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Research Article

Ultrasonic Pre-Treatment and Vacuum Effect on the Drying of *Cancer Pagurus* Meat

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ABSTRACT

This study investigates the impacts of vacuum and ultrasonic pre-treatment on drying kinetics, mathematical modeling, and color changes of *Cancer pagurus* (brown crab). The Midilli & Kucuk model provided the best match for all the drying techniques examined. Using a variety of drying techniques such as oven drying (OD), vacuum oven drying (VOD), ultrasonic pre-treated oven drying (US-OD), and ultrasonic pre-treated vacuum oven drying (US-VOD), effective moisture diffusivities (D_{eff}) and activation energies (E_a) were calculated. According to the findings of the study, vacuum and ultrasonic pretreatment shortened drying times, which is crucial for improving drying effectiveness and lowering costs. On the other hand, the OD method had the lowest D_{eff} values (0.397-0.673 × 10^{-10} m^2/s), indicating that it was the least efficient method for removing moisture. The study also found that the highest E_a value was observed in the US-VOD method (44.60 kJ/mol) and the lowest in the OD method (25.69 kJ/mol). Interestingly, the US-VOD method also had the lowest ΔE values (17.09 - 20.33), indicating that both US pre-treatment and vacuum application were successful in preserving the color of the brown crab.

Keywords: Crab, oven, seafood, ultrasonic pre-treatment, vacuum oven

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INTRODUCTION

Owing to their high production costs and short shelf life, meat and meat products are in need of high-cost storage and transfer, such as a cold chain. These products, with high nutritional values and water activities, are prone to microbiological and biochemical degradation. Today, many different methods are used to prevent meat and its derivatives from degradation, to extend their shelf life, to ensure microbial safety, and to reduce transfer costs (Ozbay & Sarıcoban, 2015a, b). As an alternative to meat products, seafood stands out with its distinct tastes and high nutritional values. For products which have unit prices higher than many meat products conservation processes are very desirable and cost-effective.

The edible crab or brown crabs, scientifically known as *Cancer pagurus,* belongs to the *Cancridae* family of large crabs and is found in the eastern Atlantic and Mediterranean regions. The length of the species is about 6-15 cm. The edible crab lives in shallow and rocky areas and is carnivorous (Tonk & Rozemeijer, 2019). *Cancer pagurus* is one of the most economically important crab species in terms of commercial value. These ten-legged shellfish are the most caught crab species in Western Europe, and the world annual production is over 1.25 million tons (FAO, 2020).

Drying is the predominant preservation method in the food industry, relying on the evaporation of water from food products through the application of thermal energy. However, high temperatures involved in this process can adversely impact the visual quality of food products due to enzymatic browning, leading to quality deterioration (Mothibe, Zhang, Nsor-atindana, & Wang, 2011). To overcome such challenges, innovative drying methods are continuously being developed with a focus on minimizing quality losses that consumers associate with processed products while maximizing drying efficiency to minimize processing costs. Additional applications are used to meet these expectations, especially in thermally sensitive foods such as seafood. The most common side applications used in drying are vacuum and ultrasound pre-treatment.

In traditional drying methods, fishery products are generally sundried (Ozbay & Sarıcoban, 2015a, b). As this method takes a long time and relies on weather conditions, it is not a very efficient one. Besides that, oven drying operates on a similar principle, but using a constant temperature commonly used in food drying applications.

Supporting drying with vacuum and ultrasound pre-treatment increases the drying rate and quality parameters of the dried product. The vacuum process provides a protective effect from oxidation, especially for oxygen-sensitive products (Punathil & Basak, 2016). Ultrasound is a method based on creating micro-channels in the structure of the product with sound waves at frequencies between 20 kHz and 1 MHz (Soria & Villamiel, 2010). Sufficient ultrasound power reduces the surface tension on the product surface, disrupting tissue continuity, and causing the pores to expand. This increases the mass transfer rate (Nowacka, Wiktor, Śledź, Jurek, & Witrowa-Rajchert, 2012). The decrease in the drying time with the application of vacuum and the increase in the porosity with ultrasound enable the texture, color, and taste changes of the dried product to decrease (Punathil & Basak, 2016).

Consumption amounts of dried foods is rising day by day, and therefore, the product range is diversifying. Especially, dry meat derivatives are very popular products due to their high protein content and easy accessibility. Among the diversified dried meat products, seafood also finds its place and diversifies the range of products. Examples can be given for drying-related studies of meat and seafood. Kipcak & Ismail (2021) studied microwave drying of various meat products, including fish, chicken, and beef, and Kumar, Tarafdar, Kumar, & Badgujar (2019) studied convective drying of chicken breast slices. Compared to other meat products, investigations on seafood are less common. Some examples of studies on drying seafood include Shamsuddeen, Cha, Kim, & Kim (2021), who studied hybrid heat pump vacuum drying of oysters, Nguyen, Ngo, & Le, (2019) who investigated convective hot air drying of shrimps, and Kouhila et al. (2020) who studied the effects of convective and solar drying of Mediterranean mussels. Kipcak, Doymaz & Derun, (2019) examined infrared drying of blue mussel and drying kinetics, Kipcak (2017) studied microwave drying of blue mussels, Duan, Jiang, Wang, Yu, & Wang, (2011) studied hot air-microwave drying of tilapia fish fillets.

In addition to these studies, studies on vacuum and ultrasound pre-treatment, which reduce drying time and are effective in preserving visual quality, are often performed on fruit and vegetable products. Examples that can be given as; Tao et al. (2021) studied airborne and contact ultrasound effect on air drying of blackberry, Li, Wang, Wu, Wan, & Yang, (2020) studied ultrasound-assisted vacuum drying of hawthorn fruit juices, and Bozkir, Ergün, Serdar, Metin, & Baysal, (2019) examined ultrasound assisted drying of persimmon fruit. Nowacka et al. (2012) studied apple drying with ultrasound pre-treatment, da Silva et al. (2019) investigated ultrasound and vacuum effect on drying nectarine, and Wang, Ye, Wang, & Raghavan, (2019) studied drying of kiwifruit slices with ultrasound pre-treatment.

Among the numerous drying studies performed with oven drying, sea creatures have rarely been studied. Therefore, this study aims to explore the impact of temperature on the drying rate of a well-known shellfish, *Cancer pagurus.* The drying process was carried out at 60, 70, and 80°C using both an oven dryer and a vacuum oven dryer, and the effect of ultrasonic pre-treatment was also examined. Additionally, effective moisture diffusivity, activation energy, and color changes were calculated to gain a better understanding of how the drying process affected the product.

MATERIALS AND METHODS

Samples and equipment

Cancer pagurus was purchased from a regional market in July 2019 and stored in a freezer at -18°C. Prior to experimentation, the frozen crab was defrosted at a temperature of +4°C, and its hard shell was broken with the aid of a hammer to extract all the edible meat. The extracted crab meat was weighed to approximately 5 ± 0.1 g for each drying process and subsequently pelletized to dimensions of 2.4 ± 0.2 cm in length, 2.4 ± 0.2 cm in width, and 2 ± 0.1 mm in thickness. The impact of pretreatment on drying efficiency was investigated using both pretreated and untreated samples. Moisture content was determined through the use of an oven (KH-45; Kenton, Guangzhou, China) at a temperature of 105°C for 3 hours. Ultrasonic pretreatment (US) was administered using an Isolab Ultrasonic Bath at an ultrasonic power of 180 W (Isolab, Escau, Germany). Drying experiments were conducted using a Nüve EV-018 (Nüve, Ankara, Turkey) at temperatures of 60, 70, and 80°C. Vacuum assistance was provided by a KNF N022AN.18 (KNF, Freiburg, Germany) operating at a frequency of 40 kHz and 100 W. This equipment was employed to examine the effect of temperature on the drying rate of *Cancer pagurus* meat.

Experimental method

Cancer pagurus pellets of 5±0.1 g were placed onto watch glasses. Drying parameters were selected as 60, 70, and 80°C. During the drying processes for each method, the samples for each temperature were weighed at 15-minute intervals. In the first stage, OD was performed with the aforementioned parameters. In the second stage, VOD was applied with the same drying parameters. The pressure inside the oven was kept constant at 0.32 atm during the drying process using a vacuum pump. During the drying process, the samples were weighed at 15-minute intervals to determine the rate of moisture loss. The experimental procedures were divided into four stages. In the first stage, oven drying (OD) was performed at the selected temperatures. In the second stage, vacuum oven drying (VOD) was applied with the same drying parameters. In the third stage, ultrasonic pre-treatment was applied before the drying process, and in the fourth and final stage, the same procedure was applied with vacuum assistance (US-VOD).

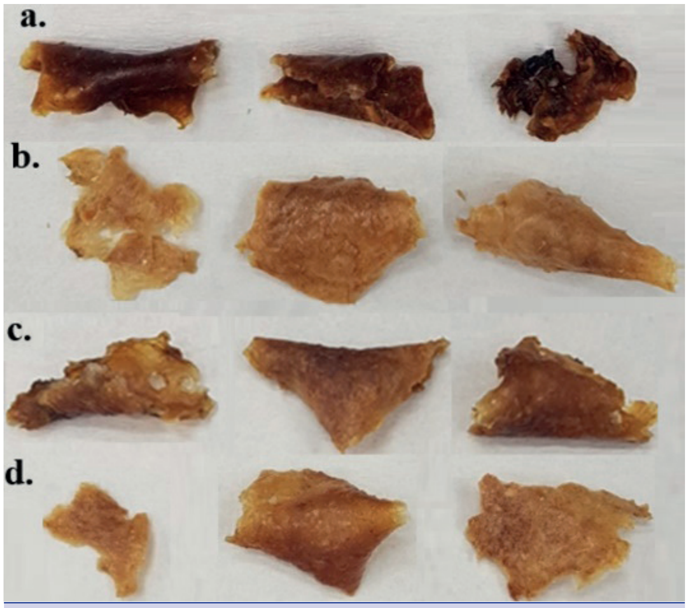

Figure 1. Dried samples of *Cancer pagurus* with the methods of a. OD, b. VOC, c. US-OD, d. US-VOD at 60, 70 and 80 °C, respectively.

Drying processes ended when the humidity of the samples dropped below 10%. After all the drying processes were completed, the samples shown in Figure 1 were placed in polyethylene bags and placed in a desiccator to protect them from moisture.

Mathematical modeling of drying curves

The drying process is governed by Fick's second law, which describes the diffusion of water from the interior to the surface of the sample during drying. To model the drying rate of *Cancer pagurus*, moisture content (*M*), moisture ratio (*MR*), and drying rate (*DR*) were calculated using equations (1), (2), and (3) developed by Kipcak & Ismail (2018), Kipcak, Doymaz, & Derun (2019), and Sevim, Derun, Tugrul, Doymaz, & Kipcak, (2019):

$$M = \frac{m_w}{m_d} \tag{1}$$

Here, M represents the moisture content in kgW/kgDM, m_w represents the water content in kg, and m_d represents the dry matter content in kg.

$$DR = \frac{M_{t+dt} - M_t}{dt} \tag{2}$$

DR represents the drying rate in kgW/kgDM × min, *t* is the drying time in minutes, and M_{t+dt} is the moisture content at time *t+dt* in kgW/kgDM.

$$MR = \frac{M_t - M_e}{M_0 - M_e} \tag{3}$$

MR represents the moisture ratio, which is dimensionless. M_t, M_0, and M_e and represent the moisture content at any time, initial, and equilibrium states, respectively. In most cases, the moisture content at the equilibrium state is negligible compared to the initial and any other moment during the drying process, so it can be neglected in the calculations (Doymaz, Kipcak, & Piskin, 2015; Kipcak, 2017). The calculated values of *M*, *MR*, and *DR* were used to draw drying rate curves for modeling the drying process of *Cancer pagurus*.

Regression analysis of the data to be obtained as a result of drying seafood was done with the help of Statistica 10.0 (StatSoft Tulsa, USA) program. Levenberg-Marquardt algorithm was used for the parameter estimation in nonlinear regression in the modeling of the data, and it was examined in the 14 most widely used models taken from the studies of Doymaz, Kipcak, & Piskin, 2015; Silva et al., 2014).

In determining the suitability of the models for all models used, the value of the regression coefficient (R^2) was taken into consideration first. Besides R^2, the lowest root mean square error (*RMSE*) and reduced Chi-square (χ^2) values were evaluated. Coefficients are calculated using Eq. (4), (5), and (6) (Tunckal & Doymaz, 2020).

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

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

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N - z} \tag{6}$$

The moisture ratios, $MR_{exp,i}$ and $MR_{pre,i}$ denote the calculated and predicted values of moisture content, respectively. The parameter *N* signifies the total number of experiments conducted, while *z* refers to the constant values incorporated in the models (Kipcak, 2017; Tunckal & Doymaz, 2020).

Effective moisture diffusivity

Removal of moisture in the structure during the drying process in foodstuffs takes place in a constant or falling rate period and features a complex mass transport mechanism. Fick's second diffusion equation is commonly used in determining the effective moisture diffusion coefficient in foodstuffs as given in Eq. (7).

While solving this equation, assumptions in which the shrinkage was neglected, the diffusion coefficient was accepted as constant, and the mass transfer occurred symmetrically with respect to the center only by diffusion were made. The applicable unsteady state condition equation of Fick's second law thin layer is given in Eq. (7) (Kipcak & Doymaz, 2020; Doymaz et al., 2015):

$$MR = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-\frac{(2n+1)^2\pi^2 D_{eff}\times t}{4L^2}\right) \quad (7)$$

The moisture ratio is denoted by *MR*, where n is a positive integer, *t* represents the time in seconds, D_{eff} represents the effective moisture diffusivity in square meters per second, and *L* denotes the half-thickness of the sample in meters. However, when the drying time is long, n is considered as 1 (Kipcak & Doymaz, 2020). To derive the exponential equation, the natural logarithm of MR is plotted against *t* using Eq. (8), which is obtained by taking the naturel logarithm of Eq. (7). The slope of the ln(*MR*) versus *t* graph allows for the calculation of D_{eff}.

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

Activation energy

The activation energy plays a significant role in the drying process of food products. It is the energy required to separate water molecules from the product, which makes it a crucial factor in the thermodynamics of drying. A lower activation energy implies a faster drying process. To determine the relationship between the drying process's Eq. (9)-derived D_{eff} and temperature change (Kara & Doymaz, 2015). The D_{eff} in m^2/s, the pre-exponential factor (D_0) in m^2/s, the activation energy (E_a) in kJ/mol, the universal gas constant (R) in kJ/mol K, and the drying temperature (T) in Celsius are all taken into account in this equation (Kipcak & Doymaz, 2020).

$$D_{eff} = D_o exp\left(-\frac{E_a}{R(T+273.15)}\right) \quad (9)$$

The natural logarithm of Eq. (9) is applied to calculate the E_a, resulting in Eq. (10). The activation energy can then be determined by calculating the slope of the graph of D_{eff} versus 1/T, as given in Eq. (11). It is worth noting that E_a is an important parameter in the drying process since a lower activation energy implies a faster drying rate, making it a crucial factor to consider in food processing (Tunckal & Doymaz, 2020).

$$\ln\left(D_{eff}\right) = \ln(D_0) - \left(\frac{E_a}{R}\right)\left(\frac{1}{T}\right) \quad (10)$$

$$slope = -\frac{E_a}{R} \quad (11)$$

Color analysis

The color of food products is an essential feature that conveys information about the product to consumers. In fact, consumers often expect treated products to have consistent color with their pre-processing color. One of the widely used methods for analyzing color is the Hunter color analysis, which involves measuring the lightness-darkness value *L**, redness-greenness value *a**, and yellowness-blueness value *b**. To measure the color parameters of the samples, a hand-held PCE-CSM 1 model colorimeter from PCE Instruments UK Ltd. was used. Samples were measured at least five times before and after each method to ensure accuracy. To calculate the total color changes (ΔE), Eq. (12) was used. The accurate measurement and analysis of color parameters are crucial to ensure that the final product meets the consumers' expectations (Tunckal & Doymaz, 2020).

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

where *"0"* represents the fresh sample.

RESULTS AND DISCUSSION

Drying curves

Initial moisture content was calculated as 75.27% on a wet basis, 3.0431 kg water/kg dry matter (kgW/kgDM) for unpretreated samples and as 75.99% on a wet basis, 3.1651 kgW/kgDM for US pre-treated samples. The moisture content of the sample was reduced to 0.2704, 0.2400, and 0.2189 kgW/kgDM for 60, 70, and 80 °C, respectively, and the drying process took 420, 360, and 255 minutes using the OD method. On the other hand, for the VOD method, the moisture content was reduced to 0.2573, 0.2268, and 0.1997 kgW/kgDM for 60, 70, and 80 °C, respectively, and the dryings took only 345, 285, and 210 minutes. These results indicate that the vacuum effect significantly reduces the drying time compared to the standard OD method, and can be considered a more efficient method for drying food products.

Moving on to the next method, US-OD, the initial moisture content was higher at 3.1651 kgW/kgDM, but it was still reduced to 0.2773, 0.2406, 0.2397 kgW/kgDM for 60, 70, 80°C, respectively, with drying times of 255, 195, and 135 minutes. The fourth method, US-VOD, reduced the moisture content even further to 0.2294, 0.1817, 0.1048 kgW/kgDM for 60, 70, 80°C, respectively, with drying times of 240, 180, and 120 minutes. These results are also presented in Figure 2 and demonstrate that the US pre-treat-

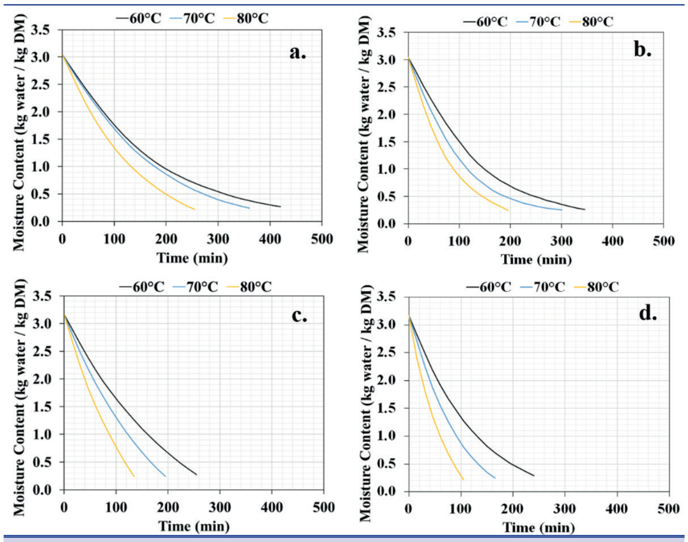

Figure 2. Moisture content versus time of a. OD, b. VOD, c. US-OD, d. US-VOD.

ment method, similar to the vacuum effect, can significantly reduce the drying time when compared to the OD method. This highlights the potential of US-OD and US-VOD as effective and efficient alternatives for drying food products.

Drying rate curves

During the drying process, as the water content in the sample decreases, the structure of the material shrinks, and the number of pores decreases, as explained in Sarpong et al. (2019). As a result, the resistance to water loss increases, making it more difficult for water to escape, which leads to a falling rate period in the drying process (Doymaz et al., 2015; Kipcak, 2017). This phenomenon was also observed in the drying of *Cancer pagurus*, as shown in Figure 3. The drying rates obtained in the OD process were between 0.0141 - 0.0014, 0.0158 - 0.0022 and 0.0202 - 0.0041 kgW/kgDM × min for 60, 70 and 80 °C, respectively. Meanwhile, in vacuum oven drying (VOD), the drying rates were observed between 0.0175 - 0.0019, 0.0229 - 0.0026 and 0.0307 - 0.0037 kgW/kgDM × min for 60, 70 and 80 °C, respectively. The drying rates were found to increase with increasing temperature, as higher temperature results in faster heat and mass transfer, and hence faster water loss. Furthermore, the results indicated that vacuum application effectively accelerates the drying process.

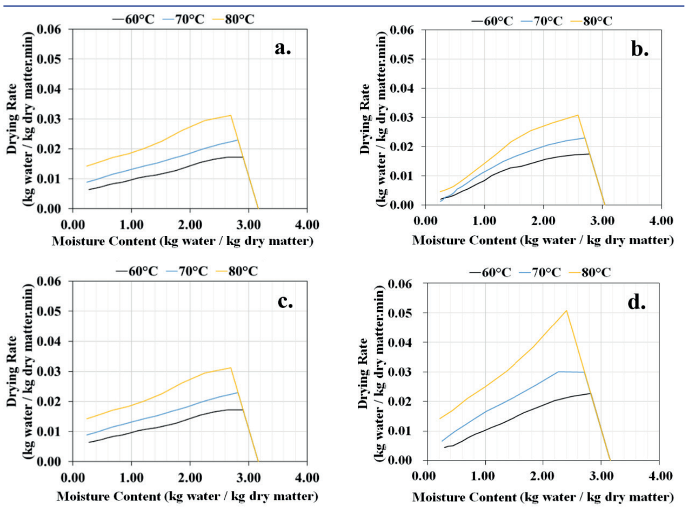

Figure 3. Drying rate versus moisture content of a. OD, b. VOD, c. US-OD, d. US-VOD.

Modeling and regression analyses results

Experimentally obtained moisture ratios and drying times were tested in 14 different mathematical models. In order to find the model that best fits with experimental data, R^2, value is expected to be close to 1, while the lowest χ^2 and *RMSE* values are desired. All data placed on the 45° line and the most suitable models were listed in Table 1 and Table 2 with values $R^2 > 0.9998$.

The most compatible model for all drying methods was observed with Alibas model. For OD, the coefficients were found as 0.999967, 0.999970, 0.999995 R^2; 0.000003, 0.000003, 0.000001 χ^2 and 0.001541, 0.001498, 0.000622 *RMSE* for 60, 70 and 80 °C, respectively. For VOD, the coefficients were found as 0.999831, 0.999956, 0.999977 R^2; 0.000013, 0.000004, 0.000003 χ^2 and 0.003301, 0.001822, 0.001354 *RMSE* for 60, 70 and 80 °C, respectively. For US-OD, the coefficients were found as 0.999985, 0.999996, 0.999986 R^2; 0.000002, 0.000001, 0.000003 χ^2 and 0.001117, 0.000583, 0.001179 *RMSE* for 60, 70 and 80 °C, respectively. For US-VOD, the coefficients were found as 0.999996, 0.999987, 0.999996 R^2; 0, 0.000002, 0.000001 χ^2 and 0.000567, 0.001085, 0.000634 *RMSE* for 60, 70 and 80°C, respectively.

Effective moisture diffusivity results

The calculation of effective moisture diffusivity values was based on the slope of the ln(MR) versus drying time graphs, and the results were obtained for temperatures of 60, 70, and 80 °C. The first two methods, OD and VOD, resulted in effective moisture diffusivities of 3.97×10^{-11}, 4.78×10^{-11}, and 6.73×10^{-11} m^2/s, and 4.90×10^{-11}, 6.12×10^{-11}, and 8.67×10^{-11} m^2/s, respectively. It was observed that the temperature increased, and low-pressure medium resulted in a slight increase in the effective moisture diffusion values. The third and fourth methods, US-OD and US-VOD, resulted in effective moisture diffusivities of 6.08×10^{-11}, 8.31×10^{-11}, and 1.20×10^{-10} m^2/s, and 7.2×10^{-11}, 1.05×10^{-10}, and 1.75×10^{-10} m^2/s, respectively. These results indicated that ultrasonic pre-treatment was a factor that increased the effective moisture diffusivities values. Upon evaluating all the results, it was seen that the US-VOD method yielded the best diffusion values among the methods. Furthermore, it was determined that all the calculated values were within the range of 10^{-8} to 10^{-12} m^2/s specified in the literature for diffusion coefficients of biological materials (Ayriksa et al., 2022). Overall, the study provides valuable insights into the effective moisture diffusivity values for various temperatures and models, highlighting the importance of ultrasonic pre-treatment in enhancing the diffusion process.

Activation energy results

The effect of temperature on diffusivity is defined by the Arrhenius equation, and the activation energy is obtained from the slope of the ln(D_{eff}) plot against $1/T$ by multiplying by universal gas constant R (8.314 J/mol × K).

In the first method of OD, the slope of the graph was obtained as 3090 K, hence, the activation energy of drying was calculated as 25.69 kJ/mol. In the next methods, the slopes were obtained as 3287, 3994.5, and 5364.5 K, hence the activation energies as 27.33, 33.21, and 44.60 kJ/mol for VOD, US-OD, and US-VOD stages, respectively. When the results were examined, it is seen that vacuum and US pre-treatment have an increasing effect on the activation energy.

Color analysis results

When the *Cancer pagurus* color parameters given in Table 4 were compared, from the highest to lowest, *L** values were obtained in US-VOD, VOD, US-OD, and OD, respectively. Accordingly, it is seen that vacuum application and subsequent US pre-treatment are quite effective in preventing discoloration due to the shortening of drying times.

As the drying time increased, *a** redness-greenness value increased inversely to *L** values. The highest *a** value was obtained in the OD, US-OD, VOD, and US-VOD methods, respectively. In addition, *b** blueness-yellowness values were obtained from the highest to the

Table 1. OD and VOD methods coefficients and statistical data.

Method	Model	Parameter	60°C	70°C	80°C
OD	Alibas	*a*	0.826245	1.125136	0.750317
		k	0.003378	0.003859	0.006218
		n	1.141137	1.067582	1.099287
		b	-0.000269	0.000175	-0.000891
		g	0.171153	-0.126821	0.249788
		R^2	0.999967	0.999970	0.999995
		χ^2	0.000003	0.000003	0.000001
		RMSE	0.001541	0.001498	0.000622
OD	Midilli & Kucuk	*a*	1.000793	0.997232	1.001945
		k	0.003768	0.003837	0.006250
		n	1.085134	1.088471	1.044227
		b	0.000048	-0.000056	-0.000225
		R^2	0.999928	0.999966	0.999966
		χ^2	0.000010	0.000003	0.000003
		RMSE	0.002291	0.001608	0.001621
OD	Verma	*a*	-0.047378	-1.142330	-3.667693
		k	0.045039	0.002930	0.014252
		g	0.005961	0.004220	0.012623
		R^2	0.999921	0.999677	0.999378
		χ^2	0.000006	0.000028	0.000059
		RMSE	0.002403	0.004969	0.007023
VOD	Alibas	*a*	0.907010	0.978223	0.786354
		k	0.007020	0.005348	0.008596
		n	1.004697	1.136896	1.142108
		b	-0.000060	0.000113	-0.000774
		g	0.096707	0.019303	0.212804
		R^2	0.999831	0.999956	0.999977
		χ^2	0.000013	0.000004	0.000003
		RMSE	0.003301	0.001822	0.001354
VOD	Midilli & Kucuk	*a*	1.006291	0.998019	1.002602
		k	0.007431	0.005441	0.009861
		n	0.971580	1.128988	1.052590
		b	0.000101	0.000166	0.000021
		R^2	0.999797	0.999955	0.999824
		χ^2	0.000135	0.000004	0.000019
		RMSE	0.010851	0.001853	0.003795
VOD	Two-term	*a*	0.906495	0.000074	-0.034320
		b	-0.007166	0.019274	-2.639500
		c	0.097983	1.021629	1.034320
		d	-0.000791	-0.009614	-0.012820
		R^2	0.999831	0.999071	0.999867
		χ^2	0.000012	0.000083	0.000013
		RMSE	0.003297	0.008444	0.003297

lowest in US-VOD, VOD, US-OD, and OD with L^* values and in contrast to a^* values. When Table 4 is examined, it is seen that increasing drying temperatures reduce the change in color values. This is because the increasing temperature reduces the drying time. In addition, it was stated in the literature that the temperature increase increased the L^* and b^* values and decreased a^* values for all drying methods, and it was found to be compatible with this study (Isik, Ozdemir, & Doymaz, 2019). Total change of color ΔE values was obtained as 22.67, 21.84, 21.18 in OD; as 21.57, 19.23, 18.00 in VOD; as 22.30, 21.63, 19.85 in US-OD and as 20.33, 17.69, 17.09 in US-VOD at 60, 70 and 80 °C, respectively. When the ΔE values given in Table 4 were evaluated, as expected, the US-VOD was the least color change, and the OD was the method with the highest color change. It can be said that the drying-thermal exposure time plays an im-

Table 2. US-OD and US-VOD methods coefficients and statistical data.

Method	Model	Parameter	60°C	70°C	80°C
US-OD	Alibas	*a*	0.819830	1.576497	0.556739
		k	0.005351	0.005091	0.011153
		n	1.036487	0.992529	1.067161
		b	-0.000972	0.000233	-0.003223
		g	0.180970	-0.576187	0.443556
		R^2	0.999985	0.999996	0.999986
		χ^2	0.000002	0.000001	0.000003
		RMSE	0.001117	0.000583	0.001179
US-OD	Logarithmic	*a*	1.359024	1.439650	1.519793
		k	0.004374	0.005260	0.006919
		c	-0.357436	-0.439931	-0.520653
		R^2	0.999975	0.999995	0.999934
		χ^2	0.000002	0.000000	0.000009
		RMSE	0.001437	0.000630	0.002515
US-OD	Midilli & Kucuk	*a*	1.001334	0.999696	1.001047
		k	0.005029	0.006301	0.009206
		n	1.017187	1.017572	0.999035
		b	-0.000614	-0.000942	-0.001585
		R^2	0.999983	0.999992	0.999968
		χ^2	0.000002	0.000001	0.000010
		RMSE	0.001191	0.000858	0.002515
US-Oven	Peleg	*a*	1.006000	1.003000	1.002100
		k_1	-159.3560	-125.9880	-91.13980
		k_2	-0.462000	-0.431000	-0.405200
		R^2	0.999938	0.999954	0.999968
		χ^2	0.000006	0.000005	0.000004
		RMSE	0.002242	0.001995	0.001761
US-VOD	Alibas	*a*	1.037983	1.138559	1.537330
		k	0.006203	0.007587	0.014648
		n	1.060824	1.073670	0.928680
		b	0.000022	0.000207	0.000912
		g	-0.037979	-0.138069	-0.537275
		R^2	0.999996	0.999987	0.999996
		χ^2	0.000000	0.000002	0.000001
		RMSE	0.000567	0.001085	0.000634

Table 4. Color parameters for each method.

Method	T (°C)	L*	a*	b*	ΔE
Fresh	-	35.93	-6.56	-7.13	-
OD	60	18.15±0.20	10.86±0.25	4.95±0.67	22.67
	70	18.99 ±0.61	9.81±0.20	6.17±0.31	21.84
	80	19.36±0.05	8.50±0.18	7.23±0.17	21.18
VOD	60	20.61±0.58	9.50±0.22	8.15±0.23	21.57
	70	23.12±0.40	6.76±0.27	9.52±0.07	19.23
	80	25.23±1.04	5.48±0.11	10.25±0.01	18.00
US-OD	60	19.08±0.18	10.46±0.28	6.31±0.12	22.30
	70	20.57±0.56	9.70±0.74	7.93±0.42	21.63
	80	22.15±0.15	7.65±0.65	8.79±0.79	19.85
US-VOD	60	22.84±0.40	8.38±0.04	9.36±0.02	20.33
	70	27.59±0.97	5.92±0.21	10.49±0.14	17.69
	80	30.36±0.66	4.92±0.81	11.20±0.47	17.09

portant role in the change of color values, and the color change increases in direct proportion to the exposure time. This situation is also clearly seen in Figure 1.

CONCLUSION

The study aimed to investigate the drying kinetics and color analysis of *Cancer pagurus* using various drying methods, including OD, VOD, US-OD, and US-VOD at different drying temperatures. In addition, mathematical modeling of drying curves was conducted to determine the best fit model. The results showed that vacuum and US pre-treatment significantly reduced the drying times compared to the traditional OD method. Specifically, vacuum reduced the drying times from 420 - 255 min to 345 - 210 min in the OD method, while US pre-treatment reduced the drying times to 255 - 135 min for the OD method and to 240 - 120 min for the VOD method. The Alibas model provided the best fit for the drying curve data with R^2 values greater than 0.9999. Moreover, US pre-treatment and vacuum increased the D_{eff} and E_a values, which were found to be 0.367 - 0.673 × 10^{-10} m^2/s, 0.490 - 0.867 × 10^{-10} m^2/s, 0.608 - 1.20 × 10^{-10} m^2/s, and 0.721 - 1.75 × 10^{-10} m^2/s for the OD, VOD, US-OD, and US-VOD methods, respectively. The E_a values were calculated as 25.69, 27.33, 33.21, and 44.60 kJ/mol for the OD, VOD, US-OD, and US-VOD methods, respectively. It was observed that US pre-treatment and vacuum decreased the ΔE values, which ranged from 22.67 - 21.18, 21.57 - 18.00, 22.30-19.85, and 20.33 - 17.09 for the OD, VOD, US-OD, and US-VOD methods, respectively. As a result, vacuum and US pretreatments significantly reduced drying times and increased D_{eff} and E_a, which are critical factors in final product quality. The use of pre-treatment or drying aiding technologies, such as vacuum and ultrasound, has a substantial influence on improving drying performance and the quality of the end product, according to the study's findings. The observed decrease in color change values further supports this assertion.

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