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Effects of drying methods on the drying kinetics of blanched brown crab meat

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The study was conducted to examine the effect of various drying methods on the drying kinetics of brown crab meat pre-treated by blanching in a 5% brine solution. The drying methods used in this study included oven drying, infrared (IR) drying, and microwave (MW) drying. The results obtained were analyzed and evaluated through statistical and color analyses. To conduct the study, oven and IR drying were carried out at varying temperatures between 60°C - 80°C, while MW drying was performed at different power settings between 140 W - 350 W. The data collected from these experiments were analyzed to determine the drying rates, effective moisture diffusivities (D_{eff}), and activation energies (E_a). Mathematical models were used to compare the drying times, and graphical representations were created to present the findings. The outcomes of the study showed that the microwave drying method had the highest D_{eff} value, which ranged between 2.83×10^{-9} and 9.76×10^{-9} m^2/s, while the oven drying method had the lowest D_{eff} value, which ranged between 1.90×10^{-10} and 2.62×10^{-10} m^2/s. The E_a values for the oven, IR, and MW methods were calculated as 15.74 kJ/mol, 37.55 kJ/mol, and 72.71 kW/kg, respectively. Furthermore, the highest R^2 value was obtained with Aghbashlo *et al*. model for the oven and Alibas model for IR and MW. In addition, the color analysis showed that the MW drying method caused the highest total color change (ΔE), followed by IR and oven drying.

Keywords: Activation energy, brown crab, color change, effective moisture diffusivity

INTRODUCTION

The brown crab, scientifically known as *Cancer pagurus*, is a type of crustacean with a heavy, oval-shaped reddish-brown body characterized by its large, powerful pincers with pie-crusty edges. The brown crab is highly regarded and widely appreciated as a crustacean in European countries [1]. The countries with the highest volume of brown crab catch include the United Kingdom, Ireland, Norway, and France. The main distribution of the brown crab spans from Norway in the North Sea to the coast of Portugal, primarily utilizing the English Channel [1]. In the global market, male crabs with more enormous claws are in higher demand than female crabs, due to their higher meat content [2]. The carapace of a mature *Cancer pagurus* can be up to 30 cm wide and weigh up to 3 kg. Their lifespan can vary between 20 and 50 years [3, 4]. Their growth rate depends on multiple variables such as food availability, water depth, and temperature [4]. Brown crab contains high protein, amino acids, essential elements (e,g, Zn, Se), and fatty acids while keeping fat and cholesterol levels low, making it a healthy and beneficial food choice [1, 5]. Crab meat undergoes rapid microbial degradation after hunting. It is often immediately incorporated into food processing for consumption of this product of high economic value [6].

In order to maintain and improve the quality and lifespan of food products, drying is one of the oldest and most used techniques [7]. The process itself is a combination of heat and mass transfer and needs an energy supply [8]. It requires high amounts of energy and generates phase change for the water molecules inside the food and converts liquid to vapor. The transfer mechanism for heat may vary depending on the method. It can be transferred *via* radiation, conduction with the help of a hot plate, or even microwaves using radio frequency.

There are many studies in the literature on drying seafood with different methods. Some of these studies were carried out on molluscs, crustaceans, and fish such as sea cucumber [9, 10], shrimp [11, 12], mussels [13, 14], octopus [15], calamari [16], and catfish [17]. Despite its high consumption rates, crab meat has received little attention among seafood drying studies. In this study, blanched crab meat was examined using infrared (IR) and microwave (MW) drying methods and evaluated in comparison with the results of a previous oven-drying study [18]. Drying rate, effective moisture diffusion, and activation energies were calculated and drying data were tested for 13 mathematical models to determine the best-fitting model. In addition, color analysis was performed to appoint the visual changes in drying methods.

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EXPERIMENTAL

The crab was bought from a fish market in Istanbul, Turkey in February 2021 and was kept in a refrigerator at a temperature of -18 °C. Before the experiments, the crabs were thawed at +4 °C and brought to room temperature in a desiccator. For blanching, 700 ml of distilled water containing 5% of salt was brought to boiling and the crab was boiled in this water for 10 minutes. The shell of the crab changed color from brown to red after boiling as seen in Figure 1. After the boiling process, the crabs were cooled for 5 minutes, and the meat and shells were separated from each other. The 0.5 cm thick samples weighed 5.0 ± 0.2 g, as shown in Figure 2.

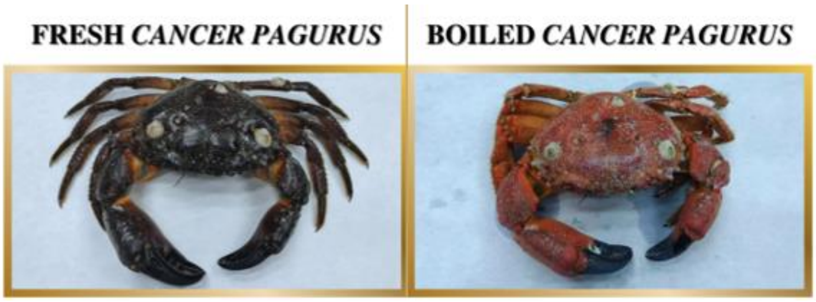


Figure 1. Crab before and after blanching

The average moisture content was determined by using a hot air-drying oven (KH-45; Kenton, Guangzhou, China) at 120°C for 3 hours. The drying temperatures were selected as 60, 70, and 80 ˚C for oven [18] and infrared (IR), and 140, 210, and 350 W were selected for the microwave (MW). During the drying process, the weight of the sample was noted at intervals of 15 minutes. Drying ended when the moisture content of the sample dropped under 10%.

Figure 2. Blanched crab meat

The weight of the sample was noted at intervals of 15 minutes [18] during the oven and IR processes, and each minute for 140 and 210 W and every 30 seconds for 350 W in MW. Drying ended when the moisture content of the sample dropped under 10%.

Mathematical modeling of drying curves

Moisture content, drying rate, and moisture ratio were calculated to draw the drying curves and test the drying data's compatibility with mathematical models (Equations 1-3). In the formulas, moisture content (M) was calculated based on kg water content (m_w) and kg dry matter (m_d). Drying rate (DR) was calculated based on the values of moisture content at time t min (M_t) and time t+dt (M_{t+dt}). The moisture ratio (MR) was calculated dimensionless depending on the initial (M_0), t-minute (M_t), and equilibrium (M_e) moisture contents [14, 19].

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

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

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

Mathematical modeling was performed with 13 different models whose formulas are given in Table 1 with Statistica 10.0 (StatSoft Tulsa, USA) program using the Levenberg-Marquardt algorithm for parameter estimation in nonlinear regression. The fit of the models was determined by the regression coefficient (R^2), the lowest root mean square error ($RMSE$), and reduced chi-square (χ^2) values [20]. Here, the calculated ($MR_{exp,i}$) and predicted values ($MR_{pre,i}$) for moisture ratios were calculated as given in equations 4-6, depending on the total number of experiments (N) and the model constant number (z) [20, 21].

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

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

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

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. Model names and equations used for the experiments [22]

Name of the model	Model equation
Aghbaslo *et al.*	$MR = \exp(-k_1t / (1 + k_2t))$
Alibas	$MR = a \times \exp((-kt^n) + bt) + g$
Henderson *et al.*	$MR = a \times \exp(-kt)$
Jena *et al.*	$MR = a \times \exp(-kt + b\sqrt{t}) + c$
Lewis	$MR = \exp(-kt)$
Logarithmic	$MR = a \times \exp(-kt) + c$
Midilli & Kucuk	$MR = a \times \exp(-kt^n) + bt$
Page	$MR = \exp(-kt^n)$
Parabolic	$MR = a + bt + ct^2$
Two-Term Exponential	$MR = a \times \exp(-k_0t) + b \times \exp(-k_1t)$
Verma *et al.*	$MR = a \times \exp(-kt) + (1 - a) \times \exp(-gt)$
Wang *et al.*	$MR = \exp(-(t/b)^a)$
Weibull	$MR = a - b \times \exp(-(kt)^n)$

Effective moisture diffusivity and activation energy

The drying mechanism in food products is explained with formulas based on Fick's second law of diffusion. The effective moisture diffusion coefficient (D_{eff}) which requires basic assumptions to be made, can be calculated with Equation 7 depending on the sample half-thickness (L) in meters and the positive integer n. Within the calculation, it is assumed that there is no shrinkage or change in the diffusion coefficient and that mass transfer occurs symmetrically with respect to the center by diffusion only. In addition, the n value is accepted as 1 due to the length of the drying time [23].

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

Activation energy (E_a) also plays an important role in the separation of water molecules from the product to be dried. Accordingly, the lower the activation energy of the water molecules, the faster the drying occurs. When this calculation is made as the energy provided by the drying devices to the product to be dried, the higher the activation energy, the faster the drying will be. The calculation of the activation energy is derived from the slope of the graph plotted against $1/T$ (T in Kelvin) of the natural logarithm of the D_{eff} value for the temperature-based furnace and IR (Equation 8). Since the MW process is based on power, the graph is drawn for $\ln(D_{eff})$ against the ratio of kg sample weight (m) to microwave power (P) as in Equation 9. The slope of this graph gives the value E_a for MW. In this calculation based on the Arrhenius equation, D_0 is the exponential factor in m^2/s and R is the universal gas constant in kJ/mol×K [20].

$$D_{eff} = D_o exp\left(-\frac{E_a}{RT}\right) \quad (8)$$

$$D_{eff} = D_0\, exp\left(\frac{E_a \times m}{P}\right) \quad (9)$$

Color analysis

Color value is one of the visual elements that change during the drying of foods. The color change (ΔE) of the product to be dried before and after processing can be obtained by calculating the change in lightness-darkness value (L^*), redness-greenness value (a^*), and yellowness-blueness value (b^*) with equation 10 [22].

$$\Delta E = \sqrt{(L_0 - L)^2 + (a_0 - a)^2 + (b_0 - b)^2} \quad (10)$$

In this equation, L_0, a_0, and b_0 values represent the color values of the samples before drying. Detection of color changes in the drying process of Blanched crabmeat was performed using a model PCE-CSM 1 colorimeter available from PCE Instruments UK Ltd., with the average of values taken from samples from 5 different areas [20].

RESULTS AND DISCUSSION

In determining the moisture content of the samples to be dried, the initial moisture content was found to be 76.05% on a wet basis, corresponding to 3.175 kg water/kg dry meat on a dry basis. The dried samples are shown in Figure 3.

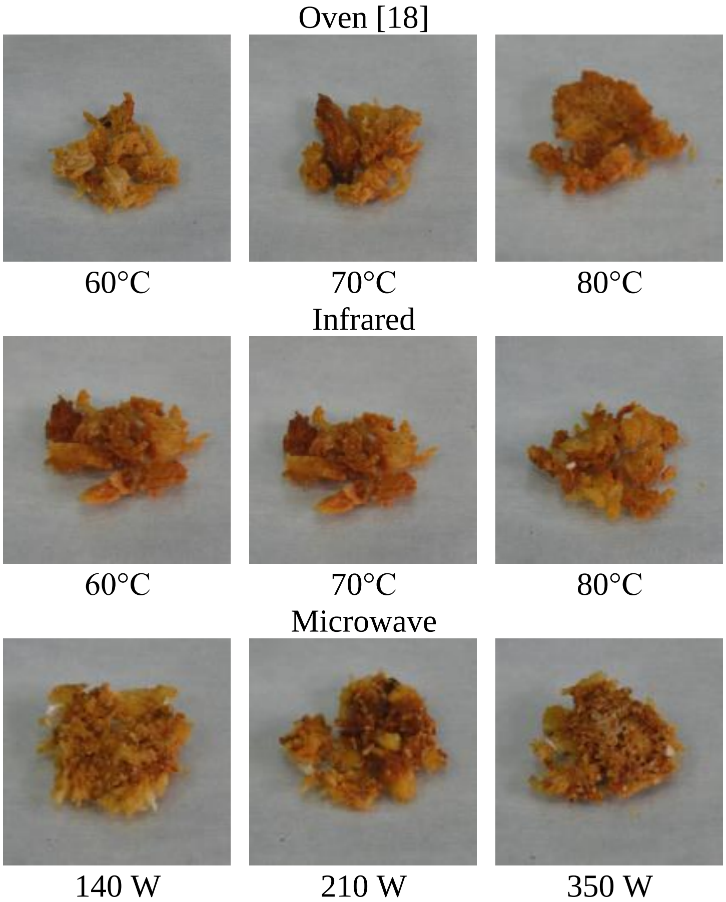


Figure 3. Dried blanched crab meat

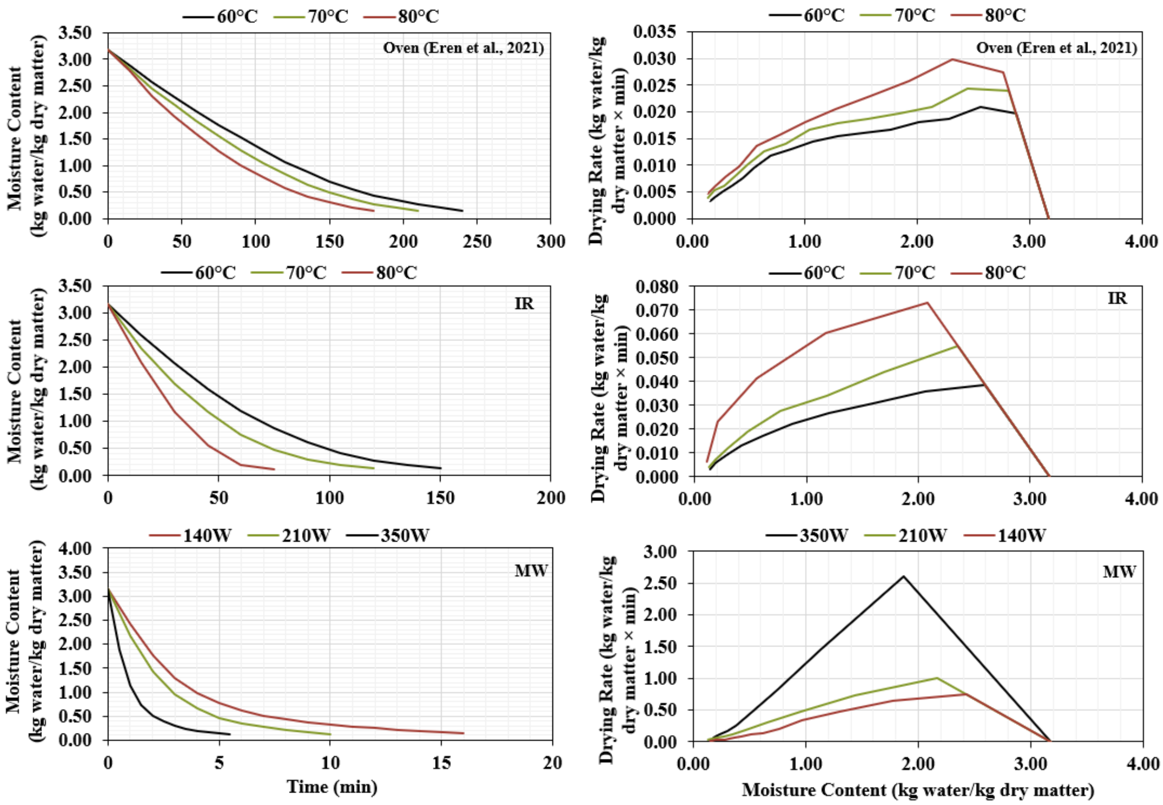


Figure 4. Moisture content *vs*. time and drying rate *vs*. moisture content plots of oven [18], IR, and MW

Mathematical modeling of drying curves

In the oven drying of the samples whose moisture content was determined, 240, 210, and 180 minutes at 60, 70, and 80 C, respectively, the final moisture contents were obtained as 0.1591, 0.1427, and 0.1389 kg water/kg dry matter [18]. For IR, drying times were 150, 120, and 75 minutes at 60, 70, and 80 °C, respectively, and final moisture contents were 0.1391, 0.1322, and 0.1113 kg water/ kg dry matter. For MW drying times were 17, 10, and 6 minutes at 140, 210, and 350W, respectively, and final moisture contents were 0.1363, 0.1269, and 0.1124 kg water/kg dry matter. The drying curves given in Figure 4 were drawn by using the moisture change *versus* time data in the drying processes. When the moisture content *versus* time plots is examined, it is seen that MW is the fastest drying method and the oven is the slowest drying method in drying processes. Additionally, it may be concluded that higher temperatures and power levels at the end of drying lead to lower final moisture content. When the graphs of moisture content *versus* drying rate were looked at, it was found that for all techniques practically all of the drying occurred in the falling rate period.

Model constants and parameters were obtained by fitting the drying data into mathematical model equations. The model outputs for the three models with the highest R^2 and the lowest χ^2 and RMSE values for each method among the 13 models applied are given in Table 2.

According to the evaluated parameters, the model with the highest compatibility with the drying data was found to be Aghbashlo *et al.* for the oven [18] with R^2 values of 0.99963, 0.99981, and χ^2 values of 0.99981, 0.00004, 0.00001, and 0.00002 and RMSE of 0.00582, 0.00354, and 0.00382, for 60, 70, and 80°C, respectively.

The most compatible methods for IR and MW were determined as Alibas. R^2 values for 60, 70, and 80°C for IR, respectively, were 0.99999, 0.99995, and 0.99999, ${}^2\chi$ values were 0.00001, 0.00001, and 0.00001 and RMSE were 0.00107, 0.00220, and 0.00081. R^2 values for 140, 210, and 350 W for MW, respectively, were 0.99991, 0.99999, and 0.99997, ${}^2\chi$ values were 0.000009, 0.000002, and 0.000003 and RMSE were 00.002506, 0.000962, and 0.001412.

Effective moisture diffusivity & activation energy results

The D_{eff} values were calculated from the slope of the graphs plotted against the drying time of In (MR) which are given in Figure 5. D_{eff} values for oven were obtained as 1.9×10^{-10}, 2.23×10^{-10}, and 2.62×10^{-10} m^2/s for 60, 70 and 80 °C, respectively. D_{eff} values for IR were obtained as 3.27×10^{-10}, 4.16×10^{-10}, and 7.08×10^{-10} m^2/s for 60, 70 and 80 °C, respectively. D_{eff} values for MW were obtained as 2.83×10^{-9}, 4.83×10^{-9}, and 9.76×10^{-9} m^2/s for 140, 210 and 350 W, respectively. It is seen that the increase in temperature and power values increases the D_{eff} values for all methods. It was observed that the calculated D_{eff} values are in the range of 10^{-8} and 10^{-12} m^2/s, which is the literature range for biological materials [24]. The obtained D_{eff} values were used to calculate the activation energy as the energy transferred to the sample by the dryers during drying. E_a values were obtained from the relationship of the slope of the graph of ln(D_{eff}) *vs*. 1/T for oven and IR with the gas constant R, and from the slope of the graph of ln(D_{eff}) against m/P for MW.

Accordingly, E_a values for oven, IR, and MW were obtained as 15.74 kJ/mol, 37.55 kJ/mol, and 72.719 kW/kg, respectively. Obtaining lower E_a with oven than with IR indicates that a lower level of energy is transferred to the samples for drying. This is also consistent with oven drying taking longer than IR.

Color analysis

The results of color analyses are shown in Figure 6 with parameters L*, a*, b*, and ΔE values which are mean values of five repeated measurements of each method in every different medium of temperature or power. L*, a*, and b* values of fresh samples were measured as 32.14, -5.453, and -2.276, respectively. MW drying was determined to have higher L* and the oven had lower values. The reason behind this result is that the drying time in MW was the shortest and in the oven was the longest. For the redness-greenness value a*, it was observed that lower temperature and power settings lead to more reddish color on the dried sample, which means it is inversely proportional to the lightness values and hence, inversely proportional to drying time. It is concluded that more reddish colors occurred in MW, IR, and oven in decreasing order due to their drying times. The yellowness-blueness value b* was seen to be directly proportional to L* but inversely proportional to a*. Also, it was observed that all three methods gave relatively close b* values in the final product.

Table 2. Mathematical model coefficients and statistical data

				Oven [18]					
Model	Aghbashlo *et al.*			Parabolic			Wang *et al.*		
Coeff.	60°C	70°C	80°C	60°C	70°C	80°C	60°C	70°C	80°C
a				1.01120	1.00617	1.00487	-0.00700	-0.00816	-0.00985
b				-0.00718	-0.00827	-0.00996	0.00001	0.00002	0.00003
c				0.00001	0.00002	0.00003			
k_1	0.00671	0.00792	0.00982						
k_2	-0.00210	-0.00234	-0.00253						
R^2	0.99963	0.99981	0.99981	0.99958	0.99980	0.99987	0.99939	0.99974	0.99983
χ^2	0.00004	0.00001	0.00002	0.00005	0.00002	0.00001	0.00006	0.00003	0.00002
RMSE	0.00582	0.00354	0.00382	0.00618	0.00431	0.00326	0.00746	0.00484	0.00383
				IR					
Model	Alibas			Parabolic			Wang *et al.*		
Coeff.	60°C	70°C	80°C	60°C	70°C	80°C	60°C	70°C	80°C
a	2.94015	2.79395	3.71385	0.99908	0.98608	1.00406	-0.01295	-0.01745	-0.02629
b	0.00701	0.00825	0.01974	-0.01293	-0.01702	-0.02648	0.00004	0.00008	0.00018
c				0.00004	0.00008	0.00018			
g	-1.94060	-1.79420	-2.71404						
k	0.00592	0.00965	0.01013						
n	1.05122	1.00628	1.08018						
R^2	0.99999	0.99995	0.99999	0.99987	0.99895	0.99986	0.99987	0.99862	0.99983
χ^2	0.00001	0.00001	0.00001	0.00002	0.00016	0.00003	0.00002	0.00018	0.00003
RMSE	0.00107	0.00220	0.00081	0.00358	0.01029	0.00409	0.00360	0.01177	0.00448
				MW					
Model	Alibas			Two Term-Exponential			Verma *et al.*		
Coeff.	140W	210W	350W	140W	210W	350W	140W	210W	350W
a	0.82899	0.86441	0.89716	0.12511	-11.8548	1.59939	0.89115	0.01815	0.84633
b	-0.00787	-0.00980	-0.01168	-0.05973	-0.38050	-0.91048			
c				0.88630	12.84920	-0.62597			
d				-0.34729	-0.38050	-0.91036			
g	0.17196	0.13544	0.10301				0.05160	0.40865	0.24733
k	0.32663	0.43575	1.20344				0.33627	-0.04496	1.25855
n	1.13913	1.11625	0.99652						
R^2	0.99991	0.99999	0.99997	0.99918	0.99784	0.98806	0.99906	0.99964	0.99998
χ^2	0.000009	0.000002	0.000003	0.000074	0.000295	0.001278	0.000079	0.004536	0.000002
RMSE	0.002506	0.000962	0.001412	0.00758	0.013703	0.029748	0.008132	0.057433	0.001179

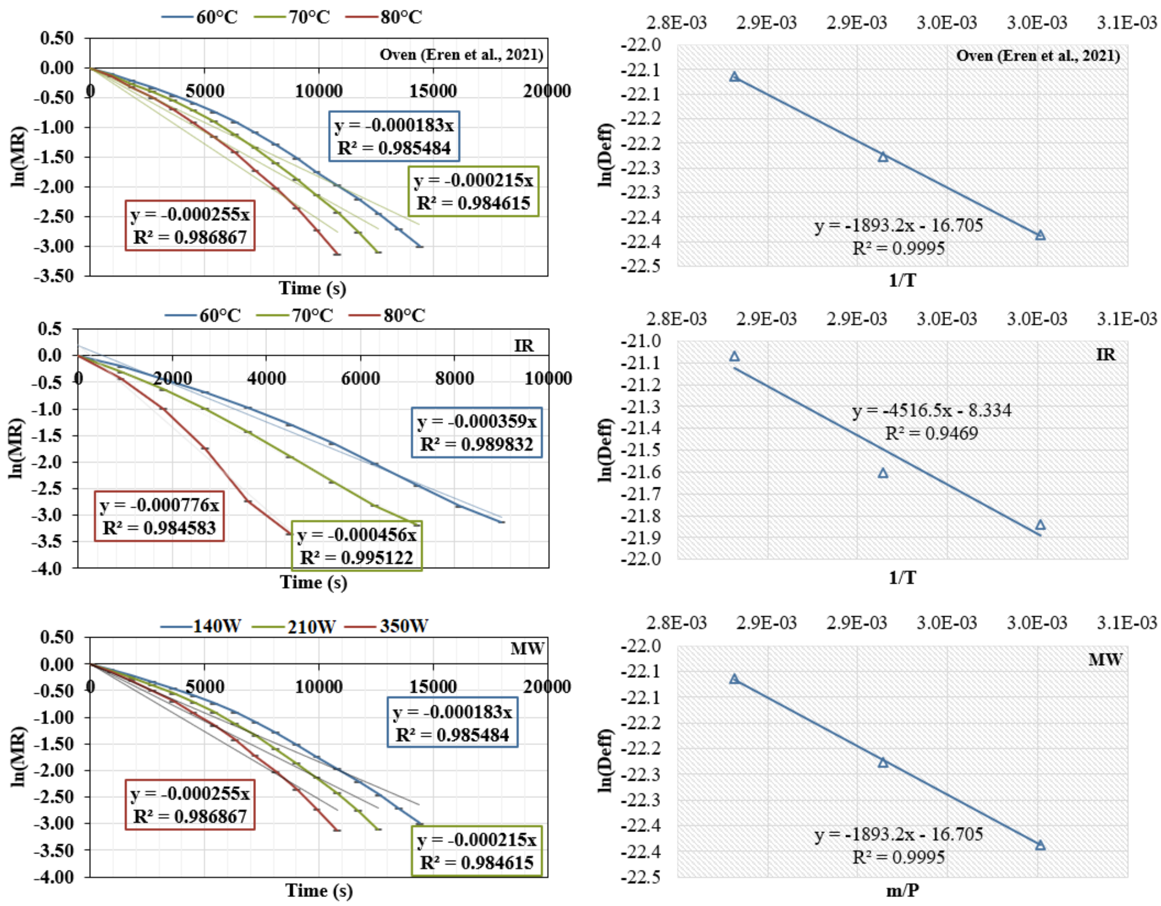
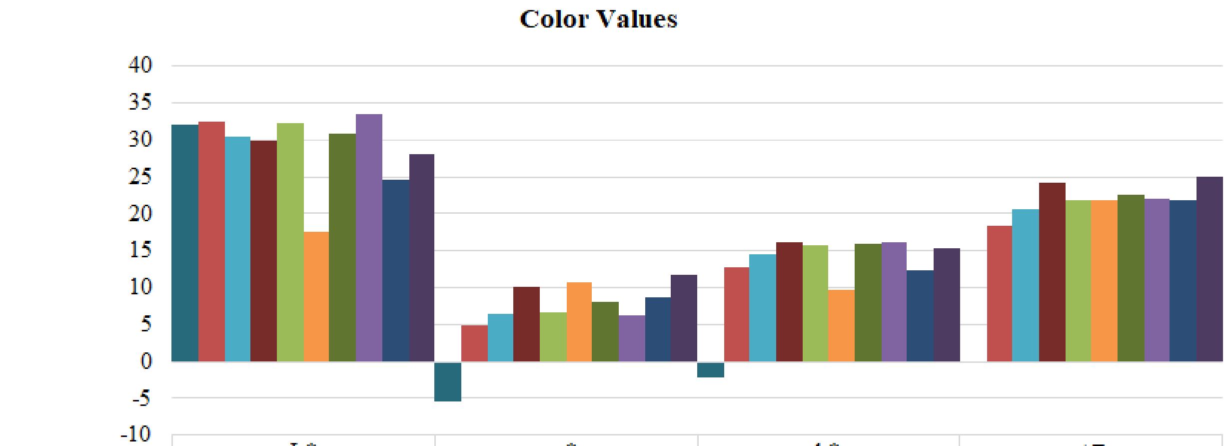


Figure 5. D_{eff} and activation energy curves for oven [18], IR, and MW



	L*	a*	b*	ΔE
Before Drying	32.14	-5.5	-2.3	0.0
Oven - 60 °C	32.46	4.96	12.81	18.33
Oven - 70 °C	30.49	6.50	14.52	20.68
Oven - 80 °C	29.79	10.16	16.09	24.23
IR - 60 °C	32.24	6.78	15.82	21.84
IR - 70 °C	17.64	10.79	9.68	21.84
IR - 80 °C	30.94	8.09	15.90	22.70
MW - 140W	33.54	6.24	16.21	21.92
MW - 210W	24.68	8.72	12.38	21.71
MW - 350W	28.12	11.81	15.33	24.99

Figure 6. Color values of oven [18], IR, and MW dried blanched crab meat

When *ΔE* values were compared, it was seen that the least change occurred in the furnace, and the highest change was in MW. It appears that the increase in temperature and power levels causes an increase in *ΔE*.

CONCLUSION

The drying kinetics and statistical analyses of blanch pre-treated brown crab (*Cancer pagurus*) with IR and MW were studied and evaluated together with the previous oven study [18]. Drying times were obtained as an average of 210 minutes in an oven, 110 minutes in IR, and 11 minutes in MW. Based on the highest R^2 and lowest χ^2 and RMSE values among the 13 models tested in mathematical models, it was determined that the Aghbashlo model for the oven and the Alibas model for IR and MW had the highest compatibility. Effective moisture diffusion coefficients are between 1.9×10^{-10} - 2.62×10^{-10} m^2/s in the oven, 3.27×10^{-10} - 7.08×10^{-10} m^2/s in the IR, and 2.83×10^{-9} - 9.76×10^{-9} m^2/s in the MW. It was determined that the effective diffusion coefficient increased with the increase in temperature and power. In the calculation of the activation energy transferred from the drying device to the crab meat, 15.74 kJ/mol for the oven, 37.55 kJ/mol for IR, and 72.719 kW/kg for MW were obtained. Accordingly, it was determined that the method with a higher activation energy value resulted in shorter drying times. In color analysis studies, it was found that the total color change was at the highest for MW and lowest for the oven. Accordingly, in a color-based evaluation, it can be said that the oven is closer to the blanched crab meat. When all outputs are evaluated, it can be said that drying with MW provides much better performance compared to other methods in terms of drying time, energy consumption, and effective diffusion.

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