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RESEARCH ARTICLE **ARAŞTIRMA MAKALESİ**

Investigation of the effect of various pretreatments on the freeze-drying process of blue mussel (*Mytilus edulis)*

Mavi midyenin (*Mytilus edulis*) dondurularak kurutma işleminde çeşitli ön işlemlerin etkisinin araştırılması

Nurgül Alp ● **Zehra Özden Özyalçın** ● **Azmi Seyhun Kıpçak***

Yıldız Technical University, Faculty of Chemical and Metallurgical Engineering, Department of Chemical Engineering, İstanbul 34210, Türkiye

*Corresponding author: skipcak@yildiz.edu.tr

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Abstract: In this study, freeze-drying of blue mussels with various pretreatments was investigated, the effective moisture diffusion value was determined, and mathematical models were applied to the drying data. Pretreatments were applied as: 1- and 5-min ultrasonication (US), 30- and 60-sec blanching (BW), 30- and 60-sec blanching in 10% salt water (BSW); 1- and 5-min osmotic dehydration (OD)in 10% salt water and 1- and 5-min OD in 20% salt water. Blue mussel samples were freeze-dried until the final moisture content dropped below 7%. The OD pretreatment provided the lowest final moisture content, while the BW had the highest final product moisture content. The highest coefficient of determination (R^2), the lowest root mean square error (RMSE), and reduced chi-square (χ^2) values were used to select the most appropriate mathematical model. The best fitting mathematical models were Alibas, Midilli & Kucuk, and two-term exponential.

Keywords: Blue mussel, *Mytilus edulis*, freeze-drying, lyophilization, mathematical modelling

Öz: Bu çalışmada, mavi midyelerin çeşitli ön işlemlerle dondurularak kurutulması incelenmiş, etkin nem difüzyon değeri belirlenmiş ve kurutma verilerine matematiksel modeller uygulanmıştır. Ön işlemler şu şekilde uygulanmıştır: 1 ve 5 dakikalık ultrasonikasyon (US), 30 ve 60 saniyelik haşlama (BW), %10 tuzlu suda 30 ve 60 saniyelik haşlama; %10 tuzlu suda (BSW) 1 ve 5 dakikalık ozmotik dehidratasyon (OD) ve %20 tuzlu suda 1 ve 5 dakikalık OD. Mavi midye örnekleri, son nem içeriği %7'nin altına düşene kadar dondurularak kurutulmuştur. OD ön işlemi en düşük son nem içeriğini sağlarken, BW en yüksek son ürün nem içeriğine sahipti. En uygun matematiksel modeli seçmek için en yüksek belirleme katsayısı (R^2), en düşük ortalama karekök hatası (RMSE) ve indirgenmiş ki-kare (χ^2) değerleri kullanılmıştır. En iyi uyum sağlayan matematiksel modeller Alibas, Midilli & Küçük ve iki terimli üstel'dir.

Anahtar kelimeler: Mavi midye, *Mytilus edulis*, dondurarak kurutma, liyofilizasyon, matematiksel modelleme

INTRODUCTION

Drying is a crucial process in food preservation, involving the removal of moisture from substances to prevent spoilage. The primary cause of food deterioration over time is its moisture content, which fosters microbial growth and enzymatic activity. By reducing moisture to specific levels, the shelf life of foods can be significantly extended through drying processes (Dweh et al., 2024). Drying methods are broadly classified into two categories: traditional and modern. Among traditional methods, sun drying has been practiced for centuries, especially during summer months, to preserve fruits such as apples, plums, and pears for off-season consumption. However, traditional methods like sun drying have notable drawbacks, including losses in shape, color, and overall product quality. Incomplete drying can also lead to microbial growth, resulting in spoilage or mold formation (Calín-Sánchez et al., 2020; Bachir Bey et al., 2017). Modern drying techniques have evolved to address these limitations, incorporating specialized equipment to enhance efficiency and product quality (Kovacı and Dikmen, 2018). Freeze-drying, or lyophilization, is one of the most advanced modern drying techniques. This method involves freezing the moisture in the material and subsequently removing it via sublimation at low temperatures and pressures. Freeze-drying produces high-quality products, preserving the color, texture, and nutritional content of the food (Li et al., 2023).

Seafoods, such as mussels, squid, crabs, and various fish species, are nutritionally valuable due to their high protein content and essential nutrients. Blue mussels (*Mytilus edulis*), also known as European mussels, are an excellent source of omega-3 fatty acids, zinc, folate, and other essential vitamins such as C and A. Mussels are highly sustainable to cultivate and have minimal environmental impact, making them an important and eco-friendly food source. They provide 26% of daily protein and 22% of daily iron requirements while being sugar-free (Murphy et al., 2019).

Like many marine organisms with high moisture content, drying is essential to stabilize the biochemical properties of mussels. Many sea creatures such as squid, crab, shrimp, sea cucumber, and fish species have been widely studied in the literature. Seafood can be dried naturally in coastal areas in a cost-effective traditional way. However, this method is highly dependent on weather conditions such as temperature and humidity, which can significantly affect the drying rate and the final product quality (Azmi et al., 2024). Apart from natural methods, many studies have aimed to improve drying processes with different pretreatments and dryer types. For example, microwave, infrared, oven, and vacuum oven drying of squid with ultrasonication pretreatment (Ozyalcin and Kipcak, 2021, 2022), oven and vacuum oven of brown crab meat with blanching pretreatment (Özyalçın and Kıpçak, 2023a), and vacuum microwave drying of tilapia fish with osmosis dehydration pretreatment (Wang et al., 2019) have been studied. There are also some studies conducted on the drying of blue mussels using microwaves (Kipcak, 2017), oven and vacuum oven (Özyalçın and Kıpçak, 2023b), cabinet-type dryer (Kıpcak et al., 2021), and black mussels using an ultrasound-assisted vacuum oven (Kocabay, 2021).

Dried seafood can be enjoyed as a standalone snack or incorporated into various dishes. Among the drying processes, freeze drying, which provides the highest preservation of the nutritional value of the food, is among the preferred methods. Mussels, a popular choice among these seafood products, are generally consumed by seasoning with salt or umami flavors. To address the lack of information in the literature, this study was designed to investigate the effect of ultrasonication, blanching, and osmotic dehydration effects on the freeze-drying of blue mussels and the compatibility of the drying data with well-known mathematical models. In the design of pretreatments, the methods preferred in the literature for similar products were enhanced with the salt addition meeting the final consumption habits.

MATERIALS AND METHODS

Sample preparation

Blue mussels were bought frozen from a local market in Istanbul, Türkiye in May 2023. The supplied products were kept in the FLV-1003 model (Flavel, Eskisehir, Türkiye) deep freezer at -20°C ± 2 °C until the experiments started and were allowed to thaw in the +4°C refrigerator for 2 hours before the experiments. Mussels were weighed approximately 10 ± 0.1 g for every drying step using a Radwag AS 220.R2 digital balance (Radwag, Radom, Poland). The moisture content was determined using a KH-45 hot air-drying oven (Kenton, Guangzhou, China) at 105°C for 4 hours (AOAC, 2005). Ultrasonic pretreatment was carried out with the Isolab Water Bath with 1°C sensitivity and 120 W ultrasonic power (Isolab, Germany) and the freeze-drying was completed in a Labart LFD-10N standard-type freeze dryer with a cold trap temperature of -56/-80 °C (ART Laborteknik, Istanbul, Türkiye). Refined iodized table salt (Billur Tuz, Izmir, Turkey) was used as salt addition in pretreatments (salt content: E536, potassium iodate 3.5/100g).

Drying experiment

Blue mussel samples weighed 10.0 ± 0.1 g for 11 experiment sets including control, ultrasonication, blanching, and osmotic dehydration pretreatments. Ultrasonication (US) pretreatments were applied for 1 min (1 min US) and 5 min (5 min US) with 1:10 (w:v) deionized water. Blanching (BW) pretreatments were applied for 30 seconds (30 sec BW) and 60 seconds (60 sec BW) with 1:10 (w:v) deionized water at 90 °C. Blanching in salt water (BSW) pretreatments were applied for 30 seconds (30 sec BSW 10%) and 60 seconds (60 sec BSW 10%) with 1:10 (w:v) deionized water with 10% salt at 90 °C. Osmotic dehydration (OD) pretreatments were applied for 1 min (1 min OD 10%) and 5 min (5 min OD 10%) with 1:10 (w:v) deionized water with 10% salt, and 1 min (1 min OD 20%) and 5 min (5 min OD 20%) with 1:10 (w:v) deionized water with 20% salt. After pre-treatment, the samples were gently drained of excess water and immediately transferred to the freeze-dryer. During freeze-drying, the vacuum of the dryer was switched off at 60-minute intervals and the samples were weighed in less than 2 min, placed back into the dryer, and the vacuum was switched on. The absence of thermal exposure during the freeze-drying process ensures that the pores of the samples are more open and absorb moisture faster than in heat-treated samples. To allow for longer storage of the dried samples, the target final moisture content was reduced from 10% to 7%, taking into account the moisture uptake after drying until packaging under vacuum. When the final moisture content of the samples reached 7%, the drying process was terminated, and the samples were packed under vacuum.

Mathematical modeling and regression analysis

Predicting drying kinetics, mathematical models facilitate the analysis of transport phenomena during drying processes. These phenomena include internal and external heat transfer, as well as mass transfer, which are critical for understanding the dynamics of moisture removal (da Conceição Silva et al., 2012).

The moisture content (M) and moisture ratio (MR) contained in the blue mussel are calculated using Equations (1) and (2). M, given in equation (1), refers to the amount of moisture (kg water/kg dry matter), m_w refers to the amount of water in the sample (kg), and m_d refers to the amount of dry matter (kg) (Kipcak et al., 2019).

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

Moisture ratio (MR), a dimensionless number calculated by equation (2) using M_t, M_e, and M_0 (Kipcak et al., 2019):

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

Where M_t is the moisture content at any drying time, M_e is the equilibrium moisture content and M_0 is the initial moisture content (kg water/kg dry matter), respectively. The M_e value is usually very small, which is neglected in calculations. The non-linear regression studies were done using the Levenberg-Marquardt algorithm to analyze experimentally acquired drying data using Statistica 8.0 (StatSoft Inc., Tulsa, USA) software package. To test which mathematical model fits the data better, Aghbashlo et al., Alibas, Jena & Das, Lewis, Logarithmic, Midilli & Kucuk, Page, Parabolic, Wang & Singh, Two Term Exponential models whose formulae are given in Table 1 were evaluated were evaluated (Ozyalcin et al., 2023). The best fitting model for the data sets was evaluated using the coefficient of determination (R^2), root mean square error ($RMSE$), and reduced chi-square (χ^2) values, selecting the higher R^2 values and lower values for χ^2 and $RMSE$. Equations for these parameters can be seen in following Equation (3), (4) and (5) (Kipcak et al., 2019).

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

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

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

where N represents the number of the total experiments, MR_{exp} and MR_{pre} represent experimental and predicted values for moisture ratios respectively and z is the number of constants in the model used for evaluation.

Table 1. Mathematical Model Equations (Ozyalcin and Kipcak, 2022; Kipcak and İsmail, 2021)

Name	Model equation
Aghbaslo et al.	$MR = \exp(-k_1t/(1 + k_2t))$
Alibas	$MR = a.\exp((-kt^n) + bt) + g$
Jena and Das	$MR = a.\exp(-kt + b\sqrt{t}) + c$
Lewis	$MR = \exp(-kt)$
Logarithmic	$MR = a.\exp(-kt) + c$
Midilli and Kucuk	$MR = a.\exp(-kt^n) + bt$
Page	$MR = \exp(-kt^n)$
Parabolic	$MR = a + bt + ct^2$
Wang and Singh	$MR = 1 + at + bt^2$
Two-Term Exponential	$MR = a.\exp(-kt) + (1-a).\exp(-kat)$

*a, b, c, g, coefficients; and n, drying exponent specific to each equation; k, k_0, k_1, k_2, drying coefficient specific to each equation; t, time (min).

Effective moisture diffusivity (D_{eff}) is a critical parameter in the drying process, influencing the rate at which moisture is removed from materials. It characterizes the intrinsic mass transport properties of moisture, including various mechanisms such as molecular diffusion, liquid diffusion, vapor diffusion, and hydrodynamic flow. D_{eff} value varies with several factors, including temperature, moisture content, and the physical properties of the material being dried. As moisture is removed, the diffusion rate tends to decrease, particularly in the later drying when the moisture content is lower. This phenomenon has been observed in studies on various agricultural products, where the drying rate is initially high but slows down significantly as the moisture approaches equilibrium (Bakal et al., 2012). D_{eff} in foodstuffs can be calculated based on Fick's second law of diffusion as given in equation (6) (Sacilik et al., 2006). The slope of the time versus the ln (MR) can also be used to calculate D_{eff} (Kipcak and Doymaz, 2020).

$$\ln(MR) = \ln\left(\frac{6}{\pi^2}\right) - \left(\pi^2 \frac{D_{eff} \times t}{R^2}\right) \tag{6}$$

RESULTS

As a result of the moisture analysis, the moisture content of the raw blue mussel was 71.89% wet basis and 2.5577 kg water / kg dry matter (kg W/kg DM). Moisture analysis was also carried out after each pretreatment to determine how much moisture the samples gained or lost during the pretreatments. Moisture analysis results are given in Table 2.

Table 2. Moisture analysis results of blue mussels

Sample	Moisture (% wet basis)	Moisture intake (% wet basis)	Moisture (kg W/kg DM)	Moisture intake (kg W/kg DM)
Control	71.89	-	2.5577	-
1 min US	74.44	2.55	2.9122	0.3545
5 min US	74.27	2.38	2.8871	0.3294
30 sec BW	69.41	-2.48	2.2692	-0.2885
60 sec BW	69.89	-2.00	2.3209	-0.2368
30 sec BSW 10%	66.26	-5.63	1.9643	-0.5934
60 sec BSW 10%	66.34	-5.55	1.9710	-0.5867
1 min OD 10%	71.09	-0.80	2.4589	-0.0988
5 min OD 10%	71.17	-0.72	2.4687	-0.0890
1 min OD 20%	68.30	-3.59	2.1543	-0.4034
5 min OD 20%	67.94	-3.95	2.1195	-0.4382

Figure 1 shows the samples before and after drying. The freeze-drying process was completed in 420 minutes for control, 1 min US, 5 min US, 30 sec BW, and 60 sec BW samples, and the final moisture contents for these samples were obtained as 0.1700, 0.1956, 0.2069, 0.1075, and 0.1620 kg water/kg dry matter, respectively. The drying time was shortened by 120 minutes with BSW treatment and completed in 300 minutes and the final moisture contents were 0.1956 and 0.2069 kg water/kg dry matter for 1 min BSW 10% and 5 min BSW 10%, respectively. Drying time increased to 480 minutes with the OD 10% pretreatment and the final moisture content was 0.1224 and 0.1092 kg water/kg dry matter for 1 min OD 10% and 5 min OD 10%, respectively. Drying took 360 minutes with the 1 min OD 20% process and 420 minutes with the 5 min OD 20% and the final moisture content was 0.1056 and 0.0763 kg water/kg dry matter, respectively.

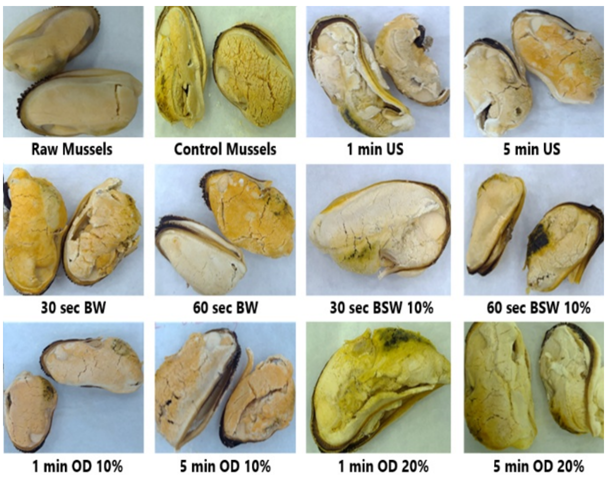

Figure 1. Raw and freeze-dried blue mussels

The drying curves of mussel samples are given in Figures 2 and 3. Among the pretreatments used, the initial moisture content of only US samples increased, as indicated in Table 2 and Figure 3. The US samples had the highest initial drying rate because of this increase. Although the drying profile of the 5 min US sample was faster than the 1 min US, the drying time remained the same. Aside from the US samples the initial moisture content of all pretreated samples have decreased. The samples that had the highest initial drying rate following the control sample were 1 min OD 10%, 5 min OD 10%, 30 sec BW, 60 sec BSW 10%, 1 min OD 20%, 60 sec BW, 5 min OD 20%, 30 sec BSW 10%, respectively.

The D_{eff} values calculated from equation (6), based on Fick's second law of diffusion, are 9.48×10^{-9}, 9.30×10^{-9}, 9.30×10^{-9}, 1.03×10^{-8}, 9.21×10^{-9}, 1.31×10^{-8}, 1.35×10^{-8}, 8.85×10^{-9}, 9.48×10^{-9}, 1.20×10^{-8}, and 1.14×10^{-8} for control, 1 min US, 5 min US, 30 sec BW, 60 sec BW, 1 min BSW 10%, 5 min BSW 10%, 1 min OD 10%, 5 min OD 10%, 1 min OD 20% and 5 min OD 20%, respectively.

Mathematical modeling and regression analysis results

The weight change data of blue mussels against time were used in the mathematical modeling of the drying process. Among the models tested to find the best-fitted model, the models with the highest R^2 and the lowest χ^2 and RMSE values were determined as Alibas, Midilli & Kucuk, and Two-Term Exponential, respectively.

The Alibas model was the best fitting model with an R^2 value of > 0.9998 in all models except 1 min OD 10%. However, the drying data of the 1 min OD 10% sample showed the highest agreement with Midilli & Kucuk with an R^2 value of 0.999965. The model coefficients for these three models are given in Table 3 for control, US, and BW samples and Table 4 for BSW and OD samples.

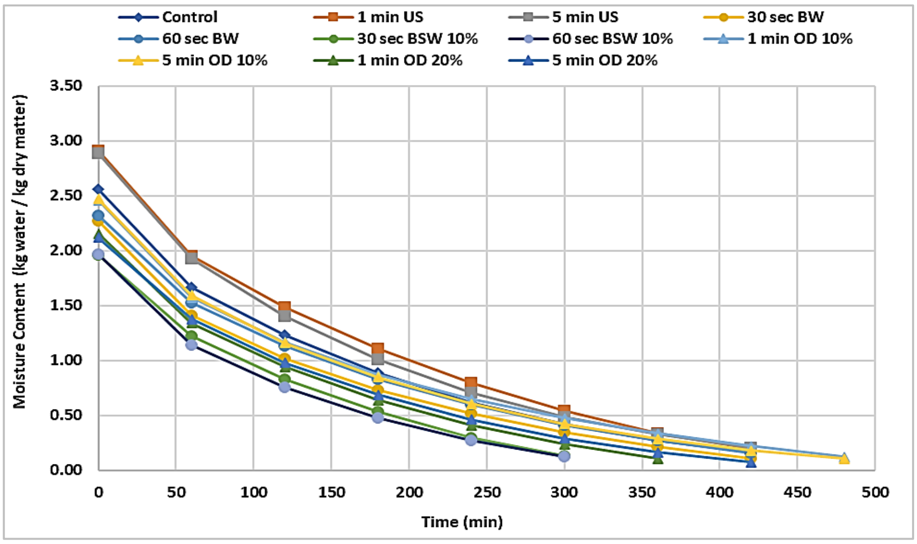

Figure 2. Moisture content versus time curves of freeze-drying blue mussels

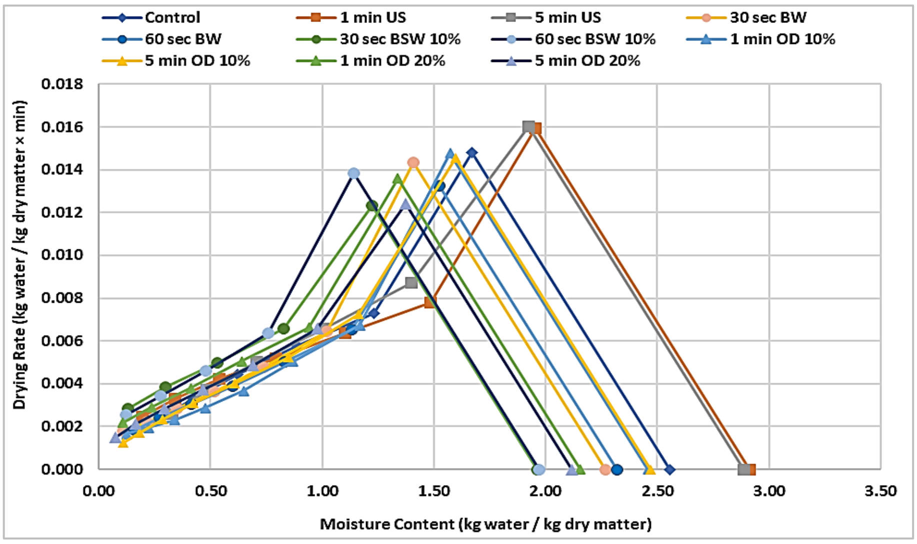

Figure 3. Drying rate versus moisture content curves of freeze-drying blue mussels

Table 3. Best-fitted model coefficients and statistical data for control, US, and BW

Model	Parameter	Control	1 min US	5 min US	30 sec BW	60 sec BW
Alibas	a	3.248950	2.098930	3.163730	1.645268	2.855050
	k	0.006080	0.009090	0.005300	0.016681	0.007480
	n	0.763900	0.729580	0.805320	0.681940	0.729720
	b	0.001320	0.000400	0.001530	0.000243	0.000900
	g	-2.249550	-1.099570	-2.164030	-0.645442	-1.855320
	R^2	0.999868	0.999802	0.999967	0.999975	0.999962
	χ^2	0.000031	0.000046	0.000008	0.000006	0.000009
	RMSE	0.003421	0.004164	0.001704	0.001485	0.001815
Midilli & Kucuk	a	0.999239	0.999331	0.999379	0.999743	0.999588
	k	0.014529	0.016187	0.011430	0.023216	0.016761
	n	0.808480	0.756242	0.859007	0.721842	0.768525
	b	-0.000204	-0.000355	-0.000145	-0.000280	-0.000260
	R^2	0.999704	0.999712	0.999849	0.999936	0.999890
	χ^2	0.000052	0.000050	0.000027	0.000011	0.000019
	RMSE	0.999852	0.005017	0.003656	0.002385	0.003085
Two Term Exponential	a	0.063696	12.478400	10.428560	0.899064	0.071323
	b	0.301166	0.006400	0.005970	0.005909	0.301865
	k_0	0.936304	-11.491900	-9.439310	0.100936	0.928677
	k_1	0.005730	0.006500	0.005970	0.309619	0.005489
	R^2	0.998730	0.995947	0.998587	0.998073	0.998438
	χ^2	0.000225	0.000708	0.000250	0.000344	0.000271
	RMSE	0.010602	0.018820	0.011185	0.013121	0.011633

Table 4. Best-fitted model coefficients and statistical data for BSW and OD samples

Model	Parameter	30 sec BSW 10%	60 sec BSW 10%	1 min OD 10%	5 min OD 10%	1 min OD 20%	5 min OD 20%
Alibas	a	1.370804	2.368910	0.362200	2.388490	3.058140	3.007880
	k	0.013105	0.012840	476.896100	0.008940	0.007840	0.006310
	n	0.776947	0.690390	0.010000	0.741240	0.729290	0.778970
	b	-0.000065	0.000680	-0.001300	0.000900	0.001060	0.001300
	g	-0.370936	-1.368960	0.637800	-1.388740	-2.058350	-2.008130
	R^2	0.999961	0.999989	0.977765	0.999979	0.999959	0.999981
	χ^2	0.000023	0.000007	0.004206	0.000004	0.000014	0.000005
	RMSE	0.001969	0.001055	0.043234	0.001355	0.001973	0.001346
Midilli & Kucuk	a	0.999856	0.999916	0.999801	0.999375	0.999716	0.999489
	k	0.016078	0.024789	0.021834	0.015491	0.018615	0.013348
	n	0.797847	0.733766	0.724848	0.803518	0.770503	0.833712
	b	-0.000512	-0.000452	-0.000204	-0.000147	-0.000362	-0.000230
	R^2	0.999946	0.999969	0.999966	0.999851	0.999899	0.999876
	χ^2	0.000016	0.000009	0.000005	0.000024	0.000023	0.000023
	RMSE	0.002324	0.001770	0.001692	0.003617	0.003116	0.003423
Two Term Exponential	a	-0.008500	0.060858	0.118894	0.916592	0.956947	0.027875
	b	1.000000	0.291881	0.388369	0.005627	0.006846	0.591097
	k_0	1.008500	0.939142	0.881106	0.083408	0.043053	0.972125
	k_1	0.007673	0.007805	0.005180	0.395296	0.282363	0.006409
	R^2	0.996468	0.997743	0.998848	0.999043	0.997052	0.997408
	χ^2	0.001053	0.000675	0.000174	0.000108	0.000659	0.000491
	RMSE	0.018734	0.015000	0.009841	0.009172	0.016809	0.015668

DISCUSSION

The results obtained in this study are intended to provide a detailed understanding of moisture dynamics, drying efficiency, and mathematical modeling of the drying process in the freeze-drying of blue mussels. Raw blue mussels with high moisture content were subjected to US, BW, BWS, and OD pretreatments, which resulted in changes in their initial and final moisture content and drying behavior. US increased the initial moisture content due to water absorption during pretreatment and although it accelerated the initial moisture removal, it did not significantly affect the overall drying time. While drying times remained the same with BW, BSW shortened the drying time. This is probably due to the osmotic effects of brine, which increases water transit through the tissue. BSW samples also exhibited lower final moisture content compared to the control, reflecting the effectiveness of BSW. OD caused different effects on drying times but resulted in the lowest final moisture content of the samples. The drying studies of blue mussels in the literature were examined, and the microwave, infrared, cabinet dryer, oven, and vacuum oven results are summarized in Table 5 along with the results obtained with a freeze-dryer. The D_{eff} values obtained in freeze-drying mussels are in accordance with the literature, and the range of 10^{-12} to 10^{-8} was obtained in the literature for the drying of foodstuffs (Doymaz, 2012).

Table 5. Comparison of literature on mussel drying

Dryer Type	Drying Condition	Duration (min)	D_{eff} (m^2/s)	Mathematical Model	Reference
Microwave	90 W	16	2.74×10^{-8}	Weibull ($R^2 > 0.998135$)	Kipcak, 2017
	180 W	5	1.00×10^{-7}		
	360 W	2	2.32×10^{-7}		
	600 W	1.33	3.75×10^{-7}		
	800 W	1	4.79×10^{-7}		
	140 W	13	1.22×10^{-7}	Alibas ($R^2 > 0.999732$)	Sevim et al., 2023
	210 W	7.5	2.33×10^{-7}		
	350 W	4.5	3.91×10^{-7}		
Infrared	88 W	110	4.24×10^{-9}	Midilli and Kucuk ($R^2 > 0.999150$)	Kipcak et al., 2019
	104 W	80	6.29×10^{-9}		
	125 W	55	9.50×10^{-9}		
	146 W	45	1.10×10^{-8}		
	60 °C	405	4.23×10^{-9}	Alibas ($R^2 > 0.999886$)	Sevim et al., 2019
	70 °C	255	7.00×10^{-9}		
	80 °C	165	1.17×10^{-8}		
Cabinet Dryer	60 °C	270	1.89×10^{-9}	Midilli and Kucuk ($R^2 > 0.9984$)	Kipcak et al., 2021
	70 °C	180	3.05×10^{-9}		
	80 °C	120	4.94×10^{-9}		
Oven	60 °C	570	0.89×10^{-9}		
	70 °C	390	1.25×10^{-9}		
	80 °C	300	1.63×10^{-9}		
Vacuum Oven	60 °C	390	1.17×10^{-9}		
	70 °C	270	1.68×10^{-9}		
	80 °C	210	2.28×10^{-9}		
Freeze Dryer	Control	420	9.48×10^{-9}	Alibas ($R^2 > 0.9998$)	This study
	1 min US	420	9.30×10^{-9}		
	5 min US	420	9.30×10^{-9}		
	30 sec BW	420	1.03×10^{-8}		
	60 sec BW	420	9.21×10^{-9}		
	1 min BSW 10%	300	1.31×10^{-8}		
	5 min BSW 10%	300	1.35×10^{-8}		
	1 min OD 10%	480	8.85×10^{-9}	Midilli & Kucuk ($R^2 = 0.999966$)	
	5 min OD 10%	480	9.48×10^{-9}	Alibas ($R^2 > 0.9999$)	
	1 min OD 20%	360	1.20×10^{-8}		
	5 min OD 20%	420	1.14×10^{-8}		

According to the literature, D_{eff} values in freeze drying are consistent with the other methods that reported for dried seafood. In the compatibility of freeze-drying data with mathematical models, it was determined that the Alibas model was the best model which explains almost all the drying processes according to the statistical parameters examined. According to Table 5, which summarizes the drying of mussels with various dryers, the mathematical models of Alibas and Midilli & Kucuk are the models with the highest agreement for microwave, infrared, cabinet dryer, oven, and vacuum oven drying. This shows that the mathematical models developed by Alibas and Midilli & Kucuk are the first models to be evaluated for blue mussel drying.

CONCLUSION

The drying kinetics and mathematical modeling of freeze-dried blue mussels that underwent osmotic dehydration, blanching, and ultrasonication pretreatments were examined in this study. The drying findings showed that blanching in 10% salt water shortened the drying time by 120 minutes, but osmotic dehydration in 10% salt water prolonged it by 60 minutes. According to this result, the use of salt in pre-treatment can shorten the drying time when supported by heat, while it can prolong the drying time when heat is not supplied. At 20% salt concentration, the drying time decreased at 1-min pretreatment and increased at 5-min. The underlying condition may be that the salt molecules migrated into the pores of the sample with the prolongation of the treatment time, causing blockages and slowing down the drying. The final moisture contents for the pretreatments and control samples were found to be relatively close to one another. With R^2 values ranging from 0.999868 to 0.999981, Alibas was found to be the ideal mathematical model in the test of fitting the drying data with mathematical models. The calculated D_{eff} values ranged from 1.35×10^{-8} m²/s – 8.85×10^{-9} m²/s. After drying, no visible degradation was seen in any of the samples. The results showed that blanching the sample with salt water was a more efficient way to accelerate the drying process than alternative pretreatments. How drying kinetics are affected by variations in pretreatment temperatures and durations should be investigated in the future.

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AUTHORSHIP CONTRIBUTIONS

All authors contributed to the idea and design of the study. Material preparation and investigation were performed by Nurgül Alp and Azmi Seyhun Kipcak. The writing/editing was carried out by Nurgül Alp and Zehra Ozden Ozyalcin, and all authors have read and approved the article.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest or competing interests.

ETHICS APPROVAL

No specific ethical approval was necessary for the study.

DATA AVAILABILITY

For any questions, the corresponding author should be contacted.

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