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Drying kinetics, mathematical modeling and color analysis of *Solen marginatus*: A comparative study of oven, infrared, and microwave drying methods

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This study investigates the drying kinetics and mathematical modeling of *Solen marginatus*, commonly known as the grooved razor shell. *Solen marginatus* is dried using three different methods: oven drying (OD), infrared drying (IRD), and microwave drying (MWD), each at various temperatures and power levels. The effects of drying equipment, temperatures, and power levels on drying time, drying rate, effective moisture diffusivity, and activation energy are analyzed, with color analysis performed for each method. Fourteen well-known mathematical models are applied, and the three models with the highest coefficient of determination ($R^2 > 0.999$) are selected. Results indicate that drying time decreases with increasing temperature or power of the equipment. The effective moisture diffusivities range from $2.00 \times 10^{-10} – 3.53 \times 10^{-10}$ m^2/s in OD, $2.53 \times 10^{-10} – 6.02 \times 10^{-10}$ m^2/s in IRD, and $4.08 \times 10^{-9} – 9.34 \times 10^{-9}$ m^2/s in MWD. The activation energies for OD, IRD, and MWD are calculated as 27.83 kJ/mol, 42.35 kJ/mol, and 40.98 kJ/kg, respectively. In terms of color retention, IRD was found to be the most effective drying method followed by oven and then MWD.

Keywords*:* clam, drying kinetics, grooved razor shell, mathematical modeling, seafood

INTRODUCTION

Solen marginatus is a bivalve characterized by two long narrow shell valves open at both ends but connected by hinges. They can be found buried in sandy-muddy seashore areas since they can adapt greatly to tides and soft sediments [1, 2]. This species is distributed from Norway to the Mediterranean Sea and North Africa; it is the only species that belongs to *Solenidae* genus in Europe [3]. *Solen marginatus* has high importance in the crustacean industry. It is seen to be sold at high prices at the international market. Since it can be used for various foods, *Solen marginatus* has become one of the competitors among crustaceans [2].

Seafood is highly perishable due to its high water content and the presence of spoilage-causing microorganisms. The spoilage mechanisms in seafood can lead to changes in color, texture, odor, and taste, making it unsafe for consumption [4]. Drying processes are crucial for seafood preservation as they remove moisture, inhibiting the growth of spoilage microorganisms and preventing enzymatic reactions that lead to deterioration [5].

In recent years, there has been a surge in interest in utilizing advanced drying techniques for seafood processing. Various methods such as microwave, infrared, and oven drying have been investigated to improve the quality and efficiency of seafood drying processes [6]. Infrared drying, for example, has garnered attention for its ability to offer superior heating uniformity, leading to enhanced quality characteristics compared to traditional methods [7]. Additionally, combined infrared and convective drying methods have been recognized for their rapid and effective heat transfer, resulting in seafood products with improved organoleptic properties [8].

Similar to the increasing consumption rates, there are many seafood drying studies in the literature. In the recent past, studies on seafood such as sea cucumber [9, 10], calamari [11], squid [12], clam [13], crab [14], yellow croaker [15], grass carp [16], and sea bass [17] have been carried out using different drying equipment such as oven, hot-air, infra-red, microwave, and lyophilizator. Despite the studies conducted with many seafood products, there is a lack of literature on drying studies with *Solen marginatus*, which has found its place in many exclusive cuisines.

In this study, the drying performance of *Solen marginatus* at different temperatures was investigated to understand the oven, vacuum oven, and microwave drying kinetics. In order to better comprehend the drying mechanism of *Solen marginatus*, the compatibility with fourteen mathematical models was tested. In addition, the effective moisture diffusion coefficient was calculated and the effects of different methods and temperatures on color change were determined by color analysis.

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MATERIAL AND METHODS

Samples and equipment

Solen marginatus samples were obtained frozen from a local fish market in Enez, Edirne, Turkey, and were kept in a refrigerator (1050T model; Arcelik, Eskisehir, Turkey) at -18 °C until the experiments. Before drying, the samples were thawed at +4 °C and rinsed with deionized water to remove sand and other admixtures. The internal organs of the samples were cleaned, and the remaining excess water was gently drained. The samples prepared with a length of 9 ± 0.8 cm and a thickness of 0.3 ± 0.02 cm were transferred to the drying process (Figure 1).

Initial moisture percentages of the samples were removed by drying at 105 °C in a Nüve EV-18 (Nüve, Ankara, Turkey) oven for 3 h. Oven drying (OD) was carried out in the same model oven, infrared drying (IRD) was carried out in a MA 50.R model infrared moisture analyzer (Radwag Balances and Scales, Radom, Poland) and microwave drying (MWD) was completed in a home-type Delonghi MW205S model microwave (Delonghi, Treviso, Italy).

Drying experiments

OD and IRD temperatures were selected as 60, 70, and 80°C and the samples' weight was noted at intervals of 15 min for each temperature level. In the third method, MWD was used at 140, 210, and 350 W. The samples' weight was recorded for 140 W at intervals of 30 sec and for 210 and 350 W at intervals of 1 min. Drying proceeded until the moisture in the product decreased to 5%. The samples were cooled at room temperature when the drying was finished. Afterwards, dried samples, which are shown in Figure 1, were packed into polyethylene bags and were placed in a desiccator to keep safe from moisture.

Mathematical modeling of drying curves

In drying processes, a diffusion equation is commonly used to explain mass transfer phenomena. The diffusion coefficient in this equation, which is influenced by moisture content, is crucial for understanding the drying process and is typically determined through experiments. This coefficient can be obtained either by analyzing drying curves or by deriving it from experimental moisture concentration data collected during the drying process [18]. The moisture content and the moisture rate of *Solen marginatus* are calculated using Eqns. (1) and (2) [17].

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

$$MR = \frac{M_t - M_e}{M_i - M_e} \quad (2)$$

As M_e value is rather small compared to M_t and M_i, it is usually neglected in the calculations. Drying rate, which indicates the rate of moisture release from a material's surface, is a crucial parameter in drying processes. It can be mathematically expressed using Eqn (3) to quantify the rate of moisture removal over time [17, 19].

$$DR = \frac{M_{t+\Delta t} - M_t}{\Delta t} \quad (3)$$

Fick's second law of diffusion is commonly used to explain the moisture diffusion process during drying. Effective moisture diffusivity encompasses various mass transfer mechanisms within foods, including liquid diffusion, vapor diffusion, surface diffusion, capillary flow, and hydrodynamic flow. Understanding moisture diffusivity and its variations under different drying conditions is essential for optimizing drying processes and ensuring product quality [20]. Additionally, determining effective moisture diffusivity and activation energy aids in comprehending the drying behavior of specific products [21].

While different geometries require different calculations in the use of Fick's second law, *Solen marginatus* was used as a thin layer in the drying processes and the moisture amount was calculated with Eqn. (4) [17].

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

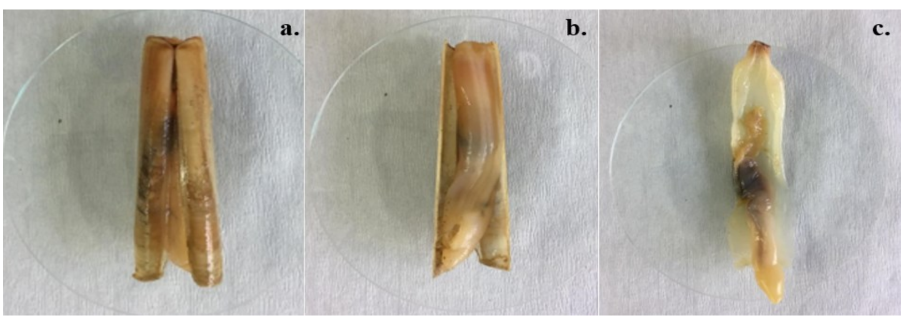


Fig. 1. Preparation of *Solen marginatus* sample for drying (a. shell view, b. meat view, c. meat view without the shell)

In the equation, t is the drying time in sec and L is the sample half-thickness in m. Since the initial terms have no bearing on the outcome, Eqn. (4) can be simplified to Eqn. (5). The slope of the graph ln(MR) *vs* t, which is created using the data collected during experiments, can be used to determine D_{eff} [17].

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

While oven and IR dryers are operated with a temperature parameter the MW is operated with a power parameter. Therefore, temperature-based (Eqn. 6) and power-based (Eqn. 7) Arrhenius equations were used when calculating E_a [17].

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{R(T+273.15)}\right) \quad (6)$$

$$D_{eff} = D_0 \exp\left(-\frac{E_a \times m}{P}\right) \quad (7)$$

Activation energy is determined *via* the slope (E_a /R) of the D_{eff} versus 1/T plot constructed from experimentally obtained data.

To find the most fitted model, coefficient of determination (R^2), root-mean-square error (RMSE) and reduced chi-square statistic (χ^2) values were calculated using Eqns. (8) - (10). Drying data were tested for Aghbashlo *et al.*, Alibas, Henderson *et al.*, Jena and Das, Lewis, Logarithmic, Midilli & Kucuk, Page, Parabolic, Peleg, Two-term exponential, Verma *et al.*, Wang *et al.* and Weibull models using nonlinear regression method in Statistica (Statistica, 2016) [22].

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{\sum_{i=1}^{n}\left(MR_{exp,i} - \left(\frac{1}{n}\right)MR_{exp,i}\right)^2} \quad (8)$$

$$RMSE = \left(\frac{1}{n}\sum_{i=1}^{n}\left(MR_{exp,i} - MR_{pre,i}\right)^2\right)^{1/2} \quad (9)$$

$$\chi^2 = \frac{\sum_{i=1}^{n}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{n-z} \quad (10)$$

The equations denote the following: n is the total number of experiments; z is the number of constants in the proposed model; MR_{exp} stands for the experimental moisture content values; and MR_{pre} stands for the predicted moisture content values.

R^2 values are intended to be near 1 when choosing the best model for the approaches. Conversely, it is anticipated that RMSE and χ^2 values will be near zero.

Color analysis

The color of food products is one of the first aspects noticed by consumers, influencing their initial perception and acceptance of the product [23]. The Hunter Lab color system is extensively used in the food industry for color analysis due to its effectiveness and prevalence. This system measures parameters such as L* (lightness/darkness), a* (redness/greenness), and b* (yellowness/blueness), providing a comprehensive assessment of color changes in food products [24]. Color analysis was performed by PCE-CSM1 colorimeter (PCE Instruments UK Ltd., Southampton Hampshire, United Kingdom). Color parameters of the samples were measured before and after the experiments for each method and equipment and total color change was calculated from Eqn. (11) [22].

$$\Delta E = \sqrt{(L_0 - L)^2 + (a_0 - a)^2 + (b_0 - b)^2} \quad (11)$$

RESULTS AND DISCUSSION

After conducting a moisture analysis to ascertain the overall moisture content, it was discovered that *Solen marginatus* had an initial moisture content of 77.42% on a wet basis. The samples were dried until their moisture level dropped to under 5%. Figure 2 depicts the appearance of *Solen marginatus* during sample preparation and drying.

The moisture content *vs.* time and drying rate *vs.* moisture content graphs shown in Figure 2 were created using the weighing data collected during drying. Looking at the plots in Figure 2, the drying rate increases with increasing temperature and power, as expected, and the drying times varied with the type of dryer. Drying took place for 255, 195 and 150 min at 60°C, 70°C and 80 °C for OD, 210, 135 and 90 min at 60°C, 70°C and 80 °C for IRD and 11, 7 and 5.5 min at 140, 210 and 350 W for MWD.

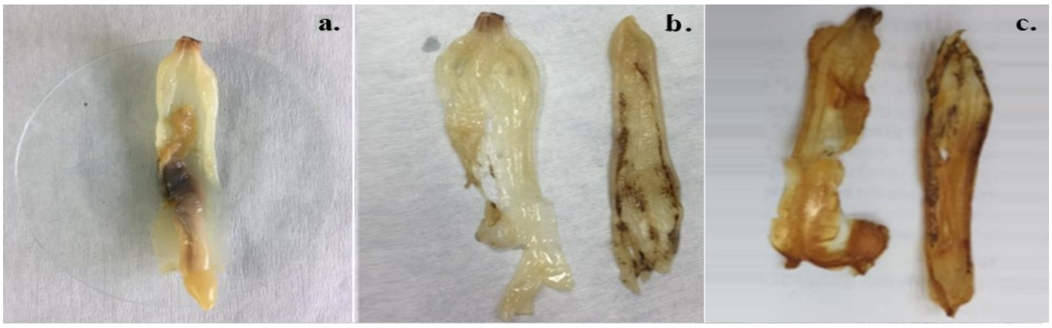


Fig. 2. *Solen marginatus* sample before and after drying (a. meat without the shell, b. cleaned meat, c. oven dried meat)

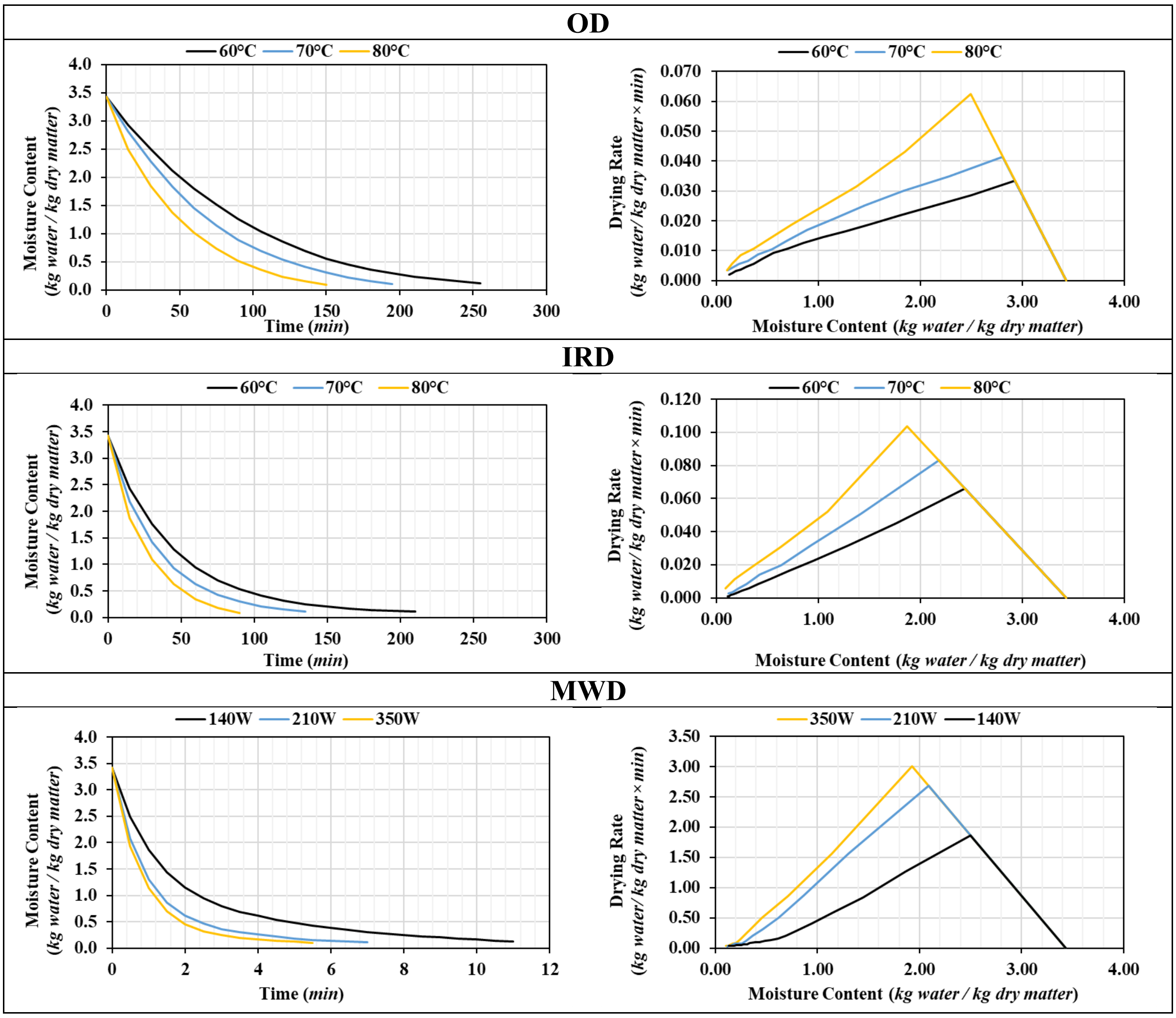


Fig. 3. Graphs of moisture content *vs*. time (left) and drying rate *vs*. moisture content (right)

It has been emphasized in the literature that practical drying of biological products mainly takes place in the falling rate period, as the conditions required for constant rate drying are rare [25]. In line with this, it can be seen that drying was carried out in the decreasing rate period for all temperatures and dryers. It can be seen that drying times are longer and final moisture contents are higher for OD compared to IRD and MWD. When evaluated on the basis of drying time, it can be interpreted that the OD process is comparatively inefficient. MWD is highlighted in the literature as the method with the shortest drying time among the drying methods in various food drying studies [26]. However, microwave drying can have limitations, such as non-uniform temperature distribution during heating, which can lead to uneven drying and potential hot and cold spots in the food being dried. This uneven energy distribution, which has also been reported in the literature, can lead to inconsistent drying results [27]. Moisture levels in the MWD samples decreased very rapidly to below 5%. Visual irregularities and regional burns were observed, particularly in the thicker regions of the samples.

The D_{eff} value was calculated based on the moisture ratios as 2.00×10^{-10}, 2.63×10^{-10}, and 3.53×10^{-10} m^2/s for OD at 60, 70 and 80°C, respectively; for IRD, 2.53×10^{-10}, 3.78×10^{-10}, and 6.02×10^{-10} m^2/s at 60, 70 and 80°C, respectively; and for MWD, 4.08×10^{-9}, 6.92×10^{-9}, and 9.34×10^{-9} m^2/s at 140, 210 and 350 W, respectively. All values obtained were found to be within the D_{eff} values given in the studies for food drying processes ($10^{-12} – 10^{-8}$ m^2/s) [28]. A dried product with a high D_{eff} indicates that the product has a greater capacity for moisture to move within its structure during the drying process [29]. It was observed that the MWD D_{eff} values were much higher compared to OD and ID due to the rapid drying.

Activation energy is a critical parameter that represents the minimum energy required to initiate the mass transfer process from the interior to the surface of the food product during drying [30].

Table 1. Modeling coefficients and statistical data of OD, IRD and MWD (avg. R^2>0.999)

Model	Parameter	OD			IRD			MWD		
		60°C	70°C	80°C	60°C	70°C	80°C	140W	210W	350W
Alibas	a	1.675636	1.106938	1.328243	0.974354	0.970026	1.207561	0.818547	0.889379	0.931961
	k	0.007328	0.010642	0.020878	0.025420	0.033665	0.047415	0.775551	1.141618	1.238055
	n	0.989727	1.045495	0.914718	0.970261	0.972430	0.868411	0.950897	0.998244	0.981440
	b	0.001680	0.000317	0.001228	-0.000018	-0.000098	0.001336	0.013627	-0.011472	-0.006927
	g	-0.676093	-0.107560	-0.328118	0.025619	0.030005	-0.207549	0.182643	0.110846	0.067924
	R^2	0.999977	0.999981	0.999991	0.999997	0.999991	0.999998	0.999832	0.999966	0.999981
	χ^2	0.000003	0.000003	0.000001	0.000001	0.000002	0.000001	0.000012	0.000003	0.000003
	RMSE	0.001387	0.001287	0.000871	0.000412	0.000877	0.000432	0.003086	0.001506	0.001215
Aghbashlo et al.	k_1	0.010182	0.013172	0.019898	0.023477	0.030986	0.039475	0.686019	1.136747	1.281111
	k_2	-0.000970	-0.001239	-0.000688	0.001652	0.001682	0.000577	0.138150	0.181083	0.158655
	R^2	0.999923	0.999972	0.999573	0.999889	0.999982	0.999635	0.999358	0.999486	0.999510
	χ^2	0.000007	0.000003	0.000047	0.000010	0.000002	0.000054	0.000040	0.000040	0.000046
	RMSE	0.002553	0.001554	0.006199	0.002925	0.001267	0.006191	0.006036	0.005924	0.006197
Midilli & Kucuk	a	0.994935	0.998520	0.999206	1.000402	1.000193	0.999859	1.007722	1.002614	1.000736
	k	0.007669	0.010541	0.022528	0.025986	0.034121	0.048995	0.624669	0.958846	1.110145
	n	1.080425	1.070695	0.967975	0.955883	0.958094	0.922522	0.773483	0.862966	0.909740
	b	-0.000063	-0.000097	-0.000212	0.000096	0.000094	-0.000222	0.002975	0.005524	0.005939
	R^2	0.999782	0.999968	0.999929	0.999988	0.999986	0.999972	0.997977	0.999023	0.999765
	χ^2	0.000024	0.000004	0.000010	0.000001	0.000002	0.000007	0.000139	0.000091	0.000028
	RMSE	0.004296	0.001669	0.002517	0.000947	0.001108	0.001716	0.010715	0.008172	0.004290

Activation energy values for drying food can be given in different ranges in the literature. E_a values calculated based on the Arrhenius equation were found to be 27.83 kJ/mol, 42.35 kJ/mol, and 40.98 kJ/kg for OD, IR and MWD, respectively, and OD and IRD E_a values were found in the range of 14.42 to 43.26 kJ/mol reported in the literature [31].

Statistical constants and coefficients calculated for the 3 models that show the highest compatibility with all drying systems among the 14 tested models are given in Table 1. According to the evaluations, the best fit was obtained in the Alibas model for OD, IRD and MWD with R^2 values between 0.999977 – 0.999991, 0.999991 – 0.999998, and 0.999832 – 0.999981, respectively; χ^2 values between 0.000001 – 0.000003, 0.000001 – 0.000002, and 0.000003 – 0.000012, respectively; RMSE values between 0.000871 – 0.001387, 0.000412 – 0.000877, and 0.001215 – 0.003086, respectively. Following Alibas, Aghbashlo *et al*. model was the second most suitable for OD, IRD and MWD with R^2 values between 0.999573 – 0.999972, 0.999635 – 0.999982, and 0.999358 – 0.999510, respectively; χ^2 values between 0.000003 – 0.000047, 0.000002 – 0.000054, and 0.000040 – 0.000046, respectively; RMSE values between 0.001554 – 0.006199, 0.001267 – 0.006191, and 0.005924 – 0.006197, respectively. The Midilli & Kucuk model was the third most compatible model for OD, IRD and MWD with R^2 values between 0.999782 – 0.999968, 0.999972 – 0.999988, and 0.997977 – 0.999765, respectively; χ^2 values between 0.000004 – 0.000024, 0.000001 – 0.000007, and 0.000028 – 0.000139, respectively; RMSE values between 0.001669 – 0.004296, 0.000947 – 0.001716, and 0.004290 – 0.010715, respectively.

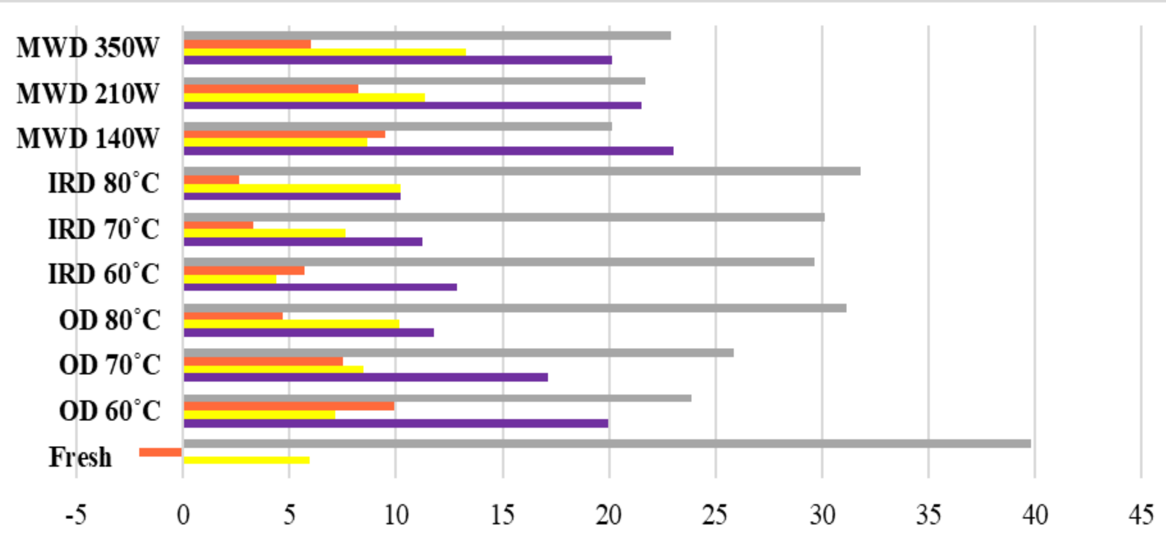
Color analysis results

It was noted that one of the main evaluation criteria for the customer regarding drying is the color change. For this reason, it is expected that the ΔE values will be as minimal as possible. Looking at the

L* values in Figure 4, it can be seen that the darkness of the dried material is highest at the lowest temperature/power for each equipment. This is because the drying time increases at the lowest drying temperature or power. Similarly, it is observed that a* values decrease with increasing drying time in OD and IRD. However, it is seen that the a* values are higher than expected due to regional burning caused by sudden drying in MWD samples. b* values exhibited an inversely proportional distribution with a* values and increased with the increase in drying time. When ΔE values are analyzed it is seen that the highest values are obtained with MWD. It was interpreted that this situation was directly related to regional burns caused by sudden drying. After MWD, it was interpreted that the reason for the high ΔE values in the OD samples was the long drying time. When all the data were compared, it was found that IRD samples gave the most efficient results in terms of ΔE.

CONCLUSION

This study investigated the drying behavior of *Solen marginatus* by oven, infrared and microwave irradiation at different temperatures and power levels. Drying data were tested using fourteen common models and total color changes were determined by color analysis. At the end of drying, it was found that oven drying caused color changes in the samples due to the long drying time and the high final moisture content. On the other hand, microwave drying was very fast, the final moisture content decreased rapidly and burnt areas appeared in the samples. Due to the local burning, the final product quality decreased and the color change was reached at the highest value. The drying time of the infrared samples was shorter than that of the oven samples. When color change values were examined, this dryer gave the best color retention. Of the mathematical models studied, the Alibas model gave the best fit for all dryers.



	Fresh	OD 60°C	OD 70°C	OD 80°C	IRD 60°C	IRD 70°C	IRD 80°C	MWD 140W	MWD 210W	MWD 350W
L	39.81	23.88	25.87	31.12	29.64	30.09	31.82	20.11	21.70	22.90
a	-2.03	9.93	7.54	4.67	5.71	3.30	2.63	9.53	8.25	6.01
b	5.93	7.17	8.50	10.18	4.36	7.62	10.22	8.66	11.38	13.28
ΔE	0	19.96	17.10	11.77	12.88	11.21	10.19	23.00	21.53	20.12

Fig. 4. Color values of *Solen marginatus*

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