

Rehydration characteristics of freeze-dried mussel, shrimp and squid

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Seafood is a vital nutrient source, but its high perishability necessitates efficient preservation methods like drying. While traditional drying often impairs quality, freeze-drying preserves the pore structure by removing ice through sublimation, facilitating rapid reabsorption of water. This study aimed to investigate the rehydration behaviour of freeze-dried shrimp, squid and mussels, both with and without ultrasonic (US) pretreatment. In the experiments, pink shrimps, blue mussels, and European squid were freeze-dried under identical conditions (control and 5-min US pre-treated), and their rehydration behaviour was monitored at 25, 40 and 60°C. Using the data obtained, effective moisture diffusion (D_{eff}) was calculated, compatibility with Peleg and Two-term exponential mathematical models was assessed, and colour changes were recorded throughout the experiments. The results demonstrated that rehydration occurred rapidly in the initial stages, with mussels and shrimps reaching maximum rates within 10-min, while squids peaked at 20-min. Across all samples, increasing the rehydration temperature led to a decrease in the final rehydration ratio. Mathematical modeling revealed that the Peleg model provided the most accurate fit for all samples across various temperatures, yielding the highest R^2 and lowest RMSE and χ^2 values. Calculated D_{eff} values ranged from 1.21×10^{-9} to 5.59×10^{-9} m²/s. Color analysis indicated that US pretreatment generally resulted in higher lightness values for rehydrated squids and shrimps.

Keywords: lyophilization; modelling; seafood; swelling; ultrasonication

INTRODUCTION

Drying is one of the oldest and most widely used preservation methods applied to maintain and improve the quality and shelf life of food products. The process is based on simultaneous heat and mass transfer and requires energy to remove water from the food matrix by converting liquid water into vapor. Since seafood products are highly perishable and may undergo rapid quality deterioration after harvesting, drying is an important processing method for extending their usability and stability. However, the quality of dried foods is strongly affected by the drying method and processing conditions, since moisture removal may cause structural, physical, and visual changes in the product [1, 2]. Among different drying techniques, freeze-drying is regarded as a high-quality drying method because the material is first frozen and then water is removed by sublimation under low pressure. This process generally causes limited structural damage and helps preserve the original shape and structure of the material [3, 4]. Freeze-drying consists of freezing, primary drying by sublimation, and secondary drying by desorption, and the freezing temperature and ice morphology can influence mass transfer during the process [1]. Because ice crystals leave pores after sublimation, freeze-drying typically creates a porous microstructure with interconnected networks. This porous structure can

support water absorption and transport during rehydration, which may result in shorter rehydration times and higher rehydration capacities compared with products dried by other methods [4].

Rehydration is a critical quality-related step for dried foods because freeze-dried products are commonly rehydrated before consumption or use in food formulations. During rehydration, water absorption, wetting of the dry matrix, penetration of water into pores, and solute leaching can occur simultaneously [3, 5]. The rehydration ability of a dried product is closely related to the structural changes occurring during drying, since microstructural damage can affect the ability of the product to regain water [4]. In freeze-dried materials, water can rapidly fill the pores of the dried structure during the initial stage of rehydration through capillary effects, followed by a slower increase until equilibrium is reached [3].

Freeze-drying and rehydration have been investigated in several food systems. Lopez-Quiroga *et al.* (2020) studied the drying and rehydration kinetics of freeze-dried tomatoes and highlighted the role of porous microstructure in water absorption [4]. Zotarelli *et al.* (2022) compared mango powders produced by cast-tape drying, freeze-drying, and spray drying, and reported that drying method influenced wetting time, solubility, color, rheology, and microstructure of reconstituted products [5]. Qiu *et al.* (2022) investigated freeze-dried and hot-air

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dried shiitake mushrooms from the perspective of pores and cell wall fibrous material and showed that freeze-drying affected rehydration characteristics through structural changes caused by ice crystal formation [6]. Fauster *et al.* (2020) reported that pretreatment affected shrinkage, rehydration capacity, and texture of freeze-dried plant materials [1]. In seafood, drying studies have been reported for molluscs, crustaceans, and fish, including sea cucumber, shrimps, mussels, octopus, calamari, and salmon [2, 7-12]. But only a few of these studies have examined rehydration behavior. The aim of this study was to investigate the rehydration behavior of freeze-dried shrimp, squid, and mussel samples produced with and without 5-min ultrasonic pretreatment. The freeze-dried samples were rehydrated in deionized water at 25, 40, and 60 °C. Effective diffusivity values were calculated to evaluate water movement during rehydration, and color parameters were analyzed before and after rehydration to determine the visual quality changes caused by the process. The study was designed to compare the effects of sample type, ultrasonic pretreatment, and rehydration temperature on the rehydration performance and color characteristics of freeze-dried seafood products.

MATERIALS AND METHODS:

Drying experiments

Shrimp, squid, and mussel were purchased from a fish market in Istanbul, Türkiye, in October 2021 and kept in a 1050T model refrigerator (Arcelik, Eskisehir, Türkiye) at 4 °C until the experiments. Samples were weighed using a Radwag AS 220.R2 digital balance with an accuracy of 0.0001 g (Radwag, Radom, Poland) and divided into two groups: control group and ultrasonic (US) pretreatment group. For the US pretreatment, the samples were placed individually into beakers containing deionized water at a 1:10 (w:v) ratio and subjected to pretreatment for 5 min using an Isolab water bath with 1°C sensitivity and 120 W ultrasonic power (Isolab, Germany). After pretreatment, excess water on the sample surfaces was gently dried. Immediately the samples were placed into a Labart LFD-10N freeze dryer (ART Labortechnik, Istanbul, Türkiye) and dried until the final moisture content fell below 5%. Following freeze-drying, the samples were subjected to color analysis using a PCE-CSM 1 colorimeter (PCE Instruments UK Ltd., Southampton, Hampshire, United Kingdom). The dried samples were stored in a desiccator until rehydration experiments.

Rehydration experiments

Rehydration procedures were carried out without stirring on an MI0102003 magnetic stirrer (Four E's, Beltsville, USA) with a heating function, in beakers containing deionized water supplied by Liston A1104 (Liston, LLC, Russia) at a ratio of 1:100 (w:v) at 25, 40, and 60 °C. The samples were divided into 1.5 g batches; accordingly, six parallel systems were set up for each of the shrimp, squid and mussel samples, comprising a control and a US-pretreated group. Temperature monitoring was carried out before and during the experiments. Shrimps and mussels were weighed at 10-min intervals, and squid at 20-min intervals, until the weights stabilized. During the weighing process, the samples were carefully removed from the water, excess water was gently drained off, and the weights were recorded.

Rehydration curves

The rehydration process can be expressed as the reabsorption of the lost water by a substance that has lost the water in its structure as a result of drying. This process occurs as a result of mass transfer. Rehydration content and rehydration rate are important properties in the rehydration process of dried substance. Equation (1) is used to calculate the rehydration content R_c (g/g dry weight).

$$R_c = \frac{w_r - w_d}{w_d} \quad (1)$$

where w_r is weight of the rehydrated sample at time t , and w_d is the weight of the original dried sample [13]. Equation 2 is used to calculate the rehydration rate RR . It is calculated based on the change in rehydration content in the sample per unit time.

$$RR = \frac{R_{c(\Delta t + t)} - R_{c(t)}}{\Delta t} \quad (2)$$

where $R_{c(t)}$ is the rehydration content at any time (g/g dry weight) and $R_{c(t+\Delta t)}$ represents the dry content-based rehydration content at a time “ $t + \Delta t$ ” [13].

Effective diffusivity coefficient

Rehydration kinetics occur by the diffusion of water from the sample surface towards its center. It can be assumed that the rehydration kinetics take place by uniform diffusion at a fixed matrix size and a fixed diffusivity value. For this reason, the concentration gradient of water is among the factors affecting mass transfer by pure diffusion [14].

For drying agricultural products in a falling rate period, Fick's second law of diffusion equation, represented as a mass-diffusion equation the equation (3) expresses the Fick's second law of unsteady state diffusion [15].

$$\frac{\partial M}{\partial t} = \nabla [D_{eff}(\nabla M)] \quad (3)$$

Fick's second law is used to propose mathematical models for the rehydration process [15]. Equation (3) can be used to determine the moisture ratio in equation (4).

$$MR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(-\frac{(2n+1)^2 \pi^2 D_{eff}}{4L^2} t\right) \quad (4)$$

where D_{eff} is the effective moisture diffusivity (m^2/s), L is the half of the sample's thickness (m) and t drying time (s), n is positive integer. For long drying periods, the above equation can be simplified to equation (5):

$$MR = \frac{8}{\pi^2} \exp\left(-\frac{\pi^2 D_{eff}}{4L^2} t\right) \quad (5)$$

When this equation is linearized by taking the natural logarithm, equation 6 is obtained:

$$\ln(MR) = \frac{8}{\pi^2} - \left(-\frac{\pi^2 D_{eff}}{4L^2} t\right) \quad (6)$$

Equation (6) represents a straight line, and the value of D_{eff} can be found by the slope of the t -dependent graph of $\ln(MR)$.

Evaluation of the mathematical modeling

The equations (7) and (8) of Peleg and Two-term mathematical models were applied to the rehydration data of shrimp, squid and mussels with computer program Statistica 8.0 (StatSoft, Tulsa, USA). The Levenberg-Marquardt algorithm was used as the nonlinear regression procedure while assuming the parameters of the models [15, 16]. Equations (9), (10), and (11) were used to calculate root mean square error (RMSE), coefficient of determination (R^2) and reduced chi-square (χ^2) values calculated by nonlinear regression [13, 14].

$$\text{Peleg model: } RR = M_0 + \frac{t}{k_1 + k_2 \times t} \quad (7)$$

$$\text{Two-term model: } RR = a \times e^{-k_0 \times t} + b \times e^{-k_1 \times t} \quad (8)$$

M_0 is the initial moisture content k_1 , k_2 are Peleg constants, a , b , k_0 , k_1 are coefficients, and t is time.

$$R^2 = 1 - \frac{\sum_{i=1}^N \frac{(RR_{exp,i} - RR_{pre,i})^2}{\sum_{i=1}^N \left(\frac{RR_{exp,i}}{\sum_{i=1}^N RR_{exp,i}} - RR_{pre,i} \right)^2}}{N} \quad (9)$$

$$\chi^2 = \frac{\sum_{i=1}^N (RR_{exp,i} - RR_{pre,i})^2}{N - n} \quad (10)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^N (RR_{pre,i} - RR_{exp,i})^2}{N}} \quad (11)$$

where RR_{pre} is the rate of predicted rehydration, and RR_{exp} is the rate of experimental rehydration, N is the number of data and n is the number of models' constants. The most appropriate model was selected based on its highest R^2 and the lowest χ^2 and RMSE [17, 18].

Color analysis

Color is the most significant factor when it comes to determining product quality and consumer choice. Hunter color analysis is a method that shows the product's lightness value as $+L^*$ (100 = white), redness value as $+a^*$, green value as $-a^*$, yellowness value as $+b^*$, and blueness value as $-b^*$ [17, 19]. Color parameters were measured using a hand-held colorimeter (PCE-CSM 1; PCE Instruments UK Ltd., Southampton Hampshire, UK) prior to and after rehydration. At least five measurements were made for each sample and the values were averaged +as shown in Table 3. Total color changes (ΔE) were calculated from equation (12), L_0 , a_0 , and b_0 are the color parameters of the dry sample [19].

$$\Delta E = \sqrt{((L_0 - L)^2 + (a_0 - a)^2 + (b_0 - b)^2)} \quad (12)$$

RESULTS AND DISCUSSION

Rehydration curves

The rehydration rates and rehydration rate curves for shrimp, squid and mussels are shown in Figures 1–3, respectively. As can be seen in Figure 1, the rehydration rates of the shrimp increased rapidly during the first 30 min, then slowed over time and eventually stabilized at levels that could be considered constant rates. It was observed that this behavior developed more rapidly as the rehydration temperature increased; samples at 60 °C rapidly reached their equilibrium weights, whilst those at 25 °C continued to absorb water. The highest rehydration rate was observed in the control sample at 25 °C, whilst the lowest rate was observed in the control sample at 60 °C. It was observed that the rehydration rates in the shrimp samples tended to be higher than those in the US-pre-treated samples at the same temperatures. The highest rates for the shrimp samples at control 25 °C, US 25 °C, control 40 °C, US 40 °C, control 60 °C, and US 60 °C were obtained at 10 min as 0.3032, 0.2705, 0.2302, 0.2546, 0.1846, and 0.2123 g/g × min; and the final rehydration ratios were obtained as 4.3308, 3.5474, 2.7161, 3.0756, 2.1373, and 2.5016 g/g at the 70th min.

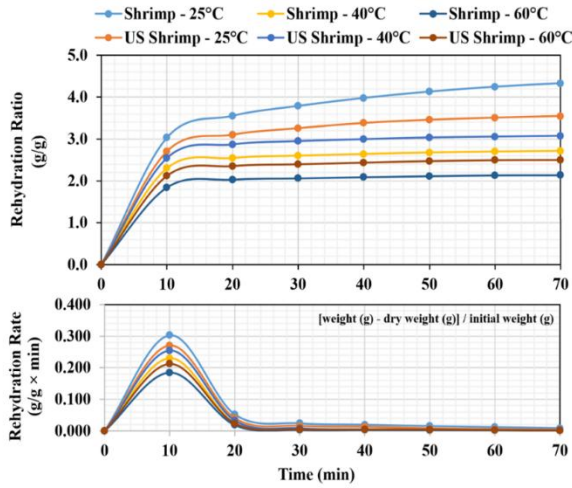


Figure 1. Rehydration ratio (g/g) and rehydration rate (g/g × min) graphs of shrimp samples

The rehydration rates of the squid samples increased rapidly during the first 20 min and then slowed down over time; however, water uptake continued for a long time compared to the other samples. The highest rehydration rate was observed in the control sample at 25 °C, whilst the lowest rate was observed in the control sample at 60 °C. It was observed that the rehydration rates in squid samples tended to be higher than those in US-pretreated samples at the same temperatures. For the shrimp samples, the highest rates at 25 °C (control), 25 °C (US), 40 °C (control), 40 °C (US), 60 °C (control) and 60 °C (US) were obtained at the 10th min as 0.0858, 0.0741, 0.0619, 0.0664, 0.0484, and 0.0556 g/g × min, respectively; and the final rehydration rates were 5.1586, 4.9373, 4.2029, 4.6321, 3.4767, and 3.8141 g/g at the 260th min.

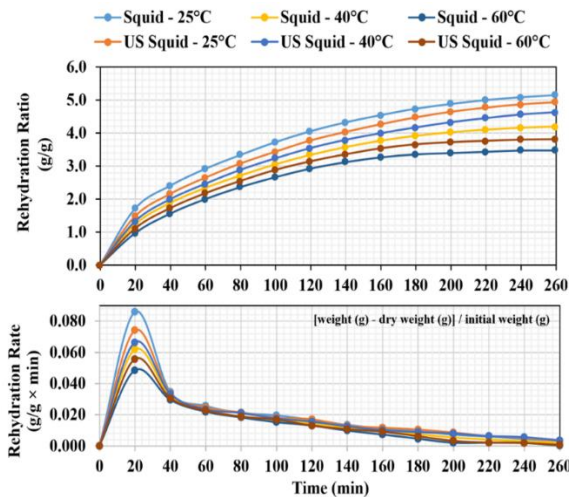


Figure 2. Rehydration ratio (g/g) and rehydration rate (g/g × min) graphs of squid samples

The mussel samples exhibited a similar profile to the shrimp samples, rehydration rates increased rapidly during the first 20 min, then slowed over

time and eventually stabilized at levels that could be considered constant rates.

Whilst the samples at 60 °C rapidly reached their equilibrium weights, those at 25 °C continued to absorb water. At all temperatures, the US samples achieved higher rehydration rates than the mussel samples. For the mussel samples, the highest rates at 10 minutes were 0.1928, 0.2096, 0.1708, 0.1795, 0.1551, and 0.1639 g/g × min; the final rehydration ratios were 2.1519, 2.2874, 1.9659, 2.0407, 1.7483, and 1.8906 g/g at 50th min for the control 25 °C, US 25 °C, control 40 °C, US 40 °C, control 60 °C, and US 60 °C samples, respectively.

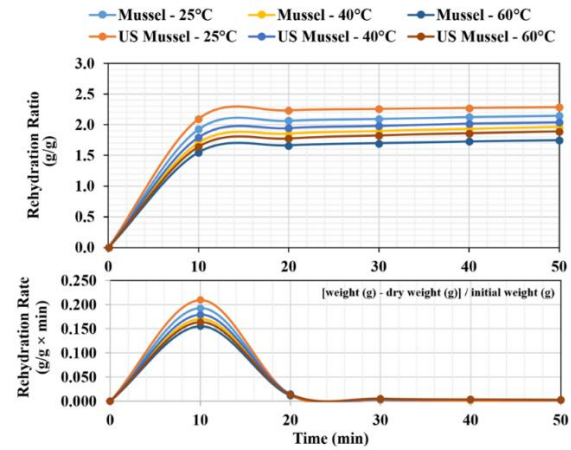


Figure 3. Rehydration ratio (g/g) and rehydration rate (g/g × min) graphs of mussel samples

Effective diffusivity coefficient results

The D_{eff} values calculated using the slopes of the $\ln(MR)$ -t graph are given in Table 1. As can be seen from the table, D_{eff} values are in the range of approximately $3.56 - 5.59 \times 10^{-9} \text{ m}^2/\text{s}$, $1.21 - 1.27 \times 10^{-9} \text{ m}^2/\text{s}$, and $5.86 - 7.38 \times 10^{-9} \text{ m}^2/\text{s}$ for shrimp, squid, and mussel, respectively. In general, mussel samples showed the highest D_{eff} values, especially at 25°C, indicating faster water diffusion into the dried matrix compared with shrimp and squid. Shrimp exhibited intermediate D_{eff} values, while squid had the lowest values at all rehydration temperatures, suggesting a slower rehydration process, probably due to a denser or less porous tissue structure after freeze drying.

Table 1. D_{eff} values of the samples ($\times 10^{-9}$)

Treatment	Temp. (°C)	Sample		
		Shrimp	Squid	Mussel
Control	25	3.56	1.27	6.28
US	25	4.16	1.24	7.38
Control	40	4.53	1.23	5.89
US	40	4.66	1.23	6.26
Control	60	5.59	1.21	6.24
US	60	5.47	1.22	5.86

Temperature affected the D_{eff} values in different ways depending on the type of sample; in general, moisture mobility increased as the rehydration temperature increase. US pretreatment did not show a uniform effect on all samples. In shrimp and mussels, US slightly increased D_{eff} at 25°C and 40°C, but a slight decrease was observed at 60°C. In squid, the differences between control and US-treated samples were very small, indicating a negligible effect of pretreatment.

Mathematical modeling results

Mathematical model constants are listed in Table 2. The appropriate models were chosen based on minimum value of root mean square error (RMSE) and chi-square (χ^2) and maximum value of coefficient of determination (R^2) for all different rehydration temperature. Both Peleg and Two-term models showed high compatibility with the rehydration data.

Table 2. Mathematical model constants

		Peleg						Two-term							
Sample	Temp (°C)	R ²	RMSE	χ ²	a	k ₁	k ₂	R ²	RMSE	χ ²	a	k ₀	b	k ₁	
Shrimp	Control	25	0.99452	0.06851	0.00597	-0.003	304.249	3.6742	0.99935	0.19726	0.05448	-0.2245	0.0104	0.22646	7.3E-05
		40	0.99456	0.00977	0.00012	-0.0067	111.45	2.0448	0.99951	0.06848	0.00657	-0.3896	0.01593	0.38893	-0.0002
		60	0.99901	0.00931	4.6E-05	-0.0009	81.3472	1.81321	0.99678	0.04619	0.00427	-0.416	0.02115	0.42057	-0.0004
	US	25	0.99452	0.01839	0.00043	-0.003	304.249	3.6742	0.99935	0.05	0.0035	-0.2245	0.0104	0.22646	7.3E-05
		40	0.99456	0.00949	0.00012	-0.0067	111.45	2.0448	0.99951	0.0197	0.00054	-0.3896	0.01593	0.38893	-0.0002
		60	0.99901	0.01034	0.00017	-0.0009	81.3472	1.81321	0.99678	0.05831	0.0068	-0.416	0.02115	0.42057	-0.0004
Squid	Control	25	0.99452	0.09346	0.01048	-0.003	304.249	3.6742	0.99452	0.99935	0.49782	0.31863	-0.2245	0.0104	0.22646
		40	0.99456	0.0752	0.00679	-0.0067	111.45	2.0448	0.99456	0.99951	0.45202	0.2627	-0.3896	0.01593	0.38893
		60	0.99901	0.06578	0.00551	-0.0009	81.3472	1.81321	0.99901	0.99678	0.36924	0.19087	-0.416	0.02115	0.42057
	US	25	0.99452	0.0898	0.00968	-0.003	304.249	3.6742	0.99935	0.4945	0.31439	-0.2245	0.0104	0.22646	7.3E-05
		40	0.99456	0.07299	0.00639	-0.0067	111.45	2.0448	0.99951	0.47066	0.28481	-0.3896	0.01593	0.38893	-0.0002
		60	0.99901	0.06092	0.00472	-0.0009	81.3472	1.81321	0.99678	0.37857	0.20065	-0.416	0.02115	0.42057	-0.0004
Mussel	Control	25	0.99452	0.01021	0.00014	-0.003	304.249	3.6742	0.99935	0.03963	0.00236	-0.2245	0.0104	0.22646	7.3E-05
		40	0.99456	0.01251	0.00021	-0.0067	111.45	2.0448	0.99951	0.04527	0.00307	-0.3896	0.01593	0.38893	-0.0002
		60	0.99901	0.00931	0.00012	-0.0009	81.3472	1.81321	0.99678	0.03392	0.00173	-0.416	0.02115	0.42057	-0.0004
	US	25	0.99452	0.00539	3.9E-05	-0.003	304.249	3.6742	0.99935	0.03635	0.00198	-0.2245	0.0104	0.22646	7.3E-05
		40	0.99456	0.01607	0.00034	-0.0067	111.45	2.0448	0.99951	0.04045	0.00245	-0.3896	0.01593	0.38893	-0.0002
		60	0.99901	0.00999	0.00013	-0.0009	81.3472	1.81321	0.99678	0.04434	0.00295	-0.416	0.02115	0.42057	-0.0004

Table 3. Color parameters of the samples

Temp.	Color Parameter	Shrimp			Squid			Mussels		
		FD	Control	US	FD	Control	US	FD	Control	US
25 °C	L	93.98	61.16	70.84	85.11	68.29	72.80	75.30	72.14	65.27
	a	0.42	2.81	2.77	1.67	0.21	1.86	10.82	8.58	22.07
	b	8.89	7.53	9.84	10.50	5.50	9.57	29.39	26.25	51.73
	ΔE	-	32.94	23.28	-	18.78	13.7	-	15.89	16.51
40 °C	L	-	67.55	73.14	-	71.07	73.02	-	73.64	68.94
	a	-	2.24	1.39	-	0.14	0.71	-	4.48	10.91
	b	-	10.96	11.23	-	7.66	9.91	-	25.26	34.99
	ΔE	-	26.58	21.00	-	15.67	13.53	-	18.71	9.40

	L	-	70.59	77.57	-	75.17	78.34	-	73.73	68.34
60 °C	a	-	2.09	1.06	-	0.11	0.67	-	7.85	12.75
	b	-	11.09	11.28	-	10.49	11.12	-	26.27	33.74
	ΔE	-	23.56	16.60	-	11.48	8.35	-	16.00	9.79

The Peleg model gave consistently high R^2 values, between 0.99452 - 0.99901, with relatively low RMSE and χ^2 values. This indicates that the Peleg model successfully described the rehydration behavior of shrimp, squid, and mussel samples under different temperatures and treatments. The Two-term model also showed very high R^2 values, generally ranging from 0.99452 - 0.99951. In several cases, especially for shrimp and mussel, the Two-term model produced slightly higher R^2 values than the Peleg model. However, for squid, the RMSE and χ^2 values of the Two-term model were relatively higher, particularly in the control samples, indicating a weaker fit compared with the Peleg model for squid rehydration.

Color analysis results

The color parameters given in Table 3 showed that rehydration led to visible color changes in all samples. For shrimp, the dried sample had a high L^* value of 93.98, indicating a very light appearance. After rehydration, L^* decreased markedly in all treatments, showing darkening of the samples. However, increasing the rehydration temperature improved lightness, especially in the US samples. The ΔE values decreased from 32.94 to 23.56 in control samples and from 23.28 to 16.60 in US samples as temperature increased from 25 to 60°C. US reduced total color difference at all temperatures, suggesting a positive effect on color preservation. For squid, the overall color change was lower than in shrimp. The L^* values increased with temperature in both control and US samples, indicating better recovery of brightness during rehydration at higher temperatures. The ΔE values decreased from 18.78 to 11.48 in control samples and from 13.70 to 8.35 in US samples. This shows that squid color was better preserved at 60°C, and ultrasonication further reduced the total color difference. Squid also had the lowest ΔE values among the three seafood samples, suggesting the most stable color after rehydration.

For mussel, the color response was different from shrimp and squid because of its naturally higher a^* and b^* values. Rehydration caused changes mainly in redness and yellowness. In control samples, ΔE values remained relatively high and did not decrease regularly with temperature. However, US-treated mussels showed much lower ΔE values at 40 and 60°C, especially 9.40 and 9.79, compared with the

control samples. This suggests that US was effective in reducing color changes in mussel, particularly at higher rehydration temperatures.

CONCLUSION

This study evaluated the rehydration behavior, effective moisture diffusivity, mathematical modeling compatibility, and color changes of freeze-dried shrimp, squid, and mussel samples produced with and without ultrasonic pretreatment. The results showed that seafood type, rehydration temperature, and ultrasonic pretreatment influenced the rehydration performance and visual quality of the samples. In all the samples, water uptake occurred rapidly during the initial stage of rehydration and then gradually slowed until reaching equilibrium. This behavior confirmed the typical rehydration pattern of freeze-dried products, where water first penetrates rapidly into the porous structure and then continues more slowly as the matrix approaches saturation.

Among the tested seafood products, squid showed the highest final rehydration ratios but the lowest effective diffusivity values, indicating that although squid absorbed a higher amount of water overall, water movement into its structure occurred more slowly. Mussel samples exhibited the highest effective diffusivity values, suggesting faster water diffusion into the dried matrix, while shrimp showed intermediate behavior. Rehydration temperature affected the samples differently; higher temperatures generally accelerated the approach to equilibrium, while lower temperatures often resulted in higher final rehydration ratios. Ultrasonic pretreatment did not produce a uniform effect on rehydration kinetics. It slightly improved effective diffusivity in shrimp and mussel at 25 and 40 °C, whereas its effect on squid was limited.

The mathematical modeling results showed that both the Peleg and Two-term models successfully described the rehydration behavior of freeze-dried seafood samples. The Peleg model provided consistently high compatibility for all samples, while the Two-term model also showed strong fitting performance, particularly for shrimp and mussel. Therefore, both models can be considered suitable for predicting the rehydration kinetics of freeze-dried seafood products under different temperature and pretreatment conditions. Color analysis

demonstrated that rehydration caused visible color changes in all samples. However, higher rehydration temperatures and ultrasonic pretreatment generally reduced total color difference, especially in squid and mussel samples. The results suggest that ultrasonic pretreatment and suitable rehydration temperatures may improve color preservation and, in some cases, enhance water diffusion, contributing to the optimization of rehydrated freeze-dried seafood quality.

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