MATHEMATICAL MODELING OF MICROWAVE ASSISTED FLUIDIZED BED DRYING OF HAZELNUTS

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ABSTRACT

Microwave assisted fluidized bed drying is a novel drying technique which reduces drying time and yields higher quality products. In this study the effect of this method on drying kinetics of hazelnuts was studied. Drying experiments were conducted in three temperatures (40,50 and 60) and microwave power levels (0, 450 and 900W). The results showed that the effect of microwave power was more dominant than drying air temperature. Mathematical modeling was performed in order to predict the moisture changes during drying process. It was concluded that two term thin layer drying model was the best model to predict the drying kinetics of hazelnut with coefficient of determination and mean square of deviation as 0.999 and 0.02096 respectively.

Keywords: hazelnut, modeling, thin layer models, microwave, fluidized bed dryer

1. INTRODUCTION

Hazelnuts (*Corylus avellana L.*) are very important raw materials to the confectionary and chocolate industries (Kibar and Öztürk, 2009). High quality hazelnut varieties are cultivated in Northern parts of Iran. Iran is the 6th producer of hazelnut in the world (Hosseinpour et al., 2013). Hazelnuts are enriched of essential minerals, sterols, tannins, free phenolic acids, sugars, organic acids and phenolic compounds which make its unique sensory properties. High polyphenol content, makes hazelnuts an excellent source of natural antioxidants also high content of unsaturated fatty acids, α-tocopherol and carotenoids in hazelnuts have important health benefits (Ciarmiello et al., 2013).

Post-harvest storage of hazelnuts with high moisture content results in considerable qualitative and quantitative losses and drying process is required to inhibit the growth of various mycotoxins and to preserve the product (Demirtas et al., 1998). On the other hand, due to climate changes in the season of hazelnut harvest, the hazelnuts cannot be naturally dried on the tree and the nuts would be harvested with a moisture content about 25 % accordingly it should be processed to lower its moisture content to a safe level for storage. The best moisture content to prevent the microbial growth is 7 to 8 % for unshelled hazelnuts and 4 to 5 % for shelled hazelnuts (Lopez et al., 1997). Using Conventional drying methods may have negative biochemical, chemical and organoleptic effects which decline products quality and reduce consumer acceptance (Askari et al., 2013; Demirhan and Özbek, 2015; Nadian et al., 2015).

Dipolar interaction of water molecules inside the food material causes heat generation in microwave ovens. The polar water molecules align themselves with changing electric field and the friction between oscillating molecules results in heat. This accelerated volumetric heat generation causes the pressure build up and results in rapid evaporation of water (Kumar et al., 2014). Microwave drying has various benefits such as less startup time, operation speed, energy consumption efficiency, space savings, precise process control, selective heating and for some products, superior quality of dried products (Wu and Mao, 2008). Aside from this beneficial features, microwave drying also can deteriorate product's quality if it is not used properly. The combination of microwave power with hot air convective drying has recently been proposed to overcome some limitations of single microwave processing such as possible damage to textural, color and nutritional properties, uneven heat distribution and limited penetration of the microwave radiation inside the product (Reyes et al., 2007; Askari et al., 2008).

Accurate prediction of drying process of food and agricultural products is critical to decline quality loss along with the energy consumption, and increasing the drying capacity. Thin-layer mathematical models are useful tools in designing and improvement of drying systems and analysis of mass transfer changes with time during drying process (Malekjani et al., 2013; Belghith et al., 2015). Due to complicated phenomenon and various factors required, in this study the drying kinetics have been investigated using a mathematical model. Although many attempts have been made to mathematically investigate the drying kinetic of foods during microwave and fluidized bed drying treatments such as tomato (Belghith et al., 2015), paddy (Golpour et al., 2015), canola (Malekjani et al., 2013), pistachio (Kouchakzadeh and Shafeei, 2010), macadamia nut (Silva et al., 2006) and many other food and agricultural products, efficient models are still needed to predict the drying behavior in the microwave assisted fluidized bed drying of nuts especially hazelnut. The objective of this work is to study the effect of temperature and microwave power variations in microwave assisted fluidized bed drying on drying kinetics of hazelnuts and proposing the best model for prediction of nut moisture content with drying time.

2. MATERIAL AND METHODS

2.1. Sample Preparation

Freshly harvested hazelnut was used in this study. The hazelnuts were obtained from a local garden in Eshkevarat, Guilan, Iran and kept at 4°C refrigerator until beginning the experiments. Before the experiments hazelnut samples were unshelled manually, the poor quality hazelnuts were also removed and classified as 11–13 mm kernels using a digital micrometer.

2.2. Drying Experiments

A laboratory scale microwave assisted fluidized bed dryer was used for drying experiments (Fig. 1.). The drying air velocity, temperature and microwave power were accurately controlled in the dryer. The drying chamber consisted of a Plexiglas cylinder (10 cm diameter and 35 cm height). For all experiments, air velocity was maintained constant. For stabilization the drying parameters in the drying chamber, the dryer was run without the samples for 30 min before each experiment. Drying chamber was positioned on a digital balance with accuracy of 0.01 g (Fig. 1) and the samples were weighted when the blowing air was switched off, instead of the less reliable method of removing the sample from the drying chamber.

The drying experiments were conducted at three hot air temperature levels (40, 50 and 60 ° C) combined with three microwave power levels (0, 450 and 900 W). The initial moisture content of the samples was measured before the experiments and it was 24-25% (d.b). 100 gr raw unshelled hazelnut was utilized for each run. The drying experiments were continued until the moisture content of the samples reached 5-6 % which was determined by weighting the samples during drying.

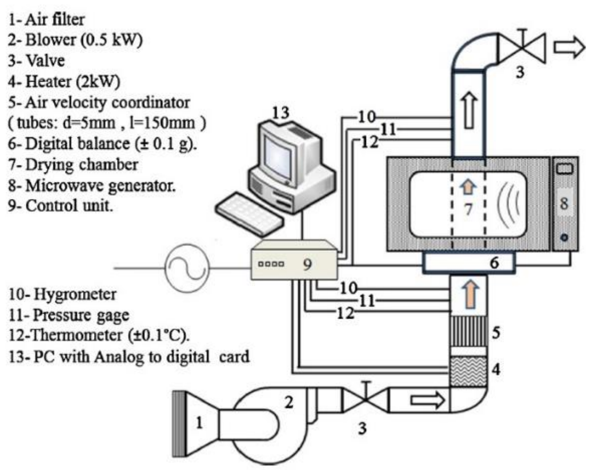

Fig 1. Drying apparatus (picture adapted by (Askari *et al.*, 2013))

2.3. Mathematical Modeling

Moisture ratio estimated from Eq. (1):

$$Moisture\ ratio\ (MR) = \frac{M - M_e}{M_0 - M_e} \tag{1}$$

Where MR, M, M_0, M_e are the moisture ratio, moisture content at any time, initial moisture content and equilibrium moisture content respectively.

As the value of equilibrium moisture content M_e is much smaller than M and M_0, so, the moisture ratio may be simplified to M/M_0 (Kouchakzadeh and Shafeei, 2010). Seven popular thin layer drying models were used to describe the drying behavior of hazelnuts in different drying conditions in the microwave assisted fluidized bed dryer as table 1.

Table 1. thin layer drying models

Model name	Model
Newton	$MR = \exp(-kt)$
Page	$MR = \exp(-kt^n)$
Henderson Pabis	$MR = aexp(-kt)$
Logarithmic	$MR = aexp(-kt) + c$
two term	$MR = aexp(-k_0t) + bexp(-k_1t)$
two-term exponential	$MR = aexp(-kt) + (1 - a)exp(-kat)$
Midilli et al.	$MR = aexp(-kt^n) + bt$

The models were evaluated and compared with experimental data using the coefficient of determination (R^2); root mean square error (RMSE) and reduced chi-square (χ^2) based on the following relationships:

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(MR_{pre.i} - MR_{exp.i})^2}{\sum_{i=1}^{N}(\overline{MR}_{pre.i} - MR_{exp.i})^2}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}(MR_{exp.i} - MR_{pre.i})^2}{N - n}$$

$$RMSE = \left(\frac{\sum_{i=1}^{N}(MR_{pre.i} - MR_{exp.i})^2}{N}\right)^{\frac{1}{2}}$$

where $MR_{exp,i}$ is the experimental moisture ratio, $MR_{pre,i}$ is predicted moisture ratio, N is number of observation, and n is number of constants. Non-linear regression analyses were down by using statistical computer program. The model with the highest R^2 value and lowest χ^2 and RMSE was chosen as the best model.

3. RESULTS AND DISCUSSION

The microwave assisted fluidized bed drying experiments were conducted with variations of microwave power and hot-air temperature. The initial moisture content decreased until reaching the 5-6% moisture content. Figure 2 shows the effect of drying air temperature on drying kinetics. As it is shown in Fig 2a, in the treatments without microwave power, the drying time decrease with increasing the temperature. Elevating the temperature from 40 to 50 C decreased the total drying time about 40% and further increasing of the temperature to 60 C decreased it about 62%. As it is illustrated in figure 2 b and 2c, there are not significant differences between drying curves at different temperatures. This findings were expected because of high internal heat generated in treatments with microwave power which diminished the effects of higher temperatures (Silva *et al.*, 2006).

Figure 3 shows the effects of different microwave powers at constant temperatures on drying kinetics of hazelnut. As it is illustrated the effect of microwave power is significant at all three temperatures. As the microwave power increased from 0 to 450W at 40 C, the drying time decreased about 77%, further increase of microwave power to 900W, decreased this value about 96.4 %. These decrease in drying time was 65 and 95% at 50 C and 42% and 93% at 60C respectively. The results show that the significance of microwave power is higher at lower drying temperatures. The decrease in drying time with an increase in the drying microwave power density has been reported for many foodstuffs.

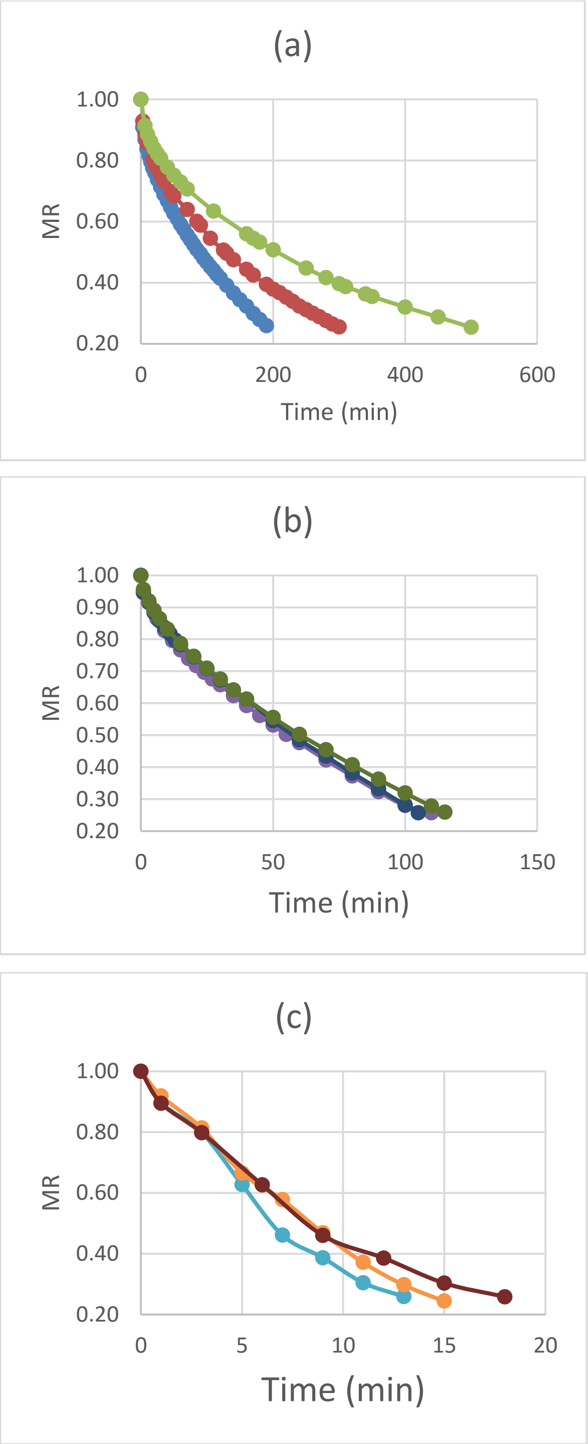

Fig 2. Effect of drying air temperature at (a) 0 W, (b) 450W, (c) 900W on hazelnut drying kinetics

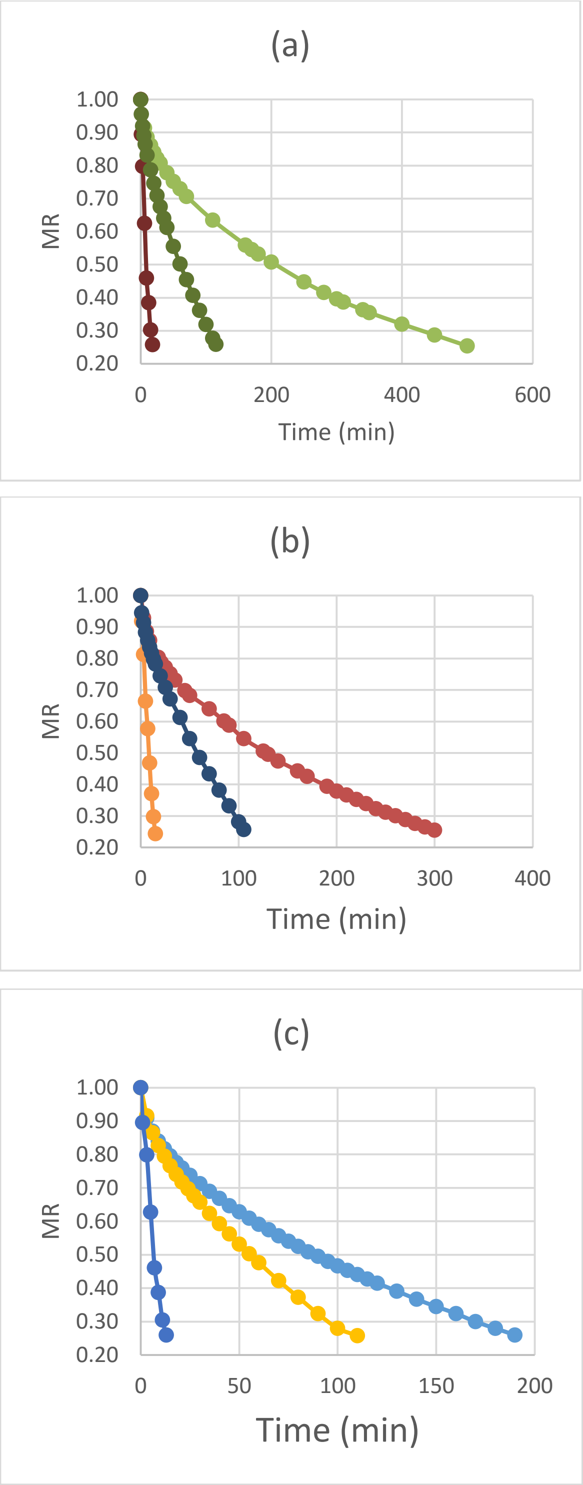

Fig 3. Effect of microwave power at (a) 40 C, (b) 50 C, (c) 60 C on hazelnut drying kinetics

The drying rates declined as the moisture content decreased and increased with the microwave power. As more heat generated within the sample due to microwave volumetric heating creating a large vapor pressure difference between the center and the surface of the product, the mass transfer within the sample was more rapid than the treatments without microwave (Fig 4). At the beginning of the drying process, the drying rates were higher. As the moisture content of the hazelnuts was higher at initial phase of the drying more absorption of microwave power and higher drying rates took place due to the higher moisture diffusion. As the drying continued, the loss of moisture in the product resulted in a decrease in the absorption of microwave power and decreasing the drying rate (Soysal *et al.*, 2009).

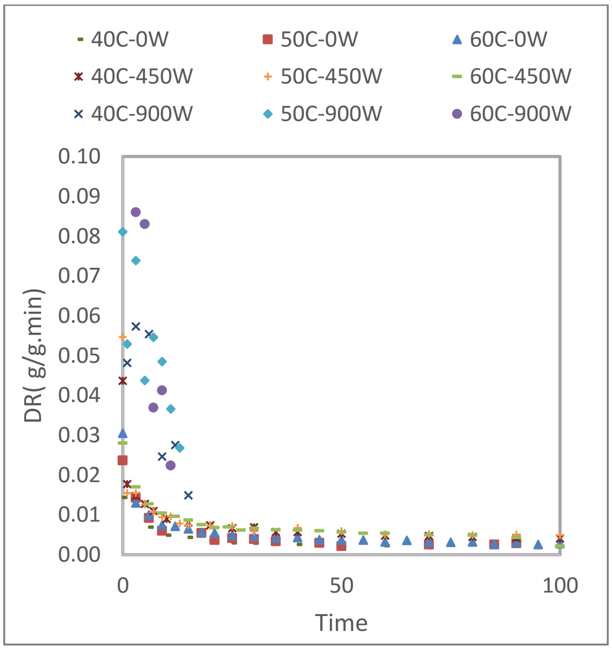

Fig 4. Drying rates at different drying condition

The statistical results from the models are shown in Table 2. In all cases, the statistical parameter estimations showed that R^2, χ^2 and RMSE values were ranged from 0.97 to 1, 0.005 to 0.299, and 0.0000282 to 0.112, respectively. The two term model had the highest coefficient of determination and the lowest χ^2 and RMSE values. Thus, it was the best model to represent the thin layer drying characteristics of hazelnuts.

4. CONCLUSION

The drying behavior of hazelnut in a microwave assisted fluidized bed dryer was investigated at different drying times and microwave power. The results showed that microwave power has more significant effect on decreasing the drying time that drying air temperature. All treatments followed falling rate period. In order to describe the drying behavior of hazelnuts seven thin layer drying models proposed in the literature were fitted with experimental data at different conditions. Two term model was the best model fitting the experimental data with the highest R^2 and lowest RMSE and χ^2. This model could characterize the exponential decrease in moisture ratio, as normally observed in drying behavior of agricultural and food products.

Table 2- Results of statistical analysis on the modeling of moisture contents and drying time for the microwave assisted dried hazelnuts

Model	T (C)	P(W)	Model constants				K Sq.	RMSE	R Sq.
			k						
Newton	40	0	0.0033				0.00431	0.06429	0.97528
	40	450	0.0120				0.00105	0.03157	0.99241
	40	900	0.0798				0.00032	0.01660	0.99619
	50	0	0.0052				0.00374	0.06022	0.99963
	50	450	0.0129				0.00126	0.03457	0.99176
	50	900	0.0864				0.00061	0.02326	0.99102
	60	0	0.0080				0.00279	0.05209	0.99977
	60	450	0.0132				0.00120	0.03381	0.99223
	60	900	0.1025				0.00088	0.02772	0.98799
Page			k	n					
	40	0	0.0223	0.6521			0.00015	0.01189	0.99908
	40	450	0.0244	0.8281			0.00029	0.01626	0.99795
	40	900	0.0879	0.9589			0.00032	0.01548	0.99659
	50	0	0.0280	0.6705			0.00024	0.01496	0.99998
	50	450	0.0253	0.8314			0.00049	0.02108	0.99686
	50	900	0.0605	1.1608			0.00016	0.01105	0.99819
	60	0	0.0317	0.6965			0.00023	0.01469	0.99998
	60	450	0.0274	0.8159			0.00029	0.01620	0.99819
	60	900	0.0778	1.1338			0.00062	0.02157	0.99338
			k	a					
Handerson and Pabis	40	0	0.0027	0.8954			0.00087	0.02823	0.99487
	40	450	0.0110	0.9499			0.00028	0.01574	0.99806
	40	900	0.0786	0.9895			0.00033	0.01570	0.99647
	50	0	0.0043	0.8896			0.00078	0.02710	0.99992
	50	450	0.0116	0.9478			0.00033	0.01735	0.99787
	50	900	0.0889	1.0199			0.00058	0.02119	0.99303
	60	0	0.0066	0.8961			0.00051	0.02198	0.99996
	60	450	0.0118	0.9383			0.00033	0.01745	0.99789
	60	900	0.1049	1.0166			0.00094	0.02651	0.98960
			k	a	c				
Logaritmic	40	0	0.0045	0.7155	0.2018		0.00055	0.02140	0.99699
	40	450	0.0119	0.9094	0.0439		0.00023	0.01384	0.99852
	40	900	0.0787	0.9848	0.0035		0.00009	0.00885	0.99894
	50	0	0.0067	0.7393	0.1737		0.00074	0.02492	0.99995
	50	450	0.0116	0.9478	0.0000		0.00029	0.01552	0.99829
	50	900	0.0889	1.0199	0.0000		0.00019	0.01272	0.99786
	60	0	0.0092	0.7641	0.1498		0.00061	0.02263	0.99997
	60	450	0.0129	0.8957	0.0475		0.00031	0.01612	0.99814
	60	900	0.1049	1.0166	0.0000		0.00027	0.01500	0.99694
			a	k0	k1	b			
Two Term	40	0	0.8400	0.0025	0.0692	0.1502	0.00005	0.00642	0.99973
	40	450	0.9277	0.0105	0.4572	0.0686	0.00006	0.00704	0.99962

	40	900	0.9398	0.0874	0.0000	0.0548	0.00011	0.00937	0.99887
	50	0	0.8412	0.0040	0.1338	0.1542	0.00003	0.00475	1.00000
	50	450	0.9340	0.0113	0.9568	0.0652	0.00015	0.01100	0.99915
	50	900	0.6553	0.0889	0.0888	0.3646	0.00025	0.01422	0.99739
	60	0	0.8585	0.0061	0.1955	0.1370	0.00003	0.00501	1.00000
	60	450	0.9135	0.0112	0.3564	0.0872	0.00008	0.00776	0.99960
	60	900	0.5004	0.1049	0.1049	0.5161	0.00035	0.01677	0.99638
			k	a					
Two Term Exponential	40	0	0.0239	0.1169			0.00174	0.03998	0.99002
	40	450	0.1424	0.0745			0.00021	0.01390	0.99851
	40	900	0.1132	0.4962			0.00031	0.01532	0.99667
	50	0	0.0352	0.1246			0.00138	0.03603	0.99986
	50	450	0.1727	0.0663			0.00036	0.01789	0.99776
	50	900	0.1209	1.6976			0.00012	0.00975	0.99858
	60	0	0.0568	0.1171			0.00088	0.02874	0.99993
	60	450	0.1341	0.0847			0.00021	0.01397	0.99866
	60	900	0.1404	1.6702			0.00060	0.02124	0.99359
			a	k	n	b			
Midilli et al.	40	0	0.9737	0.0159	0.7075	0.0000	0.00016	0.01120	0.99924
	40	450	0.9697	0.0170	0.9034	0.0000	0.00021	0.01287	0.99871
	40	900	1.0139	0.1133	0.8587	0.0000	0.00021	0.01295	0.99783
	50	0	0.6442	0.1015	0.1042	0.0000	0.08314	0.25790	0.99553
	50	450	0.9593	0.0150	0.9427	0.0000	0.00035	0.01666	0.99803
	50	900	1.0000	0.0687	1.1012	0.0000	0.00010	0.00895	0.99897
	60	0	0.5137	0.1040	0.1048	0.0000	0.11167	0.29890	0.99229
	60	450	0.9691	0.0200	0.8818	0.0000	0.00028	0.01486	0.99852
	60	900	0.9947	0.0784	1.1271	0.0000	0.00023	0.01362	0.99761

REFERENCES

Askari, G., Emam-Djomeh, Z., and Mousavi, S. 2008. Investigation of the effects of microwave treatment on the optical properties of apple slices during drying. Drying Technology *26*, 1362-1368.

Askari, G., Emam-Djomeh, Z., and Mousavi, S. 2013. Heat and mass transfer in apple cubes in a microwave-assisted fluidized bed drier. Food and Bioproducts Processing *91*, 207-215.

Belghith, A., Azzouz, S., and Elcafsi, A. 2015. Desorption isotherms and mathematical modeling of thin layer drying kinetics of tomato. Heat and Mass Transfer, 1-13.

Ciarmiello, L.F., Piccirillo, P., Gerardi, C., Piro, F., De Luca, A., D'imperio, F., Rosito, V., Poltronieri, P., and Santino, A. 2013. Microwave irradiation for dry-roasting of hazelnuts and evaluation of microwave treatment on hazelnuts peeling and fatty acid oxidation. Journal of Food Research *2*, 22.

Demirhan, E., and Özbek, B. 2015. Color Change Kinetics of Tea Leaves During Microwave Drying. International Journal of Food Engineering *11*, 255-263.

Demirtas, C., Ayhan, T., and Kaygusuz, K. 1998. Drying behaviour of hazelnuts. Journal of the Science of Food and Agriculture *76*, 559-564.

Golpour, I., Amiri Chayjan, R., Amiri Parian, J., and Khazaei, J. 2015. Prediction of Paddy Moisture Content during Thin Layer Drying Using Machine Vision and Artificial Neural Networks. Journal of Agricultural Science and Technology *17*, 287-298.

Hosseinpour, A., Seifi, E., Javadi, D., Ramezanpour, S.S., and Molnar, T.J. 2013. Nut and kernel characteristics of twelve hazelnut cultivars grown in Iran. Scientia Horticulturae *150*, 410-413.

Kibar, H., and Özturk, T. 2009. The effect of moisture content on the physico-mechanical properties of some hazelnut varieties. Journal of Stored Products Research *45*, 14-18.

Kouchakzadeh, A., and Shafeei, S. 2010 .Modeling of microwave-convective drying of pistachios. Energy conversion and management *51*, 2012-2015.

Kumar, D., Prasad, S., and Murthy, G.S. 2014. Optimization of microwave-assisted hot air drying conditions of okra using response surface methodology .Journal of food science and technology *51*, 221-232.

Lopez, A., Pique, M., Boatella, J., Parcerisa, J., Romero, A., Ferrá, A., and Garcí, J. 1997. Influence of drying conditions on the hazelnut quality. I. Lipid oxidation. Drying technology *15*, 965-977.

Malekjani, N., Jafari, S.M., Rahmati, M.H., Zadeh, E.E., and Mirzaee, H. 2013. Evaluation of thin-layer drying models and artificial neural networks for describing drying kinetics of canola seed in a heat pump assisted fluidized bed dryer. International Journal of Food Engineering *9*, 375-384.

Nadian, M.H., Rafiee, S., Aghbashlo, M., Hosseinpour, S., and Mohtasebi, S.S. 2015. Continuous real-time monitoring and neural network modeling of apple slices color changes during hot air drying. Food and Bioproducts Processing *94*, 263-274.

Reyes, A., Ceron, S., Zuniga, R., and Moyano, P. 2007. A comparative study of microwave-assisted air drying of potato slices. Biosystems Engineering *98*, 310-318.

Silva, F., Marsaioli, A., Maximo, G., Silva, M., and Goncalves, L. 2006. Microwave assisted drying of macadamia nuts. Journal of Food Engineering *77*, 550-558.

Soysal, Y., Ayhan, Z., Eştruk, O., and Arıkan, M. 2009. Intermittent microwave–convective drying of red pepper: Drying kinetics, physical (colour and texture) and sensory quality. Biosystems Engineering *103*, 455-463.

Wu, T., and 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*, 647-653.