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Infrared and Microwave Drying of Rainbow Trout: Drying Kinetics and Modelling

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Abstract

Rainbow trout (*Oncorhynchus mykiss*) fillets were subjected to microwave and infrared drying. For microwave drying, four different microwave power levels of 90, 180, 270 and 360 W were used, while for infrared drying, three different infrared power levels of 83, 104 and 125 W were used. A comparison of the drying kinetics showed microwave drying to be more effective for shortening the drying time that was required to reach a certain moisture content when compared with infrared drying. For determination of drying kinetics of fish, the experimental data for moisture content changes with time were evaluated using various empirical drying models while the effective diffusion coefficient was evaluated using Fick's law of diffusion. The activation energy values of fish samples dried by microwave drying were relatively higher than those for infrared drying. The logarithmic model was found to be the most suitable in describing the drying characteristics of rainbow trout fillets. Kinetic parameters for the color change were determined using Hunter "L", "a", "b" values and total color difference values. "L" and "b" values increased and "a" value decreased after drying. The Hunter color parameters changed more with infrared drying.

Keywords: Infrared drying, microwave drying, rainbow trout, drying models, *Oncorhynchus mykiss*

Introduction

Fresh fish contains up to 80% water (Jain & Pathare, 2007). It is a highly perishable material and has a short storage life. Therefore, drying to a water activity unsuitable for bacterial reproduction and growth is the oldest fish handling method **(**Duan, Jiang, Wang, Yu, & Wang, 2011). Drying not only affects the water content of the product, but also alters other physical, biological, chemical and physicochemical properties such as enzymatic activity, microbial spoilage, viscosity, hardness, aroma, flavor and the palatability of foods (Calín-Sánchez, Figiel, Wojdylo, Szaryez, & Carbonell-Barrachina, 2014; Traffano-Schiffo, Castro-Giráldez, Fito, & Balaguer, 2014).

Sun-drying of fish is a traditional practice. However, sun-drying often has various disadvantages (e,g, long time to dry under non-sterile conditions often couple with poor handling during processing, resulting in a poor quality and unattractive finished product). Other drying techniques are being developed to improve the product such as solar drying, convective drying, vacuum drying, freeze-drying, infrared and microwave drying. Although widely used, hot air drying has many disadvantages such as lower energy efficiency and long drying times (Pan *et al*. 2008).

To minimize these disadvantages, several drying methods have been studied in the literature. Microwave drying has been studied during the last two decades (Sanga, Mujumdar, & Raghavan, 2000; Baltacıoğlu, Uslu, & Özcan, 2015). For industrial applications a frequency of 2450 MHz is widely applied for heating and drying. Microwaves work because of the quick absorption of energy by the water molecules, which causes rapid evaporation of the water and results in high drying rates for foods using less energy and giving a better quality of dried food (Kipcak, 2017). According to Duan, Jiang, Wang, Yu and Wang (2011), microwave drying is cost-efficient, controlled, rapid and safe when used properly.

The microwave drying of grass carp (Wu & Mao, 2008), tilapia fish fillets (Duan, Jiang, Wang, Yu, & Wang, 2011) and sardines (Darvishi, Azadbakht, Rezaeiasl, & Farhang, 2013) are some examples. Infrared drying is also viewed as an alternative drying method for foods. When infrared radiation is used to warm up or dry moist materials, it penetrates the material where the energy of radiation is converted into heat through vibration of water molecules (Hebbar & Ramesh, 2005). It also can reduce the drying time, lower energy costs, maintain a uniform temperature in the product and provide a better quality-finished product (Nowak & Lewicki, 2004). This drying method is particularly suitable for thin layers of material with large surface areas exposed to the radiation. Infrared drying of mullet fish (Tirawanichakul, Kaseng, & Tirawanichakul, 2011) and anchovy (Dongbang & Matthujak, 2013) have been studied.

There are several factors influencing the quality parameters of dried product. Some chemical and biochemical reactions such as browning reactions and lipid oxidation may alter the final color (Okos, Campanella, Narsimhan, Singh, & Weitnauer, 2007). Temperature, power level and drying time are the main factors affecting the color changes during drying (Rudra, Singh, Basu, & Shivhare, 2008).

However, the infrared drying of rainbow trout has not been studied. The main objectives of this study were to investigate the effect of microwave and infrared drying methods on the drying rate, time and color, to fit the experimental data to seven different mathematical models, and to compute effective diffusivity and activation energy of rainbow trout.

Materials and Methods

Material

Fresh rainbow trout (*Oncorhynchus mykiss*) were obtained from Carrefour SA in Istanbul, Turkey. The company had purchased the fish from fish farms in Bergama, Izmir. The mean weight and length of fish was 206 ± 9 g and 24 ± 2 cm, respectively. Fish were cut into traditional skin-on fillets by the fishermen with a maximum thickness of 0.7 ± 0.2 cm, width of 4.8 ± 0.5 cm and length of 9 ± 0.5 cm. Fish were cleaned with tap water and brought to the laboratory in ice in a styrofoam container. To preserve their original quality, they were stored in an Arcelik 1050 model refrigerator (Arcelik, Eskisehir, Turkey) for 0.5 to 7 hr at 4 °C before starting the drying experiments.

Moisture, Ash, Protein and Fat Content Analyses

Dry matter and initial moisture contents of the fresh samples were determined prior to the drying process. In these experiments approximately 10 ± 0.2 g fish pieces cut from four different parts of the fillet were dried in an oven (Memmert UM-400, Schwabach, Germany) at 105 °C for 24 h (AOAC, 1990). The average initial moisture content of fish sample was 74% on a wet weight basis.

Ash content was determined using about 1-2 g of fish samples in a platinum crucible gradually heated in a Protherm Mos 180/4 model high temperature furnace (Protherm, Ankara, Turkey) at 275 °C for 1 h, 550 °C for 1 h and 750 °C for 2 h.

A fully automatic protein measuring device Leco FP–528 (LECO Corporation, St. Joseph, MI, USA) was used for determination of the protein. A ~0.25 g ground fish pieces was quantitatively put into the instrument's capsules. Samples were then combusted for about 3 min for each sample and a percent protein value was calculated by the instrument. The actual conversion factor for nitrogen to protein is unknown.

Fat content of samples was determined using the soxhlet method (AOAC, 2000). Fat in the fish was extracted from fresh and dried fish samples with ethyl ether using a soxhlet extraction system. After fat extraction (2 h) the ethyl ether was evaporated in an oven for approximately 1 h at 105 ºC and then cooled in a dessicator. The weight of the fat was then determined. Moisture, ash, protein and fat content analyses were repeated three times and averages and standard deviations were calculated.

Drying Equipment and Drying Procedure

Infrared Drying

Drying experiments were carried out in a moisture analyzer with one 250 W halogen lamp (Snijders Moisture Balance, Snijders b.v., Tilburg, Holland). During the infrared drying process, the sample were evenly separated and spread over the entire pan. The power level was set in the control unit of equipment. The drying experiments were done at infrared power levels of 83, 104 and 125 W. The fish pieces (25 ± 0.2 g) were removed from the dryer at time intervals of 10 min during the drying process, and their weights were recorded with a digital balance (model BB3000, Mettler-Toledo AG, Greifensee, Switzerland) with an accuracy of 0.1 g. Drying was finished when the moisture content of the samples was approximately 0.19 ± 0.01 g water/g dry matter. The dried products were put in a desiccator and cooled to room temperature. Then they were placed in heat sealed low-density polyethylene bags until the analysis, a maximum of two wk.

Microwave Drying

Drying experiments were carried out in a Bosch HMT72G420 model microwave oven (Robert Bosch Hausgerate GmbH, Munich, Germany) which has a maximum output of 800 W working at 2450 MHz. In the microwave drying process, the samples were evenly separated over the entire pan. The dimensions of the microwave used for drying were 530 x 500 x 322 (ht) mm and consisted of a rotating glass plate with 300 mm diameter at the base of the oven. The adjustment of microwave output power and processing time was done with the aid of a digital control panel located on the microwave oven. Drying was done at a single power level for a fixed time and four different power levels were selected: 90, 180, 270 and 360 W. The fish pieces (approximately 20 ± 0.2 g) were removed from the dryer at time intervals of 2 and 1 min during the drying process, and their weights were recorded using the digital balance.

Both drying method experiments were triplicated and the average values of the moisture content were used for preparing drying curves.

Mathematical Modeling of Drying Curves

Moisture contents of fish samples during the thin layer drying experiments were expressed in dimensionless form as the moisture ratios *MR* using Equation 1 (Darvishi, Azadbakht, Rezaeiasl, & Farhang, 2013).

$$MR = \frac{M_t - M_e}{M_0 - M_e} \tag{1}$$

where; M_t is the mean fish samples moisture content at a specific drying time (t), M_o is the initial moisture content, M_e is the equilibrium moisture content all expressed as g water/g dry matter. The equilibrium moisture content was assumed to be zero for microwave drying as stated by Maskan (2000).

As the air humidity in the drying chamber is not constant, the expression was reduced to:

$MR = M_t / M_o$

where M_e was assumed to be negligible.

The drying rates (*DR*) of fish samples were calculated using Equation 2 (Omodara & Olanıyan, 2012).

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

where: $M_{t+\Delta t}$ is the moisture content of fish samples at $t + \Delta t$ (g water/g dry matter), Δt is the time interval between samplings.

Moreover, effective moisture diffusivity (D_{eff}) values were calculated using Equation 3 for the fish samples (Okos, Campanella, Narsimhan, Singh, & Weitnauer, 2007). Based on Fick's second law, D_{eff} was calculated using Crank's equation.

$$MR = \frac{M_t - M_e}{M_0 - M_e} = \frac{8}{\pi^2} \exp\left[-\frac{\pi^2 D_{eff} t}{4L^2}\right] \tag{3}$$

where, D_{eff} is the effective moisture diffusivity (m^2/s); *L* is the half-thickness of the fish slab (cm) and *t* is the drying time (s). Fish pieces were cut to be 0.68-0.72 cm thick.

A plot of ln *MR* versus drying time should give a straight line with a slope *K* as shown in Equation 4.

$$K = \frac{\pi^2 D_{eff}}{4L^2}. \tag{4}$$

Using the value of the slope, the effective moisture diffusivity could be determined.

Temperature was not a directly measurable quantity in the microwave or infrared during the drying process.

The dependence of the D_{eff} on the ratio of microwave and infrared output power to sample amount was evaluated using an Arrhenius type equation (Dadali & Ozbek, 2008):

$$D_{eff} = D_0 \exp\left[-\frac{E_a m}{P}\right] \tag{5}$$

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where D_0 is the pre-exponential factor of the Arrhenius equation (m^2/s), E_a is the activation energy (W/g), P is the microwave or infrared power level (W) and m is the sample weight (g).

Activation energy was calculated from a plot of ln D_{eff} versus m/P. The slope of the line is $-Ea$ and the intercept is ln D_0.

Statistical Analysis

The drying curves were fitted to seven different moisture ratio models to select the most suitable model for describing the drying process of fish samples (Table 1).

The data obtained were fitted to the models and their corresponding constants were calculated using Statistica 6.0 software (Statsoft Inc., Tulsa, OK).

Three statistical criteria were used to evaluate the relationship of the experimental data to the different models: the coefficient of determination (R^2), the reduced chi-square (χ^2) and the root mean square error ($RMSE$).

These parameters were calculated using the following equations:

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N - z} \tag{6}$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2\right]^{1/2} \tag{7}$$

where $MR_{exp,i}$ and $MR_{pre,i}$ values are the experimental and predicted dimensionless MR, respectively, N is the number of data values, and z is the number of constants in each model. The best model for describing drying was the one with the highest R^2, the lowest χ^2 and the lowest $RMSE$ (Delgado, Pereira, Baptista, Casal, & Ramalhosa, 2014).

Color

The color values of the fresh and dried fish samples were evaluated using a hand-held tristimulus colorimeter (ChromaMeter-CR-400 from Konica Minolta, Osaka, Japan). The parameters determined were L which is the approximate lightness between black and white within the range of 0-100, redness ($+a$) or greenness (a) and yellowness ($+b$) or blueness ($-b$) (Nagwekar, Tidke, & Thorat, 2016). The color of each fresh and dried fish sample was measured at five different points and averaged.

The total change in color of dried fish samples was expressed as ΔE (Šumić, Tepić, Vidović, Jokić, & Malbaša, 2013):

$$\Delta E = \sqrt{\left((L_o - L)^2 + (a_0 - a)^2 + (b_0 - b)^2\right)} \tag{8}$$

where L_0, a_0 and b_0 are values for the initial sample; and L, a and b are values for the final fish sample.

Result and Discussion

Chemical Composition of Fish Samples

The moisture content, dry matter, ash, protein and fat percentage of fresh rainbow trout are shown in Table 2.

Effect of Power Level on Drying Time

The effect of power level on the moisture content of fish samples at different times is shown in Figure 1.

The drying curves are similar to other foods. The drying curves show that microwave and infrared power levels affect the drying time as expected. Figure 2 shows how the moisture content decreased with drying time and was faster at higher power. When the microwave power level was increased from 270 to 360 W the drying rate increase was less than the increase from 90 to 180 W. This suggests that the mass transfer within the samples was more rapid with higher microwave power because more heat was generated within the sample. This created a larger vapor pressure difference between the center and the surface of the product. Fish samples with 2.79 g water/g dry matter average initial moisture content were dried to 0.19 ± 0.01 g water/g dry matter and 0.24 ± 0.02 g water/g dry matter in the infrared and microwave dryer at the different power levels, respectively. Due to more rapid drying rate in the microwave, samples could only dried to 0.24 ± 0.02 g water/g dry matter. If experiments were continued a little longer, the moisture content decreased to ≤10% and led to excessive drying of the meat. Reduction of moisture content of foods to between 10 and 20% w.b. prevents bacteria, yeast, mold and enzyme damage (Mohd Rozainee & Ng, 2010).

The required microwave drying times were 12, 8, 5 and 3 min at 90, 180, 270 and 360 W, respectively, and 420, 240 and 150 min for the infrared at 83, 104 and 125 W, respectively, showing how much faster microwave drying is. As expected at higher microwave and infrared power, the higher heat absorption resulted in higher product temperatures, higher mass transfer driving force and faster drying rates with less drying time (Tirawanichakul, Kaseng, & Tirawanichakul, 2011; Ponkham, Meeso, Soponronnarit, & Siriamornpun, 2012; Darvishi, Azadbakht, Rezaeiasl, & Farhang, 2013; Alibaş, 2015).

Effect of Power Level On Drying Rate

Figure 2 shows that significant differences in drying rate as defined in Eq. (2) were found between the two drying methods. At the beginning when the moisture content was high, the drying rate under all drying conditions increased with time corresponding to a transition period where non-isothermal conditions existed, but then decreased continuously as the moisture content was reduced. A constant-rate period was not observed in either case but only two different falling rate periods. This suggests that diffusion is the dominant physical mechanism governing moisture movements in the fish samples. Similar results were obtained by Darvishi, Azadbakht, Rezaeiasl and Farhang (2013). The absence of a constant drying rate suggests that moisture removal was driven internally by microwave energy absorption during the falling rate drying (Chua & Chou, 2005).

Figures 1 and 2 show that there was an approximate three-fold increase in drying rate at the start of the drying process when the microwave power level was increased from 90 to 360 W. A similar increase was also seen with infrared drying.

Effective Moisture Diffusivity and Activation Energy

The D_{eff} was calculated using Equation 4 and is shown in Figure 3. From previous studies of microwave drying of sardines (Darvishi, Azadbakht, Rezaeiasl, & Farhang, 2013) it was found that D_{eff} at 200 and 500 W were 0.716 and 3.05×10^{-7} m^2/s, respectively. (Mohd Rozainee & Ng, 2010) also observed that there was an increased effective moisture diffusivity in microwave-dried fish slices when power level was increased. It can be seen that D_{eff} values increased with increasing microwave and infrared power with the microwave being more effective.

The activation energy is shown in Figure 4. According to the results, the values of E_a for fish samples at microwave and infrared drying were 79 and 5.6 W/g, respectively. Darvishi, Azadbakht, Rezaeiasl and Farhang (2013) dried sardines in a microwave dryer and found an E_a of 11.1 W/g. As shown in Figure 4, the Ea for microwave drying was significantly higher that for infrared drying.

Evaluation of the Models

The experimental *MR* fitted to the seven different thin-layer drying models is shown in Table 1. The results of the statistical evaluation of each model is shown in Table 3.

An R^2 values higher than 0.95 indicates a good fit. All the models successfully described the relation between time and *MR*. Among the thin-layer drying models, the logarithmic model was found to represent the drying kinetics of fish samples best with higher R^2 values and lower χ^2 and *RMSE* values at all power levels. With the exception of the Wang and Sing, and Midilli et al. models, the other models can also be used to predict the *MR* as a function of drying time.

Color Analysis

The "*L*", "*a*", and "*b*" values for fresh and dried fish samples are shown in Table 4 ($p < 0.05$). Table 4 shows that power level and time were the main factors affecting the color of dried fish. The "*L*" values were highest with infrared drying and significantly lower ($p < 0.05$) with microwave samples at 270 and 360 W.

The redness values decreased for all dried fish samples when compared to fresh fish while the yellowness values increased.

ΔE values seem to reflect consumer discrimination of samples (Wachholz, Kauffman, Henderson, & Lochner, 1978). According to Šumić, Tepić, Vidović, Jokić and Malbaša (2013), if ΔE between two samples is less than 1.0, it is assumed that the difference would not be perceptible. The microwave dried fish had less ΔE color changes indicating that the microwave drying affected color quality less.

Conclusion

The major findings that emerged from this study were:

Statistical analysis showed that time and power level affected the moisture content and color of dried fish samples ($p < 0.05$). The moisture content of the fish samples decreased but the final moisture with the microwave was statistically higher ($p < 0.05$) than the infrared. As the infrared and microwave drying power increased, drying rate increased and drying time decreased as expected. Microwave drying times were much shorter than those for infrared drying. It was significantly higher for microwave drying. Seven different thin layer drying models were evaluated and the logarithmic model gave the best representations of the drying data for all the experimental conditions. The microwave drying had less influence on the color of fish samples that the infrared drying.

References

Aghbashlo, M., Kianmehr, M. H., Khani, S., & Ghasemi, M. (2009). Mathematical modeling of thin-layer drying of carrot. *International Agrophysics*, 23(4), 313-317.

Alibaş, I. (2015). Drying of thin layer mango slices with microwave technique. *Anadolu Journal of Agricultural Sciences*, 30(2), 99-109. https://doi.org/10.7161/anajas.2015.30.2.99-109

AOAC. (1990). Official Methods of Analysis. 15th Ed., *Association of Official Analytical Chemists*. Arlington, VA, USA.

AOAC. (2000). Meat and Meat products. In: Official Methods of Analysis. 17th Ed., *Association of Official Analytical Chemists*, Gaithersburg, MD, USA.

Baltacıoğlu, C., Uslu, N., & Özcan, M. M. (2015). Optimization of microwave and air drying conditions of quince (*cydonia oblonga*, miller) using response surface methodology. *Italian Journal of Food Science*, 27(1), 1-7. http://dx.doi.org/10.14674/1120-1770%2Fijfs.v85

Başlar, M., Kılıçlı, M., Toker, O. S., Sağdıç, O., & Arici, M. (2014). Ultrasonic vacuum drying technique as a novel process for shortening the drying period for beef and chicken meats. *Innovative Food Science and Emerging Technologies*, 26, 182–190. http://dx.doi.org/10.1016/j.ifset.2014.06.008

Calín-Sánchez, A., Figiel, A., Wojdylo, A., Szaryez, M., & Carbonell-Barrachina, A. A. (2014). Drying of garlic slices using convective pre-drying and vacuum-microwave finishing drying: kinetics, energy consumption, and quality studies. *Food and Bioprocess Technology*, 7, 398-408. doi: 10.1007/s11947-013-1062-3

Chua, K. J., & Chou, S. K. (2005). A comparative study between intermittent microwave and infrared drying of bioproducts. *International Journal of Food Science and Technology*, 40, 23–39. doi: 10.1111/j.1365-2621.2004.00903.x

Darvishi, H., Azadbakht, M., Rezaeiasl, A., & Farhang, A. (2013). Drying characteristics of sardine fish dried with microwave heating. *Journal of the Saudi Society of Agricultural Sciences*, 12, 121–127. http://dx.doi.org/10.1016/j.jssas.2012.09.002

Delgado, T., Pereira, J. A., Baptista, P., Casal, S., & Ramalhosa, E. (2014). Shell's influence on drying kinetics, color and volumetric shrinkage of castanea sativa mill. fruits. *Food Research International*, 55, 426–435. http://dx.doi.org/10.1016/j.foodres.2013.11.043

Dongbang, W., & Matthujak, A. (2013). Anchovy drying using infrared radiation. *American Journal of Applied Sciences*, 10(4), 353-360. doi: 10.3844/ajassp.2013.353.360

Duan, Z. H., Jiang, L. N., Wang, J. L., Yu, X. Y., & Wang, T. (2011). Drying and quality characteristics of tilapia fish fillets dried with hot air-microwave heating. *Food and Bioproducts Processing*, 89(4), 472-476. http://dx.doi.org/10.1016/j.fbp.2010.11.005

Hebbar, U. H., & Ramesh, M. N. (2005). Optimisation of processing conditions for infrared drying of cashew kernels with taste. *Journal of the Science of Food and Agriculture*, 85, 865-871. doi: 10.1002/jsfa.2045

Henderson, S. M., & Pabis, S. (1961). Grain drying theory I. Temperature effect on drying coefficient. *Journal of Agricultural Engineering Research*, 6, 169–174.

Jain, D., & Pathare, P. B. (2007). Study the drying kinetics of open sun drying of fish. *Journal of Food Engineering*, 78(4), 1315-1319. http://dx.doi.org/10.1016/j.jfoodeng.2005.12.044

Kipcak, A. S. (2017). Microwave drying kinetics of mussels (*Mytilus edulis*). *Research on Chemical Intermediates*, 43(3), 1429-1445. doi: 10.1007/s11164-016-2707-4

Maskan, M. (2000). Microwave/air and microwave finish drying of banana. *Journal of Food Engineering*, 44(2), 71–78. http://dx.doi.org/10.1016/S0260-8774(99)00167-3

Midilli, A., Kucuk, H., & Yapar, Z. (2002). A new model for single-layer drying. *Drying Technology*, 20(7), 1503-1513. http://dx.doi.org/10.1081/DRT-120005864

Mohd Rozainee, T., & Ng, P. S. (2010). Microwave assisted hot air convective dehydration of fish slice: drying characteristics, energy aspects and colour assessment. *World Engineering Congress 2010-Conference on Advanced Processes and Materials* (pp. 41-46). Sarawak, Malaysia.

Nagwekar, N., Tidke, V., & Thorat, B. N. (2016). Microbial and biochemical analysis of dried fish and comparative study using different drying methods. *Drying Technology*, Article in press, http://dx.doi.org/10.1080/07373937.2016.1256889

Nowak, D., & Lewicki, P. P. (2004). Infrared drying of apple slices. *Innovative Food Science and Emerging Technologies*, 5, 353-360. http://dx.doi.org/10.1016/j.ifset.2004.03.003

Okos, M. R., Campanella, O., Narsimhan, G., Singh, R. K., & Weitnauer, A. C. (2007). Food dehydration. In: *Handbook of Food Engineering*, D.R. Heldman & D.B. Lund (Eds), (pp. 601-744). CRC Press, Boca Raton, FL, USA, 1040 pp.

Omodara, M. Y., & Olanıyan, A. M. (2012). Effects of pre-treatments and drying temperatures on drying rate and quality of african catfish (*Clarias gariepinus*). *Journal of Biology, Agriculture and Healthcare*, 2(4), ISSN 2224-3208 (Paper) ISSN 2225-093X (Online) 2(4)

Page, G. E. (1949). *Factors Influencing the Maximum Rates of Air-Drying Shelled Corn in Thin Layers* (MSc Thesis). Purdue University, West Lafayette, IN, USA.

Pan, Z., Khir, R., Godfrey, L. D., Lewis, R., Thompson, J. R., & Salim, A. (2008). Feasibility of simultaneous rough rice drying and disinfestations by infrared radiation heating and rice milling quality. *Journal of Food Engineering*, 84, 469-479. http://dx.doi.org/10.1016/j.jfoodeng.2007.06.005

Ponkham, K., Meeso, N., Soponronnarit, S., & Siriamornpun, S. (2012). Modeling of combined far-infrared radiation and air drying of a ring shaped-pineapple with/without shrinkage. *Food and Bioproducts Processing*, 90, 155-164. http://dx.doi.org/10.1016/j.fbp.2011.02.008

Rudra, S. G., Singh, H., Basu, S., & Shivhare, U. S. (2008). Enthalpy entropy compensation during thermal degradation of chlorophyll in mint and coriander puree. *Journal of Food Engineering*, 86, 379–387. http://dx.doi.org/10.1016/j.jfoodeng.2007.10.020

Sanga, E., Mujumdar, A. S., & Raghavan, G. S. V. (2000). Drying technology in agriculture and food sciences, In: Arun S. Mujumdar (Ed.), *Principles and Application of Microwave Drying* (pp. 253-286). Science Publishing, Inc., Enfield, CT, USA, 313 pp."

Šumić, Z., Tepić, A., Vidović, S., Jokić, S., & Malbaša, R. (2013). Optimization of frozen sour cherries vacuum drying process. *Food Chemistry*, 136, 55-63. http://dx.doi.org/10.1016/j.foodchem.2012.07.102

Tirawanichakul, Y., Kaseng, S., & Tirawanichakul, S. (2011). Infrared and hot air arying of mullet fish: drying kinetics, qualities and energy consumption. *Thai Journal of Agricultural Science*, 44(5), 384-390.

Traffano-Schiffo, M. V., Castro-Giráldez, M., Fito, P. J., & Balaguer, N. (2014). Thermodynamic model of meat drying by infrared thermography. *Journal of Food Engineering*, 128, 103-110. http://dx.doi.org/10.1016/j.jfoodeng.2013.12.024

Wachholz, D., Kauffman, R. G., Henderson, D., & Lochner, J. V. (1978). Consumer discrimination of pork color at the market place. *Journal of Food Science*, 43(4), 1150-1152. doi: 10.1111/j.1365-2621.1978.tb15257.x

Wang, C. Y., & Singh, R. P. (1978). Use of variable equilibrium moisture content in modelling rice drying, *Transaction of ASAE*, 11, 668-672.

Wu, T., & Mao, L. (2008). Influences of hot air drying and microwave drying on nutritional and odorous properties of grass carp (*Ctenopharyngodon idellus*) fillets. *Food Chemistry*, 110(3), 647–653. http://dx.doi.org/10.1016/j.foodchem.2008.02.058

Table 1. Mathematical models applied to the drying curves

Model name	Equation	Reference
Lewis	$MR = \exp(-k.t)$	(Başlar, Kılıçlı, Toker, Sağdıç, & Arıcı, 2014)
Henderson and Pabis	$MR = A_o \exp(-k.t)$	(Henderson & Pabis, 1961)
Page	$MR = \exp(-k.t^n)$	(Page, 1949)
Aghbashlo et al.	$MR = \exp((-k_1.t)/(1+k_2.t))$	(Aghbashlo, Kianmehr, Khani, & Ghasemi, 2009)
Wang and Sing	$MR = 1 + a.t + b.t^2$	(Wang & Singh, 1978)
Logarithmic	$MR = a \exp(-k.t)+c$	(Jain & Pathare, 2007)
Midilli et al.	$MR = a \exp((-k.t^n) + (b.t))$	(Midilli, Kucuk, & Yapar, 2002)

A_o, a, b, c, k, n: Constants in models, MR: Moisture ratio, t: Drying time

Table 2. Chemical composition (%) of the rainbow trout flesh

Moisture content	Dry matter	Protein	Fat	Ash
74.0 ± 0.04	26.0 ± 0.04	20.2 ± 0.2	4.1 ± 0.2	1.66 ± 0.04

Table 3. Statistical results obtained with the different thin-layer drying models for rainbow trout compared with experimental values

Models	Parameters	Microwave conditions	Infrared conditions

		90W	180W	270W	360W	83W	104W	125W
Lewis	R^2	0.9949	0.9992	0.9902	0.9703	0.9961	0.9986	0.9949
	$\chi2$	0.00043	0.00010	0.00101	0.00430	0.00032	0.00013	0.00058
	RMSE	0.01920	0.00914	0.02905	0.05681	0.01723	0.0107	0.0219
Henderson & Pabis	R^2	0.9953	0.9992	0.9903	0.9706	0.9962	0.9987	0.9950
	$\chi2$	0.00060	0.00014	0.00126	0.00639	0.00034	0.000143	0.000724
	RMSE	0.02069	0.00909	0.02892	0.05653	0.01717	0.01055	0.02192
Page	R^2	0.9987	0.9994	0.9903	0.9776	0.9967	0.9988	0.9952
	$\chi2$	0.00016	0.00010	0.00125	0.00487	0.00030	0.000146	0.000688
	RMSE	0.01080	0.00778	0.02888	0.04937	0.01613	0.01066	0.02138
Aghbashlo et al.	R^2	0.9925	0.9995	0.9902	0.9704	0.9961	0.9985	0.9946
	$\chi2$	0.00009	0.00008	0.00124	0.00645	0.000346	0.000162	0.000775
	RMSE	0.00830	0.00727	0.01271	0.05681	0.01723	0.01122	0.02269
Wang and Sing	R^2	0.9840	0.9953	0.9825	0.9869	0.9913	0.9899	0.9898
	$\chi2$	0.00206	0.00085	0.00227	0.00296	0.000788	0.001122	0.001448
	RMSE	0.03836	0.02263	0.03881	0.03851	0.02599	0.02952	0.03101
Logarithmic	R^2	0.9999	0.9997	0.9910	0.9918	0.9984	0.9990	0.9968
	$\chi2$	0.000004	0.00008	0.00175	0.00164	0.000375	0.000124	0.000611
	RMSE	0.00156	0.00558	0.02779	0.02586	0.01723	0.00909	0.01748
Midilli et al.	R^2	0.9999	0.9998	0.9964	0.9767	0.9644	0.9998	0.9580
	$\chi2$	0.000006	0.000027	0.00061	0.00186	0.003809	0.000026	0.004784
	RMSE	0.00157	0.00330	0.01749	0.00880	0.05259	0.00376	0.03696

Table 4. Color parameters of fresh and dried rainbow trout flesh samples

Drying method	Drying condition	Color Parameters			ΔE
		L	*a*	*b*	
Microwave	Fresh	48.3 ± 0.1^{b}	19.0 ± 0.2^{b}	14.5 ± 0.3^{b}	-
	90 W	52.9 ± 0.2^{a}	12.9 ± 0.2^{c}	22.9 ± 0.3^{a}	11.4
	180 W	50.1 ± 0.3^{b}	16.8 ± 0.2^{b}	24.1 ± 0.2^{b}	10.0
	270 W	47.9 ± 0.2^{c}	14.6 ± 0.2^{a}	21.7 ± 0.2^{c}	8.4
	360 W	46.9 ± 0.3^{c}	18.7 ± 0.2^{a}	21.4 ± 0.2^{c}	7.2
Infrared	83 W	54.9 ± 0.4^{b}	14.8 ± 0.2^{b}	22.9 ± 0.3^{a}	11.4
	104 W	51.8 ± 0.3^{c}	17.7 ± 0.3^{a}	24.3 ± 0.2^{b}	10.52
	125 W	50.5 ± 0.2^{a}	13.4 ± 0.2^{c}	22.2 ± 0.2^{a}	9.72

$^{a\text{–}c}$Means within column and sample with differing superscripts are significantly different ($p < 0.05$).

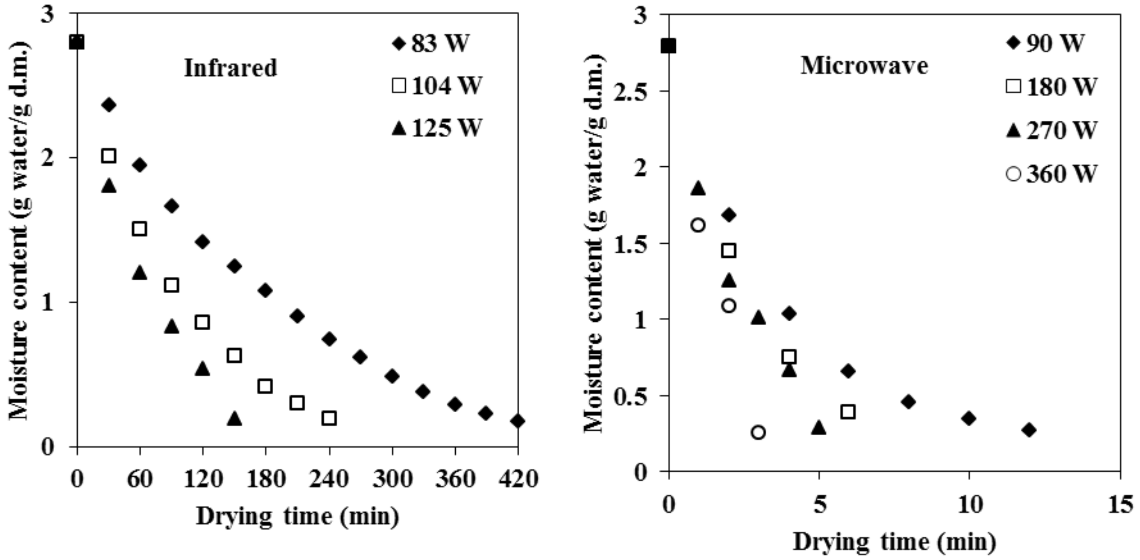

Figure 1. Infrared and microwave drying curves of fish samples. (Dry mater: d.m.)

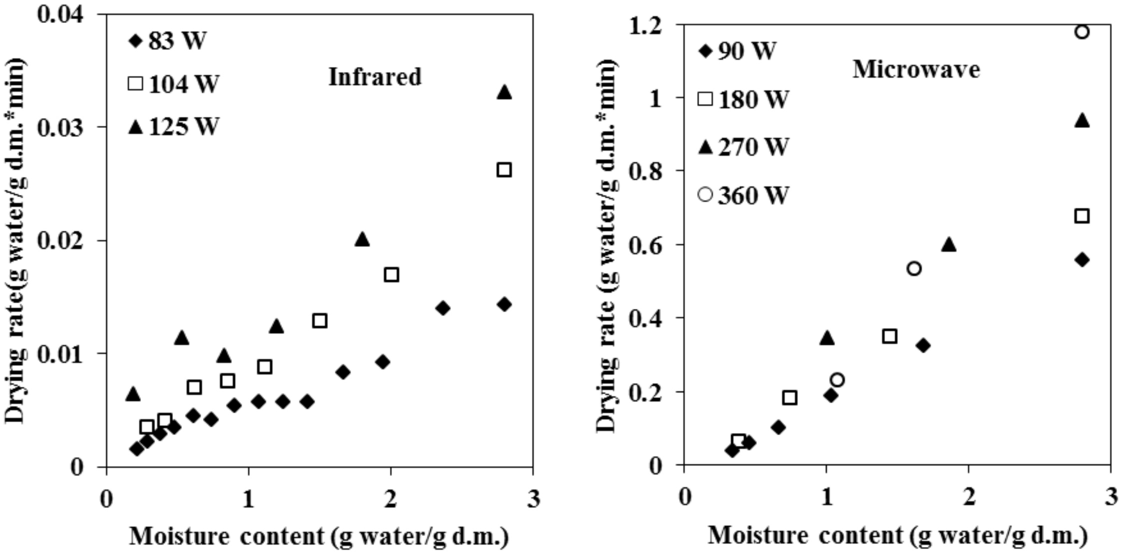

Figure 2. Infrared and microwave drying rate curves of fish samples. (Dry mater: d.m.)

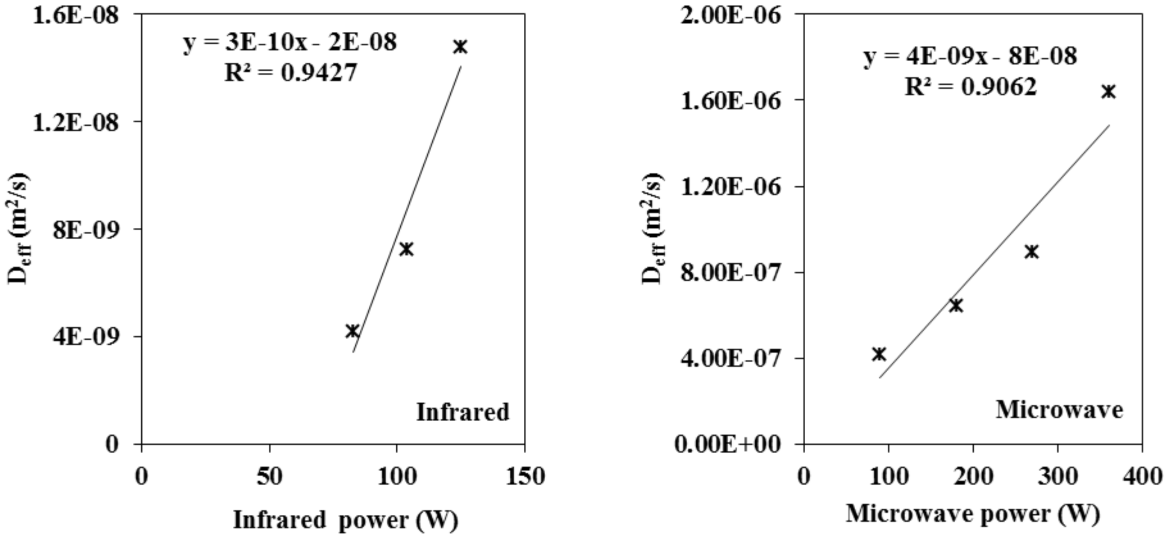

Figure 3. Variation of effective moisture diffusivity with power level

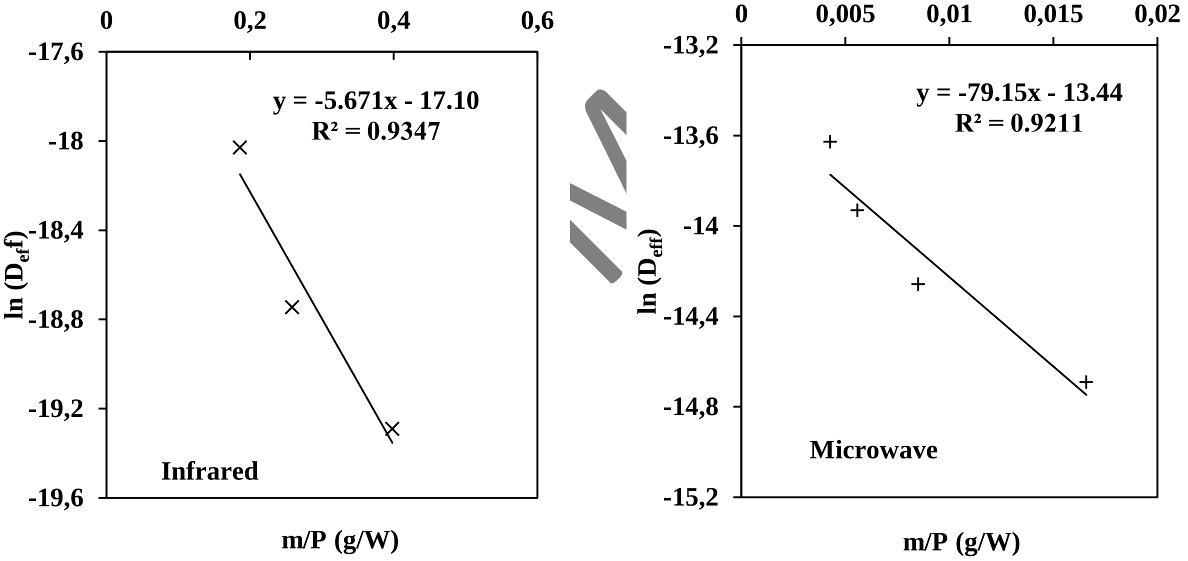

Figure 4. Arrhenius-type relationship between effective moisture diffusivity and power level