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ARAŞTIRMA MAKALESİ **RESEARCH ARTICLE**

The Influence of Various Pretreatments on Freeze-Drying Process of Seabass (*Dicentrarchus labrax*)*

Çeşitli Ön İşlemlerin Levreğin (*Dicentrarchus labrax*) Dondurarak Kurutma Sürecine Etkisi

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Abstract

European seabass is the fish species with the greatest commercial significance in Mediterranean countries. The effective preservation of sea bass, which possesses significant nutritional benefits, is a matter of considerable importance. This study investigated the freeze-drying of seabass meat (*Dicentrarchus labrax*) and the effects of various pretreatments on the drying behavior. Ten pretreatment sets, including two sets of ultrasonication, two sets of blanching, two sets of saltwater blanching and four sets of saltwater immersion (osmotic dehydration), were evaluated in comparison with control samples. Moisture content, drying rate, and moisture ratio of freeze-dried sea bass samples were determined. The drying rate was used to determine the effective moisture diffusivity coefficient (D_{eff}) and to test for agreement with mathematical models, and the extent of color change was determined throughout all processes. All drying processes were completed between 480 and 720 minutes, and it was found that salt water immersion increased the drying time. Among the mathematical models analysed, the best fit was observed in Alibas, Midilli and Two Term Exponential models. D_{eff} values, which are closely related to drying times, showed a decreasing trend as the duration of ultrasonication process increased. D_{eff} values, which are closely related to drying times, showed a decreasing trend as the duration of ultrasonication process increased. In addition, these values increased with prolonged blanching and decreased with increasing salt concentration in the salt water immersion process. D_{eff} values of sea bass samples were calculated between 4.12×10^{-10} - 2.30×10^{-10}. Compared to other pretreatments, the samples blanched in 10% salt water had the highest D_{eff} values, and the samples immersed in salt water had the lowest D_{eff} values. All sea bass samples showed an increase in the brightness parameter "L" value after freeze drying and the color of the samples turned whiter. The least color change was observed in the samples blanched for 60 seconds and the highest color change was observed in the samples immersed in 20% salt water for one minute.

Keywords: Blanching, Lyophilization, Saltwater, Osmotic dehydration, Ultrasonication

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Öz

Levrek, Akdeniz ülkelerinde en büyük ticari öneme sahip balık türüdür. Besinsel açıdan önemli faydalara sahip olan levreğin etkin bir şekilde muhafazası büyük önem taşımaktadır. Bu çalışmada levrek etinin (*Dicentrarchus labrax*) dondurularak kurutulması ve çeşitli ön işlemlerin kurutma davranışı üzerindeki etkileri araştırılmıştır. İki set ultrasonikasyon, iki set haşlama, iki set tuzlu suda haşlama ve dört set tuzlu suya daldırma (ozmotik dehidrasyon) dahil olmak üzere on ön işlem seti, kontrol numuneleri ile karşılaştırılarak değerlendirilmiştir. Dondurularak kurutulmuş levrek örneklerinin nem içeriği, kuruma hızı ve nem oranı belirlenmiştir. Kurutma hızı, etkin nem difüzivite katsayısı (D_{eff}) ve matematiksel modellerle uyumluluğun test edilmesinde kullanılmıştır ve tüm süreçler boyunca renk değişiminin kapsamı belirlenmiştir. Tüm kurutma işlemleri 480 - 720 dakika arasında tamamlanmış ve tuzlu suya daldırmanın kuruma süresini arttırdığı tespit edilmiştir. Analiz edilen matematiksel modeller arasında en iyi uyum Alibas, Midilli ve İki Terimli Üstel modellerde görülmüştür. Kuruma süreleri ile yakından ilişkili olan D_{eff} değerleri, ultrasonikasyon işleminin süresi arttıkça azalan bir eğilim sergilemiştir. Bunun yanında, bu değerler uzun süreli haşlama işlemi ile yükselmiş ve tuzlu suya daldırma işlemindeki tuz konsantrasyonu arttıkça azalmıştır. Levrek örneklerinin D_{eff} değerleri 4.12×10^{-10} – 2.30×10^{-10} arasında hesaplanmıştır. Diğer ön işlemlere kıyasla %10 tuzlu suda haşlanan numuneler en yüksek, tuzlu suya daldırılan numuneler ise en düşük D_{eff} değerlerine sahip olmuştur. Tüm levrek örneklerinde dondurarak kurutma sonrası aydınlık parametresi olan "L" değerinde artış görülmüş, numunelerin renginde beyazlama olmuştur. En az renk değişimi 60 saniye süre ile haşlanmış örneklerde, en fazla renk değişimi ise bir dakika süre ile %20 tuzlu suya daldırılmış örneklerde görülmüştür.

Anahtar Kelimeler: Haşlama, Liyofilizasyon, Tuzlu su, Ozmotik dehidrasyon, Ultrasonikasyon

1. Introduction

Seafood is an excellent source of nutrients for humans. It is a concentrated source of many essential nutrients (Wang and Zheng, 2025). Fish and shellfish such as salmon, oysters and prawns are particularly high in protein, vitamins (B12, D) and minerals (selenium, zinc, iodine) (Wang and Zheng, 2025). The American Heart Association (AHA) recommends consuming two portions of fish per week, particularly oily fish (American Heart Association [AHA], 2024). The omega-3 fatty acids (EPA and DHA) found in oily fish are key components that help lower blood pressure, regulate heart rhythm and thus reduce the risk of heart disease or stroke (AHA, 2024).

European sea bass (*Dicentrarchus labrax*) is one of the most important commercial fish species farmed in the Mediterranean and Black Sea basins. According to Global Aquatic Processed Production Statistics Quantity (1976 - 2023), Turkiye is the largest producer, followed by Greece, Egypt, and Spain (FAO, 2024; Eurostat, 2024). Sea bass is a seafood product with important nutritional values such as high protein, omega-3 fatty acids, vitamins and minerals. The nutritional composition of sea bass meat varies depending on the age of the fish, feeding method (natural/farming) and season (Montero et al., 2023). On average, a 100 gram edible portion contains: Protein: 18-20%, Fat (Lipid): 1-7%, Moisture: 70-78% and Carbohydrates: close to 0 grams (Munekata et al., 2020; Montero et al., 2023).

However, due to their high water activity, neutral pH, free amino acid content, and the presence of autolytic enzymes, seafood is susceptible to microbiological, chemical (lipid oxidation), and enzymatic (autolytic) spoilage (Wang and Zheng, 2025). This susceptibility requires special processing and storage conditions to keep seafood fresh. The freeze-drying process, known as lyophilization, has gained significant traction in the food industry, particularly for preserving fish products (Wu et al., 2024). This method involves the removal of water from the fish under low temperature and pressure conditions, which helps maintain the nutritional quality and sensory attributes of the product (Wu et al., 2024). The literature reveals various aspects of freeze-drying fish, including its effects on moisture content, protein quality, and potential applications in food products (Li et al., 2025). One of the primary advantages of freeze-drying fish is its ability to produce products with low moisture content, which is crucial for extending shelf life (de Souza et al., 2025). Research on Pacific salmon species demonstrated that freeze-dried cubes could achieve a moisture content of less than 4% (de Souza et al., 2025) and a water activity of less than 0.4, with processing yields ranging from 26% to 28.4% depending on the species. This low moisture content is essential for inhibiting microbial growth and enzymatic reactions that can lead to spoilage (Wang and Zheng, 2025). Additionally, the rapid rehydration of freeze-dried fish products enhances their usability in various culinary applications, such as ready-to-eat meals and snacks (Sahana et al., 2024). Freeze-drying also offers advantages over traditional methods in terms of flavor, color, and texture. For example, in a study examining the drying of hairtail fish using hot air drying, microwave vacuum drying, and freeze-drying, freeze-drying was shown to be superior in both drying and sensory parameters (Hu et al., 2013). Similarly, it has been noted that freeze-drying results in minimal changes in the flavour characteristics of dried catfish fillets compared to other drying methods (Zhang et al., 2017). In terms of nutritional value, freeze-dried fish products are rich in essential fatty acids, proteins, and minerals, making them a valuable addition to the diet. Research has shown that freeze-dried tilapia retains significant amounts of fat, protein, and essential nutrients, which are critical for health (Li et al., 2018). The application of pretreatments prior to freeze-drying fish is a critical area of research aimed at enhancing the efficiency of the drying process and improving the quality of the final product. Various pretreatment techniques, including ultrasound, salt water immersion (osmotic dehydration), and blanching, have been investigated for their potential to optimize freeze-drying outcomes. Studies show, ultrasound pretreatment improves fish drying by increasing thermal efficiency and reducing energy use (Fikry et al., 2023; Xu et al., 2021), osmotic dehydration speeds up drying and helps retain flavor and color (Yildiz and Reyhan, 2023; Dziki, 2020), and blanching preserves protein and enhances drying by reducing enzyme activity and microbial load (Walin et al., 2022; Hai-ou et al., 2018).

This study was prepared with the objective of enriching the literature on the freeze-drying of seabass. The study aimed to investigate the freeze-drying performance of seabass under the effects of ultrasound, salt water immersion (osmotic dehydration), and blanching pretreatments. Drying kinetics, effective moisture diffusivity, and the effects of drying on color change were also examined. The data obtained in this study were also tested with fourteen of the most widely used mathematical models and their data compatibility was analysed.

2. Materials and Methods

2.1. Sample preparation

Seabass fillets were bought fresh from a local fish market in Istanbul, Türkiye in May 2023. The sea bass fillets were cut into pieces measuring 1.5 cm thick, 1 cm long and 1 cm wide and weighed to approximately 10 ± 0.2 g using a Radwag AS 220.R2 digital balance (Radwag, Radom, Poland). The sized samples were placed in polyethylene bags and stored at +4°C in a refrigerator (model 1050T; Arçelik, Eskisehir, Turkey) prior to the experiments. All experiments were carried out within 2 hours. KH-45 hot air drying oven (Kenton, Guangzhou, China) was used for the moisture determination at 105°C for 4 hours. Ultrasonic pretreatment was carried out with the Isolab Water Bath with 120 W ultrasonic power (Isolab, Germany) and the freeze-drying was completed in a Labart LFD-10N model freeze dryer (ART Laborteknik, Istanbul, Turkey).

2.2. Drying experiments

Seabass samples were prepared in 10.0 ± 0.2 g for 11 sets of control and pretreatments. For ultrasonication, samples were ultrasonicated for 1 min (1 min US) and 5 min (5 min US) in beakers containing 100 mL deionized water. For blanching, samples were immersed in beakers containing 100 mL deionized water at 90°C for 30 sec (30 sec BW) and 60 sec (60 sec BW). For blanching with 10% salt water, samples were immersed for 30 sec (30 sec BSW 10%) and 60 sec (60 sec BSW 10%) in 100 mL deionized aqueous solution at 90 °C containing 10% (w/v) salt. For 10% salt water immersion, samples were immersed in room temperature deionized aqueous solutions containing 10% (w/v) salt and held for 1 min (1 min ISW w/10%) and 5 min (5 min ISW w/10%). For 20% salt water immersion, the samples were immersed in room temperature deionized aqueous solutions containing 20% (w/v) salt and kept for 1 min (1 min ISW w/20%) and 5 min (5 min ISW w/20%). After the pretreatments, excess water was drained and the samples were sent immediately to the freeze drier. During the freeze-drying process, the vacuum of the drying chamber was turned off every 60 minutes and the samples were weighed and photographed in less than 2 minutes. Then, the samples were put back into the dryer, and the vacuum was turned back on. Drying ended and the dry samples were vacuum-packed when their moisture content dropped below 5% of their dry weight.

2.3. Mathematical modeling

The amount of moisture content (M, kg water/kg dry matter) contained in the seabass and its moisture ratio (MR, dimensionless) are given in the equations. m_w in the equation represents the amount of water in the sample (kg), and m_d represents the amount of dry matter (kg) (Crank, 1975; Sevim et al., 2023).

$$M = \frac{m_w}{m_d} \quad \text{(Eq. 1)}$$

In Equation 2, M_t represents the amount of moisture at any given moment, M_0 represents the initial amount of moisture, and M_e represents the amount of moisture at equilibrium. Since the moisture content at equilibrium is very low compared to other moisture values, it has been neglected in the calculations (Henderson & Pabis, 1961; Ersan et al., 2025):

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad \text{(Eq. 2)}$$

Data obtained for dried seabass were analyzed using Statistica 8.0 program (StatSoft Tulsa, USA) utilizing the Levenberg-Marquardt algorithm (Levenberg, 1944; Marquardt, 1963). First, the suitability of the model for all models used in mathematical modeling was determined by using regression parameters. After that, a stepwise regression technique was employed to determine the functional connection between the drying constants and the process variables (Madamba et al., 1996). One of the criteria used to test the fit of experimental data to the model equations is the coefficient of determination (R^2) value given in Equation 3. The R^2 value close to 1 indicates the compatibility of the data with the model (Kipcak et al., 2021):

$$R^2 \equiv 1 - \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{\sum_{i=1}^{N}\left(MR_{exp,i} - \left(\frac{1}{n}\right)\sum_{i=1}^{N} MR_{exp,i}\right)} \quad \text{(Eq. 3)}$$

The other criteria examined are the chi-square (χ^2), which is the mean of the squares of the drying data and the predicted data obtained using the model equation, and the root mean square error (RMSE), which represents the square

root of the mean of the differences between the drying data and the predicted values. The closeness of these values, whose equations are given in Equations 4 and 5, to 0 indicates high compatibility of the models with drying data (Ozyalcin et al., 2023):

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i}-MR_{pre,i}\right)^2}{N-z} \quad \text{(Eq. 4)}$$

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

The expressions $MR_{experinemtal}$ and $MR_{predicted}$ given in Equations 3-5 represent the moisture ratio values calculated with the experimental and model equations, respectively, the N value represents the total number of experiments, and the z value represents the constant numbers in the models.

2.4. Effective moisture diffusivity

When the drying process of food products occurs, moisture removal from the structure occurs at a constant or decreasing rate and shows a complex mass transfer mechanism that includes moisture diffusion, liquid vapor diffusion, evaporation-condensation, hydrodynamic flow, and other mass transfer mechanisms. Fick's second law of diffusion is widely used to determine the effective moisture diffusivity coefficient (D_{eff}) in foods (Equation 6). D_{eff} is affected by many factors such as the components in the food structure, moisture content, drying temperature, and porosity of the food (Crank, 1975; Kipcak and Doymaz, 2020).

$$\frac{\partial M}{\partial t} = \nabla\left[D_{eff}(\nabla M)\right] \quad \text{(Eq. 6)}$$

D_{eff} can be calculated from the slope of the plot of ln(MR) versus time (Equation 7).

$$\ln(MR) = \ln\left(\frac{6}{\pi^2}\right) - \left(\pi^2\frac{D_{eff}\times t}{R^2}\right) \quad \text{(Eq. 7)}$$

2.5. Color analysis

Color is a critical element in enhancing the ultimate appetizing quality and consumer acceptance of foods and beverages (Subhashish et al., 2022). The color measurement was conducted using a PCECSM 1 model colorimeter (PCE Instruments UK Ltd., Southampton Hampshire, United Kingdom). The color analysis of the samples was performed by taking the average of the color values read from five different points for fresh (unpretreated), pretreated, and dried samples. The colorimeter was calibrated before the measurements were taken.

The color values are defined as “L”, “a”, and “b”. The L value indicates lightness-darkness on a scale from 0 (black) to 100 (white), the “a” value represents greenness-redness, and the “b” value indicates blueness-yellowness. The total color difference (ΔE) was calculated according to Equation 8 (CIE, 1976; Ozyalcin and Kipcak, 2022).

$$\Delta E = \sqrt{((L_0-L)^2+(a_0-a)^2+(b_0-b)^2)} \quad \text{(Eq. 8)}$$

3. Results and Discussion

In the moisture determination prior to the drying experiments, the moisture content of the seabass samples was determined as 2.2222 ± 0.05 kg water/kg dry matter. The photographs of sea bass recorded during the drying processes are given in *Figure 1*.

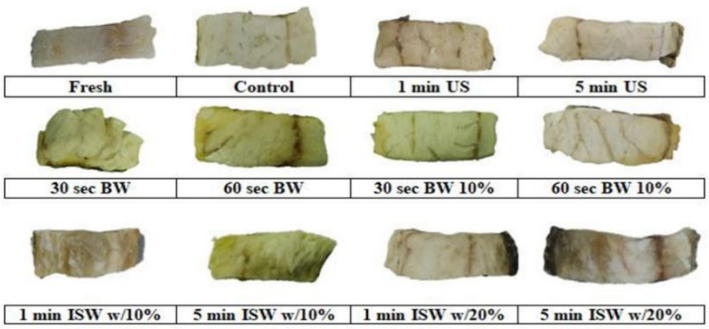


Figure 1. Freeze-dried seabass samples

The graphs of the change of moisture content with time and the change of drying rate with moisture content are given in Figures 2 and 3. The freeze-drying process took 480 min for control, 1 min US, 5 min US, 30 sec BW, 60 sec BW, and 60 sec BSW 10%, samples and the final moisture content was reduced to 0.0767, 0.1354, 0.2034, 0.1695, 0.1101, 0.1085 kg water/kg dry matter, respectively. The shortest drying time was achieved with 30 sec BW 10% pretreatment as 420 min and the final moisture content was found to be 0.1037 kg water/kg dry matter. In ISW pretreatments drying time increased to 660, 540, 660, and 720, and the final moisture content reduced to 0.0626, 0.0984, 0.1679, and 0.0849 kg water/kg dry matter with, 1 min ISW w/10%, 5 min ISW w/10%, 1 min ISW w/20% and 1 min ISW w/20% pretreatments, respectively. In the samples that reached saturation with pretreatments, there was an increase in drying times due to the pores being filled with salt after pretreatment. Furthermore, apart from the fact that the US pre-treatment does not shorten the drying time, the increase in final moisture content compared to the control sample is unexpected; the sample may have absorbed/carried excess water during processing.

Due to the collection of weighing data at 60-minute intervals during drying, some samples have the same total drying time. In addition, the varying final moisture values may reflect the effect of pre-treatments on the drying processes of the samples. When the drying times and final moisture contents were analyzed, it was observed that 1 min US, 5 min US, 30 sec BW, 60 sec BW, and 60 sec BSW 10% pretreatments did not reduce the drying time, and the final moisture contents were higher compared to the control sample. While the increase in US pretreatment time increased the final moisture, the increase in BW pretreatment time decreased the final moisture. On the other hand, in BSW 10% samples, 30 s treatment time both shortened the drying time and the final moisture content was lower than the aforementioned pre-treatments. This can be interpreted as the increase in the contact time with salt and the clogging of the pores with salt, making drying difficult. In support of this, drying time increased in all ISW samples.

3.1. Mathematical modeling results

Aghbaslo et al., Alibas, Henderson & Pabis, Jena & Das, Lewis, Logarithmic, Midilli et al., Page, Parabolic, Verma et al., Wang and Singh, Weibull, Two-Terms, and Two Term Exponential mathematical models were examined (Kipcak et al., 2019; Sevim et al., 2019). However, the best-fitted models were the Alibas, Midilli, and

Table 1. Best-fitted model coefficients for control, US, and BW pretreated samples

Model	Parameter	Control	1 min US	5 min US	30 sec BW	60 sec BW
Alibas	a	3.997180	3.872410	2.951300	2.702120	3.525000
	k	0.004110	0.004730	0.006600	0.006880	0.004670
	n	0.777100	0.732070	0.701200	0.760810	0.790620
	b	0.001250	0.000880	0.000510	0.001030	0.001380
	g	-2.998300	-2.873600	-1.952400	-1.702300	-2.525500
	R^2	0.999570	0.999610	0.999550	0.999980	0.999950
	χ^2	0.000050	0.000074	0.000080	0.000003	0.000010
	RMSE	0.004728	0.005735	0.005977	0.001138	0.002085
Midilli	a	0.998674	0.998790	0.998875	0.999390	0.999066
	k	0.012336	0.015130	0.016856	0.013489	0.011406
	n	0.804428	0.748759	0.719038	0.814519	0.838560
	b	-0.000293	-0.000333	-0.000336	-0.000141	-0.000192
	R^2	0.999543	0.999440	0.999415	0.999880	0.999796
	χ^2	0.000074	0.000085	0.000084	0.000018	0.000033
	RMSE	0.006422	0.006878	0.006825	0.003185	0.004267
Two Term Exponential	a	0.564654	0.048794	0.069763	0.076184	-3.553400
	b	0.005404	0.323906	0.320171	0.286352	0.006670
	k_0	0.429987	0.951206	0.930237	0.923816	4.541680
	k_1	0.005404	0.004786	0.004402	0.005151	0.006400
	R^2	0.994801	0.995856	0.997064	0.999372	0.997468
	χ^2	0.000845	0.000630	0.000421	0.000096	0.000406
	RMSE	0.021667	0.018711	0.015293	0.007296	0.015021

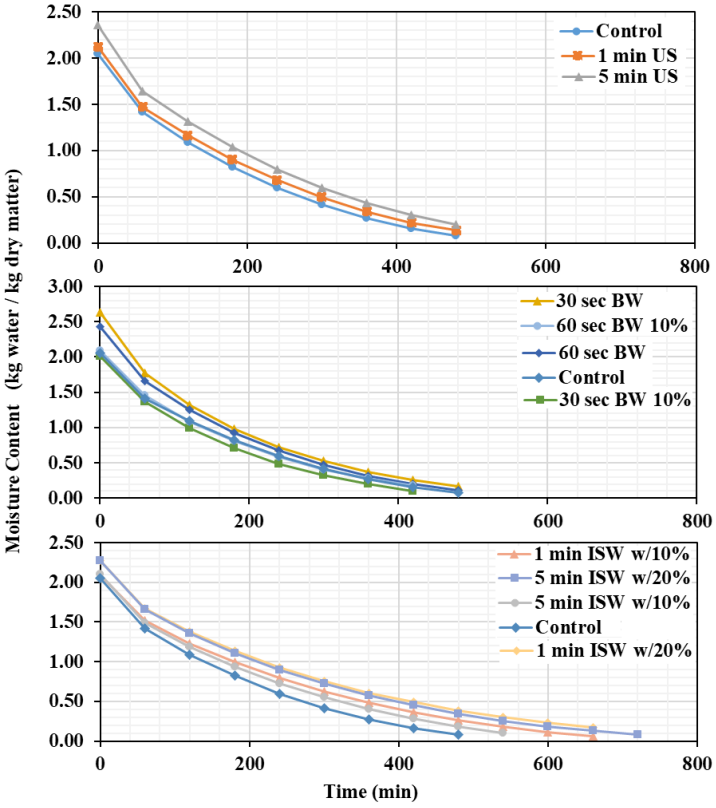


Figure 2. Moisture content versus time curves of seabass samples

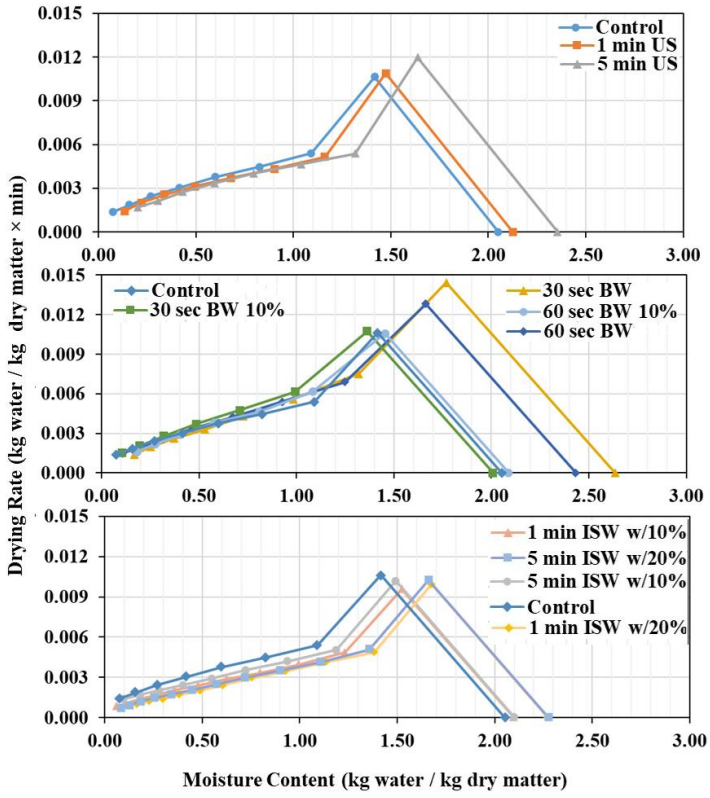


Figure 3. Drying rate versus moisture content graphs seabass samples

Two Term Exponential models, respectively, with the highest R^2 and lowest χ^2 and RMSE values. The statistical results of the mathematical modeling studies carried out on Statistica 8.0 and the data of the most suitable models for all pre-processes are given in Tables 1 and 2. With the Alibas model, R^2 values found as 0.999570, 0.999610, 0.999550, 0.999980, 0.999950, 0.999950, 0.999960, 0.999790, 0.999840, 0.999830 and 0.999810 for control, 1 min US, 5 min US, 30 sec BW, 60 sec BW, 30 sec BSW 10%, 60 sec BSW 10%, 1 min ISW 10%, 1 min ISW 20%, 5 min ISW 10% and 5 minutes ISW, respectively.

3.2. Effective moisture diffusivity results

D_{eff} values data were determined with the help of the slopes of the In(MR)-time graph. D_{eff} values of seabass samples were calculated as 3.90×10^{-10}, 3.32×10^{-10}, 2.99×10^{-10}, 3.36×10^{-10}, 3.76×10^{-10}, 4.12×10^{-10}, 3.47×10^{-10}, 3.03×10^{-10}, 3.21×10^{-10}, 2.30×10^{-10}, and 2.63×10^{-10} $m^2 s^{-1}$ for control, 1 min US, 5 min US, 30 sec BW, 60 sec BW, 30 sec BSW 10%, 60 sec BSW 10%, ISW w/10% (1 min and 5 min), ISW w/20% (1 min and 5 min), respectively. 30 sec BW 10% has the highest D_{eff} value as the pretreatment that provides the fastest drying. Except for this sample, all D_{eff} values are lower than the control sample. D_{eff} values of ISW pretreatment were found to be the lowest compared to other pretreatments. D_{eff} values, which are directly related to the drying times, showed a decreasing profile with increasing treatment time in US samples, increasing with increasing treatment time in BW samples, and decreasing with increasing salt content in ISW samples compared to the control sample.

D_{eff} values were found to be competitive with the D_{eff} values in various seafood drying studies. As an example of these studies, D_{eff} values were found between 6.57×10^{-10} - 1.35×10^{-9} $m^2 s^{-1}$ in infrared drying of calamari (Ozyalcin & Kipcak, 2021), between 2.74×10^{-8} - 4.79×10^{-7} $m^2 s^{-1}$ in microwave drying of mussels (Kipcak, 2017), and between 3.97×10^{-11} - 6.73×10^{-11} $m^2 s^{-1}$ in oven, 4.90×10^{-11} - 8.67×10^{-11} in vacuum oven, 8.31×10^{-11} - 1.20×10^{-10} $m^2 s^{-1}$ in ultrasound pretreated oven, and 7.2×10^{-11} - 1.05×10^{-10} $m^2 s^{-1}$ in ultrasound pretreated vacuum oven drying of crab meat (Ozyalcin and Kipcak, 2023).

Table 2. Best-fitted model coefficients for BW 10% and ISW pretreated samples

Model	Parameter	30 sec BW 10%	60 sec BW 10%	1 min ISW w/10%	5 min ISW w/10%	1 min ISW w/20%	5 min ISW w/20%
Alibas	a	2.320330	3.518420	3.107110	2.917540	3.550930	3.302440
	k	0.006010	0.004010	0.004640	0.005670	0.004110	0.004460
	n	0.826290	0.829090	0.762620	0.738050	0.751950	0.755240
	b	0.000980	0.001610	0.000790	0.000640	0.000850	0.000830
	g	-1.320700	-2.518800	-2.108900	-1.918500	-2.552300	-2.304300
	R^2	0.999950	0.999960	0.999790	0.999840	0.999830	0.999810
	χ^2	0.000011	0.000008	0.000029	0.000026	0.000021	0.000023
	RMSE	0.002053	0.001834	0.004125	0.003627	0.003500	0.003796
Midilli	a	0.999309	0.998977	0.997636	0.998805	0.998039	0.997263
	k	0.010068	0.009066	0.010742	0.013375	0.011151	0.010674
	n	0.874277	0.884862	0.802770	0.765689	0.783964	0.801188
	b	-0.000216	-0.000148	-0.000180	-0.000278	-0.000144	-0.000135
	R^2	0.999847	0.999790	0.999516	0.999712	0.999641	0.999495
	χ^2	0.000028	0.000034	0.000060	0.000040	0.000040	0.000058
	RMSE	0.003766	0.004335	0.006345	0.004917	0.005187	0.006334
Two Term Exponential	a	-4.582950	-4.084540	5.815580	-0.000107	0.924378	0.969691
	b	0.007960	0.006810	-0.005090	0.011127	-0.003497	-0.003836
	k_0	5.575190	5.075380	-4.838380	0.977767	0.075622	-0.000082
	k_1	0.007550	0.006510	-0.005310	-0.004472	-0.282754	0.008087
	R^2	0.998050	0.998413	0.995425	0.997208	0.998923	0.996897
	χ^2	0.000362	0.000255	0.000571	0.000391	0.000121	0.000356
	RMSE	0.013451	0.011906	0.019502	0.015319	0.008988	0.015708

3.3. Color analysis results

The importance of color preservation extends beyond aesthetic appeal; it is also linked to the retention of phytochemicals and antioxidants, which are crucial for the health benefits associated with many foods (Chanukya and Rastogi, 2016). The color changes were calculated as the average of 5 measurements for each sample before (fresh), after (treated), and after freeze drying (FD), and the total color change ΔE values were calculated. The complete color measurements are presented in Figure 4. Accordingly, the samples with the highest extent of color change from fresh to dry were 37.02, 34.59, and 33.97 for 1 min ISW w/20%, 5 min US, and 5 min ISW w/10%, respectively; the samples with the lowest color change were 15.29, 17.31 and 17.37 for 60 sec BSW 10%, 1 min ISW w/10%, and 30 sec BSW 10%, respectively.

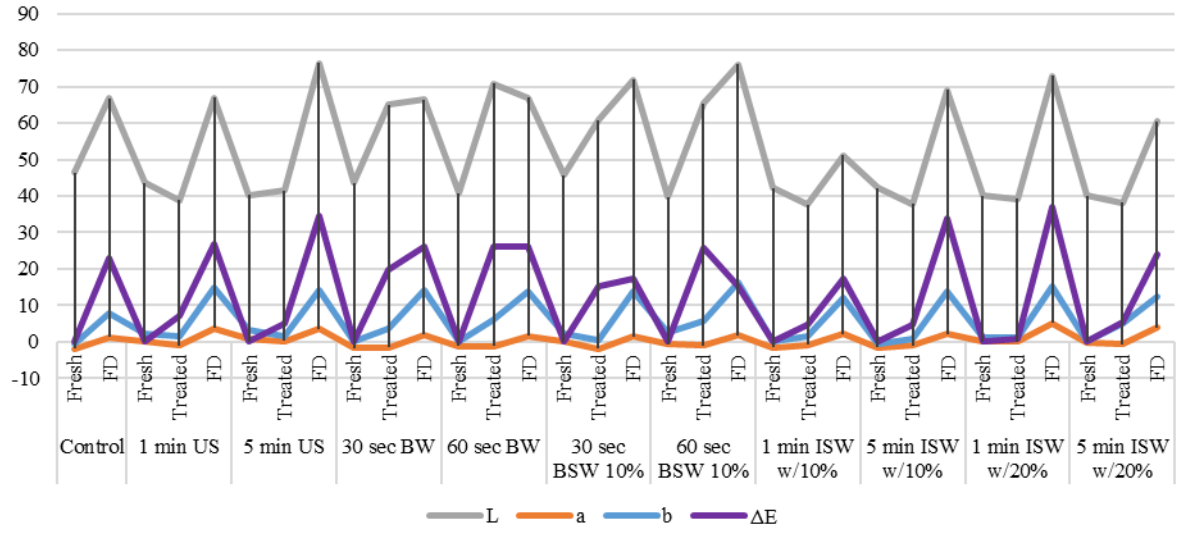


Figure 4. Color changes of seabass samples during the whole processes

4. Conclusions

In this study, the effect of various pretreatments on freeze drying of seabass was investigated. The drying process was completed within 420 to 720 minutes. According to the mathematical modelling applied using the data obtained from the drying processes, the highest fit was achieved with the Alibas model. Color measurements were taken throughout the entire process, and the pre-treatment with the highest drying time and color change was found to be immersion in salt water (ISW). The pre-treatment with the minimum change in both drying time and color change was found to be blanching in water containing 10% salt (BSW 10%). Accordingly, it can be said that the pre-boiling process supported by a low amount of salt is an effective pre-treatment for freeze-drying. Especially in large-scale industrial production, the drying time can be significantly reduced without causing visual changes

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Ethical Statement

There is no need to obtain permission from the ethics committee for this study.

Conflicts of Interest

We declare that there is no conflict of interest between us as the article authors.

Authorship Contribution Statement

Concept: Kipcak, A. S., Alp, M.; Design: Ozyalcin, Z. O., Kipcak, A. S., Alp, M.; Data Collection or Processing: Alp, M.; Statistical Analyses: Kipcak, A. S., Alp, M.; Literature Search: Ozyalcin, Z. O., Alp, M; Writing, Review and Editing: Ozyalcin, Z. O., Kipcak, A. S., Alp, M.

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