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Microwave Drying Kinetics of Osmotically Dehydrated Bonito Fish (*Sarda sarda*)

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Abstract

In this study, the microwave drying characteristics of osmotically dehydrated bonito fish was investigated at three different microwave powers: 90, 180, and 360 W. The total drying times were found to be 11.25, 6.5, and 1.75 min for 90, 180, and 360 W, respectively. Drying occurred entirely in the falling-rate period, indicating that internal moisture diffusion was the main mechanism governing the drying process. The effective moisture diffusivity (D_{eff}), calculated using Fick's second law and determined as 3.349×10^{-8} m²/s, 6.409×10^{-8} m²/s, and 2.418×10^{-7} m²/s for 90, 180, and 360 W, respectively, showing a clear increase with microwave power. The activation energy was calculated as 19.6 W/g. Experimental data were fitted to six drying models. The Midilli et al. model provided the best fit to the experimental data at all microwave power levels according to the coefficient of determination (R^2), chi-square (χ^2), and root mean square error (RMSE) values.

***Keywords*:** bonito, drying, fish, microwave, kinetics.

1. Introduction

Fish is highly susceptible to microbial and enzymatic spoilage due to its high moisture and unsaturated fat content. In order to prevent spoilage, appropriate storage conditions must be provided. The main preservation methods used to slow down the spoilage process of fish, enable long-term storage, and extend shelf life are; chilling, freezing, salting, drying, smoking, canning, marination, and surimi technology [1, 2].

Drying is the removal of moisture from food materials. Thus, by reducing the moisture level in food, it is lowered to a level that prevents microbial growth. With these properties, drying is one of the simple and common preservation methods for various products. Drying is affected by many factors such as temperature, drying air velocity, drying surface area, the moisture content of the environment and the sample, and ambient pressure. During drying, chemical changes such as browning reactions and lipid oxidation; physical changes such as rehydration, shrinkage, and crust formation; and losses in nutritional value may occur in foods. These changes vary depending on the food material being dried, the drying method, and the determined drying conditions [3].

The preservation of foods by drying is one of the oldest methods known and has been practiced since ancient times. Sun drying is one of the oldest known drying methods for food preservation. Although sun drying is a low-cost method, it has been replaced by technological methods due to disadvantages such as exposure to environmental contaminants like dust and dirt, difficulty to reduce the moisture content to the desired level, and long drying times. These technological methods include convective hot air drying, fluidized bed drying, freeze drying, vacuum drying, spray drying, infrared drying, and microwave drying [4].

Compared with conventional drying methods, microwave drying provides several

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advantages such as low energy requirement, high energy efficiency, and short drying time. In contrast, conventional drying methods may lead to undesirable quality changes in foods such as, textural deterioration, loss of flavor and aroma, and reduction in nutritional value, due to the long drying time and high drying temperature required [5].

Mathematical methods developed to predict the behavior of a system are referred as kinetic modeling. The extent to which a developed model reflects reality is determined by comparing the experimental results with the model predictions. Kinetic models explaining drying behavior are used in many areas such as explaining the drying behavior of foods, understanding moisture transfer mechanisms, determining the effects of pre-treatments on drying, dryer design, and optimization of drying parameters [6].

Microwave drying has been applied to various fish and aquatic products in previous studies. Sardine fish was dried using microwave heating at various power levels and its drying characteristics were modeled using empirical thin-layer models [7]. Jaya fish was dried at different microwave power levels and its drying kinetics were modeled using thin-layer mathematical models [8]. Rainbow trout fillets were subjected to microwave and infrared drying to evaluate drying behavior and quality changes [9]. Seafood products; *Mytilus chilensis* and *Dosidicus gigas* were dried using the microwave method to investigate drying kinetics, energy performance, and moisture diffusivity [9]. Microwave drying of mussels (*Mytilus edulis*) was also examined at different power levels to determine drying time, effective diffusivity, and energy consumption [10]. In addition, more advanced microwave-based techniques such as intermittent microwave convective drying have been investigated for fish drying to evaluate drying efficiency and quality attributes under modified microwave application strategies [11].

Although several studies have investigated microwave drying of fish products, limited information is available on the drying kinetics and effective moisture diffusivity of osmotically dehydrated bonito fish under different microwave power levels. Therefore, this study aims to investigate the microwave drying behavior of osmotically dehydrated bonito at different power levels, determine the effective moisture diffusivity and activation energy, and evaluate the suitability of various thin-layer drying models.

2. Materials and method

2.1. Sample preparation and microwave drying

Fresh bonito fish (*Sarda sarda*) were obtained from local market in Konya, Türkiye. According to the traceability label information, the bonito fish was harvested from the Black Sea and subjected to analysis within three days of capture. Fish were first cut into skin-on fillets and then sliced into pieces with a thickness of 1 ± 0.2 cm and a weight of 10 ± 0.5 g each. For osmatic dehydration, fish slices were uniformly covered with salt for 1 hour. After 1 hour excess salt was carefully removed. The initial moisture content of the dehydrated fish samples was determined by drying the samples in a hot-air oven at 105°C until a constant weight was obtained [12].

The osmotically dehydrated samples were dried in a microwave oven (Bosch HMT84G451, Germany) at power levels of 90, 180, and 360W. The weights of the samples were measured at intervals of 60s, 45s, and 30s, respectively, using a precision balance (OHAUS PA224C). For each microwave power level, drying was performed three times, and the procedure was continued until the moisture content reached below 0.1 g water/g dry matter.

Table 1. Mathematical models applied to the drying curves

Model name	Equation	Reference
Midilli	$MR = a*(-kt^n) + bt$	[13]
Page	$MR = exp(-kt^n)$	[14]
Henderson and Pabis	$MR = a * exp(-kt)$	[15]
Logarithmic	$MR = a * exp(-kt) + b$	[16]
Aghbashlo	$MR = exp(-(k t^n) + bt)$	[17]
Wang and Sing	$MR = 1 + at + bt^2$	[18]

a,b,c,k,n: Model constants, *MR*: Moisture ratio, *t*: Drying time

2.2. Mathematical modeling of drying curves

The moisture content, moisture ratio, and drying rate of the samples were calculated using the following equations[19]:

$$M = \frac{M_w}{M_d} \quad (1)$$

M: moisture content (kg water / kg dry matter)
M_w: amount of moisture present in the sample (kg)
M_d: amount of dry matter present in the sample (kg)

$$MR = \frac{M}{Mo} \quad (2)$$

MR: moisture ratio
M: moisture content of the sample at any given time (g water/g dry matter)
M_o: initial moisture content of the sample before drying (g water/g dry matter)

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

DR: drying rate (kg water / kg dry matter*min)
M_t: moisture content at time t (kg water/kg dry matter)
M_{t+dt}: moisture content at time $t+dt$ (kg water/kg dry matter)

During drying, the removal of moisture from the food results in a mass transfer process. The effective diffusion coefficient is used to describe this mass transfer. The effective diffusion coefficient is calculated as shown in Equation 4 by simplifying Fick's second law of diffusion. Here, L represents the half thickness of the sample (cm).

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

When the natural logarithm of the experimental MR values is plotted as a function of drying time, a linear relationship is obtained, and the slope of this line represents the effective diffusion coefficient.

$$Slope = -\frac{(\pi^2 D_{eff})}{(4 L^2)} \quad (5)$$

The activation energy was calculated using the equation obtained by modifying the Arrhenius equation for microwave drying.

$$D_{eff} = D_0 \exp\left[-\frac{(E_a m)}{P}\right] \quad (6)$$

2.3. Statistical Analysis

Thin-layer drying models were fitted to the experimental moisture ratio data using nonlinear regression analysis implemented in Python (SciPy library, version 1.16.3). The goodness of fit was evaluated using the coefficient of determination (R^2), reduced chi-square (χ^2), and root mean square error (RMSE).

In order to determine the model that best describes the drying behavior, the coefficient of determination (R^2), chi-square value, and root mean square error (RMSE) were calculated using the equations given below. A high R^2 value and low chi-square and RMSE values indicate a good fit of the model to the drying data. [20].

$$R^2 = 1 - \left[\frac{\left(\Sigma_{\{i=1\}}^{\{N\}}\left(MR_{\{experimental\}} - MR_{\{predicted\}}\right)^2\right)}{\left(\Sigma_{\{i=1\}}^{\{N\}}\left(MR_{\{experimental\}} - MR_{(experimental)}\right)^2\right)}\right] \quad (7)$$

$$RMSE = \sqrt{\frac{1}{N} * \Sigma_{\{i=1\}}^{\{N\}}\left(MR_{\{predicted\}} - MR_{\{experimental\}}\right)^2} \quad (8)$$

$$\chi^2 = \left[\frac{\left(\Sigma_{\{i=1\}}^{\{N\}}\left(MR_{\{experimental\}} - MR_{\{predicted\}}\right)^2\right)}{(N - n)}\right] \quad (9)$$

3. Results and Discussion

3.1. Drying curves

The variation of moisture content as a function of drying time at different microwave power levels is shown in Figure 1. The initial moisture content of osmotically dehydrated bonito fish (*Sarda sarda*) was determined as 1.07 kg water/kg dry matter. An increase in microwave power resulted in a reduction in drying time. The total drying times for samples dried at 90 W, 180 W, and 360 W were 11.25 min, 6.5 min, and 1.75 min, respectively. Similar results have been found in the literature with microwave-drying of sardine fish and rainbow trout [7, 21, 22].

The variation of drying rate as a function of moisture content at different microwave power levels is shown in Figure 2. For all microwave powers, the drying process occurred entirely within the falling-rate period. No constant-rate drying stage was observed. At the beginning of the drying, the drying rate values were found relatively high at particularly at higher

microwave powers. The highest drying rate was obtained at 360 W, followed by 180 W and 90 W. As the moisture content decreased, the drying rate progressively declined for all power levels.

The reduction in drying rate with decreasing moisture content indicates that internal moisture diffusion controlled the drying mechanism. At higher moisture contents, moisture migration was faster due to the stronger internal vapor pressure gradients generated by microwave heating. However, as drying progressed and moisture content decreased, the available free water diminished, resulting in a gradual reduction in the drying rate.

Moreover, increasing microwave power significantly enhanced the drying rate throughout the process. The higher drying rates observed at 360 W can be attributed to increased internal heat generation and accelerated moisture movement within the sample structure.

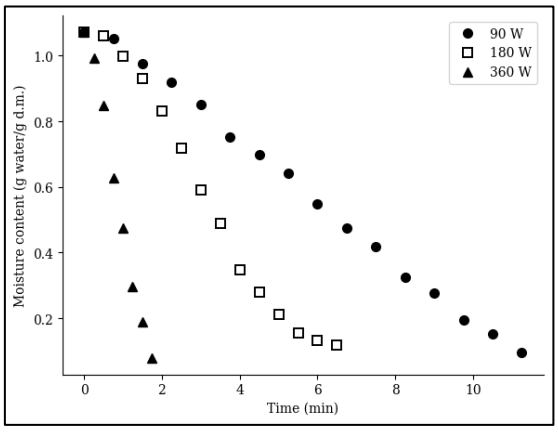

Figure 1. - Drying curves of *Sarda Sarda* slices at different microwave power levels

3.3. Effective Moisture Diffusivity and Activation Energy

To determine the effective moisture diffusivity, the natural logarithm of the moisture ratio (ln(*MR*)) was plotted against drying time (Figure 3). The effective diffusion coefficient is calculated from the slope of this graph as given in Equation 5. Accordingly, the effective moisture diffusivity values were found; 3.349×0^{-8} m²/s for samples dried at 90 W, 6.409×10^{-8} m²/s at 180 W, and 2.418×10^{-7} m²/s at 360 W.

The effective moisture diffusivity increased as microwave power increased (Figure 4). Higher microwave power causes a faster rise in the internal temperature of the sample. This leads to an increase in vapor pressure inside the material and accelerates moisture movement. As a result, the diffusion rate becomes higher at higher microwave powers. Similar findings have been reported in previous studies on fish and other aquatic products, where increasing microwave power resulted in higher effective moisture diffusivity [14-17].

Activation energy is an indicator of the minimum amount of energy required for moisture to be removed from the sample during drying. Activation energy values are obtained from the slope of the graph of the natural logarithm of the effective diffusion coefficient ($\ln(D_{eff})$) versus m/P (sample mass/microwave power), as shown in Figure 5. Accordingly, the activation energy (E_a) for microwave dried fish samples was calculated as 19.6 W/g.

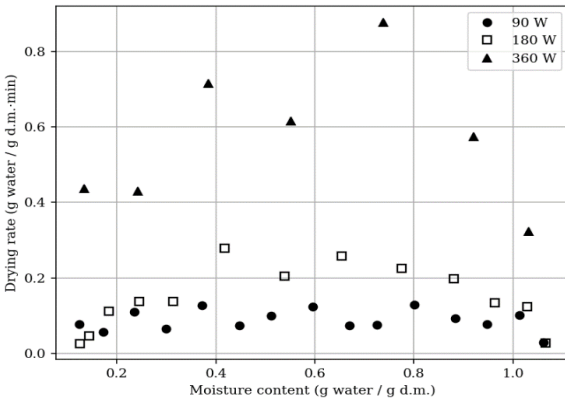

Figure 2. – Drying rate curves of *Sarda Sarda* slices at different microwave power levels

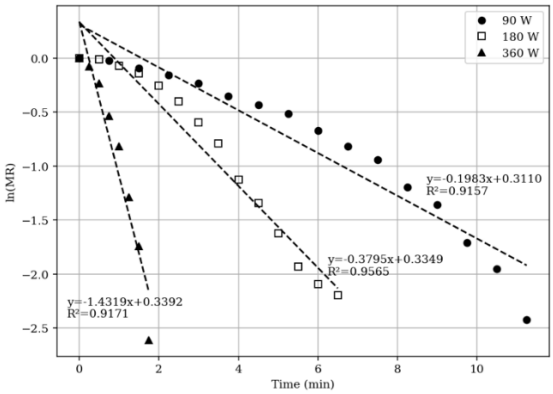

Figure 3. – Variation in ln(*MR*) and drying time for samples dried at different microwave power

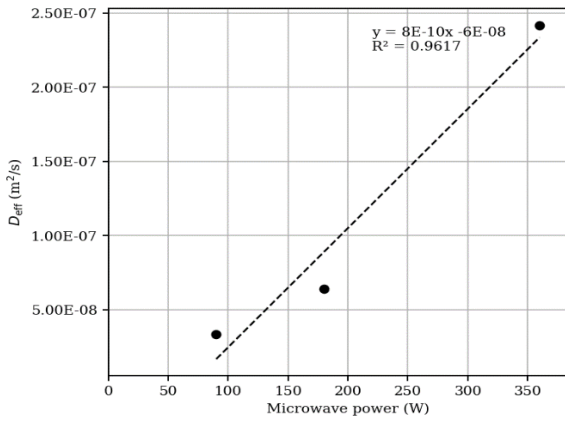

Figure 4. - Variation of effective moisture diffusivity and microwave power

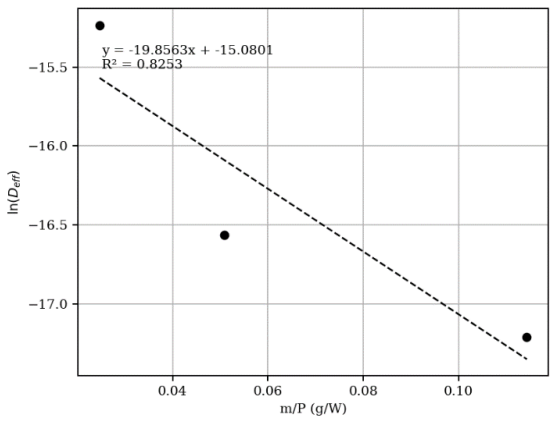

Figure 5. Arrhenius type relationship between effective moisture diffusivity and microwave power

Table 2. Results of statistical analysis with different models

Model	P (W)	Model constants	R^2	χ^2	RMSE
Henderson&	90	a = 1.11861, k = 0.14587	0,9455	0,00547	0,06920
Pabis	180	a = 1.15674, k = 0.284146	0,9306	0,00871	0,08639
	360	a = 1.10634, k = 0.989831	0,9346	0,00931	0,08358
Page	90	k = 0.033074, n = 1.70419	0,9950	0,0005	0,02100
	180	k = 0.0704299, n = 1.93679	0,9976	0,0003	0,01604
	360	k = 0.856657, n = 1.82277	0,9986	0,00019	0,01207
Wang and Singh	90	a = -0.0746874, b = -0.000783899	0,9957	0,00043	0,01935
	180	a = -0.145928, b = -0.000686389	0,9680	0,00402	0,05868
	360	a = -0.524902, b = -0.0133675	0,9879	0,00173	0,03600
Logarithmic	90	a = 126.587, k = 0.000679243, c = -125.554	0,9974	0,00028	0,01507
	180	a = 3.27738, k = 0.0591249, c = -2.19529	0,9776	0,00307	0,04908
	360	a = 7.43125, k = 0.0820593, c = -6.39057	0,9907	0,00159	0,03154
Midilli et al.	90	a = 1.00577, k = 0.0330252, n = 1.45583, b = -0.0216646	0,9990	0,00012	0,00946
	180	a = 0.9922, k = 0.0624978, n = 2.13628, b = 0.011059	0,9994	0,00009	0,00801
	360	a = 1.00128, k = 0.775962, n = 1.73517, b = -0.0290607	0,9991	0,00019	0,00968
Aghbashlo	90	k = 0.00194841, n = 2.75644, b = -0.0647532	0,9981	0,00021	0,01301
	180	k = 0.115921, n = 1.72816, b = 0.0579186	0,9980	0,00028	0,01484
	360	k = 0.700407, n = 2.0231, b = -0.146141	0,9988	0,00020	0,01122

3.3. Evaluation of the Models

Thin-layer drying models were applied to describe the drying behavior of bonito samples under different microwave power levels (90, 180, and 360 W). The goodness-of-fit of the models was evaluated using the coefficient of determination (R^2), chi-square (χ^2), and root mean square error (RMSE).

The goodness-of-fit parameters (R^2, χ^2, and RMSE) along with the estimated model coefficients for the six drying models are given in Table 2. Among the tested models, the Midilli et al. model provided the best fit for all microwave power levels, showing the

highest R^2 values and the lowest χ^2 and RMSE values.

The R^2 values for the Midilli et al. model were above 0.99 for all microwave powers, indicating excellent agreement between experimental and predicted moisture ratio data.

The Aghbashlo and Page models also showed high predictive capability, with R^2 values close to those of the Midilli et al. model. However, simpler models such as Lewis and Verma exhibited lower R^2 values and higher error parameters, suggesting limited ability to accurately describe the drying kinetics under microwave conditions.

Overall, the results indicate that multi-parameter models, particularly the Midilli et al. model, are more suitable for describing the microwave drying behavior of osmotically dehydrated bonito fish samples.

Previous studies have similarly reported that the Midilli et al. the model best describes the microwave drying behavior of fish products. In sardine fish [7], Jaya fish [8], and osmotically pretreated freshwater sea bream [23], the Midilli et al. model was identified as the most suitable model for explaining the drying kinetics.

4. Conclusion

In this study, the microwave drying behavior of osmotically dehyrated bonito fish was investigated at three different microwave power levels (90, 180, and 360 W). As expected, increasing microwave power significantly shortened the drying time. The total drying time decreased from 11.25 min at 90 W to 1.75 min at 360 W, clearly showing the strong effect of microwave intensity on moisture removal. The drying process occurred entirely in the falling-rate period, indicating that internal moisture diffusion was the dominant mechanism controlling drying.

The effective moisture diffusivity increased with increasing microwave power, confirming that higher energy input enhanced internal heat and mass transfer within the samples. The calculated activation energy value also demonstrated the sensitivity of the diffusion process to microwave power. The experimental drying data were successfully described using thin-layer drying models, and among the evaluated models, the Midilli et al. model provided the best fit at all microwave power levels according to the statistical criteria.

Overall, the findings of this study show that microwave power is a critical parameter in determining drying kinetics and moisture transfer behavior during microwave drying of bonito fish. These results may contribute to better understanding and optimization of microwave drying processes for fish products.

Conflicts of interest / Competing interests: No conflict of interest

Ethics approval: No ethic situation.

Availability of data and material: The data have been reviewed depending on the literature.

References

1. Shahriar, M.F.; Joardder, M.U.H.; Karim, A., Recent trends and future potential of microwave-assisted fish drying, *Drying Technology* **2022**, 40(16), 3389–3401, doi:10.1080/07373937.2022.2072316
2. Mahmud, A.; Abraha, B.; Samuel, M.; Mohammedidris, H.; Abraham, W.; Mahmud, E., Fish preservation: a multi-dimensional approach, *MOJ Food Processing & Technology* **2018**, 6(3), doi:10.15406/MOJFPT.2018.06.00180
3. Mujumdar, A.S., Drying Technology in Agriculture and Food Science, *Drying Technology* **2001**, 19(6), 1217–1218, doi:10.1081/DRT-100104817
4. Indiarto, R.; Asyifaa, A.H.; Adiningsih, F.C.A.; Aulia, G.A.; Achmad, S.R., Conventional and advanced food-drying technology: a current review, *International Journal of Scientific & Technology Research* **2021**, 10(1), 99–107.
5. Microwave drying of fruits and vegetables, *Stewart Postharvest Review* **2006**, 2(6), 1–7, doi:10.2212/SPR.2006.6.4
6. Amer, B.M.A.; Azam, M.M.; Saad, A.G., Monitoring temperature profile and drying kinetics of thin-layer banana slices under controlled forced convection conditions, *Processes* **2023**, 11(6), 1771, doi:10.3390/pr11061771
7. Darvishi, H.; Azadbakht, M.; Rezaeiasl, A.; Farhang, A., Drying characteristics of sardine fish dried with microwave heating, *Journal of the Saudi Society of Agricultural Sciences* **2013**, 12(2), 121–127, doi:10.1016/j.jssas.2012.09.002
8. Ghimire, A.; Basnet, S.; Poudel, R.; Ghimire, A., Mathematical modeling of thin layer microwave drying of Jaya fish (Aspidoparia jaya), *Food Science and Technology*

International **2021**, 27(6), 508–516, doi:10.1177/1082013220969353
9. Kouhila, M.; Moussaoui, H.; Bahammou, Y.; Tagnamas, Z.; Lamsyehe, H.; Lamharrar, A.; Idlimam, A., Exploring drying kinetics and energy exergy performance of Mytilus chilensis and Dosidicus gigas undergoing microwave treatment, *Heat and Mass Transfer* **2020**, 56(11), 2985–2999, doi:10.1007/s00231-020-02909-7
10. Kipcak, A.S., Microwave drying kinetics of mussels (Mytilus edulis), *Research on Chemical Intermediates* **2017**, 43(3), 1429–1445, doi:10.1007/s11164-016-2707-4
11. Joardder, M.U.H.; Parvej, A.M.; Shahriar, M.F.; Faysal, M.F.; Rahman, M.M.; Karim, A., Enhancing fish drying efficiency and quality: A comparative study of intermittent microwave convective drying (IMCD) and conventional methods, *Future Foods* **2025**, 12, 100717, doi:10.1016/j.fufo.2025.100717
12. AOAC, Official Methods of Analysis, Association of Analytical Chemists, Washington DC **2003**.
13. Midilli, A.; Kucuk, H.; Yapar, Z., A new model for single-layer drying, *Drying Technology* **2002**, 20(7), 1503–1513, doi:10.1081/DRT-120005864
14. Page, G.E., Factors influencing the maximum rates of air drying shelled corn in thin layers, Purdue University **1949**.
15. Doymaz, I., The kinetics of forced convective air-drying of pumpkin slices, *Journal of Food Engineering* **2007**, 79(1), 243–248, doi:10.1016/j.jfoodeng.2006.01.049
16. Yaldiz, O.; Ertekin, C., Thin layer solar drying of some vegetables, *Drying Technology* **2001**, 19(3–4), 583–597, doi:10.1081/DRT-100103936
17. Aghbashlo, M.; Kianmehr, M.; Khani, S.; Ghasemi, M., Mathematical modelling of thin-layer drying of carrot, *International Agrophysics* **2009**, 23, 313–317.
18. Wang, G.Y.; Singh, R., Single layer drying equation for rough rice, ASAE **1978**.
19. Inyang, U.E.; Oboh, I.O.; Etuk, B.R., Kinetic models for drying techniques—food materials, *Advances in Chemical Engineering and Science* **2018**, 8(2), 27–48, doi:10.4236/aces.2018.82003
20. Pandey, S.K.; Diwan, S.; Soni, R., Review of mathematical modeling of thin layer drying process, *International Journal of Current Engineering and Scientific Research* **2015**, 2(11).
21. Ismail, O.; Kocabay, O.G., Infrared and microwave drying of rainbow trout: Drying kinetics and modelling, *Turkish Journal of Fisheries and Aquatic Sciences* **2018**, 18(2), 259–266, doi:10.4194/1303-2712-v18_2_05
22. Kipcak, A.S.; Ismail, O., Microwave drying of fish, chicken and beef samples, *Journal of Food Science and Technology* **2021**, 58(1), 281–291, doi:10.1007/s13197-020-04540-0
23. Bing, L.; Chuan, L.; Zhen-hua, D.; Yan, L.; Qun, Y.; Shi-lin, R., Characteristics of osmotic-vacuum microwave drying of tilapia fillets and its drying kinetics, *Science and Technology of Food Industry* **2017**, (18), 30–35, doi:10.13386/J.ISSN1002-0306.2017.18.006