of the osmotic temperature. This may be due to elevating the osmotic temperature led to increase the molecular energy of samples and speed up the molecular motion<sup>[22]</sup>. Consequently, the numbers of solute molecules collide with the samples increase at the identical time, which

bring about a faster penetrating rate into the scallop adductor muscle. Moreover, elevating the osmotic temperature can also lead to reduce the resistance of surrounding molecules to solute migration. As can be seen from Figure 3, coated samples generally showed higher ( $P<0.05$ ) values of WL than non-coated ones at the corresponding temperature. Lenart and Dabrowska<sup>[3]</sup> indicated that purity gum as coating agent in apples could achieve larger or similar level of water removal in comparison with non-coated ones. Kowalska and Lenart<sup>[33]</sup> also reported the performance of LMP and confirmed that samples coated with LMP have higher WL than non-coated samples with various osmotic dehydration times. In addition, the maximum value of WL was observed in SA coated samples at 35 °C while the sodium chloride concentration was 30%. Coating treatment prior to osmotic dehydration process may be considered as a structural modification to food cell membranes due to its ability of endurance during osmotic dehydration process. As shown in Figure 4, coated samples presented a similar behavior for SG with non-coated ones at different temperatures. The values of SG between each treatment are slightly different. However, it can be clearly seen that the highest value of SG was observed in the sample without coating at 35 °C with the sodium chloride concentration of 30%. Further comparison indicated that the application of coatings would lead to impediment of salt uptake. This fact is in agreement with previous findings of Lewicki et al.<sup>[35]</sup>, Singh et al.<sup>[36]</sup> and Matsuka et al.<sup>[19]</sup> for osmotic dehydration of apples, pineapple and strawberries.

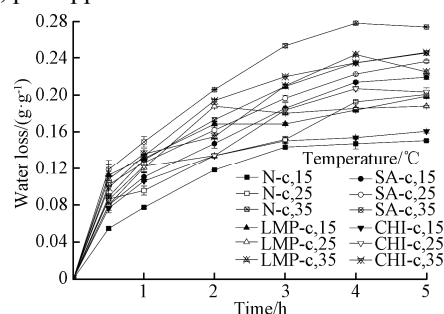


Fig.3 Effect of temperature on water loss during osmotic dehydration of scallop adductors (NaCl concentration of 30%)

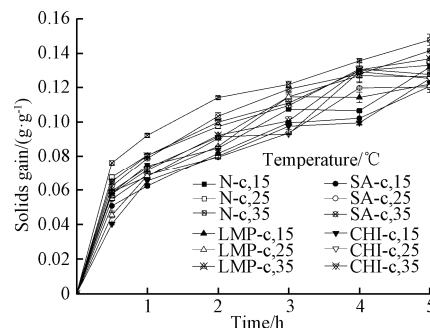


Fig.4 Effect of temperature on solids gain during osmotic dehydration of scallop adductors (NaCl concentration of 30%)

## 2.3 Kinetic model

The kinetic models developed by Peleg<sup>[28]</sup> (i.e., Eqs. (3) and (4)) were used to investigate the mass transfer in coated and non-coated scallop adductors. The values of the initial

rate of water loss/solids gain and the amount of water loss/solids gain at equilibrium were evaluated by linear regression and the results are shown in Tables 1-4.  $R^2$  ranged from 0.8974 to 0.9983 for WL and 0.948 to 0.9963 for SG, respectively. The initial rate of water loss ( $1/k_1^w$ ) for different salt concentrations, temperatures and types of treatments (i.e., non-coated, chitosan coated, LMP coated and SA coated) is shown in Table 1. At the constant solution concentration,  $1/k_1^w$  in all 4 types of treatments was increased as the temperature increased from 15 °C to 35 °C. In addition,  $1/k_1^w$  was increased as the concentration increased from 20% to 30% at a constant temperature. The maximum values of  $1/k_1^w$  were observed in higher concentrations of NaCl and higher temperatures, which is due to a cellular response to the osmotic pressure increment<sup>[37-38]</sup>.  $1/k_1^w$  in coated samples was lower than that in non-coated ones, which might be due to the characteristic changes in the membrane properties after coating. With respect to the water loss at equilibrium (viz.,  $1/k_2^w$ ), similar tendency was observed to that of the initial rate of water loss (viz.,  $1/k_1^w$ ). The value of  $1/k_2^w$  was increased with increasing in temperature and concentration of the osmotic medium (Table 2). The water loss at equilibrium was more dependent on the concentration in comparison with the temperature of the osmotic medium. Higher concentrations showed more obvious effects on the water loss at equilibrium.

**Table 1 Influence of temperature and concentration of salt solution on initial rate of water loss**

Samples	Concentration of salt /%	Initial rate of water loss/( $\times 10^{-4}$ g·g <sup>-1</sup> ·s <sup>-1</sup> )		
		15 °C	25 °C	35 °C
N-c	20	2.111±0.143 <sup>c</sup>	2.553±0.424 <sup>c</sup>	2.581±0.310 <sup>c</sup>
	30	3.633±0.238 <sup>a</sup>	3.658±0.245 <sup>b</sup>	3.886±0.450 <sup>ab</sup>
CHI-c	20	0.944±0.066 <sup>c</sup>	1.003±0.076 <sup>d</sup>	2.250±0.177 <sup>c</sup>
	30	3.367±0.144 <sup>ab</sup>	3.776±0.170 <sup>a</sup>	4.153±0.358 <sup>a</sup>
LMP-c	20	1.725±0.057 <sup>d</sup>	2.353±0.263 <sup>c</sup>	2.496±0.206 <sup>c</sup>
	30	3.014±0.020 <sup>b</sup>	3.142±0.190 <sup>b</sup>	3.297±0.396 <sup>b</sup>
SA-c	20	1.892±0.276 <sup>cd</sup>	2.469±0.044 <sup>c</sup>	2.525±0.057 <sup>c</sup>
	30	3.156±0.062 <sup>b</sup>	3.297±0.167 <sup>ab</sup>	3.333±0.033 <sup>b</sup>

Note: Data are mean ± SD ( $n=3$ ) and means in the same column with different superscripts are significantly different ( $P<0.05$ ); N-c indicates non-coated; CHI-c indicates chitosan coated; LMP-c indicates low methoxyl pectinate coated; SA-c indicates sodium alginate coated. The same below.

**Table 2 Influence of temperature and concentration of salt solution on water loss at equilibrium**

Samples	Concentration of salt /%	Equilibrium water loss/(g·g <sup>-1</sup> )		
		15 °C	25 °C	35 °C
N-c	20	0.0895±0.0085 <sup>c</sup>	0.0974±0.0034 <sup>d</sup>	0.1448±0.0024 <sup>c</sup>
	30	0.1740±0.0064 <sup>a</sup>	0.1886±0.0082 <sup>a</sup>	0.1912±0.0018 <sup>a</sup>
CHI-c	20	0.0870±0.0031 <sup>c</sup>	0.0949±0.0024 <sup>d</sup>	0.1335±0.0013 <sup>d</sup>
	30	0.1354±0.0083 <sup>b</sup>	0.1499±0.0198 <sup>bc</sup>	0.1870±0.0025 <sup>a</sup>
LMP-c	20	0.0855±0.0013 <sup>c</sup>	0.0999±0.0014 <sup>d</sup>	0.1438±0.0047 <sup>c</sup>
	30	0.1319±0.0007 <sup>b</sup>	0.1431±0.0007 <sup>c</sup>	0.1694±0.0083 <sup>b</sup>
SA-c	20	0.0824±0.0047 <sup>c</sup>	0.0941±0.0018 <sup>d</sup>	0.1485±0.0027 <sup>c</sup>
	30	0.1703±0.0006 <sup>a</sup>	0.1661±0.0020 <sup>b</sup>	0.1836±0.0025 <sup>a</sup>

The initial rate of solids gain ( $1/k_1^s$ ) for different solution concentrations and temperatures are given in Table 3. The higher the temperature and salt concentration,

the higher the value of  $1/k_1^s$  was. This was not only due to the large osmotic pressure gradient between the materials and osmotic solution but also due to higher temperature can lead to a loss of cell membrane selectivity in scallop adductors. The values of  $1/k_1^s$  in coated scallop adductors were lower in comparison with the values in non-coated ones (Table 3). Coatings can protect the cellular from damaging might be the reason of this phenomenon. Table 4 displays the effects of different salt concentrations and temperatures on the salt uptake at equilibrium ( $1/k_2^s$ ). The values of  $1/k_2^s$  were lower than  $1/k_1^s$ , which can be explained for the fact that water can diffuse easier than solids through the cell membrane at equilibrium condition<sup>[39-40]</sup>. In addition, both coated and non-coated samples showed a similar behavior for the salt uptake at equilibrium. Generally, the salt uptake at equilibrium in coated and non-coated samples was significantly affected by salt concentrations. For example, at temperature of 35 °C,  $1/k_2^s$  of samples coated with SA at salt concentration of 20% and 30 % were 0.0128 and 0.0210 kg/kg, respectively. However, the value of  $1/k_2^s$  of non-coated samples was significantly higher ( $P<0.05$ ) than the value observed in coated ones.

**Table 3 Influence of temperature and concentration of salt solution on initial rate of salt uptake**

Samples	Concentration of salt /%	Initial rate of salt uptake/( $\times 10^{-5}$ g·g <sup>-1</sup> ·s <sup>-1</sup> )		
		15 °C	25 °C	35 °C
N-c	20	2.156±0.188 <sup>c</sup>	3.692±0.051 <sup>c</sup>	3.711±0.011 <sup>b</sup>
	30	4.003±0.182 <sup>a</sup>	4.197±0.098 <sup>a</sup>	4.356±0.124 <sup>a</sup>
CHI-c	20	2.133±0.269 <sup>c</sup>	2.783±0.018 <sup>f</sup>	3.400±0.199 <sup>c</sup>
	30	3.056±0.041 <sup>b</sup>	3.964±0.013 <sup>b</sup>	4.164±0.074 <sup>a</sup>
LMP-c	20	2.086±0.249 <sup>c</sup>	2.750±0.086 <sup>f</sup>	3.175±0.065 <sup>d</sup>
	30	3.328±0.058 <sup>b</sup>	3.369±0.027 <sup>d</sup>	3.625±0.035 <sup>b</sup>
SA-c	20	2.047±0.054 <sup>c</sup>	3.139±0.011 <sup>c</sup>	3.283±0.025 <sup>c</sup>
	30	3.072±0.023 <sup>b</sup>	3.461±0.088 <sup>d</sup>	3.742±0.028 <sup>b</sup>

**Table 4 Influence of temperature and concentration of salt solution on salt uptake at equilibrium**

Samples	Concentration of salt /%	Equilibrium salt uptake/(g·g <sup>-1</sup> )		
		15 °C	25 °C	35 °C
N-c	20	0.0154±0.0011 <sup>ab</sup>	0.0164±0.0010 <sup>cd</sup>	0.0175±0.0008 <sup>c</sup>
	30	0.0163±0.0010 <sup>a</sup>	0.0203±0.0004 <sup>a</sup>	0.0229±0.0014 <sup>a</sup>
CHI-c	20	0.0135±0.0008 <sup>bc</sup>	0.0162±0.0011 <sup>cd</sup>	0.0173±0.0011 <sup>c</sup>
	30	0.0159±0.0011 <sup>ab</sup>	0.0173±0.0006 <sup>cd</sup>	0.0190±0.0013 <sup>bc</sup>
LMP-c	20	0.0110±0.0006 <sup>c</sup>	0.0150±0.0008 <sup>d</sup>	0.0171±0.0011 <sup>c</sup>
	30	0.0149±0.0020 <sup>ab</sup>	0.0197±0.0016 <sup>ab</sup>	0.0212±0.0003 <sup>ab</sup>
SA-c	20	0.0123±0.0003 <sup>c</sup>	0.0124±0.0008 <sup>c</sup>	0.0128±0.0007 <sup>d</sup>
	30	0.0154±0.0007 <sup>ab</sup>	0.0177±0.0008 <sup>bc</sup>	0.0210±0.0010 <sup>ab</sup>

## 2.4 Diffusion model

The effective diffusivities of water and solids were calculated by using the developed model (i.e., Eq. (6) and Eq. (7)) based on Fick's second law. The estimation of the effective moisture and solute diffusivities ( $D_{ew}$  and  $D_{es}$ ) in both coated and non-coated samples were calculated by non-linear regression and the values are listed in Table 5.

**Table 5 Effective diffusion coefficient of water and salt**

Samples	Concentration of salt/%	$D_{ew}/(\times 10^{-9} \text{ m}^2 \cdot \text{s}^{-1})$			$D_{es}/(\times 10^{-9} \text{ m}^2 \cdot \text{s}^{-1})$		
		15 °C	25 °C	35 °C	15 °C	25 °C	35 °C
N-c	20	1.541±0.007 <sup>d</sup>	1.774±0.008 <sup>d</sup>	1.950±0.057 <sup>c</sup>	1.318±0.007 <sup>b</sup>	1.494±0.006 <sup>b</sup>	1.785±0.021 <sup>b</sup>
	30	1.658±0.042 <sup>c</sup>	1.888±0.041 <sup>c</sup>	1.974±0.008 <sup>c</sup>	1.455±0.027 <sup>a</sup>	1.608±0.025 <sup>a</sup>	1.894±0.008 <sup>a</sup>
CHI-c	20	1.224±0.008 <sup>c</sup>	1.397±0.013 <sup>c</sup>	1.894±0.010 <sup>c</sup>	1.206±0.006 <sup>d</sup>	1.369±0.020 <sup>c</sup>	1.508±0.007 <sup>c</sup>
	30	2.259±0.075 <sup>a</sup>	2.343±0.011 <sup>a</sup>	2.466±0.010 <sup>a</sup>	1.308±0.011 <sup>b</sup>	1.401±0.008 <sup>bc</sup>	1.643±0.003 <sup>c</sup>
LMP-c	20	2.058±0.018 <sup>b</sup>	2.146±0.054 <sup>b</sup>	2.320±0.008 <sup>b</sup>	1.264±0.006 <sup>c</sup>	1.435±0.057 <sup>bc</sup>	1.572±0.013 <sup>d</sup>
	30	2.233±0.023 <sup>a</sup>	2.263±0.020 <sup>a</sup>	2.321±0.113 <sup>b</sup>	1.306±0.006 <sup>b</sup>	1.640±0.113 <sup>a</sup>	1.754±0.013 <sup>b</sup>
SA-c	20	1.653±0.025 <sup>d</sup>	2.077±0.065 <sup>b</sup>	2.168±0.018 <sup>d</sup>	1.152±0.016 <sup>c</sup>	1.386±0.028 <sup>bc</sup>	1.533±0.018 <sup>c</sup>
	30	1.663±0.008 <sup>c</sup>	2.097±0.044 <sup>b</sup>	2.221±0.021 <sup>cd</sup>	1.262±0.008 <sup>c</sup>	1.412±0.014 <sup>bc</sup>	1.599±0.016 <sup>d</sup>

For both coated and non-coated samples, the values of  $D_{ew}$  and  $D_{es}$  were affected concurrently by salt concentrations and temperatures. Increasing the salt concentration led to an increment in the driving force for mass transfer between samples and osmotic solution, thus increased in the amount of mass transfer. In addition, the values of  $D_{ew}$  and  $D_{es}$  increased with the increase in osmotic dehydration temperature. This behavior could be due to the fact that higher temperature can increase the molecular energy, thus accelerate the molecular motion, leading to the higher values of  $D_{ew}$  and  $D_{es}$ . This finding is similar to those obtained by Ganjloo et al.<sup>[41]</sup> for osmotic dehydration of guava. As shown in Table 5, high temperature promoted fast diffusion of water from materials to the coating solutions, and accelerated mass transfer at the surface of the coatings as well. Lower values ( $P<0.05$ ) of  $D_{ew}$  were found in chitosan coated samples at salt concentration of 20%, in comparison with that in non-coated samples. It could be due to chitosan coating can be a barrier to water removal in 20% salt solution. However, higher ( $P<0.05$ ) values of  $D_{ew}$  were found in LMP coated and SA coated samples compared with the values found in non-coated ones. This can be due to the strong hydrophilic nature of coatings and both the coating and the food tissue contributed to the effective diffusivity value<sup>[31,42]</sup>. These facts were related to the water diffusivity in coatings which was greater than in raw materials while the water diffusivity in coated samples existed in both the food tissue and the coating. This trend was slightly different from the result of Khin et al.<sup>[4]</sup> for potato cubes. Probably, the salt concentrations, osmotic temperatures and chemical compositions of materials could contribute the differences. Table 5 shows the effect of variables on  $D_{es}$ . A similar behavior for the values of  $D_{es}$  in coated samples was found compared to that in non-coated ones. Increasing the salt concentrations caused increased gradient in the osmotic pressure, which leading to faster mass transfer of solute. It was observed that coating pretreatments effectively limited the amount of salt diffusion. Salt diffusivities in SA, LMP and chitosan coated samples were less than those observed in non-coated ones, which indicated a better control of extensive solute uptake problem. The reason might be due to the fact that coating could effectively be a barrier to prevent solute permeating into the food matrix. The ‘barrier effect’ like this for solute transfers is possibly due to the increase in

the viscosity of the solution<sup>[43]</sup>. Therefore, coatings can be used to prevent extensive salt permeating into scallop adductors, thus improving the quality of products.

Dehydration efficiency index is defined as the ratio of diffusivity of water to diffusivity of solute ( $D_{ew}/D_{es}$ ), which was used as criteria for optimizing conditions of osmotic dehydration<sup>[4]</sup>. The influence of coatings on  $D_{ew}/D_{es}$  at different salt concentrations and temperatures are given in Table 6.

**Table 6 Osmotic dehydration efficiency index for non-coated, SA-coated, LMP-coated and chitosan-coated samples**

Samples	Concentration of salt/%	$D_{ew}/D_{es}$		
		15 °C	25 °C	35 °C
N-c	20	1.169±0.001 <sup>d</sup>	1.187±0.001 <sup>d</sup>	1.092±0.019 <sup>c</sup>
	30	1.140±0.008 <sup>d</sup>	1.174±0.007 <sup>d</sup>	1.042±0.001 <sup>f</sup>
CHI-c	20	1.015±0.002 <sup>c</sup>	1.021±0.006 <sup>c</sup>	1.256±0.001 <sup>d</sup>
	30	1.727±0.042 <sup>a</sup>	1.372±0.002 <sup>a</sup>	1.501±0.004 <sup>a</sup>
LMP-c	20	1.628±0.022 <sup>b</sup>	1.495±0.022 <sup>b</sup>	1.476±0.007 <sup>a</sup>
	30	1.710±0.001 <sup>a</sup>	1.380±0.085 <sup>c</sup>	1.323±0.055 <sup>c</sup>
SA-c	20	1.357±0.004 <sup>c</sup>	1.499±0.017 <sup>b</sup>	1.414±0.005 <sup>b</sup>
	30	1.318±0.002 <sup>c</sup>	1.485±0.016 <sup>b</sup>	1.389±0.001 <sup>b</sup>

The values of  $D_{ew}/D_{es}$  in LMP and SA coated were higher ( $P<0.05$ ) than that in non-coated ones. This can be due to the fact that LMP and SA can not only decrease the amount of salt into the raw material, but also promote water seepage from the raw material. In addition,  $D_{ew}/D_{es}$  values of chitosan coating were lower than those of LMP and SA coating.  $D_{ew}/D_{es}$  values of chitosan coating were close to those of non-coated one at salt concentration of 20% and temperature lower than 25 °C. This observation can be explained that although as a strong barrier the chitosan coating well controlled the solute uptake, it also influenced the water removal to large extent, thus leading to a decreased  $D_{ew}/D_{es}$  ratio. However, these values were higher than non-coated one as the salt concentration increased to 30%. The osmotic dehydration efficiency for all coated samples was better than that of non-coated ones at temperature of 35 °C, which owing to the enhancement of internal mass transfer of water from the sample surface to osmotic medium as well. Coating may also prevent cell collapse during osmotic dehydration process. Coating prior to osmotic dehydration can be regarded as a structural modification to cell membranes, because of its ability to

suffer high temperature osmotic medium<sup>[4]</sup>. For the non-coated scallop adductors,  $D_{ew}/D_{es}$  ratio decreased as osmotic dehydration temperature higher than 25 °C. The reason might be the damaged cell structure as a result of thermal effect gave rise to a large impregnation by the external osmotic solution. Similar observations were reported by Khin<sup>[4]</sup> for osmotic dehydration of potato.

### 3 Conclusions

Water loss, solids gain and model parameters were significantly ( $P<0.05$ ) influenced by the types of coating materials, the concentration of salt solution and temperature of osmotic medium. Water loss and solids gain increased ( $P<0.05$ ) with increasing salt solution and temperature of osmotic medium. The initial rates of water loss and salt uptake and the amounts of water loss and salt uptake at equilibrium in coated samples were lower ( $P<0.05$ ) than that in non-coated ones. Effective diffusivity coefficients increased with increasing temperature and were found ranged from  $1.224\times10^{-9}$  m<sup>2</sup>/s to  $2.466\times10^{-9}$  m<sup>2</sup>/s and  $1.152\times10^{-9}$  m<sup>2</sup>/s to  $1.894\times10^{-9}$  m<sup>2</sup>/s for water and salt, respectively. Coatings treatments prior to osmotic dehydration could effectively monitor the solute uptake at high temperatures, while maintaining the amount of water loss. Coating with sodium alginate and low methoxyl pectinate prior to osmotic dehydration led to higher effective diffusion coefficient of water/effective diffusion coefficient of salt ratio ( $D_{ew}/D_{es}$ ) than those of non-coated ones. However, coating with chitosan resulted in higher  $D_{ew}/D_{es}$  ratio than non-coated ones as salt concentration of 30% irrespective of temperature or 20% with temperature of 35 °C. SA and LMP coatings provided good barriers against salt uptake and maintain high dehydration efficiency ( $D_{ew}/D_{es}$  ratio) during osmotic dehydration of scallop adductors.

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## 适宜涂膜预处理提高扇贝柱渗透脱水效率

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**摘 要:** 溶质在渗透脱水过程中过多渗入组织不利于渗透脱水进程, 同时对营养、感官特性与外观形态等均会产生不利影响。为了抑制渗透脱水过程中溶质过多渗入扇贝柱, 提高渗透脱水效率, 研究了壳聚糖、低甲氧基果胶与海藻酸钠等 3 种不同成膜预处理对扇贝柱渗透脱水过程中传质特性影响。采用 Peleg 模型拟合扇贝柱渗透脱水过程中传质和动力学参数; 采用 Fick's 第二扩散定律评估水分扩散系数 ( $D_{ew}$ ) 和溶质扩散系数 ( $D_{es}$ ) 以及渗透脱水效率 ( $D_{ew}/D_{es}$ )。扇贝柱渗透脱水过程受到成膜材料种类、渗透溶液温度和氯化钠质量分数影响显著 ( $P<0.05$ )。成膜预处理扇贝柱的水分损失和氯化钠渗入的初始速率与平衡速率均低于 ( $P<0.05$ ) 未经涂膜的对照组。有效扩散系数随着渗透脱水温度的升高而增加, 水分和氯化钠有效扩散系数范围分别为  $1.224\times 10^{-9}\sim 2.466\times 10^{-9}\text{ m}^2/\text{s}$  和  $1.152\times 10^{-9}\sim 1.894\times 10^{-9}\text{ m}^2/\text{s}$ 。成膜预处理可在维持较高失水率的同时有效地控制高温渗透脱水过程中氯化钠的渗入。海藻酸钠与低甲氧基果胶成膜预处理后扇贝柱的脱水效率 ( $D_{ew}/D_{es}$ ) 高于 ( $P<0.05$ ) 对照组。然而, 对于壳聚糖成膜预处理, 当氯化钠液质量分数高于 30% 或者质量分数为 20% 且温度为 25℃ 时, 扇贝柱脱水效率高于 ( $P<0.05$ ) 对照组。扇贝柱渗透脱水过程中, 为了调控固形物增加和提高渗透脱水效率, 成膜预处理是一种行之有效的方法, 具有广阔的应用前景。

**关键词:** 涂膜; 脱水; 传质; 扇贝柱