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INFRARED DRYING KINETICS OF BLUE MUSSELS AND PHYSICAL PROPERTIES

Article Highlights

- Food product shelf life and storage can be extended using the drying processes
- Infrared drying kinetics of whole mussels was studied
- In the drying process the Midilli and Kucuk model best fit the drying data
- D_{eff} values and E_a were found between 4.24×10^{-9} and 1.10×10^{-8} m^2/s and 20.85 kW/kg
- The colour values were slightly affected by the change in infrared power

Abstract

As an alternative to fish and beef, blue mussels (Mytilus edulis) can be consumed due to their high protein content. In this study, the drying kinetics and quality changes (cook loss, area shrinkage and colour change) in whole blue mussels were investigated with several infrared power levels between 88-146 W. Various thin-layer drying models were applied to the blue mussel and the Midilli et al., model best fits the experimental data (R^2: 0.999150-0.999750, χ^2: 0.000104-0.000030, RMSE: 0.008309-0.004797). The effective moisture diffusivity was determined to be between 4.24×10^{-9} and 1.10×10^{-8} m^2/s. The activation energy was found to be 20.85 kW/kg. The cook loss and area shrinkage increased with increasing power level and drying time. Most cook loss (30%) and area shrinkage (30%) were obtained between 15-23 min and 8-20 min of drying time, respectively. The colour change was slightly affected by the change in infrared power level.

Keywords: activation energy, blue mussel, effective moisture diffusivity, infrared drying, colour change.

For thousands of years mussels are eaten either cooked or raw, as an alternative meat product. Mussels belong to the family of *Mytilidae* and are known as blue mussels (*Mytilus edulis*). The major producers of mussels in the world are USA, Canada, Channel Islands, Spain, France and Germany, with an approximate production of 1.756 million t (96621 t by capture production), which has an estimated value of 3.32 billion dollars [1-3].

Due to microbiological activity, foods can easily spoil and decay [3]. So, these microbiological activities must be inhibited. Drying methods can be used for the inhibition of microbiological activities. The most common method of food drying is hot-air drying. However, in the hot-air drying method, low energy efficiency, quality loss and long drying time during the falling rate period come up as the disadvantages. To minimize these disadvantages researchers have been studying several alternative methods. One of these methods is the infrared drying method. Infrared heating offers many advantages over conventional drying under similar conditions. Infrared radiation energy is transferred from the heating element to the product, heating the material more rapidly and uniformly without heating the surrounding air [4]. Various agricultural and animal products have been successfully dried by the infrared application and/or by a combined infrared-assisted convection process such as; the effects of different drying conditions (infrared power, air temperature and velocity) on the quality of strawberries were evaluated by Adak *et al.* [4]. They reported that drying time increased with increased infra-

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red power, air temperature and velocity. Sheridan and Shilton [5] studied the efficiency of cooking hamburger patties by infrared sources. The results of their study showed that with the higher energy source, the change in core temperature follows closely the change in surface temperature and cooking time was short and was independent of the fat content of the samples. In a study by Nowak and Lewicki [6], they dried apple slices by two different drying methods (near infrared heating and convection) for comparing quality properties (color, kinetics of water adsorption, mechanical properties, and microstructure) of apple slices. The thin-layer infrared drying behaviour of industrial tomato residues, peels and seeds, was experimentally investigated by Celma *et al.* [7]. They reported that the drying rate was found to have increased with temperature, hence reducing the total drying time. Doymaz *et al.* [8] investigated the effect of infrared power on drying kinetics, rehydration and colour characteristics of green beans. They reported that drying, rehydration and color characteristics were greatly influenced by infrared power.

In the literature, despite the studies about the infrared drying of several agricultural products, blue mussels drying kinetics was not studied. Hence, to contribute to the published literature, the infrared drying kinetics of blue mussels was studied in this study. The moisture ratios were modelled using five thin-layer drying models. Furthermore, the values of effective moisture diffusivity, activation energy, cook loss, area shrinkage and colour changes were studied.

EXPERIMENTAL

Samples

Fresh mussels, which are grown by Marfrío S.A. (Marfrío S.A., Pontevedra, Spain) were provided from a local store in İstanbul in February 2017 and were kept in a refrigerator (1050T model; Arcelik, Eskisehir, Turkey) at a temperature of 4 °C. In the experiments, similar sized mussels were selected and the average diameter measured as 2±0.1 cm. By using the AOAC method [9], the initial moisture content of mussels was determined as 1.93 kg water/kg dry matter. The oven used in the AOAC method was Ecocell LSIS-B2V/EC55 (MMM Medcenter Einrichtungen GmbH, Planegg, Germany).

Drying experiments

Prior to the experiments, the mussels were removed from the refrigerator and were left at room temperature in a desiccator for 2 h. Drying experiments were conducted using a Snijders moisture analyser, which has a 250 W halogen lamp (Snijders b.v., Tilburg, the Netherlands). 10.46±0.58 g mussels were weighed using an Ohaus PA214C digital balance, which has an accuracy of 0.001 g (Ohaus Corporation, New York, USA). The infrared dying process was carried out at infrared power levels of 88, 104, 125 and 146 W. The weighing intervals were set at 10 min for 88 W, and 5 min at the other power levels. Drying was terminated when the moisture content of mussels was decreased to 0.09±0.01 kg water/kg dry matter. The fresh and the dried mussels are given in Figure 1.

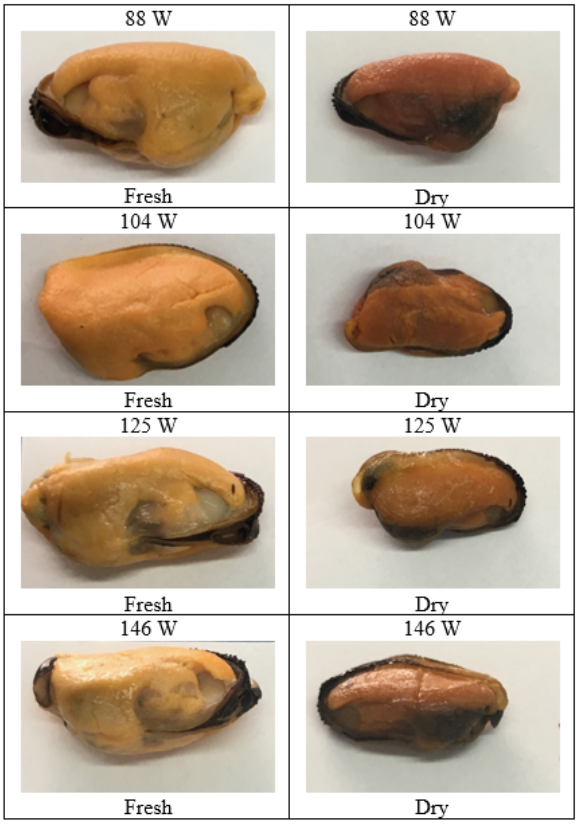


Figure 1. Fresh and dried mussels at different infrared power levels.

The dried mussels were cooled in a desiccator and were packed in low-density polyethylene bags. All drying procedures were repeated three times.

Modelling and regression analyses

Mussels moisture content (M), drying rates (DR), and moisture ratio (MR) were calculated using (1), (2) and (3) [3]:

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

where M, m_w, m_d are the moisture content (kg water/kg dry matter), water content (g), dry matter content (g), respectively.

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

where DR, M_{t+dt} and t are the drying rate (kg water/(kg dry matter min)), moisture content at $t + dt$ (kg water/ /kg dry matter) and drying time (min), respectively.

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

where MR is the moisture ratio (dimensionless), M_t, M_e and M_i are the moisture content at selected time, at equilibrium and the initial value in kg water/kg dry matter.

The drying curves were fitted to sixteen different moisture ratio models, according to their coefficient of determination (R^2) value. The highest five among them are selected and given in Table 1.

Regression analysis was done by using the Statistica 8.0 (StatSoft Inc., Tulsa, USA). Using a non-linear regression procedure based on the Lavenberg-Marquardt algorithm, the model parameters were estimated. The models used to predict the drying data were evaluated using R^2, reduced chi-square (χ^2), and root mean square error ($RMSE$). In the literature, it was given that the higher R^2 values and lower χ^2 and $RMSE$ values were accepted as better results [14,15]. The equations of R^2, χ^2 and $RMSE$ are given in Eqs. (4)-(6), respectively:

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

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

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

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

Effective moisture diffusivity determination

Fick's second law of diffusion symbolizes the equation of mass diffusion. Moreover, it can be used in a falling rate period for drying agricultural products [3,4]. The analytical solution with the assumptions of moisture migration due to diffusion, negligible shrinkage, constant diffusion coefficients, and temperature during the drying process in unsteady state diffusion in spherical coordinates can be given with Eq. (7) [16]:

$$MR = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(-n^2\pi^2\frac{D_{eff}t}{R^2}\right) \tag{7}$$

where D_{eff}, R and t are the effective moisture diffusivity (m^2/s), the radius of the sample (m) and drying time (s), respectively. Since the second and other (3^{rd},4^{th}, etc…) terms of the equations will not affect the results significantly, these terms can be neglected and Eq. (7) can be simplified, as given in (8):

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

From the slope of the *ln(MR) versus t*, D_{eff} can easily be calculated.

Activation energy determination

The dependence of the effective diffusivity with temperature is described by the Arrhenius equation [17]. But in the infrared drying process, direct measurement of temperature cannot be accomplished without using an infrared thermometer or some other form of non-contact thermometer. Hence, in order to calculate the activation energy, without temperature measurement, a modified form of the Arrhenius equation can be used [8]:

Table 1. Models used in fitting the experimental data; a, b, c, k, k_1, k_2, n: empirical constants and coefficients in drying models

Model	Equation	Reference
Aghbashlo *et al.*	$MR = \exp\left(-\frac{k_1 t}{1 + k_2 t}\right)$	[10]
Jena and Das	$MR = a\exp\left(-kt + bt^{0.5}\right) + c$	[11]
Midilli and Kucuk	$MR = a\exp(-kt^n) + bt$	[12]
Logaritmic	$MR = a\exp(-kt) + c$	[3]
Page	$MR = \exp\left(-kt^n\right)$	[13]

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

where D_0, E_a, m and P are the pre-exponential factor of Arrhenius equation (m^2/s), activation energy (W/kg), sample weight (kg) and infrared power (W), respectively.

Cook loss and area shrinkage

Cook loss and area shrinkage values were calculated according to Eqs. (10) and (11) [18]:

$$\text{Cook loss} = 100(\text{Weight of raw sample} - \text{Weight of cooked sample})/\text{Weight of raw sample} \quad (10)$$

$$\text{Area shrinkage} = 100(\text{Area of raw sample} - \text{Area of cooked sample}) / \text{Area of raw sample} \quad (11)$$

Colour measurement

Colour is considered to be one of the most important criteria on determining product quality and consumer preference. The colour was expressed as the *L*, *a* and *b* values of the Hunter colour system. The Hunter colour parameters *L*, *a* and *b* have been widely used to describe colour changes during thermal processing of products. Colour values were measured before and after the infrared drying process using a handheld tristimulus colorimeter (CR-400 Chroma Meter; Konica Minolta, Osaka, Japan). For each mussel three measurements were performed. *L* represents the whiteness value from 0 to 100, *a* represents the red for positive and green for negative values, *b* represents the yellow for positive and blue for negative values.

RESULTS AND DISCUSSION

Drying curves

The influence of different infrared power levels on the drying of mussels is shown in Figure 2. The initial average moisture content of mussels was 1.93 kg water/kg dry matter, and the dried mussels decreased to 0.09±001 kg water/kg dry matter. From the curves, it is seen that the increase in infrared power reduced the dehydration time. This situation was explained in the literature as follows: higher infrared power leads to higher heat absorption, higher product temperature, higher mass transfer driving force, faster drying rates and shorter drying times [14,19,20]. The plot type of the drying curve is similar to the study of Kipcak [3]. Moreover, the results obtained are in agreement with the meat type products [21-24].

During the heat treatment process, the fat inside meats degrades to peroxides. Thus, fat oxidation causes deterioration in the taste and quality of meat products and decreases their shelf life and nutritional value [25]. So, the decrease of drying time is very important. Herewith in infrared drying, the drying times are shorter than the conventional drying methods.

In the literature, it is indicated that the drying of food products usually occurs in the falling-rate period [26-28]. The drying rate change for different infrared power levels with respect to moisture content is given in Figure 3. From the curves, it is seen that the drying rates increased with increasing infrared power levels. The rising rate period was seen from the initial moisture content to 1.55, 1.44, 1.39 and 1.04 kg water/kg dry matter, for the infrared power levels 88, 104, 125

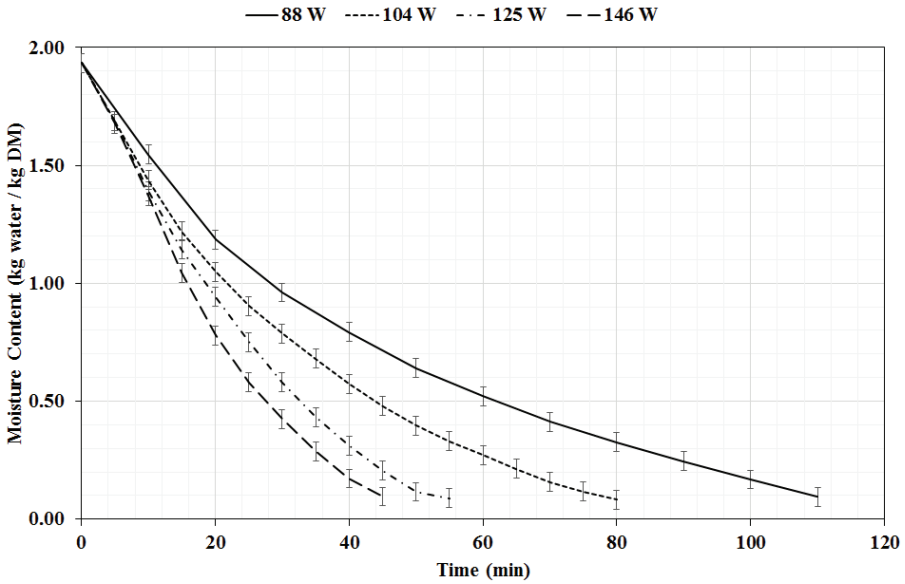


Figure 2. Drying curves of mussels at different infrared power levels.

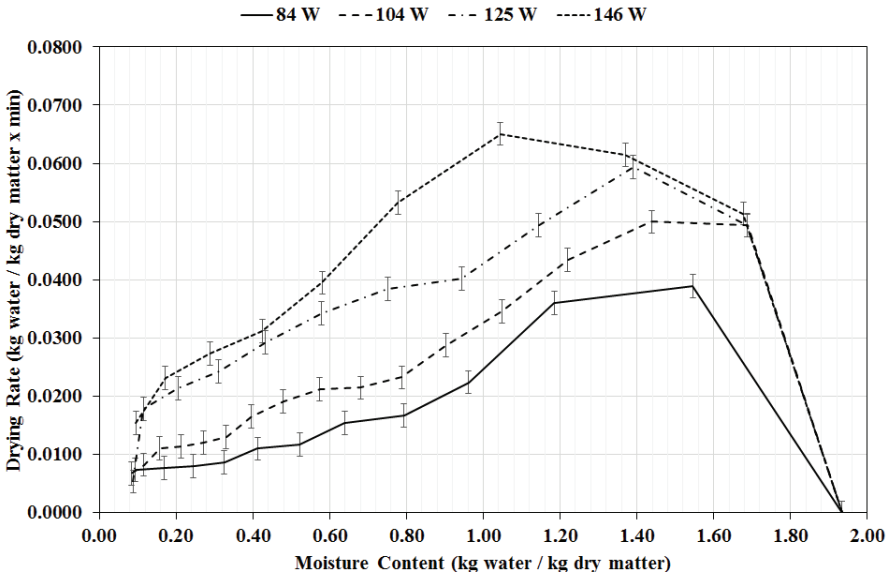


Figure 3. Drying rate curves of mussels at different infrared power levels.

and 146 W, respectively. On the other hand, the falling-rate period was seen from the indicated values that rising-rate period had finished to the 0.09, 0.08, 0.10 and 0.09 kg water/kg dry matter, for the infrared power levels 84, 104, 125 and 146 W, respectively. Constant-rate period was not seen in any of the drying curves. In literature, the falling-rate periods were also seen in the studies of Jain and Pathare [23] who studied open sun drying of prawn and Chilwa fish, and Kipcak [3], who studied microwave drying of mussels.

The fact that the drying rate decreased may be relevant to the porosity reduction in the samples due to shrinkage, which increases the resistance to water movement and leads to further decrease of the drying rates [8,29].

Modelling and regression analyses results

The experimental data were fitted with some empirical models (Aghbashlo *et al.*, Jena and Das, Midilli and Kucuk, Logaritmic and Page) for thin-layer drying of blue mussels (Table 1). Performances of the models were evaluated in terms of R^2, χ^2 and *RMSE*, which represent the coefficient of determination, reduced chi-square and the root mean square error of non-linear regression analysis, respectively. The higher the R^2, lower the χ^2 and *RMSE*, the better is the goodness of fit. Table 2 shows that among the selected models, the Midilli and Kucuk model gave the highest R^2 with an average value of 0.999573 and the lowest χ^2 and *RMSE* with average values of 0.000059 and 0.006129, respectively, considering all the treatments. Therefore, the Midilli and Kucuk model was selected as a suitable drying model to represent the drying behavior of blue mussels in infrared dryer within the experimental range.

In Figure 4, the predicted *MR versus* experimental *MR* is given for the Midilli and Kucuk model. Since the data plotted is very near the straight line, it can be said that experimental data and predicted data are in good agreement.

Values of the effective moisture diffusivity

From the plot of the ln(*MR*) *versus* drying time (s), obtained equations are given as Eqs. (12)–(15):

$$88\,\mathrm{W}: \ln(MR) = -0.000418t + 0.082363 \quad (R^2 = 0.978358) \tag{12}$$

$$104\,\mathrm{W}: \ln(MR) = -0.000621t + 0.148854 \quad (R^2 = 0.981102) \tag{13}$$

$$125\,\mathrm{W}: \ln(MR) = -0.000938t + 0.271034 \quad (R^2 = 0.966004) \tag{14}$$

$$146\,\mathrm{W}: \ln(MR) = -0.001087t + 0.260699 \quad (R^2 = 0.967487) \tag{15}$$

From the slope of the equations, which are given in Eqs. (12)–(15), D_{eff} values are estimated as 4.24×10^{-9}, 6.29×10^{-9}, 9.50×10^{-9} and 1.10×10^{-8} m^2/s for the infrared power levels of 88, 104, 125 and 146 W, respectively. The values reported herein are within the general range of 10^{-8} to 10^{-12} m^2/s for biological materials [30]. The calculated values of D_{eff} were in consistency with the values given in literature [3,31]. The increase in the infrared power level causes a rapid temperature increase of the meat products,

Table 2. Estimated coefficients and statistical data obtained from different models

Model	Power, W	88	104	125	146
Aghbashlo *et al.*	k_1	0.022394	0.027964	0.029450	0.033091
	k_2	-0.000330	-0.002668	-0.009018	-0.011636
	R^2	0.997637	0.999010	0.999606	0.998091
	χ^2	0.000230	0.000092	0.000045	0.000240
	RMSE	0.013859	0.009002	0.006151	0.013866
Jena and Das	*a*	0.302385	0.296333	0.175437	0.668797
	k	0.022585	0.035419	0.057556	0.072384
	b	-0.001442	0.024034	0.085728	0.115706
	c	1.194940	1.210317	1.730434	0.395534
	R^2	0.997577	0.997571	0.994282	0.996663
	χ^2	0.000295	0.000260	0.000824	0.000560
	RMSE	0.014035	0.014094	0.023434	0.018336
Midilli and Kucuk	*a*	1.004023	1.004353	1.000087	1.001518
	k	0.031791	0.031216	0.020500	0.017214
	n	0.884854	0.970513	1.165679	1.304322
	b	-0.000671	-0.000875	-0.001424	-0.000726
	R^2	0.999150	0.999719	0.999674	0.999750
	χ^2	0.000104	0.000030	0.000061	0.000042
	RMSE	0.008309	0.004794	0.006396	0.005018
Logarithmic	*a*	1.020186	1.079586	1.285367	1.337294
	k	0.021131	0.026648	0.026914	0.030340
	c	-0.030681	-0.081494	-0.268587	-0.309182
	R^2	0.998069	0.999589	0.998779	0.996583
	χ^2	0.000209	0.000041	0.000156	0.000393
	RMSE	0.012528	0.005799	0.010827	0.016590
Page	*k*	0.022943	0.023261	0.015340	0.015008
	n	0.998675	1.083918	1.295956	1.367207
	R^2	0.997561	0.998096	0.997746	0.999414
	χ^2	0.000238	0.000026	0.000072	0.000010
	RMSE	0.014081	0.004816	0.007772	0.002796

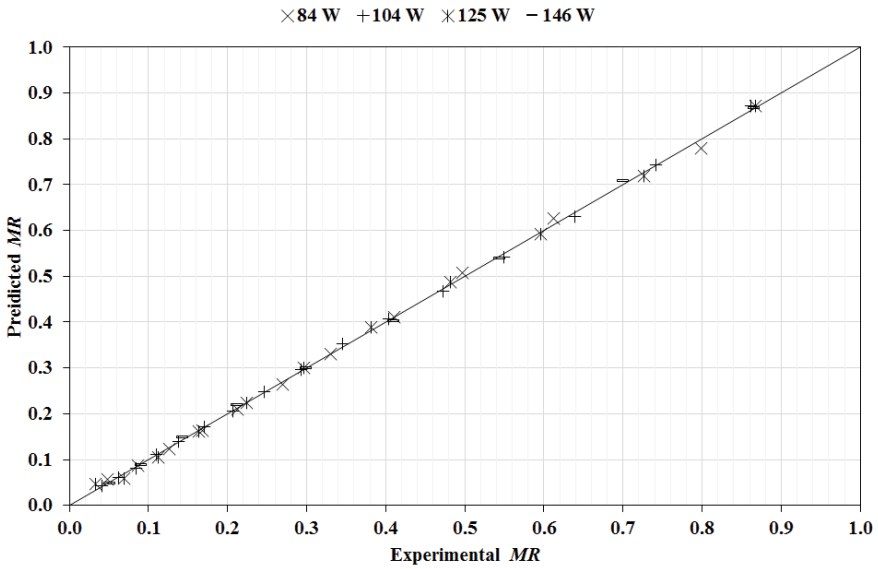


Figure 4. Experimental and predicted moisture ratios for mussels using the model of Midilli and Kucuk.

which increases the vapour pressure [3,29] so the increase in the D_{eff} values with increase in the infrared power level can be explained by this phenomenon. Obtained D_{eff} values with respect to the infrared power level are shown in Figure 5.

From Figure 5, the effect of infrared power level on the D_{eff} values can be calculated by using (16):

$$D_{eff} = 2.35\times10^{-9}P + 1.87\times10^{-9} (R^2 = 0.9828) \quad (16)$$

Values of the activation energy

E_a can be calculated from the slope of the plot of ln D_{eff} *vs.* m/P, which is shown in Figure 6. The obtained equation is given as Eq. (17):

$$D_{eff} = 5.12\times10^{-8} \exp\left(-20854\frac{m}{P}\right) \quad (17)$$

The estimated values of D_0 *and* E_a are 5.12×10^{-8} m^2/s and 20.85 kW/kg, respectively.

Cook loss and area shrinkage

In Figure 7, cook loss *versus* drying time is given. From Figure 7a it is seen that the increase in the infrared power level increased the cook loss significantly. The highest cook loss value was found to be 62.70, 63.08, 62.89 and 62.66% for the infrared power levels of 88, 104, 125 and 146 W, respectively. About 30% cook loss occurred within 20 min for the infrared power levels between 104 and 146 W and within 23 min for 88 W. The slope of the curves gradually decreased with increasing drying time. At higher temperatures, greater cook loss occurs due to the depletion of moisture [18,32]. Total cook loss of the mussels was in consistency with the total cook loss in

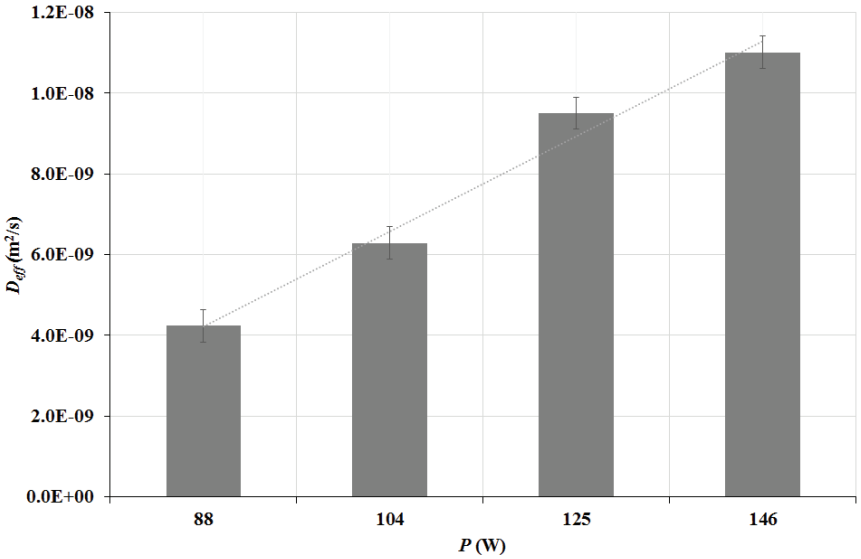


Figure 5. Effective moisture diffusivity values with respect to infrared power level.

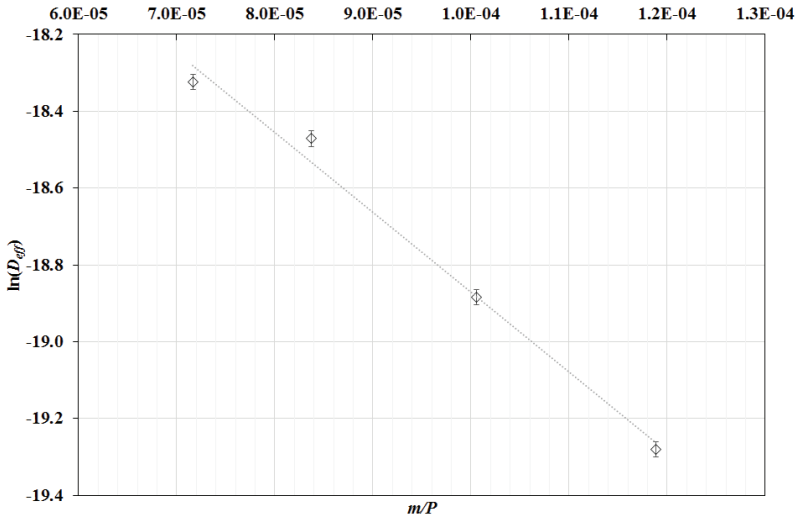
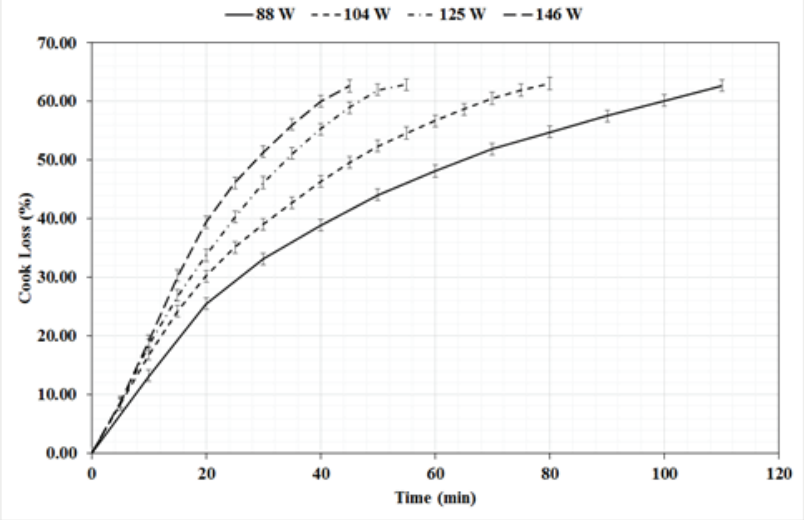
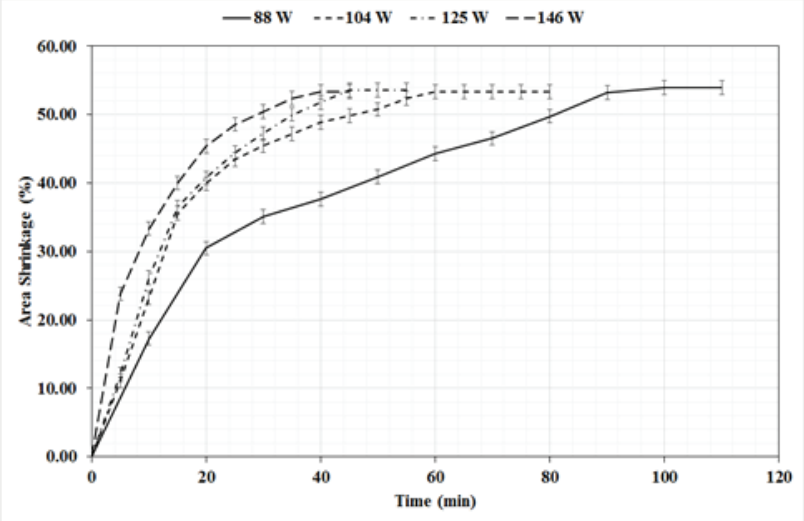


Figure 6. The plot of ln D_{eff} with respect to m/P.



(a)



(b)

Figure 7. The change of the physical properties of mussels at different infrared power levels (a) cook loss, (b) area shrinkage.

the study of Ovissipour *et al.* [18], who studied the effects of pasteurization temperatures on the blue mussels. Obtained cook loss values were higher than the salmon fish, which was studied by Kong *et al.* [33,34].

Area shrinkage of the mussels increased with increases in both infrared power level and drying time and are given in Figure 7b. The maximum shrinkage values were found to be 53.92, 53.31, 53.57 and 53.37% for the infrared power levels of 88, 104, 125 and 146 W, respectively. Similar to the cook loss, the most area shrinkage was obtained during the first 20 min of drying time. Area shrinkage is a result of protein denaturation and liquid loss. Thus, protein denaturation causes shrinkage of muscle diameter and length resulting in water soluble proteins and fats being expelled from the tissue [18,33,34]. Similar data were obtained for the salmon fish [33,34].

Colour values

The results of the colour parameters of fresh and dried samples are given in Figure 8. The *L*, *a* and *b* values were affected by the infrared power. The *L* and *a* values mean that the whiteness and the redness values were increased with the increase in infrared power. The highest *L* and *a* values were obtained in the dried products at 146 W. On the contrary, the *b* values mean the greenness values decreased with the increase in infrared power.

CONCLUSION

In this study, infrared drying kinetics of whole mussels was studied and the physical properties were determined. In the drying process, the Midilli and Kucuk model best fits the drying data with very high

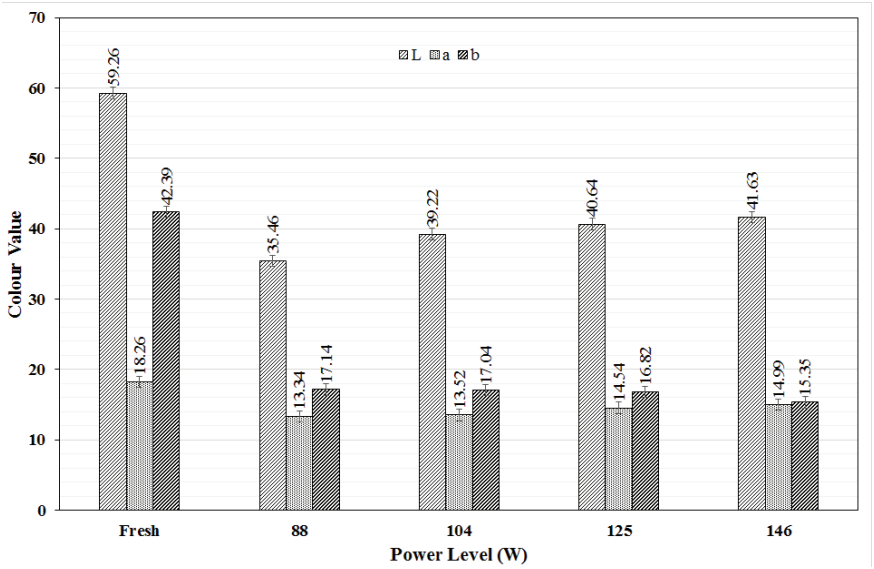


Figure 8. Colour values of mussels at different infrared power levels.

R^2 values for all of the drying power levels. The drying took place in the rising-rate period first and then in the falling-rate period. D_{eff} values and E_a were found to be between 4.24×10^{-9} and 1.10×10^{-8} m^2/s and 20.85 kW/kg, respectively. Both cook loss and area shrinkage increased with increasing drying time and infrared power level and most cook loss and most area shrinkage occurred in the first 20 min. The colour values were slightly affected by the change in infrared power. As the infrared power increases, *L* and *a* values increase while *b* values decrease.

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NAUČNI RAD

KINETIKA SUŠENJA INFRACRVENIM ZRAČENJEM PLAVE DAGNJE I FIZIČKE OSOBINE

Zbog visokog sadržaja proteina, plava dagnja (Mitilus edulis) može da se jede umesto ribe i govedine. U ovom radu je istražena kinetika sušenja i promena kvaliteta (gubitak kuvanjem, smanjenje površine i promjena boje) u celoj plavoj dagnji pri nekoliko intenziteta infracrvenog zračenja u opsegu 84-146 W. Različiti kinetički modeli za sušenje u tankom sloju primenjeni su na sušenje plave dagnje. Model Midilli i saradnici najbolje fituje eksperimentalne podatke (R^2: 0,999-1.000, χ^2: 0.000104-0.000030, RMSE: 0.00831-0.00480). Utvrđena je efektivna difuzivnost vlage između $4{,}24\times10^{-9}$ i $1{,}10\times10^{-8}$ m^2/s. Utvrđeno je da je energija aktivacije 20,85 kW/kg. Gubitak kuvanjem i smanjenje površine su se povećali s povećanjem intenziteta infracrvenog zračenja i vremena trajanja sušenja. Veći deo gubitka kuvanjem (30%), odnosno smanjenja površine (30%) se desio između 15-23 min, odnosno 8-20 min. Promena intenziteta infracrvenog zračenja je blago uticala na promenu boje.

Ključne reči: energija aktivacije, plava dagnja, efektivna difuzivnost vlage, infracrveno sušenje, promena boje.