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**Research Article**

# Rehydration characteristics and kinetics of traditionally dried mussels at different temperatures

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## ABSTRACT

The rehydration kinetics is an important element in both the manufacture and consumption of dry goods. The rehydration behavior and effective diffusion coefficients of blue mussels (*Mytilus edulis*) dried with traditional methods were investigated in this study at various drying and rehydration temperatures, as well as under vacuum and non-vacuum environments. The drying temperatures in the early study were between 60 and 80°C, whereas the rehydration temperatures were between 20 and 40°C. The maximum rehydration rates for mussels were calculated between 0.0094 - 0.0022 g/g×min for the oven drying and between 0.0127 - 0.0070 g/g×min for vacuum oven drying. Vacuum application has been seen to boost the rehydration rate and rehydration ratio by shortening the time it takes to reach rehydration saturation. The compatibility of the obtained rehydration data with the Peleg, Two-Term and Weibull mathematical models was examined and a higher agreement was reached with the Two-Term model for almost all experimental sets.

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## INTRODUCTION

Consumption of seafood is becoming increasingly widespread as production methods and consumption habits evolve. Mussels are one of the main seafood products harvested from both natural sources and farms. The blue mussel (*Mytilus edulis*) is an edible bivalve mollusk belong the family *Mytilidae* [1]. The natural habitat of this mussel is shallow tidal zones along coastlines from the northeast Atlantic to the English Channel [2]. Blue mussel is one of the two most prevalent mussel species cultivated in Europe. Spain, France, Italy, Denmark, and Netherlands are the top European producers, whereas Spain, Belgium, Italy, and France are the top European consumers of blue mussels. According to FAO, global mussel production reached 2.2 million tons in 2018, resulting in a significant price increase of US$ 2.00 per kilogram of live weight [3, 4].

Drying is one of the most prevalent preservation processes in the food sector [5]. The drying process is utilized in the production of dry end products as well as in the intermediate stages of the food production process. The products subject to the drying process, the main purpose

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of which is to stop the microbial activity until they are used, are usually consumed and/or used by rehydrating [6].

Rehydration is a complicated procedure that reconstructs raw material qualities and is not to be confused with reverse dehydration. The amount of rehydration varies depending on the surface damage in the dry product. During rehydration of dried plant tissues, the absorption of water into the dried material, swelling, and leaching of soluble chemicals are all occurred simultaneously. Mathematical models based on empirical equations are used to design and optimize drying and rehydration procedures [6, 7].

There have been numerous studies on rehydration, which has proven to be quite beneficial in terms of dry food intake and usability. As examples of these studies; Feng et al. (2020) investigated the rehydration properties of garlic that has dried using a variety of drying methods [8] and Pashazadeh et al. (2020) have studied the drying and rehydration modeling of *Rosa pimpinellifolia* fruits in various mathematical models [9]. Izli & Polat (2019) examined rehydration of ginger that has dried by convective and microwave [10]. Lopez et al. (2020) have studied mathematical modeling of freeze-drying and rehydration kinetics of tomatoes [11] and Fauster et al. (2019) studied the rehydration capacity of freeze dried plant materials [12]. Since the drying of food products is mostly focused on fruits and vegetables, rehydration studies have primarily focused on vegetative samples. There are also studies on meat and seafood, albeit few compared to plant-derived products. Examples to these studies can be given as; Rehydration modeling study of chicken breast meat studied by Özünlü et al. (2021) [13] and Mewa et al. (2018) studied drying parameters effect on the quality and rehydration kinetics on dried beef [14]. Tamarit et al. (2020) investigated the rehydration properties of Chilean sea cucumber [15] and Castañeda-López et al. studied (2021) the drying and rehydration modeling of pretreated shrimps [16]. Phahom & Rouduat (2021) examined the drying and rehydration kinetics and mathematical modeling of crab stick by-product [17].

The majority of studies on rehydrating dried foods are on fruits and vegetables, while the number of studies on rehydrating seafood is fairly limited. The goal of this research is to evaluate the rehydration behavior of blue mussels that have been dried using traditional methods and to investigate the results using mathematical models.

## MATERIALS AND METHODS

### Samples

Dried mussels, which are used in this study were the products of our previous study of Kipcak et al. (2021) [18]. In the study of Kipcak et al. (2021), characteristic drying behavior and kinetics of blue mussels, which were dried with the traditional methods of oven, and vacuum oven drying were studied. In this study, the oven and vacuum-oven dried products at 60, 70, and 80°C were taken as raw materials. The detailed drying process was explained in the study of Kipcak et al. (2021).

### Experimental Method

Three parallel experiments were conducted for the rehydration experiments. Rehydration experiments were made by taking 1.00 ± 0.05 grams of dried samples and for each drying method.

All samples were rehydrated in the beakers that were filled with distilled water obtained from Liston A1104 model Water Distiller (Liston LLC, Zhukov, Russia). The weight to volume percentage of the samples to water was selected as 1:100 (w:v) and the rehydration temperatures selected as 20, 30, and 40°C. To heat the beaker Four E's Scientific MI0102003 model Hot Plate Magnetic Agitator Stirrer (Four E's Scientific, Guangzhou, China) was used. Rehydrated samples were removed from the water at a 30-minute interval and excess water was carefully drained with tissue paper, weighed by using Radwag AS 220.R2 Plus Analytical Balance (RADWAG Balances and Scales, Radom, Poland). After weighting, samples were placed back into the same beakers. Samples were rehydrated until the samples' weight was stabilized.

### Rehydration Ratio and Rehydration Rate Calculations

The most important features of dried products are the rehydration ratios and rehydration rates. The rehydration ratio can be calculated with the following equation (1) and rehydration rate is determined as the change in rehydration ratio per unit time in the sample and is calculated using the equation (2) [19]:

$$R_c = \frac{w_r - w_d}{w_d} \tag{1}$$

$$R_R = \frac{R_{c\,(\Delta t + t)} - R_{c\,(t)}}{\Delta t} \tag{2}$$

### Diffusion of Water Inside Mussels

Benseddik et al. (2019), explained the rehydration kinetics can be assumed to occur by simple mass transport of water from the surface to the center, with a uniform diffusion at a constant matrix size and a constant diffusivity value. Thus, the concentration gradient of the water content directly affects mass transfer by pure diffusion [7].

The moisture ratio (MR) may be expressed as follows [18]:

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

The analytical solution of Fick's second law, unsteady state diffusion in spherical coordinates with the assumptions of moisture migration due to diffusion, negligible shrinkage, constant diffusion coefficients, and temperature during the drying process, is given in equation 4 [1]:

$$MR = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} exp\left(-n^2 \pi^2 \frac{D_{eff}}{R^2} t\right) \tag{4}$$

As the first terms of the equations are not affecting the results, they were neglected; hence, equation (4) is simplified as equation (5):

$$\ln(MR) = \ln\left(\frac{6}{\pi^2}\right) - \left(\pi^2 \frac{D_{eff}}{R^2} t\right) \tag{5}$$

$D_{eff}$ can be calculated from the slope of ln(MR) versus t graph.

**Evaluation of the Mathematical Modeling**

The mathematical model equations (6-8) of Peleg, Two-term and Weibull were fitted to the experimental data of rehydration ratios [1, 20, 21].

$$Peleg \qquad MR = a + t/(k_1 + k_2 \times t) \tag{6}$$

$$Two-Term \qquad MR = a.\exp(k_0 t) + b.\exp(k_1 t) \tag{7}$$

$$Weibull \qquad MR = \exp\left(-\left({}^{t}/_{b}\right)^{a}\right) \tag{8}$$

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

In modeling Statistica 6.0 software (Statsoft Inc., Tulsa, OK) were used for the nonlinear regressions based on the Levenberg-Marquardt procedure and parameters, coefficient of determination ($R^2$), reduced chi-square ($\chi^2$) and root mean square error (RMSE) were calculated by equations (9-11) [7, 19];

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(RR_{exp,i} - RR_{pre,i})^2}{\sum_{i=1}^{N}\left(\frac{RR_{exp,i}}{\frac{\sum_{i=1}^{N} RR_{exp,i}}{N}} - RR_{exp,i}\right)^2} \tag{9}$$

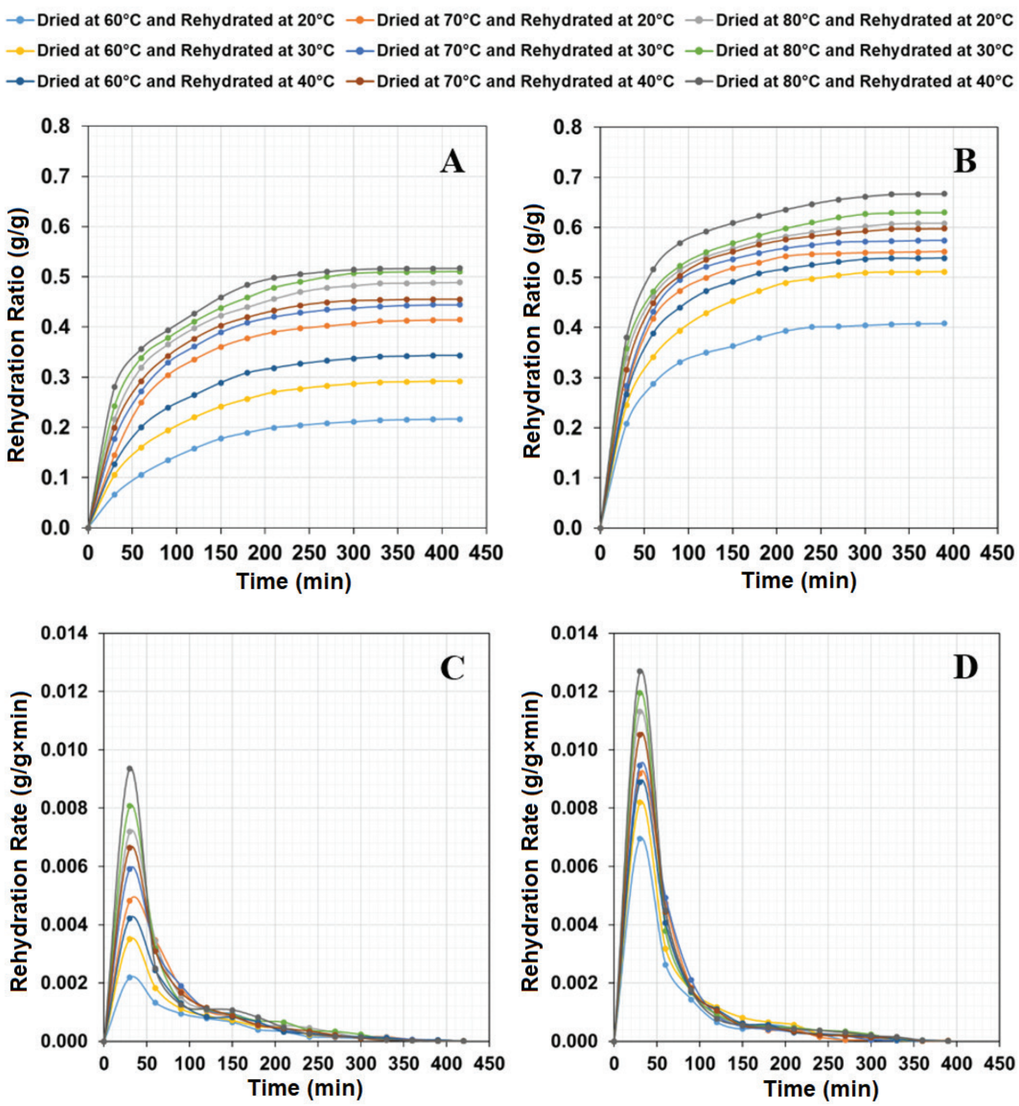


**Figure 1.** Rehydration ratio curves of A. oven dried mussel, B. vacuum-oven dried mussel, and rehydration rate curves of C. oven dried mussel, D. vacuum-oven dried mussel.

$$\chi^2 = \frac{\sum_{i=1}^{N}(RR_{exp,i}-RR_{pre,i})^2}{N-n} \tag{10}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(RR_{exp,i}-RR_{pre,i})^2}{N}} \tag{11}$$

The most relevant model was chosen as the highest $R^2$ and the least $\chi^2$ and RMSE [22, 23, 24].

## RESULTS AND DISCUSSION

### Rehydration Curves

The rehydration ratio and rehydration rate curves of mussels, which were dried by the methods of oven and vacuum-oven are given in Figure 1. From the rehydration ratio curve obtained, all rehydrated samples have came to equilibrium at 450 min. In the methods, as the drying temperature and rehydration temperature increased, rehydration ratios were increased. This rehydration ratio increase by increasing the drying temperature can be explained with lower drying times obtained in high temperature hence the collapses of the pores of mussels were decreased. Furthermore, in comparison with the drying methods since the drying times in vacuum-oven lower than the oven, the rehydration ratio increase was expected. In addition, it was determined that the increase in the rehydration rate with the increase in temperature and the shortening of the rehydration time with the vacuum effect were compatible with

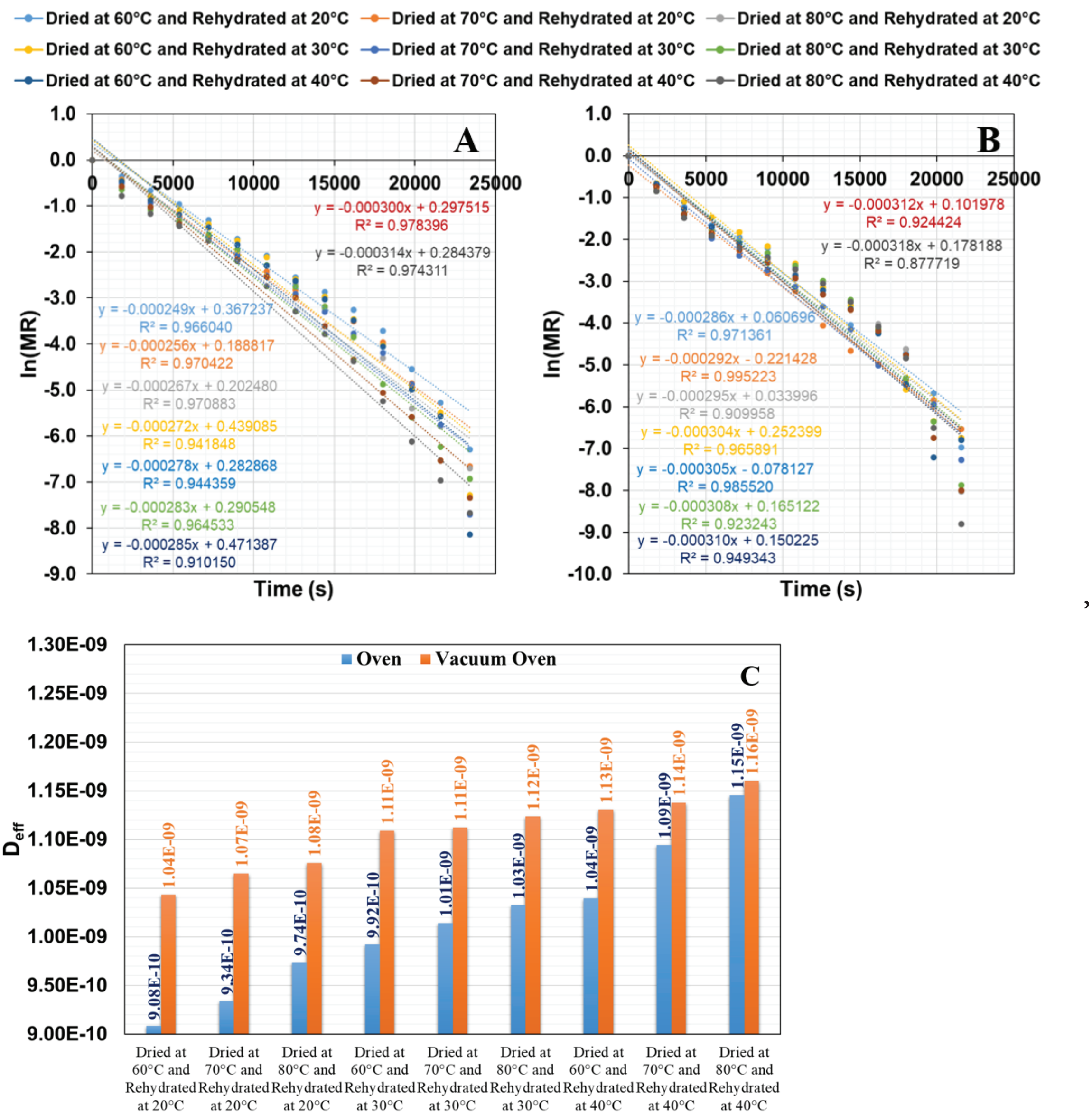


**Figure 2.** ln(MR) versus time plots for the calculation of $D_{eff}$ for a. oven dried mussel, b. vacuum-oven dried mussel and c. $D_{eff}$ versus samples plots.

the rehydration data of microwave dried mussels [1] and oven and vacuum oven dried shrimps [25].

The maximum rehydration ratios (g/g) were obtained in the mussels dried at 80°C and rehydrated at 40°C, as 0.5169 ± 0.0024 g/g and 0.6668 ± 0.0031 g/g in the methods of oven and vacuum-oven, respectively. The lowest rehydration ratios (g/g) were obtained in the mussels dried at 60°C and rehydrated at 20°C, as 0.2165 ± 0.0015 g/g and 0.4082 ± 0.0018 g/g in the methods of oven and vacuum-oven, respectively.

In the rehydration rate curve, the maximum rehydration rates (peak values) were seen at the time between 0 to 30 min, which this region can be called as increasing rehydration-rate period and the region between 30 to 420 min can be called a decreasing rehydration-rate period. The maximum peak values obtained in the mussels dried at 80°C and rehydrated at 40°C and these peak values were calculated as 0.0094 ± 0.00008 g/g×min and 0.0127 ± 0.00010 g/g×min, in the methods of oven and vacuum-oven, respectively. The lowest peak values obtained in the mussels dried at 60°C and rehydrated at 20°C calculated as 0.0022 ± 0.00005 g/g×min and 0.0070 ± 0.00006 g/g×min, in the methods of oven and vacuum-oven, respectively.

### Diffusion Mass Transfer Coefficient Results

In Figure 2, ln(*MR*) versus time and $D_{eff}$ versus sample plots were given for the calculation and comparison of $D_{eff}$ values, respectively. Obtained slope of ln(*MR*) vs t and calculated $D_{eff}$ values were given in Table 1:

Obtained $D_{eff}$ values were calculated in the range of 0.908 - 1.15 × $10^{-9}$ $m^2/s$, 1.04 - 1.16 × $10^{-9}$ $m^2/s$, for the methods of oven and vacuum-oven, respectively. As expected as the rehydration ratio increases $D_{eff}$ values are increased. The higher $D_{eff}$ values are calculated at the method of vacuum-oven.

### Mathematical Modeling Results

The mathematical models of Peleg, Two-Term were fitted well with the experimental rehydration ratio values but Weibull model was not fitted well, so the values obtained from Weibull model was not included in Table 2. According to the Table 2, data were fitted better than Peleg model.

In the oven method and at 20°C rehydration temperature the highest $R^2$ and lowest $\chi^2$ and RMSE values were found by Two-Term model (dried at 70°C) with the values of 0.999511, 0.002554 and 0.000009, respectively. In the vacuum-oven method and at 20°C rehydration temperature the highest $R^2$ and lowest $\chi^2$ and RMSE values were found by Two-Term model (dried at 70°C) with the values of 0.999341, 0.003827 and 0.000021, respectively.

In the oven method and at 30°C rehydration temperature the highest $R^2$ and lowest $\chi^2$ and RMSE values were found by Two-Term model (dried at 70°C) with the values of 0.999059, 0.003737 and 0.000019, respectively. In the vacuum-oven method and at 30°C rehydration temperature the highest $R^2$ and lowest $\chi^2$ and RMSE values were found by Peleg model (dried at 80°C) with the values of 0.999584, 0.003345 and 0.000014, respectively.

In the oven method and at 40°C rehydration temperature the highest $R^2$ and lowest $\chi^2$ and RMSE values were found by Two-Term model (dried at 60°C) with the values of 0.998133, 0.004111 and 0.000023, respectively. In the vacuum-oven method and at 40°C rehydration temperature the highest $R^2$ and lowest $c^2$ and RMSE values were found by Two-term model (dried at 70°C) with the values of 0.999308, 0.004170 and 0.000024, respectively.

The calculated rehydration ratio values versus experimental rehydration ratio values were given in Figure 3 for oven and Figure 4 for vacuum-oven method. When the figures are examined, it is seen once again that the rehydration ratio increases as the temperature rise and vacuum assistance. Furthermore, the distribution of rehydration data on the 45° linear line reveals that the applied Peleg and Two-Term models are very compatible with the rehydration data among the mathematical models used to explain the rehydration.

**Table 1.** Obtained slope of ln(*MR*) vs t and calculated $D_{eff}$ values

| Method | Oven | | Vacuum-oven | |
|---|---|---|---|---|
| **Details** | **Slope** | **$D_{eff}$ ($m^2/s$)** | **Slope** | **$D_{eff}$ ($m^2/s$)** |
| Dried @ 60°C & Rehydrated @ 20°C | -0.000249 | $9.08\times10^{-10}$ | -0.000286 | $1.04\times10^{-9}$ |
| Dried @ 70°C & Rehydrated @ 20°C | -0.000256 | $9.34\times10^{-10}$ | -0.000292 | $1.07\times10^{-9}$ |
| Dried @ 80°C & Rehydrated @ 20°C | -0.000267 | $9.74\times10^{-10}$ | -0.000295 | $1.08\times10^{-9}$ |
| Dried @ 60°C & Rehydrated @ 30°C | -0.000272 | $9.92\times10^{-10}$ | -0.000304 | $1.09\times10^{-9}$ |
| Dried @ 70°C & Rehydrated @ 30°C | -0.000278 | $1.01\times10^{-9}$ | -0.000305 | $1.11\times10^{-9}$ |
| Dried @ 80°C & Rehydrated @ 30°C | -0.000283 | $1.03\times10^{-9}$ | -0.000308 | $1.11\times10^{-9}$ |
| Dried @ 60°C & Rehydrated @ 40°C | -0.000285 | $1.04\times10^{-9}$ | -0.000310 | $1.12\times10^{-9}$ |
| Dried @ 70°C & Rehydrated @ 40°C | -0.000300 | $1.09\times10^{-9}$ | -0.000312 | $1.13\times10^{-9}$ |
| Dried @ 80°C & Rehydrated @ 40°C | -0.000314 | $1.15\times10^{-9}$ | -0.000318 | $1.16\times10^{-9}$ |

**Table 2.** Obtained mathematical model coefficients and statistical data

| Rehydration Temperature | Model | Parameter | Dried by Oven | | | Dried by Vacuum Oven | | |
|---|---|---|---|---|---|---|---|---|
| | | | Temperature (°C) | | | Temperature (°C) | | |
| | | | 60 | 70 | 80 | 60 | 70 | 80 |
| 20 °C | Peleg | $R^2$ | 0.994521 | 0.994558 | 0.999007 | 0.998946 | 0.993384 | 0.999336 |
| | | RMSE | 0.004650 | 0.008519 | 0.004114 | 0.003538 | 0.012127 | 0.004101 |
| | | $\chi^2$ | 0.000027 | 0.000091 | 0.000021 | 0.000016 | 0.000187 | 0.000021 |
| | | a | -0.003000 | -0.006700 | -0.000940 | -0.000580 | -0.004520 | -0.001230 |
| | | $k_1$ | 304.2492 | 111.4501 | 81.34717 | 75.08385 | 47.94921 | 39.80463 |
| | | $k_2$ | 3.674200 | 2.044800 | 1.813210 | 2.218270 | 1.629980 | 1.524590 |
| | Two-Term | $R^2$ | 0.999354 | 0.999511 | 0.996783 | 0.996746 | 0.999341 | 0.998907 |
| | | RMSE | 0.001596 | 0.002554 | 0.007404 | 0.006217 | 0.003827 | 0.005263 |
| | | $\chi^2$ | 0.000003 | 0.000009 | 0.000075 | 0.000054 | 0.000021 | 0.000039 |
| | | a | -0.224525 | -0.389640 | -0.416041 | 0.355441 | 0.522983 | 0.535193 |
| | | $k_0$ | 0.010404 | 0.015931 | 0.021149 | -0.000405 | -0.000153 | -0.000367 |
| | | b | 0.226457 | 0.388927 | 0.420569 | -0.352636 | -0.522961 | -0.533418 |
| | | $k_1$ | 0.000073 | -0.000167 | -0.000409 | 0.026146 | 0.024878 | 0.031204 |
| 30 °C | Peleg | $R^2$ | 0.997461 | 0.996918 | 0.998033 | 0.999026 | 0.993200 | 0.999584 |
| | | RMSE | 0.004123 | 0.006763 | 0.005981 | 0.004319 | 0.012785 | 0.003345 |
| | | $\chi^2$ | 0.000021 | 0.000057 | 0.000045 | 0.000024 | 0.000208 | 0.000014 |
| | | a | -0.001200 | -0.003880 | 0.001690 | -0.000270 | -0.004880 | 0.000210 |
| | | $k_1$ | 194.6250 | 97.54277 | 75.55351 | 69.99398 | 46.49928 | 39.37757 |
| | | $k_2$ | 2.854000 | 1.940380 | 1.757650 | 1.740560 | 1.567340 | 1.479260 |
| | Two-Term | $R^2$ | 0.997655 | 0.999059 | 0.993334 | 0.996336 | 0.999501 | 0.997530 |
| | | RMSE | 0.003962 | 0.003737 | 0.011010 | 0.008376 | 0.003463 | 0.008151 |
| | | $\chi^2$ | 0.000021 | 0.000019 | 0.000165 | 0.000098 | 0.000017 | 0.000093 |
| | | a | -0.264194 | -0.407264 | -0.420209 | 0.444358 | 0.540701 | -0.534270 |
| | | $k_0$ | 0.013771 | 0.017115 | 0.023230 | -0.000412 | -0.000170 | 0.033310 |
| | | b | 0.268905 | 0.410744 | 0.426872 | -0.438847 | -0.541453 | 0.536686 |
| | | $k_1$ | -0.000232 | -0.000213 | -0.000493 | 0.022875 | 0.025044 | -0.000469 |
| 40 °C | Peleg | $R^2$ | 0.997748 | 0.997735 | 0.995650 | 0.998129 | 0.997984 | 0.999122 |
| | | RMSE | 0.004515 | 0.005854 | 0.008869 | 0.006260 | 0.007117 | 0.005140 |
| | | $\chi^2$ | 0.000025 | 0.000043 | 0.000098 | 0.000050 | 0.000064 | 0.000034 |
| | | a | -0.002300 | -0.002230 | 0.002460 | -0.002610 | -0.002540 | -0.000990 |
| | | $k_1$ | 148.5560 | 86.50138 | 61.33171 | 55.27826 | 43.30310 | 34.48765 |
| | | $k_2$ | 2.468900 | 1.925610 | 1.768840 | 1.671880 | 1.530430 | 1.400020 |
| | Two-Term | $R^2$ | 0.998133 | 0.997532 | 0.988083 | 0.998937 | 0.999308 | 0.998834 |
| | | RMSE | 0.004111 | 0.006111 | 0.014680 | 0.004718 | 0.004170 | 0.005925 |
| | | $\chi^2$ | 0.000023 | 0.000051 | 0.000294 | 0.000031 | 0.000024 | 0.000049 |
| | | a | -0.306910 | -0.409075 | -0.434120 | 0.483568 | 0.538329 | -0.579761 |
| | | $k_0$ | 0.015494 | 0.019019 | 0.026167 | -0.000314 | -0.000300 | 0.033519 |
| | | b | 0.310589 | 0.414314 | 0.442850 | -0.481659 | -0.536965 | 0.580949 |
| | | $k_1$ | -0.000271 | -0.000260 | -0.000436 | 0.025123 | 0.028001 | -0.000399 |

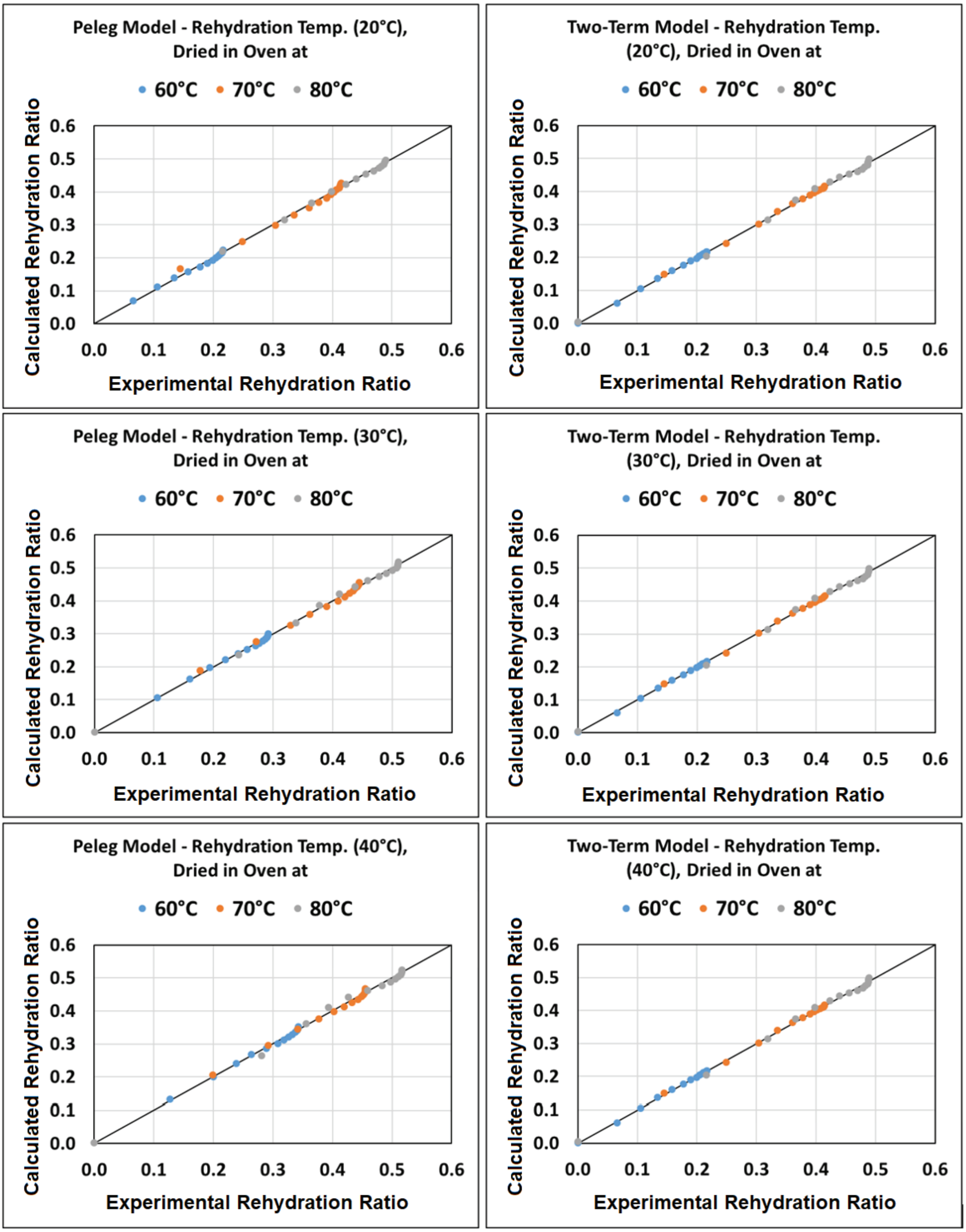


**Figure 3.** Experimental and calculated rehydration ratio values obtained from the models of Peleg and Two-Term Exponential for oven dried mussel.

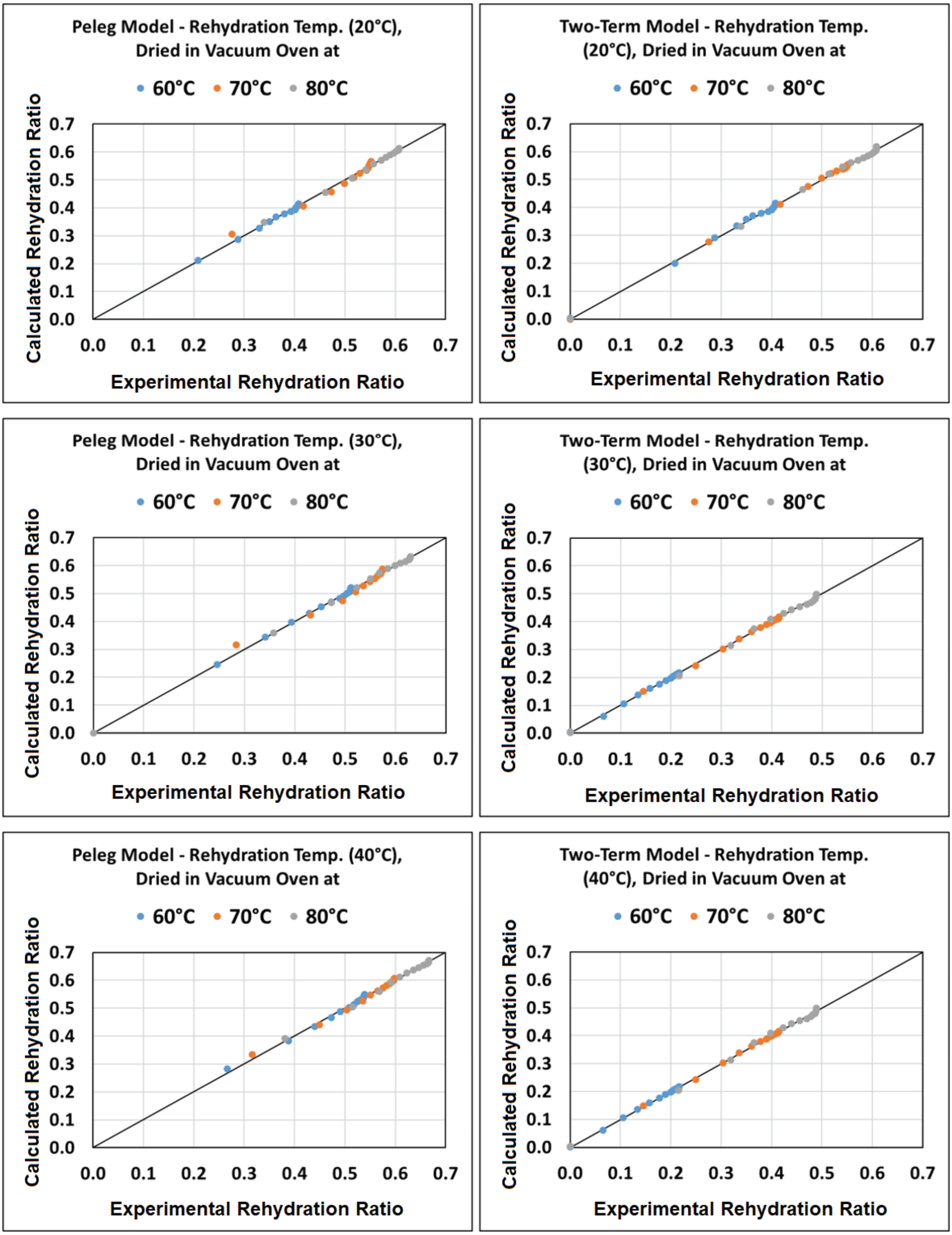


**Figure 4.** Experimental and calculated rehydration ratio values obtained from the models of Peleg and Two-Term Exponential for vacuum-oven dried mussel.

## CONCLUSION

The rehydration behavior of blue mussels dried using traditional methods was investigated in this study. When the curves with the obtained rehydration data were examined, it is obvious that applying vacuum reduces the time to reach rehydration saturation and hence enhances the rehydration ratio and rate. The effective diffusivity values estimated for vacuum aided studies were found to be higher in all experimental sets, and they also increased as the rehydration temperature rose. Furthermore, of the three mathematical models used, the rehydration data fitted well with Peleg and Two-Term while Weibull did not fit at all, but the Two-Term mathematical model has the best compatibility for both oven and the vacuum oven studies.

## NOMENCLATURE

| | |
|---|---|
| $D_{eff}$ | The effective diffusivity, $m^2/s$ |
| $M_0$ | Initial water content, kg water/kg dry matter |
| $M_e$ | Water content at equilibrium, kg water/kg dry matter |
| $M_t$ | Water content at time t, kg water/kg dry matter |
| $MR$ | Moisture ratio |
| $n$ | Number of models' constants |
| $N$ | Number of data |
| $R$ | The radius of the sample, m |
| $R_c$ | Rehydration ratio, g/g dry weight |
| $R_{c(t)}$ | Rehydration ratio at any time, g/g dry weight |
| $R_{c(t+\Delta t)}$ | Dry-content based rehydration ratio at a time "t + Δt", g/g dry weight |
| $RR_{exp,i}$ | The experimental rehydration ratio |
| $RR_{pre,i}$ | The experimental predicted ratio |
| $t$ | Time, s |
| $w_d$ | Weight of the original dried sample, g |
| $w_r$ | Weight of the rehydrated sample at time t, g |

## AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

## DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

## CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

## ETHICS

There are no ethical issues with the publication of this manuscript.

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