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Research Article

Infrared and microwave drying methods on the rehydration behaviour and mass transfer diffusion coefficient of *Loligo vulgaris*

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ABSTRACT

In this study, the effect of various drying methods on the rehydration behaviour and mass transfer diffusion coefficients of squid (*Loligo vulgaris*) is investigated. Drying methods were selected as infrared (IR), ultrasonic pre-treated infrared (US-IR) and microwave (MW). In IR and US-IR method drying temperatures were within 60 – 80 °C and in MW drying the power levels were in between 140 – 350 W. The rehydration process was carried out for all samples in 180 minutes at room temperature with 30-minute weighing intervals. Obtained rehydration data were applied to the mathematical models of Peleg and Two-Term Exponential. The rehydration ratios were changed between 1.78 – 2.50, 1.91 – 2.66 and 2.78 – 3.83 g/g dry matter for IR, US-IR, and MW respectively. Mass transfer diffusion coefficients of effective moisture diffusion (D_{eff}) values were changed between 1.01×10^{-7} – 1.07×10^{-7}, 1.02×10^{-7} – 1.08×10^{-7}, and 1.12×10^{-7} – 1.22×10^{-7} m^2/s, for IR, US-IR, and MW respectively. Peleg and Two-Term Exponential mathematical models showed matched well with the experimental data. In addition, colour values found to be changed particularly in the brightness values due to rehydration process.

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INTRODUCTION

Seafood has been consumed for many years due to its high nutritional value and product diversity. Considering its commercial value, *Loligo vulgaris* is one of the most important marine species on the Mediterranean and southern European coasts. *Loligo vulgaris*, usually referred as the European squid, is a large squid belonging to the family *Loliginidae* that is known for its habitat along the eastern coast of the Atlantic Ocean, particularly in the Mediterranean. As one of the most well-known European cephalopods, it has long been the subject of marine research [1, 2]. According to the FAO, Spain, Italy and, Croatia produce the majority of the world's projected yearly production of *Loligo vulgaris*, which totals more than 2190 tons [3].

The microbiologic activity that leads to deterioration under normal circumstances ceases in an environment with low humidity, making drying one of the most effective ways of preservation. Microwave (MW) and infrared (IR) drying

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have been the prominent techniques for drying a variety of items for the past few decades [4, 5]. Due to its superior thermal efficiency and rapid drying rate per response time, MW drying saves time and energy. Energy is also saved by IR drying since it rapidly and evenly heats the material without heating the surrounding air. Compared to many other drying techniques, IR drying also provides a superior textural quality to the final product due to its uniform temperature distribution [6].

Various pre-treatments are used in the drying process to reduce drying time and increase end product quality parameters. Ultrasonic pre-treatment (US) is one of the most preferred methods among these pre-treatments, with its positive effect on drying and end-product quality parameters and easy applicability. Ultrasound waves vibrate at frequencies between 20 kHz and 100 MH as they pass through a material, lowering both internal and exterior mechanical resistances [7, 8]. Microscopic channels are created and aid in the transfer of the substance when the stresses in the mechanism are stronger than the surface tension of the water molecules in the material's capillaries [9]. The softer the material is, the easier it is to compress and expand mechanically as the porosity rises.

A significant number of dried foods are rehydrated before or during usage. Rehydration is a complex process that reconstructs raw product properties and material properties that cannot be considered the reverse of dehydration. During rehydration, three main phenomena occur simultaneously: the absorption of water into the dried material, and the rehydration and leaching of soluble compounds [10, 11].

Some important changes take place during the drying of foods as structural and physicochemical modifications influence the quality of the finished product. The composition variables such as bleaching, drying process, and parameters, physical structure, chemical composition, environment characteristics such as temperature and pH, sample volume and density, and salt content in the water affect the rehydration process [12, 13]. Colour values are also one of the fundamental quality parameters for rehydrated samples. The end-of-process colours of the rehydrated products are expected to be very similar to the colour characteristics of the fresh sample. Determining rehydration conditions and minimizing colour changes during the drying/rehydration processes is of great economic importance [10].

There are a lot of studies have been carried out on rehydration, which plays an important role in the consumption or secondary production of dried products. Most of these experiments were carried out on foodstuffs such as garlic slices [14], pumpkin [15], tomatoes [16], apple slices [17], carrot slices [18], and kiwifruits [19]. Rehydration studies on products other than fruits and vegetables are very rare. Nevertheless, there are some studies on dried meat and seafood. As an example of these studies; Aksoy et al. (2019) investigated the effects of different drying methods on the rehydration of minced meat [20]. Ozunlu et al. (2021) studied the rehydration kinetics of hot air dried chicken breast [21]. Jiang et al. (2022) investigated varied pre-treatment methods for the drying and rehydration of sea cucumbers [22]. Kiin-Kabari & Obasi (2020) examined the rehydration properties of periwinkles, oysters, and whelk [23]. Castañeda-López et al. (2021) studied the influence of a variety of pre-treatments on the structural and rehydration properties of dried shrimp [24].

Despite the fact that there are numerous research on the rehydration of dried foods, dried meat and seafood have received very little attention. The objective of this report study is to identify the experimental rehydration behavior of *Loligo vulgaris*, which was dried using various drying techniques, as a function of initial moisture content and time, and then use the data obtained to investigate the rehydration coefficients and parameters for the chosen models. In addition, the values of effective moisture diffusivity (D_{eff}) and the color changes during rehydration in the study were determined for comparison with the dried samples. In this manner, the impact of the drying method and the pre-treatment on rehydration performance and the colour values, which is a fundamental quality characteristics, will be ascertained for *Loligo vulgaris*.

MATERIALS AND METHODS

Samples

The rehydration process was carried out using previously dried samples. *Loligo vulgaris* samples, which are produced by Kerevitaş (Kerevitaş Industry and Commerce Inc., Bursa, Turkey), were purchased from the local market in Turkey in February 2019 and dried with IR and MW methods in our previous study. *Loligo vulgaris* samples were dried as a thin layer with a thickness of 6 ± 0.05 mm and a weight of 10.0 ± 0.2 g [25].

The IR drying process was carried out using MA 50.R model infrared moisture analyser (Radwag Balances and Scales, Radom, Poland) working with 230 V at 50 MHz. Pre-treatment was carried out using an ultrasonic bath (Isolab, Germany) with ultrasonic precision of 1°C and 120 W. MW drying experiments were performed with a home-type Delonghi MW205S model microwave oven (Delonghi, Treviso, Italy) operating in the range of 140 – 790 W. The drying temperatures were chosen as 60, 70 and 80 °C for IR and US-IR dryings. The US pre-treatment was applied at 30 °C and 10 minutes before IR drying. Furthermore, MW power levels were chosen as 140, 210 and 350 W. The average moisture content of the samples before drying was determined as 3.87 kg water/kg dry matter for the unpre-treated samples and 7.197 kg water/kg dry matter for the US pre-treated samples. The post-drying moisture contents were reduced to 0.0922 ± 0.0156, 0.3337 ± 0.0865, and 0.1628 ± 0.0372 kg water/kg dry matter for IR, US-IR, and MW, respectively. After the drying processes were completed, the samples, which came to room temperature, were placed in polyethylene bags and stored in a desiccator until swelling studies [25].

Experimental Method

The rehydration experiments were carried out by taking 1 gram of sample and repeated 3 times for each dried sample. Samples were placed into beakers filled with distilled water for rehydration. The rehydration performed at a temperature of 25 °C with a water-to-sample ratio of 1:100 (w:v). At intervals of 30 minutes, samples were taken out of the water, and any excess water was gently blotted away with tissue paper. The samples were then immediately weighed and put back into the beakers., The dried samples were rehydrated for 180 minutes in order to stabilize their weight.

Rehydration Ratio and Rehydration Rate Calculations

Rehydration ratio (R_c, g/g dry weight) and rehydration rate (R_R, g/g×min) are among the most important features of a dried product. The R_c was calculated with the following equation (1):

$$R_c = \frac{w_r - w_d}{w_d} \quad (1)$$

where w_r is the weight of the rehydrated sample at time t, and w_d is the weight of the original dried sample [26]. Furthermore, R_R is calculated using equation (2) and is defined as the variation in R_c per unit time in the sample:

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

where $R_{c(t)}$ is R_c at any time (g/g dry weight) and $R_{c(t+\Delta t)}$ represents the dry-content based R_c at a time "t + Δt". R_c and rate were shown in Fig. 1 for different drying methods [26].

Diffusion Mechanism of the Moisture Inside Samples

Rehydration kinetics can be predicated on the straightforward mass transfer of moisture, with uniform diffusion at constant matrix size and diffusivity value, from the surface to the interior. Consequently, mass transfer via pure diffusion is directly impacted by the concentration gradient of the moisture content [11]. The following are various ways to express the moisture ratio (MR):

$$MR = \frac{M_t - M_e}{M_i - M_e} \quad (3)$$

where M_t, M_0, and M_e represent the moisture contents at time t, initial moisture content, and equilibrium (kg water/kg dry matter), respectively. Equation (4) can be used to represent a variety of mathematical models proposed employing Fick's second rule to describe rehydration activities [4]:

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

where D_{eff} states the effective diffusivity (m^2/s), L the half of the sample's thickness (m), and t drying time (s). Since the first terms of the equations had no bearing on the outcomes, they were disregarded, leading to the simplification of equation (4) into equation (5):

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\pi^2\frac{D_{eff}}{4L^2}t\right) \quad (5)$$

The slope of the graph of ln(MR) vs t can be used to determine D_{eff} values.

Evaluation of the Mathematical Modelling

The model parameters were established by experimental data from rehydration studies to define the best suited model, Statistica 6.0 software (Statsoft Inc., Tulsa, OK) was utilized. The Levenberg-Marquardt approach was used to generate the nonlinear regression, and equations (6–8) were utilized to determine the parameters, coefficient of determination (R^2), reduced chi-square (χ^2), and root mean square error (RMSE) [11, 26];

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

$$\chi^2 = \frac{\sum_{i=1}^{N}(RR_{exp,i} - RR_{pre,i})^2}{N-n} \quad (7)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(RR_{exp,i} - RR_{pre,i})^2}{N}} \quad (8)$$

where $RR_{exp,i}$ is the experimental R_R, and $RR_{pre,i}$ is the predicted R_R. *N* is the data number, and n is the number of models' constants. The best-fitted model was chosen as the highest R^2 and the least χ^2 and RMSE [4, 27].

RESULTS AND DISCUSSION

Rehydration Curves

R_c and R_R curves of *Loligo vulgaris* are given in Figure 1, which were dried with different methods of IR, US-IR, and MW. According to Figure 1 all rehydrated samples reach equilibrium at the rehydration time of 210 min. In each method, as the drying temperature increases, R_R values increase. This situation can be explained as; the drying times were reduced with increasing the temperature so the collapses of the pores of *Loligo vulgaris* were lower at the higher temperatures.

At IR method R_c values are calculated as 1.78, 2.12, and 2.50 g/g dry weight for the temperatures 60, 70, and 80 °C, respectively. These R_c values are increased to 1.91, 2.32, and 2.66 g/g dry weight for the temperatures 60, 70, and 80 °C, respectively at the US-IR method. It can be said that US pre-treatment transforms the body into a looser and more porous structure. In this way, capillaries create channels that provide better and faster water uptake, total water absorption capacity and R_c values are increased due to US waves [28]. On the other hand, in MW dried *Loligo vulgaris* R_c values are found higher than both two methods with the values of 2.78, 3.39, and 3.83 g/g dry weight for

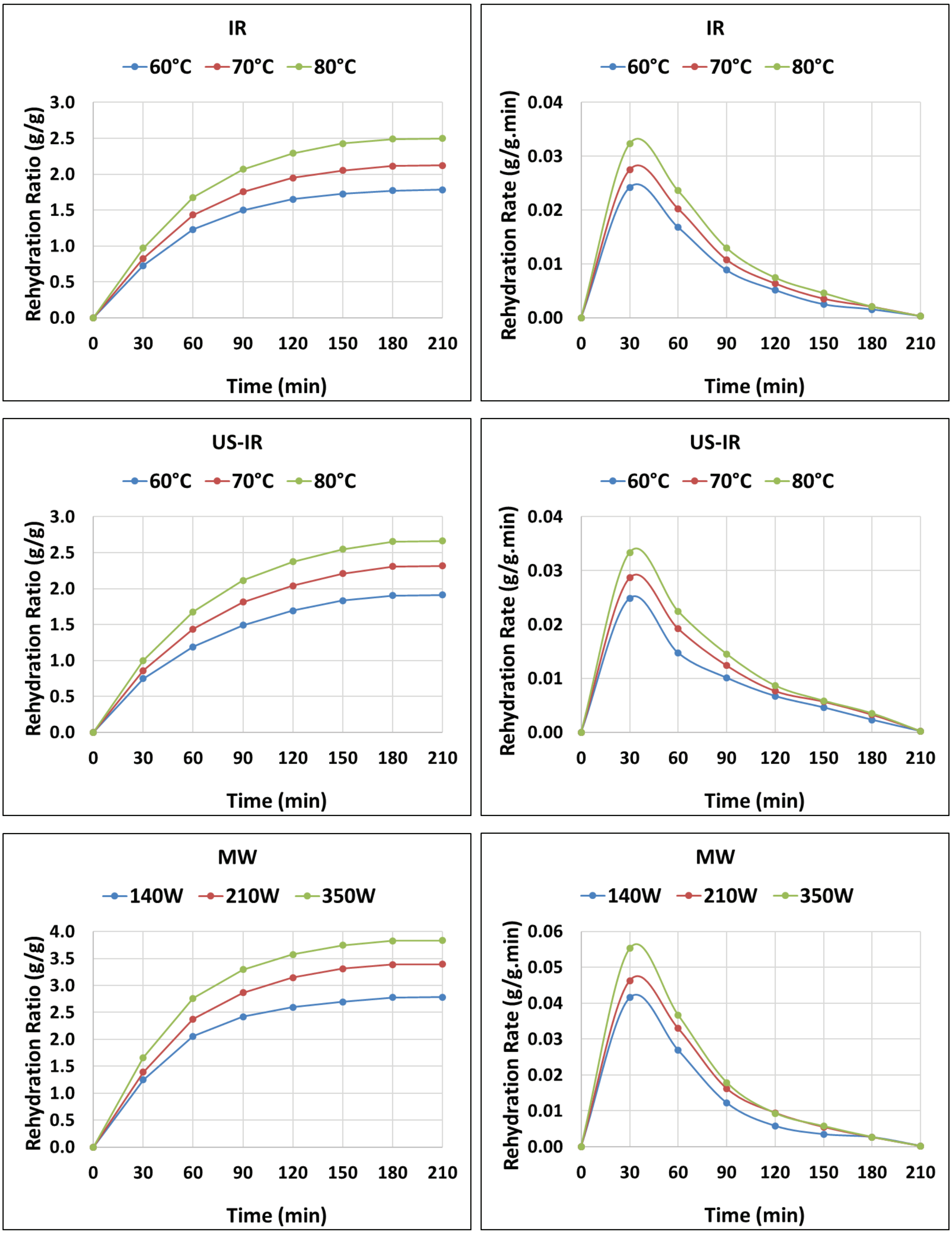

Figure 1. R_c and R_R curves of IR, US-IR and MW.

the MW power levels of 140, 210, and 350W, respectively. As aforementioned before, since in the method of MW the drying times were much lower than other two methods, so the collapse of the pores was not as much as in the other two methods [29].

In the R_R curves, two periods of increased-rate and falling-rate are seen for each method. The peak point (highest point) in the rehydration-rate plot represents the point in which the increased-rate stop and falling-rate start. In IR dried *Loligo vulgaris*, the peak values are found as 0.0242, 0.0275, and 0.0323 g/g dry weight × time, for the

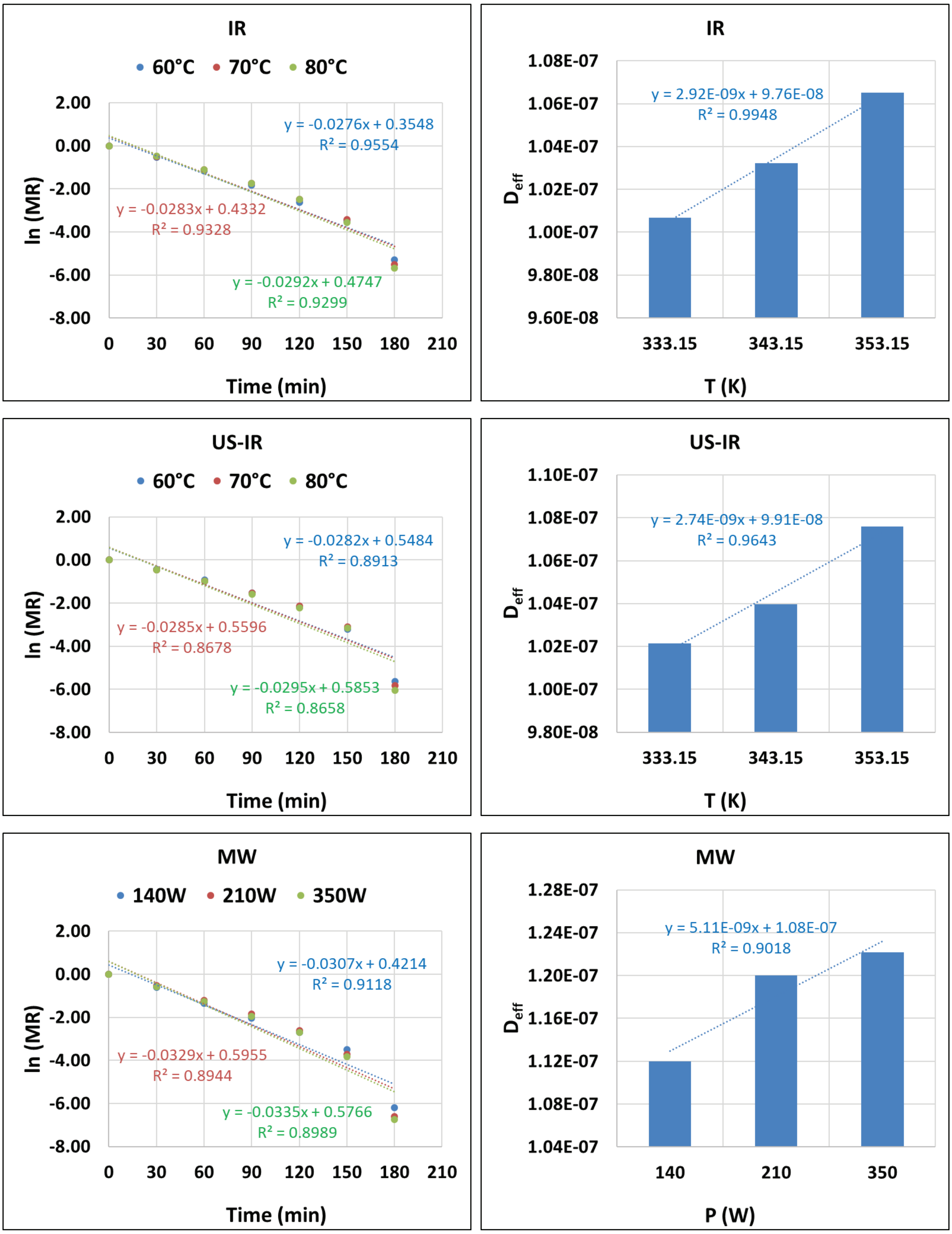

Figure 2. ln(MR) vs time where D_{eff} values are calculated and the plot of D_{eff} vs temperature and D_{eff} vs power.

temperatures 60, 70 and 80 °C, respectively. These peak values are increased to 0.0249, 0.0287, and 0.0334 g/g dry weight × time for the temperatures 60, 70, and 80 °C, respectively. At the MW dried *Loligo vulgaris*, the peak values are calculated as 0.0415, 0.0463, and 0.0533 g/g dry weight × time for the MW power levels of 140, 210, and 350 W, respectively. As in the R_c values, rehydration peak rates are increased with US pre-treatment and the highest rehydration peak rates are found at the MW dried *Loligo vulgaris*.

Diffusion Mass Transfer Coefficient Results

Plots of ln(MR) vs time where D_{eff} values are calculated and the plot of D_{eff} vs temperature and D_{eff} vs power are given in Figure 2.

Obtained equations are given in (9) through (17):

$$\text{IR } 60°C \rightarrow \ln(MR) = -0.0276t + 0.3548 \ (R^2 = 0.9554) \quad (9)$$

$$\text{IR } 70°C \rightarrow \ln(MR) = -0.0283t + 0.4332 \ (R^2 = 0.9328) \quad (10)$$

$$\text{IR } 80°C \rightarrow \ln(MR) = -0.0292t + 0.4747 \ (R^2 = 0.9299) \quad (11)$$

$$\text{IR-US } 60°C \rightarrow \ln(MR) = -0.0282 + 0.5484 \ (R^2 = 0.8913) \quad (12)$$

$$\text{IR-US } 70°C \rightarrow \ln(MR) = -0.0285t + 0.5596 \ (R^2 = 0.8678) \quad (13)$$

$$\text{IR-US } 80°C \rightarrow \ln(MR) = -0.0295t + 0.5853 \ (R^2 = 0.8658) \quad (14)$$

$$\text{MW } 140 \text{ W} \rightarrow \ln(MR) = -0.0307t + 0.4214 \ (R^2 = 0.9118) \quad (15)$$

$$\text{MW } 210 \text{ W} \rightarrow \ln(MR) = -0.0329t + 0.5955 \ (R^2 = 0.8944) \quad (16)$$

$$\text{MW } 350 \text{ W} \rightarrow \ln(MR) = -0.0335t + 0.5766 \ (R^2 = 0.8989) \quad (17)$$

D_{eff} values are calculated from the slope of the given equations. For IR dried *Loligo vulgaris* rehydration D_{eff} values are found as 1.01×10^{-7}, 1.03×10^{-7}, and, 1.07×10^{-7} m^2/s for the drying temperatures of 60, 70, and 80 °C, respectively. For US-IR samples rehydration D_{eff} values are calculated as 1.02×10^{-7}, 1.04×10^{-7}, and 1.08×10^{-7} m^2/s for the drying temperatures of 60, 70, and 80°C, respectively. As it is seen that the US pre-treatment had a small effect on the rehydration D_{eff} values. For MW dried *Loligo vulgaris* rehydration D_{eff} values are found as 1.12×10^{-7}, 1.20×10^{-7}, and, 1.22×10^{-7} m^2/s for the MW power levels of 140, 210 and 350 W, respectively. The obtained rehydration D_{eff} values show that the MW method had the highest rehydration D_{eff} coefficient values.

The effect of IR temperature and MW power level on rehydration D_{eff} values can be computed with the use of the equations between (18 – 20):

$$\text{IR} \rightarrow D_{eff} = 2.92 \times 10^{-9} \times T + 9.76 \times 10^{-8} \ (R^2 = 0.9948) \quad (18)$$

$$\text{IR-US} \rightarrow D_{eff} = 2.74 \times 10^{-9} \times T + 9.91 \times 10^{-8} \ (R^2 = 0.9643) \quad (19)$$

$$\text{MW} \rightarrow D_{eff} = 5.11 \times 10^{-9} \times P + 1.08 \times 10^{-7} \ (R^2 = 0.9018) \quad (20)$$

Mathematical Modelling Results

Non-linear regression analysis was used to apply the Peleg and Two-Term Exponential mathematical models to the experimental R_c values. Table 1 displays the model parameters and statistical information that were obtained. The most compatible was chosen by comparing R^2, χ^2, and RMSE.

As is seen from Table 1, both two methods fitted the experimental data perfectly with R^2 values higher than 0.99. Between these two methods, Two-Term Exponential had a better fit.

In the rehydration of *Loligo vulgaris* dried by IR, R^2, χ^2, and RMSE values were found between 0.9931 – 0.9942, 0.0034 – 0.0078, and 0.0462 – 0.0697 for Peleg model and 0.9995 – 0.9997, 0.0002 – 0.0005, and 0.0111 – 0.0156 for Two-Term Exponential model, respectively. In US-IR dried *Loligo vulgaris* rehydration R^2, χ^2, and RMSE values were found between 0.9951 – 0.9967, 0.0031 – 0.0050, and 0.0443 – 0.0561 for Peleg model and 0.9998 – 0.9999, 0.00004 – 0.0002, and 0.0044 – 0.0104 for Two-Term Exponential model, respectively. And in MW dried *Loligo vulgaris* rehydration R^2, χ^2 and RMSE values were found between 0.9927 – 0.9932, 0.0092 – 0.0182, and 0.0757 - 0.1068 for Peleg model and 0.9992 – 0.9996, 0.0013 – 0.0014, and 0.0254 – 0.0265 for Two-Term Exponential model, respectively.

In Figure 3, the calculated R_c values are displayed alongside the experimental R_c results. It may be inferred that the data in both models are in good agreement because the projected and experimental data plots match as a nearly straight line. Numerous research on rehydration have used the Peleg and Two-Term exponential models. Peleg's model has consistently offered the best agreement between experimental and predicted values of dried foods, including chestnuts [10], spinach [13], potato [30], and kiwi fruit [31].

Colour Analysis Results

Colour parameters "L", "a", "b" of rehydrated *Loligo vulgaris* dried by different methods are shown in Figure 4.

Table 1. Obtained model coefficients and statistical data

Method	Model	Parameter	60°C	70°C	80°C
IR	Peleg	a	0.9821	-0.0265	-0.0312
		k_1	21.767	20.965	17.912
		k_2	0.4178	0.3479	0.2946
		R^2	0.9942	0.9931	0.9931
		χ^2	0.0034	0.0055	0.0078
		RMSE	0.0462	0.0588	0.0697
IR	Two-Term Exponential	a	2.3135	3.0174	3.7129
		b	-0.0010	-0.0013	-0.0014
		c	-2.3190	-3.0252	-3.7208
		d	-0.0145	-0.0129	-0.0125
		R^2	0.9996	0.9995	0.9997
		χ^2	0.0002	0.0005	0.0005
		RMSE	0.0111	0.0152	0.0156
US-IR	Peleg	a	-0.0219	-0.0204	-0.0258
		k_1	28.344	22.607	18.983
		k_2	0.3627	0.3060	0.2687
		R^2	0.9951	0.9967	0.9960
		χ^2	0.0032	0.0031	0.0050
		RMSE	0.0449	0.0443	0.0561
US-IR	Two-Term Exponential	a	4.2974	3.1217	3.7625
		b	-0.0023	-0.0009	-0.0011
		c	-4.2973	-3.1199	-3.7622
		d	-0.0085	-0.0119	-0.0118
		R^2	0.9999	0.9998	0.9999
		χ^2	0.00004	0.0002	0.0001
		RMSE	0.0044	0.0104	0.0086
Method	Model	Parameter	140W	210W	350W
MW	Peleg	a	-0.0261	-0.0395	-0.0394
		k_1	12.7586	12.0610	9.8630
		k_2	0.2837	0.2227	0.2017
		R^2	0.9932	0.9927	0.9930
		χ^2	0.0092	0.0150	0.0182
		RMSE	0.0757	0.0968	0.1068
MW	Two-Term Exponential	a	3.0681	4.4456	4.6089
		b	-0.0004	-0.0010	-0.0007
		c	-3.0784	-4.4574	-4.6203
		d	-0.0189	-0.0146	-0.0166
		R^2	0.9992	0.9995	0.9996
		χ^2	0.0013	0.0014	0.0014
		RMSE	0.0254	0.0260	0.0265

Colour values of fresh *Loligo vulgaris* are; “L” is 35.93, “a” is -6.56 and “b” is -7.13. As seen that all three colour parameters are increased after the drying and rehydration process.

As seen in Figure 4, the highest “L” values, which represents the lightness value (100 = white), are found in MW dried than rehydrated *Loligo vulgaris*. This situation can be explained with the drying times. As the drying time increases darker samples are obtained. So as the drying times decreased “L” is increased. For the comparison of IR and US-IR, IR had “L” values higher than US-IR. In

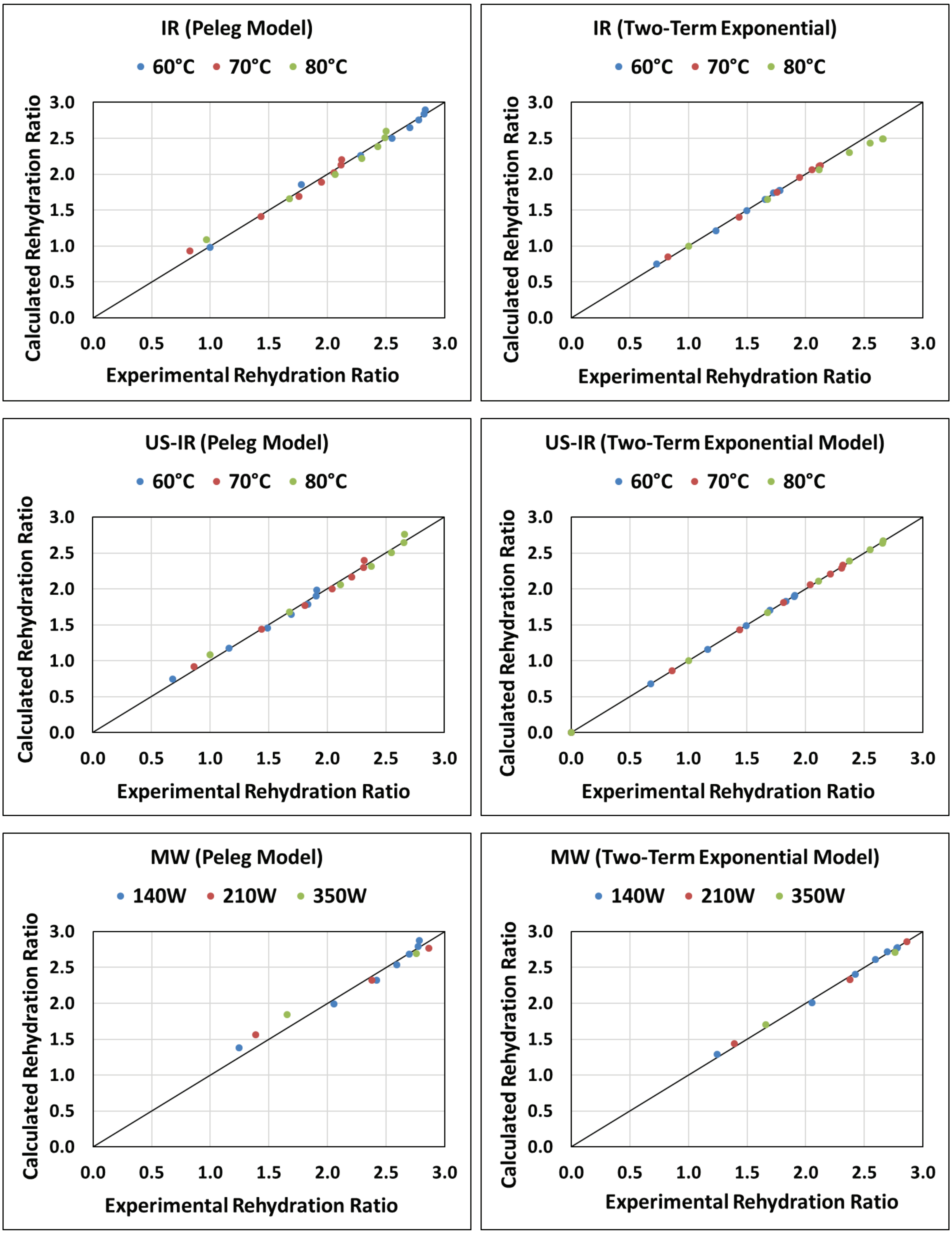

Figure 3. Experimental vs calculated R_R values obtained from the mathematical models.

comparison with the drying times, in the US pre-treatment process, *Loligo vulgaris* have taken some moisture and the drying times were last longer than the unpretreated process.

For the comparison of "a" values, which represents the redness value for positive integers, as expected like in "L" values, as the drying times increased redder coloured *Loligo vulgaris* were obtained. Hence higher values of "a" was obtained at US-IR than unpretreated IR. But in MW, the highest "a" values were obtained. This may happen due to the highest energy applied in MW than the other methods and samples could be partly cooked.

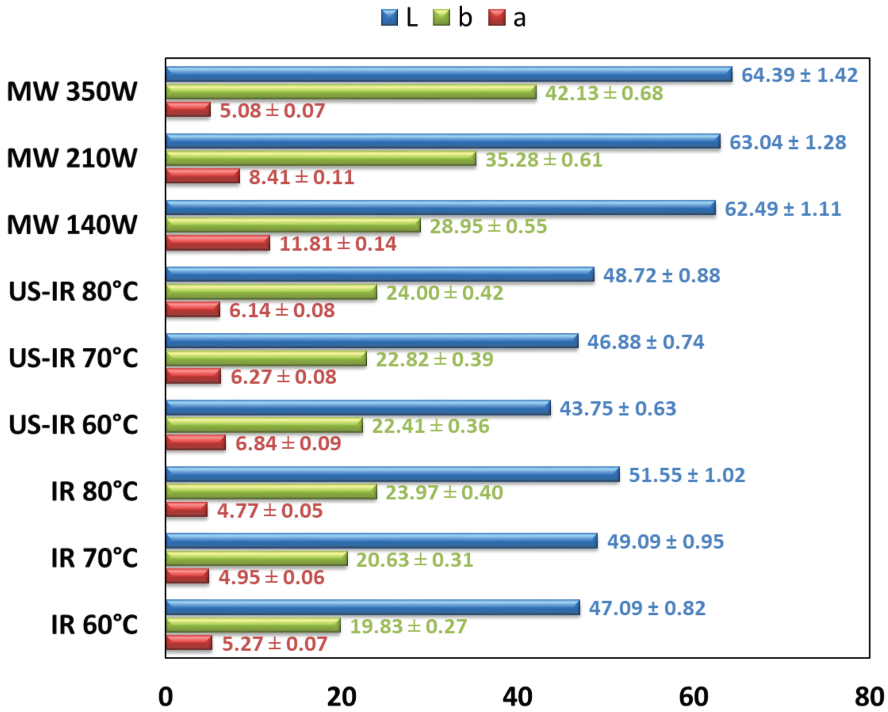

Figure 4. Colour values of the rehydrated *Loligo vulgaris*.

For the comparison of "b" values, which represents the yellowness value for positive integers, the highest values were obtained in MW dried and rehydrated samples. Than followed by US-IR and IR dried and rehydrated samples. Since "a" value and "b" value are inversely proportional obtained colour values are in mutual agreement [10].

CONCLUSION

In this study, the rehydration behaviour of thin-layer *Loligo vulgaris* samples dried by IR, US-IR, and MW at different temperatures and power levels were studied. Sample weights recorded at 30-minute intervals during the 180-minute rehydration procedures were used for kinetic investigations of the rehydration mechanism. According to the curves drawn from the rehydration data, the MW method gave the highest R_R and Rc values. Additionally, it was found that the values of R_R and Rc rose as the drying process's temperature and power level rises. Likewise, the MW method had the highest D_{eff} and it was found that US pre-treatment increased D_{eff} as it increased porosity. In the applied mathematical models, Peleg and Two-Term Exponential, showed both good overlaps with the data, while Two-Term Exponential model is found to be more compatible with higher R^2 values and lower RMSE and χ^2 values. In addition, the changes in colour values were determined as fresh and after rehydration to observe the physical changes during the process. When the color values were evaluated, it became clear that the MW samples' color parameters, particularly the brightness values, increased significantly more than those of the other samples. Overall analysis of the rehydration studies reveals that rehydration performance of the MW drying is more suitable in terms of the criteria being studied.

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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