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SCIENTIFIC PAPER

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DRYING CHARACTERISTICS OF BLUE MUSSELS BY TRADITIONAL METHODS

Article Highlights

- Characteristic drying kinetics of mussels, dried by cabinet, oven and vacuum oven are studied
- Midilli and Kucuk model best fits experimental data with high coefficient of determination
- D_{eff} were found to be 1.89×10^{-9}-4.94×10^{-9} m^2/s, 0.892×10^{-9}-1.63×10^{-9} m^2/s for cabinet and oven, respectively
- D_{eff} were found to be 1.17×10^{-9}-2.28×10^{-9} m^2/s for vacuum oven
- E_a values were calculated to be 46.90, 29.57 and 32.85 kJ/mol for cabinet, oven and vacuum oven, respectively

Abstract

In this study, characteristic drying behaviour and kinetics of blue mussels, which were dried with the traditional methods of cabinet-type, oven and vacuum oven drying, are studied. In a cabinet-type dryer there is air flow while in an oven dryer there is no air flow. In each method, D_{eff} *and* E_a *are calculated and colour analyses are done. According to the results, mussels are dried between 270-120 min, 570-300 min and 390-210 min, for the cabinet-type dryer, oven and vacuum oven, respectively. In each method, the Midilli and Kucuk model best fits experimental data with high coefficient of determination (*R^2*) between 0.9995-0.9984, 0.9996-0.9993, and 0.9997-0.9993 for cabinet-type, oven and vacuum oven dryer, respectively.* D_{eff} *values were calculated between 1.89-4.94×*10^{-9} *m*^{2}*/s, 0.89-1.63×*10^{-9} *m*^{2}*/s and 1.17-2.28×*10^{-9} *m*^{2}*/s for cabinet-type dryer, oven and vacuum oven methods, respectively. Also,* E_a *values were found to be 46.90, 29.57 and 32.85 kJ/mol, for cabinet-type dryer, oven and vacuum oven methods, respectively. The colour change was slightly affected by the change in the temperature.*

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

Marine molluscs, which have high protein content, have been eaten for many years, both cooked and uncooked. Most commonly known and consumed sea molluscs are mussels and clams. Mussels come from the Latin family Mytilidae and are known as *Mytilus edulis*. *M. edulis* are commonly harvested for food throughout the world, from both wild and farmed sources. The largest mussel producers in the world are USA, Canada, Channel Islands, Spain, France and Germany. The estimated produced annual amount is 1.756 million tons which has a 3.32 billion dollars market value. Mussels are a staple of many seafood dishes in various cuisines. Mussels acquire proteins, lipids, carbohydrates, and other components from phytoplankton and use these compounds to build their own biomass. The polyunsaturated fatty acids (PUFAs), eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA) are some of the nutritionally most valuable components of marine biomasses. Mussels are mainly processed through pre--cooking, freezing or canning. The main effect of processing on mussel components is concentration due to water loss [1-5].

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Food products can be easily degraded due to microbiological activity. Degradation of food products can be prevented by reducing the moisture content by drying. Drying increases the shelf-life of the products as well. There are many drying methods that can be found in the literature. For the past two decades, microwave and infrared drying have been attracting interest as modern methods [6] in the area of dehydration of agricultural products. These modern techniques cause rapid evaporation of water and increased drying rates, thus reducing the drying time and therefore lower energy consumption. However, it is difficult to prevent some overheating of products in the microwave and infrared techniques [7-9]. Therefore, hot-air drying technique is the simplest and the most convenient way. Cabinet, oven and vacuum-oven methods can be classified as hot-air drying, hence, traditional drying.

The tradition of drying food products coming from the old times has led to a differentiation in food products as well as the increase in consumption of dry foods. Although many studies have been carried out about the drying of vegetables and fruits in the literature, studies on meat and seafood products are not sufficient. Examples of drying studies with different meat products include the following; Başlar *et al.* (2014) studied ultrasonic vacuum drying of beef and chicken meat [10]. Ahmat *et al.* (2015) studied convective drying of beef [11]. Simal *et al.* (2003) studied drying of meat-based products [12]. Ayanwale *et al.* (2007) studied the drying of meat and chicken pieces in the sun and by oven drying [13]. Natharankule *et al.* (2007) studied superheated steam drying of chicken pieces [14]. Hii *et al.* (2014) studied the drying of raw and cooked chicken meat in a convection oven [15]. Sa-Adchom *et al.* (2011) studied pork drying with superheated steam [16]. Drying studies related to sea products is extremely rare. Examples of drying studies with seafoods include the following; Vega-Gálvez *et al.* (2008) studied the convective drying of the brown algae [17]. Kipcak (2017) studied the microwave drying of the mussel [9]. Kipcak *et al.* (2019) studied the infrared drying of the mussel [18]. Tribuzi and Laurindo studied the oven, vacuum and freeze drying of cooked *Perna perna* mussels [19]. For the drying of fish, Jain and Pathere (2007) studied sun-drying [20], and Mohd Rozainee and Ng (2010) studied microwave-convective hot air drying [21].

As it can be seen from the literature studies examined, the drying methods of non-meat products have been studied for many years. Studies for drying meat products, and thus increasing shelf life, have gained great importance in the recent years. In this context, expanding the scope would be adding fish and seafood. Drying of animal meat, chicken and fish products has increased in recent years with an growing trend. Despite the few studies about seafoods, drying of raw mussels by conventional drying methods have not been studied in great detail. For these reason, this study should have a unique value and contribute new findings to the literature. The mussels, freshly retrieved, were dried at various temperatures by traditional drying methods of cabinet, oven and vacuum oven drying. The data obtained from drying experiments were applied to a wide variety of mathematical drying models presented in literature and the most appropriate model for each method was determined. Then, effective moisture diffusion coefficients and activation energies were calculated and the study was additionally enriched with colour analysis of the dried mussels.

MATERIALS AND METHODS

Samples

Fresh mussels, which are bred 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 -18 °C for one night. In the experiments, similar-sized and similarly coloured mussels were selected and the average diameter was measured as 2±0.1 cm. All of the experiments were conducted in February 2017. Using the AOAC method [22], the initial moisture content of the mussels was determined as 1.9879 kg of water/kg dry matter, which is equal to 66.53% wet basis. Calculated initial moisture content value is very similar with the moisture content of 1.85-1.93 kg of water/kg dry matter (dry basis) given in the literature [9,18].

Cabinet-type dryer

Drying of the samples was carried out in a cabinet drier (APV & Pasilac Ltd., Carlisle, Cumbria, UK). The drying cabinet is a pilot-scale dryer, which can provide airflow at the desired temperature, suitable for drying various materials in a perforated tray. The dryer is made of steel and it is coated with 50 mm thick semi-rigid insulating material. The speed of the air circulated in the cabinet can be controlled by the circulating fan whose speed can be changed. The circulation fan operates with an electric motor of 0.37 kW. The heating of the air to be used is provided by 14 strip heaters located opposite the circulation fan. It is possible to work up the temperature to 200 °C in the dryer. The desired temperature settings can be adjusted from the digital temperature display on the control panel on the device.

Oven dryer

Drying experiments were carried out in Ecocell 111 model oven (MMM Medcenter Einrichtungen GmbH, Planegg, Germany), which has an internal volume of 111 litres. The inner volume is 39×54×53 cm^3 and the maximum working power is 1.8 kW. The temperature setting is in the range of 1 °C and can be increased up to 250 °C if desired.

Vacuum oven dryer

Vacuum drying tests were performed in a laboratory type vacuum oven with 800 W power output (Nuve EV 018, Turkey). The temperature setting is in the range of 1 °C and can be increased up to 250 °C if desired. Vacuum drying volume is 30×20×25 cm^3 and vacuum conditions are provided by a laboratory-type vacuum pump (KNF N026 1.2 AN 18, Turkey).

Experimental method

Before the drying experiments, similar-sized mussels were removed from freezer part of the refrigerator and left at the room temperature for 2 h to equalize with the mussel temperature with the room temperature. All drying experiments were conducted on 12.5 cm watch glass and 25±1 g of mussels were weighed. Hence, the sieve load of each equipment was 1.6±0.064 kg/m^2. The drying process was carried out between the drying temperatures of 60–80 °C with cabinet, oven and vacuum oven dryers. Every 30 min, samples were taken from the driers and weighed for 10 s. The drying process was terminated when the moisture content of mussels decreased about 0.10±±0.02 kg water/kg dry matter (dry basis). The air velocity in the cabinet-type dryer was adjusted to 2.0 m/s, and in the vacuum oven the pressure of air was adjusted to 0.3 atm.

The dried mussels were cooled in a desiccator and were packed in LDPE bags. All drying procedures were repeated three times.

Modeling and regression analyses

The moisture content (M), drying rate (DR) and moisture ratio (MR) of the mussels were calculated using Eqs. (1)-(3) [7-9,23]:

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

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

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

where DR, $M_{t+\Delta t}$ and t are the drying rate (kg water/(kg dry matter min)), moisture content at $t + \Delta t$ (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, respectively. The values of M_e are relatively small when compared to M_t and M_i, hence the equation can be simplified as $MR = M_t/M_i$ [8,23].

The drying curves were fitted to the most widely used mathematical models, which are given in Table 1, for each dryer type.

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

Model	Equation
Aghbaslo *et al.*	$MR = \exp\left(-k_1 t/\left(1+k_2 t\right)\right)$
Alibas	$MR = a\exp\left(\left(-kt^n\right)+bt\right)+g$
Henderson *et al.*	$MR = a\exp\left(-kt\right)$
Jena and Das	$MR = a\exp\left(-kt+b\sqrt{t}\right)+c$
Lewis	$MR = \exp\left(-kt\right)$
Logarithmic	$MR = a\exp\left(-kt\right)+c$
Midilli and Kucuk	$MR = a\exp\left(-kt^n\right)+bt$
Page	$MR = \exp\left(-kt^n\right)$
Parabolic	$MR = a+bt+ct^2$
Peleg	$MR = a+t/\left(k_1+k_2 t\right)$
Two-term	$MR = a\exp(-bt)+c\exp(-dt)$
Verma *et al.*	$MR = a\exp\left(-kt\right)+\left(1-a\right)\exp\left(-gt\right)$
Wang *et al.*	$MR = \exp\left(-\left(t/b\right)^a\right)$
Weibull	$MR = a-b\exp\left(-\left(kt\right)^n\right)$

Regression analysis was conducted by using the Statistica 8.0 software (StatSoft Inc., Tulsa, OK, USA). Model parameters were estimated by using a non-linear regression procedure based on the Levenberg-Marquardt algorithm. To predict the drying data, all models used and all models were evaluated by coefficient of determination (R^2), reduced chi-square (χ^2) and root mean square error ($RMSE$) parameters.

Higher R^2 values and lower χ^2 and *RMSE* values were accepted as better results in the literature [4-6]. R^2, χ^2 and *RMSE* equations are given in Eqs. (4)-(6), respectively:

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

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

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

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 is concerns mass diffusion. Furthermore, it can be used in a falling rate period for drying agricultural products [7-9]. The analytical solution of Fick's second law, 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 as Eq. (7) [17]:

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

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 first term of the question will mostly affect the results, other terms are neglected and Eq. (7) can be simplified as given in Eq. (8):

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

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

Activation energy determination

The dependence of the effective moisture diffusivity with temperature described by the Arrhenius equation is given in Eq. (9):

$$D_{eff}=D_0\exp\left(-\frac{E_a}{R(T+273.15)}\right) \quad (9)$$

where D_0 (m^2/s), E_a (kJ/mol), R (kJ/(mol K)) and T (°C) are the pre-exponential factor of the Arrhenius equation, activation energy, universal gas constant and temperature, respectively.

Colour measurement

On determining product quality and consumer choice, colour is the most important criteria. In the Hunter colour system "*L*" represents the lightness or darkness value (100 for white, 0 for black), "*a*" represents redness and greenness value and "*b*" represents yellowness and blueness values. These colour parameters were measured before and after the three different drying processes using a hand-held colorimeter, which has a silicon photoelectric diode sensor and a LED blue light source (PCE-CSM 1; PCE Instruments UK Ltd., Southampton Hampshire, UK). The total change in color (ΔE) of dried samples was estimated using Eq. (10) [24]:

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

where L_o, a_0 and b_0 are the color values of fresh samples before drying. L, a and b color parameters of samples were measured from five points of every sample just after the drying processes.

RESULTS AND DISCUSSION

Drying curves

The effect of different drying methods and drying temperatures on the drying of mussels is shown in Figure 1. The initial average moisture content of mussels was 1.9879 kg water/kg dry matter, and the dried mussels decreased between 0.1072 and 0.0804 kg water/kg dry matter for cabinet dryer, 0.1381 and 0.1231 kg water/kg dry matter for oven and 0.1378 and 0.1189 kg water/kg dry matter for vacuum oven. This is due to the increasing energy of the water molecules at increased temperature, which can escape faster and more easily. In the cabinet dryer, drying times were found as 270, 180 and 120 min for the temperatures of 60, 70 and 80 °C, respectively. In the oven, drying times were found as 570, 390 and 300 min for the temperatures of 60, 70 and 80 °C, respectively. And in the vacuum oven, drying times were found as 390, 270 and 210 min for the temperatures of 60, 70 and 80 °C, respectively. For the comparison of the drying methods, the lowest drying times were found in the cabinet-type dryer due to the flowing air inside the cabinet, which leads to faster moisture removal and the highest drying times are found in the oven. Therefore, in the vacuum oven

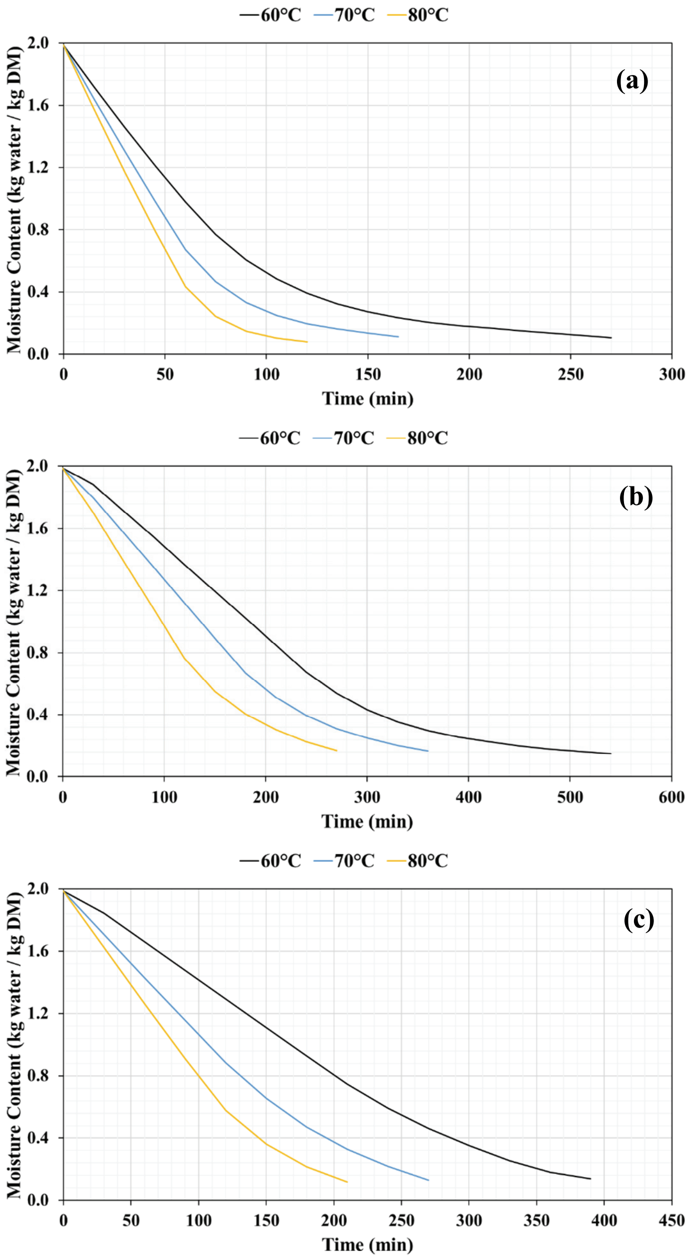

Figure 1. Drying curves of mussels dried with: a) cabinet; b) oven; c) vacuum oven.

the low pressure leads to faster moisture removal than in the oven. Obtained drying times were higher than the modern methods of microwave method [9] and infrared method [18], as expected. The results are consistent with the results of previous studies on meat drying [18,21].

In the literature, it has been explained that the moisture transfer from the food product is explained by using Fick's second law and the drying of food products generally follows the falling-rate period [25]. The drying rate plots with respect to moisture content of the mussels dried with different methods are given in Figure 2. It can be seen from the plots that drying rates increased with increasing drying temperature. All three periods of rising-rate, constant-rate and falling-rate periods are seen in Figure 2.

In the cabinet dryer, the rising-rate period is observed between 1.9878-1.7183, 1.9878-1.6417 and 1.9878-1.5754 kg water/kg dry matter for the temperatures of 60, 70 and 80 °C, respectively. The constant-rate period is likewise not obtained in the studies of microwave [9] and infrared drying [18] given in the literature. After the critical moisture contents of 1.7183, 1.6417 and 1.5754 kg water/kg dry matter, the falling-rate period is observed to final moisture content values of 0.1072, 0.0936 and 0.0804

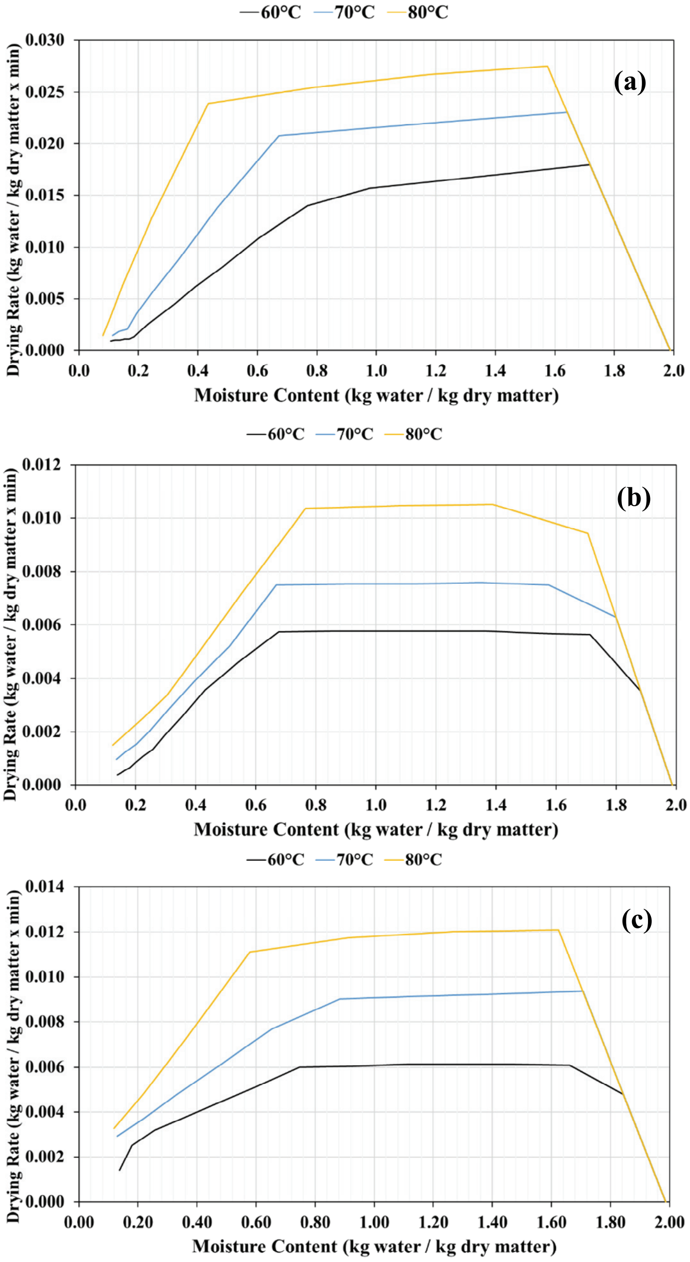

Figure 2. Drying rate curves of mussels dried with: a) cabinet; b) oven; c) vacuum oven.

kg water/kg dry matter for the temperatures of 60, 70 and 80 °C, respectively.

In the oven, the rising-rate period is seen between 1.9878-1.5417, 1.9878-1.5738 and 1.9878--1.3891 kg water/kg dry matter for the temperatures of 60, 70 and 80 °C, respectively. The constant-rate period is obtained between 1.5417-0.6764, 1.5738--0.6687 and 1.3891-0.7645 kg water/kg dry matter for the temperatures of 60, 70 and 80 °C, respectively. After the critical moisture contents of 0.6764, 0.6687 and 0.7645 kg water/kg dry matter, the falling-rate period is observed to final moisture content values of 0.1381, 0.1362 and 0.1231 kg water/kg dry matter for the temperatures of 60, 70 and 80 °C, respectively.

In the vacuum oven, the rising-rate period is found between 1.9878-1.6612, 1.9878-1.7067 and 1.9878-1.6247 kg water/kg dry matter for the temperatures of 60, 70 and 80 °C, respectively. The constant-rate period is obtained between 1.6612-0.7474, 1.7067-0.8845 and 1.6247-1.2640 kg water/kg dry matter for the temperatures of 60, 70 and 80 °C, respectively. After the critical moisture contents of 0.7474, 0.8845 and 1.2640 kg water/kg dry matter, the falling rate period is observed to final moisture content values of 0.1378, 0.1302 and 0.1189 kg water/kg dry matter for the temperatures of 60, 70 and 80 °C, respectively.

Generally, for all of the three drying methods, the drying primarily takes place during the falling-rate period. Many studies show that in the drying of meat-type products, the major drying phase is the falling-rate period due to the fact that the drying rate decreased, as it may be related 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 [8,9].

Modeling and regression analyses results

The experimental data were fitted to the mathematical models, which are given in Table 1 by using non-linear regression analysis. The best model was evaluated in terms of the coefficient of determination (R^2), reduced chi-square error (χ^2) and root mean square error (*RMSE*). The best model is selected by comparing the values. The model parameters and statistical data are presented in Table 2. The R^2 values below 0.998 were not given in any of the drying methods.

In Table 2, it is seen that the Midilli and Kucuk model best fits the experimental data for all of the drying methods of cabinet-type, oven and vacuum oven dryers. The R^2 values are found between 0.9995-0.9984, 0.9996-0.9993, and 0.9997-0.9993 for the cabinet-type, oven and vacuum oven dryer, respectively. The χ^2 values are calculated between 0.0003-0.0001, 0.0001-0.0001 and 0.0002-0.0001 for the cabinet-type, oven and vacuum oven dryer, respectively. The RMSE values are obtained between 0.0134-0.0067, 0.0083-0.0063 and 0.0087-0.0055 for the cabinet-type, oven and vacuum oven dryer, respectively.

In microwave drying [9], the best model was found to be Weibull with R^2 values between 0.998135-0.999929. In infrared drying [18], the best model was also found to be Midilli and Kucuk's with the R^2 values between 0.9992-0.9998. As it is seen, the Midilli and Kucuk model is a good approximation in the drying of mussels.

In Figure 3, the predicted *MR versus* experimental *MR* is given for the Midilli and Kucuk model. As it is seen, the data predicted plotted against experimental data is very near the straight line, therefore it can be said that the experimental data and predicated data are in good agreement.

Table 2. Estimated coefficients and statistical data obtained from different models (R^2 > 0.998)

Method	Model	Parameter	*T* / °C		
			60	70	80
Cabinet	Midilli and Kucuk	a	0.9982	0.9953	0.9907
		k	0.0050	0.0047	0.0037
		n	1.2199	1.3330	1.4632
		b	0.0002	0.0003	0.0001
		R^2	0.9995	0.9993	0.9984
		χ^2	0.0001	0.0001	0.0003
		RMSE	0.0067	0.0082	0.0134
Oven	Midilli and Kucuk	a	0.9867	0.9891	0.9961
		k	0.0002	0.0005	0.0013
		n	1.5882	1.4824	1.3910
		b	0.0001	0.0001	0.0001
		R^2	0.9993	0.9993	0.9996
		χ^2	0.0001	0.0001	0.0001
		RMSE	0.0083	0.0082	0.0063
Oven	Weibull	b	234.4543	173.9294	127.7725
		a	1.4009	1.3793	1.3023
		R^2	0.9988	0.9988	0.9990
		χ^2	0.0003	0.0001	0.0001
		RMSE	0.0177	0.0108	0.0100
Vacuum oven	Aghbashlo *et al.*	k_1	0.0030	0.0051	0.0066
		k_2	-0.0016	-0.0019	-0.0027
		R^2	0.9985	0.9994	0.9986
		χ^2	0.0002	0.0001	0.0002
		RMSE	0.0118	0.0079	0.0120
Vacuum oven	Midilli and Kucuk	a	0.9916	0.9953	0.9950
		k	0.0004	0.0016	0.0017
		n	1.4249	1.2841	1.3566
		b	-0.0001	-0.0002	-0.0002
		R^2	0.9996	0.9997	0.9993
		χ^2	0.0001	0.0001	0.0002
		RMSE	0.0064	0.0055	0.0087
Vacuum oven	Page	k	0.0003	0.0012	0.0015
		n	1.4955	1.3654	1.4079
		R^2	0.9985	0.9988	0.9988
		χ^2	0.0002	0.0001	0.0002
		RMSE	0.0118	0.0106	0.0110

Effective moisture diffusivity values

From the slope of the ln (*MR*) *versus* drying time (s) on different drying methods, D_{eff} values are calculated. For the cabinet-type dryer, D_{eff} values are found as 1.89×10^{-9}, 3.05×10^{-9} and 4.94×10^{-9} m^2/s for the temperatures of 60, 70 and 80 °C, respectively. For the oven dryer, D_{eff} values are found as 0.89×10^{-9}, 1.25×10^{-9} and 1.63×10^{-9} m^2/s for the temperatures of 60, 70 and 80 °C, respectively. For the vacuum oven dryer, D_{eff} values are found as 1.17×10^{-9}, 1.68×10^{-9} and 2.28×10^{-9} m^2/s for the temperatures of 60, 70 and 80 °C, respectively. As seen from the obtained D_{eff} values, the cabinet-type dryer had the highest diffuseion coefficient values, followed by the vacuum-oven

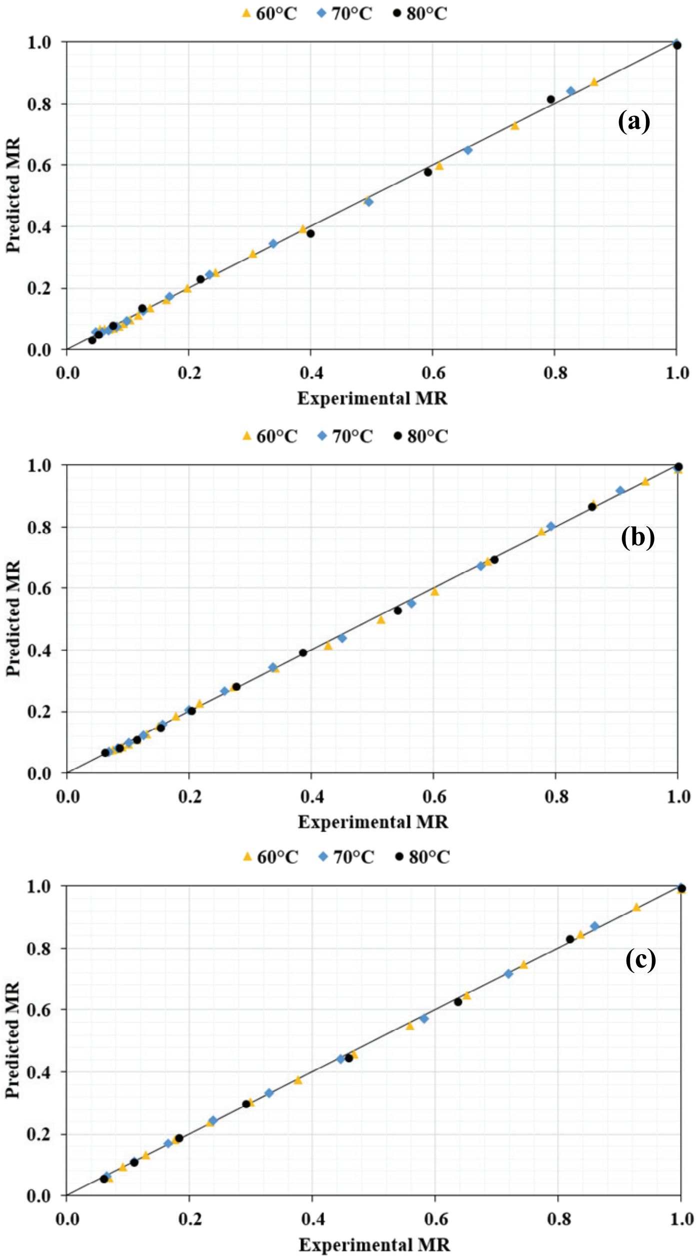

Figure 3. Comparison of the experimental and predicted MR values obtained from Midilli and Kucuk model: a) cabinet; b) oven; c) vacuum oven.

dryer, while the oven dryer had the lowest diffusion coefficient values. The diffusion coefficient values for the biological materials are within the general range of 10^{-8} to 10^{-12} m^2/s [26]. Hence, the calculated values of D_{eff} are in mutual agreement with the literature [27]. The increase in the temperature causes a temperature increase of meat-type products, which increases the vapour pressure [28,29]. The effect of temperature on the D_{eff} values can be calculated by using Eqs. (11)-(13):

$$\text{Cabinet} \rightarrow D_{eff} = 1.52\times10^{-9}T + 2.47\times10^{-10} \quad \left(R^2 = 0.9808\right) \tag{11}$$

$$\text{Oven} \rightarrow D_{eff} = 3.70\times10^{-10}T + 5.17\times10^{-10} \quad \left(R^2 = 0.9994\right) \tag{12}$$

$$\text{Vacuum oven} \rightarrow D_{eff} = 5.57\times10^{-10}T + 5.94\times10^{-10} \quad \left(R^2 = 0.9824\right) \tag{13}$$

The D_{eff} values calculated in this study are lower than D_{eff} values calculated previously in modern methods of microwave and infrared drying [9,18], which is expected due to the lower drying rates obtained compared to the modern methods of microwave and infrared drying.

Activation energy values

E_a can be calculated from the slope of the plot of ln (D_{eff}) *vs*. 1/T (1/K) and estimated E_a values are 46.90, 29.57 and 32.85 kJ/mol, for the cabinet-type, oven and vacuum oven dryer, respectively. The highest activation energy was found for the cabinet-type dryer and the lowest activation energy was found for the oven. The values of activation energy lie within the general range of 12.7-110 kJ/mol for food materials [26] so the results are consistent with the literature.

Colour values

In Table 3, "*L*", "*a*", "*b*", values of the dried mussels by different methods are shown. For the comparison of the drying methods, the highest "*L*" values are seen for the cabinet-type dryer. Since *L* value represents the lightness (100) and darkness (0), due to the shorter drying times in comparison with the other methods, higher "*L*" values were obtained in the cabinet-type dryer as expected. On the other hand, the highest drying times were obtained in the oven dryer, hence, where the lowest "*L*" values are seen. The highest and the lowest redness values of "*a*" are obtained in the cabinet-type dryer and oven, respectively. The highest and the lowest yellowness values of "*b*" are obtained in the oven dryer and cabinet-type dryer, respectively. Colour changes are mostly affected by the drying time. Therefore, the decrease in the "*L*" lightness value and increase in the redness value of "*a*" are expected for the increase in the drying times. For the comparison of total colour changes, the highest colour change is obtained in the oven due to the higher drying times and the lowest colour change is obtained in the cabinet-type dryer due to the lower drying times. Similar results were obtained for various agricultural products [30,31].

CONCLUSIONS

In this study, cabinet-type, oven and vacuum oven drying curves and kinetics of mussels were studied for the drying temperatures of 60, 70 and 80 °C. For the drying, the Midilli and Kucuk model best fits the drying data with very high R^2, and very low χ^2 and *RMSE* values for all of the three drying methods. In oven and vacuum oven dryers, all three periods of rising-rate, constant-rate and falling-rate are obtained, and in the cabinet-type dryer, the constant-rate period was not obtained. The highest D_{eff} and E_a values were obtained in the method of the cabinet-type dryer as 4.94×10^{-9} m^2/s and 46.90 kJ/mol, respectively. The lowest D_{eff} and E_a values were obtained in the oven method as 0.89×10^{-9} m^2/s and 29.57 kJ/mol, respectively. "*L*" and "*b*" values decrease with increasing temperature. In contrast, "*a*" values are increased. Considering the industrial usage, the cabinet-type dryer can be used, due to the shorter drying times leading to a cheaper final product. Considering human consumption, the cabinet-type dryer can be used due to better colour parameters as well, with the resulting colours being lighter and more yellow than using other methods, having the lowest total colour change values.

Table 3. Colour values of mussels dried with cabinet, oven and vacuum oven dryers

Temperature (°C)	*L*	*a*	*b*	Δ*E*
Fresh [18]	59.26±0.42	18.26±0.11	42.39±0.35	-
		Cabinet-type		
80	48.83±0.38	13.47±0.10	31.14±0.27	16.07±0.08
70	46.92±0.36	14.95±0.11	30.51±0.26	17.45±0.10
60	38.02±0.30	16.11±0.12	29.93±0.25	24.72±0.15
		Oven		
80	35.09±0.28	11.08±0.09	22.04±0.19	32.40±0.21
70	34.41±0.27	12.88±0.10	21.14±0.20	33.14±0.21
60	33.32±0.25	15.49±0.11	21.01±0.18	33.73±0.21
		Vacuum oven		
80	36.51±0.29	10.18±0.08	25.03±0.22	29.71±0.18
70	36.45±0.28	11.46±0.10	23.94±0.21	30.12±0.19
60	35.12±0.27	13.90±0.11	21.69±0.19	32.10±0.22

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KARAKTERISTIKE SUŠENJA PLAVIH DAGNJI TRADICIONALNIM METODAMA

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NAUČNI RAD

U ovom radu, proučavana se karakteristična ponašanja i kinetika sušenja plave dagnje u tradicionalnim ormanima, peći i vakuum peći. U sušnici tipa ormana postoji protok vazduha, dok u peći, nema protoka vazduha. Za svaku tehniku sušenja izračunate su vrednosti D_{eff} i E_a i analizira se boja. Prema rezultatima, školjke se suše 270-120 min, 570-300 min i 390-210 min za sušare tipa ormana, peći i vakuum peći, redom. Za sve tehnike sušenja, Midili-Kučukov model najbolje odgovara eksperimentalnim podacima sa visokim koeficijentom determinacije (R^2) 0,9995-0,9984, 0,9996-0,9993 i 0,9997-0,9993 za sušare tipa ormana, peći i vakuum peći, redom. D_{eff} vrednosti su $1,89\times10^{-9}$-$4,94\times10^{-9}$ m^2/s, $0,89\times10^{-9}$-$1,63\times10^{-9}m^2/s$ i $1,17\times10^{-9}$-$2,28\times10^{-9}m^2/s$ za orman, peć i vakuum peć, redom. Takođe, vrednosti E_a su 46,90, 29,57 i 32,85 kJ/mol, sušare tipa ormana, peći i vakuum peći, redom. Na promenu boje blago je uticala promena temperature.

Ključne reči: energija aktivacije, plava dagnja, efektivna difuznost vlage, tradicionalno sušenje, promena boje.