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Experimental Investigation and Mathematical Modeling of Microwave Thin Layer Drying Behaviour of Apricot, Kiwi and Mint Leaves

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ABSTRACT

In this study, experimental investigation and mathematical modeling of microwave drying behavior of some vegetables and fruits such as apricot, kiwi and mint leaves are performed. In this regard, a microwave oven is used for experiments and 23 thin layer drying curve equation in the literature are evaluated for mathematical modeling of drying behavior of those products. For this purpose, mass loss and drying time are measured depending on six different microwave powers (100W, 300W, 450W, 600W, 700W, and 800W) and dimensionless mass ratio, moisture content, drying rate and mass shrinkage ratio are estimated and variation of colors are observed. For comparison of equations obtained from modeling, 14 different evaluation criteria are used and the best five drying model are determined. Consequently, it is determined that the most suitable microwave powers were 300W, 600W, 700W and the best drying models are Modified Page, Midilli-Kucuk and Midilli-Kucuk for apricot, kiwi and mint leaves, respectively. Also, it is observed that when the microwave power increases, drying time significantly decreases. However, it is seen that microwave drying method is suitable for drying of kiwi and mint leaves but not suitable for drying of apricot especially at high microwave powers.

Keywords: Thin layer drying, Microwave drying, Apricot, Kiwi, Mint leaves, Mathematical modeling

Kayısı, Kivi ve Nane Yapraklarının Mikrodalga İnce Tabaka Kurutma Davranışının Deneysel Olarak İncelenmesi ve Matematiksel Modellenmesi

ÖZET

Bu çalışmada kayısı, kivi ve nane yaprağı gibi bazı sebze ve meyvelerin mikrodalga kurutma davranışlarının deneysel olarak incelenmesi ve matematiksel modellemesi yapıldı. Bu bağlamda deneyler için mikrodalga fırın kullanıldı ve bu ürünlerin kuruma davranışlarının matematiksel modellemesi için literatürdeki 23 ince tabaka kurutma eğrisi denklemi değerlendirildi. Bu amaçla, altı farklı mikrodalga gücü (100W, 300W, 450W, 600W, 700W ve 800W) için kütle kaybı ve kuruma süresi ölçüldü ve boyutsuz kütle oranı, nem içeriği, kurutma hızı ve büzülme oranı hesaplandı ve renk değişimleri gözledi. Modellemeden elde edilen denklemlerin karşılaştırılması için 14 farklı değerlendirme kriteri kullanıldı ve en iyi beş kurutma modeli belirlendi. Sonuç olarak en uygun mikrodalga güçlerinin kayısı, kivi ve nane yaprakları için sırasıyla 300W, 600W, 700W ve en iyi kurutma modellerinin sırasıyla Modifiye edilmiş Page, Midilli-Kucuk ve Midilli-Kucuk olduğu belirlendi. Ayrıca, mikrodalga gücü arttığında kuruma süresinin önemli ölçüde azaldığı gözlemlendi. Ancak, mikrodalga kurutma yönteminin kivi ve nane yapraklarının kurutulması için uygun olduğu fakat özellikle yüksek mikrodalga güçlerinde kayısının kurutulması için uygun olmadığı görüldü.

Anahtar Kelimeler: İnce tabaka kurutma, Mikrodalga kurutma, Kayısı, Kivi, Nane yaprakları, Matematik modelleme

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1. Introduction

Drying is an important process that reduces the moisture of the wet product to the desired levels by removing moisture from the product by diffusion and evaporation from the surface, and is widely used in sectors including chemical, agriculture, biotechnology, food, polymer, ceramics, pharmaceutical, pulp and paper, mineral and timber (Kucuk et al., 2014). Moreover, it is one of the cheapest and easiest methods that protect foods from adverse environmental conditions (Midilli et al., 1999), removing moisture from the product, reducing the speed of microbial and biochemical reactions, preserving product quality (Qiu et al., 2019). Decomposition of antioxidants in the high temperature drying process is a significant loss of quality and therefore it is important to apply a lower temperature process (Lopez-Vidana et al., 2017). However, thin layer drying can be defined as the process of removal of moisture from a material by passing of drying air through a thin layer of a product (Inyang et al., 2018).

Reducing the drying time in drying processes is very important for reducing energy costs, and it is observed that drying time is significantly reduced in drying systems where microwave integrated drying techniques are used when compared to conventional drying systems (Yurtsever, 2005; Nindo et al., 2003). Furthermore, it is observed that there is no significant difference between the color of the product in microwave drying and the color of the fresh product, only a slight decrease in color brightness (Gunasekaran, 1999; Yurtsever, 2005). In addition, one of the important parameters affecting the quality of the product during drying is the drying rate that depends on internal and external factors. External factors such as drying velocity and relative humidity of the air and the surface area of the substance are independent (Gunasekaran, 1999; Yurtsever, 2005). On the other hand, internal factors which are permeability, porosity, solubility, thermal conductivity are due to the internal structure of the material (Midilli et al., 1999; Kucuk et al., 2014). All these factors are very important for all type of drying processes.

Among the drying processes, microwave drying is very important process for vegetables and fruits, and carried out by microwave dryers that are one of the efficient dryers with their features including process control convenience, product selectivity and shortening of drying time. Moreover, compared to conventional methods, the advantage of microwave drying method is that it provides homogeneous heating at every point that absorbs the microwave (Drouzas et al., 1999). In some products where the depth of penetration of microwaves into the product is limited and burning occurs because of energy accumulation at certain points and therefore microwave drying is not suitable for all products (Drouzas et al. 1999; Won et al., 2004).

Volumetric heating is the most important feature of microwave heating. The short start-up time and homogeneous heating provided by the absorption (penetration) of the microwave into the material shorten the process time (Venkatesh and Raghavan, 2004).

Under these important considerations, a comprehensive literature review has been performed and given in Table 1.

Using the useful theoretical and experimental knowledge in the above studies, an experimental investigation and mathematical modeling of microwave drying behavior of apricot, kiwi and mint leaves has been performed in this study. For this purpose, a microwave oven is used and 23 thin layer drying curve equations are evaluated for selecting the best thin layer drying curve equations in terms of the mathematical modeling, and 14 different evaluation criteria are taken into consideration to determine the appropriate drying curve equations for representing the microwave drying behavior of these products. Considering the above explanations, as a result of the comprehensive literature review, Although it is noticed that there are limited studies on microwave drying and mathematical modeling of apricot, kiwi and mint, there is no such a comprehensive study on apricot, kiwi and mint leaves in the literature. Therefore, this is the main motivation behind this work indicating the originality of the paper.

It is expected that this research study will contribute to researchers, investors, policy makers on drying processes of vegetables and fruits in order to determine the microwave drying behavior and conditions of the vegetables and fruits as well as other agricultural products and crops.

Table 1. Literature survey for microwave drying

Product	Reference	Product	Reference
	Microwave integrated drying process		
Kiwifruits	Maskan, 2001	Mint	Yurtsever, 2005
Dusts	McMinn et al., 2005	Kocabaş carpan	Duan et al., 2005
Parsley	Soysal et al., 2006	Lactose powder	McMinn, 2006
Macadamia nuts	Silva et al, 2006	Saskatoon berry	Reddy, 2006
Spinach	Dadali et al., 2007; Özkan et al., 2007, Özbek and Dadali, 2007	Leek	Dadali and Özbek, 2008
Beef	Thiagarajan, 2008	Tomato pulp	Al-Harahsheh et al., 2009
Calcium sulfate	Ganesapillai et al., 2009	Zizyphus jujuba Miller	Wang et al., 2009
Sugar cane pulp	Shah and Joshi, 2010	Basil leaves	Demirhan and Özbek, 2010a
Purslane	Demirhan and Özbek, 2010b	Gypsum	Ganesapillai et al., 2008; Pillai et al., 2010; Ganesapillai et al., 2011
Coriander leaves	Sarimeseli, 2011	Celery leaves	Demirhan and Özbek, 2011; Karaaslan and Tunçer, 2011
Rosehip, mulberry	Evin, 2011	Sliced potato	Darvishi, 2012
Licorice	Balbay and Şahin, 2012	Ginger	Murthy and Manohar, 2012
Fig	Sharifian et al., 2012	Sardine fish	Darvishi et al., 2013
Quince	Baltacıoğlu et al., 2015	Compressed Lignite spheres	Fu et al., 2017
Oil palm veneer	Lekachaiworakul et al., 2017	Lignite	Li et al., 2018
Green peas	Chahbani et al., 2018	Apple slices	Cuccurullo et al., 2019
Low grade manganese ore	Du et al., 2020	Germinated brown rice	Shen et al., 2020
Green microalgae	Agbede et al., 2020		
	Microwave-Convection Drying Process		
Powders	McMinn et al., 2005	Lactose powder	McMinn, 2006
Grape	Bingol et al., 2008	Red pepper, Spinach, tea leaves	Karaaslan, 2008; Karaaslan and Tuncer, 2008
Beef	Thiagarajan, 2008	Dill	Eştürk and Soysal, 2010
Mushrooms	Argyropoulos et al., 2011	Banana	Ganesapillai et al., 2011
Green tea leaves	Karaaslan and Tunçer, 2011	Flax fiber	Nair et al., 2011
Wheat	Hemis et al., 2011	Soybean	Ranjbaran and Zare, 2012
Sage leaves	Esturk, 2012	Vine leaf	Alibaş, 2012
Basil, mint, oregano, celamine, parsley, arugula	Sledz and Witrowa-Rajchert, 2012	Apple slices	Zarein et al., 2015
Chamomile leaves	Motevali et al., 2016	Strawberries	Szadzinska et al., 2016
Carrot	Xu et al., 2020; Cuccurullo et al, 2019		

2. Materials and Methods

In this part of the paper, material and method are presented. In material section, the raw materials used for drying and experimental system have been introduced in detail. In method section, microwave drying process has been defined in detail.

2.1. Material

For the microwave drying experiments, Apricot (*Prunus armeniaca*), kiwi (Actinidia) and mint (Mentha) are used in drying experiments. Apricot, known as Levent type, is taken from Levent hamlet of Akçadağ district of Malatya, Turkey. Kiwi is taken from kiwifruit offered for consumption in the market. Mint is collected from fresh shoots from the garden. In the experiments, fresh apricots of 150 g, kiwi of 85 g and mint of 50 g are put on a porcelain plate with 1-2 mm diameter hole and placed on the turntable of the microwave oven. Depending on the microwave power, weight loss is measured at periodic time intervals with precision scales. The drying process continued until the natural looking drying cycle of the product. Levent type apricot, kiwi and mint samples used in the study are shown in Figure 1.

(a) **(b)** **(c)**

Figure 1. (a) Levent type apricot, (b) Kiwi, (c) Mint (Şimşek, 2018)

2.2. Method

Microwave drying experiments is carried out using a Samsung brand ME711K microwave oven, which can operate at a total power level of 6, including 100W, 300W, 450W, 600W, 700W and 800W (Figure-2a). Fakir brand Molly Digital Kitchen Scale is used to measure the weight with a sensitivity of 1g (Figure-2b). Loyka BT 3000, which has a temperature measurement range of -50 / 70C (± 1C) and a humidity measurement range of 10% -95% (± 5%), is used in the measurement of ambient temperature and humidity (Figure-2c). DFA California moisture analyzer is used for moisture determination before and after drying apricot (Figure-2d). Caliper is used in kiwi thickness measurement (Figure-2e).

2.3. Mathematical Modeling

Examining the drying process and determining the drying times of moist products are considered as two important areas for drying. Kucuk et al. (2014) perform a comparative analysis of 67 models under 28 performance evaluation criteria.

Figure 2. Devices (a) Microwave oven, (b) Balance, (c) Thermometer - Humidity measurement, (d) DFA California moisture measurement, (e) Caliper (Şimşek, 2018)

2.3.1. Drying Curve Equations

The 23 mathematical modeling equations are selected from the literature (Kucuk et al., 2014) and given in Table 2.

Table 2. Thin-layer drying-curve equations

No	Model name	Model equation	Eq. No
1	Newton (Lewis, Exponential, Single exponential)	$MR = \exp(-kt)$	(1)
2	Page	$MR = \exp(-kt^n)$	(2)
3	Modified Page	$MR = \exp\left(-(kt)^n\right)$	(3)
4	Modified Page-I	$MR = \exp\left((-kt)^n\right)$	(4)
5	Modified Page-II	$MR = \exp\left(-c\left(\frac{t}{L^2}\right)^n\right)$	(5)
6	Henderson and Pabis (Single term)	$MR = a\exp(-kt)$	(6)
7	Logarithmic (Asymptotic) Yagcioglu et al.	$MR = a\exp(-kt)+c$	(7)
8	Midilli-Kucuk (Midilli, Midilli et al.)	$MR = a\exp(-kt^n)+bt$	(8)
9	Demir et al.	$MR = a\exp(-kt)^n+b$	(9)
10	Two-Term	$MR = a\exp(-k_0t)+b\exp(-k_1t)$	(10)
11	Two-Term Exponential	$MR = a\exp(-kt)+(1-a)\exp(-kat)$	(11)
12	Verma et al. (Modified Two-Term Exponential)	$MR = a\exp(-kt)+(1-a)\exp(-gt)$	(12)
13	Approximation of Diffusion (Diffusion approach)	$MR = a\exp(-kt)+(1-a)\exp(-kbt)$	(13)
14	Modified Henderson and Pabis (Three Term Exponential)	$MR = a\exp(-kt)+b\exp(-gt)+c\exp(-ht)$	(14)
15	Thompson	$t = a\ln(MR)+b(\ln(MR))^2$	(15)
16	Wang and Singh	$MR = 1+at+bt^2$	(16)
17	Hii et al.	$MR = a\exp(-kt^n)+c\exp(-gt^n)$	(17)
18	Simplified Fick's diffusion (SFFD)		(18)
19	Weibull	$MR = \exp\left(-\left(\frac{t}{a}\right)^b\right)$	(19)
20	Aghbashlo et al.	$MR = \exp\left(-\frac{k_1t}{1+k_2t}\right)$	(20)
21	Parabolic	$MR = a+bt+ct^2$	(21)
22	Balbay and Şahin	$MR = (1-a)\exp(-kt^n)+b$	(22)
23	Alibas (Modified Midilli-Kucuk)	$M_R = a\exp(-kt^n)+bt+g$	(23)

2.3.2. Evaluation Criteria

The most used evaluation criteria in the literature for thin layer and thin layer drying models are coefficient of determination, reduced chi-square, root mean square error, mean relative percentage error, standard error of estimate, mean bias error and reduced sum square error, respectively. The 14 evaluation criteria of thin-layer drying curve-equations are selected and used in the light of review paper by Kucuk et al. (2014) and given in Table 3.

Table 3. Evaluation criteria of thin-layer drying curve-equations

No	Evaluation parameters	Equation	Eq. No
1	Correlation coefficient	$r=\frac{N\sum_{i=1}^{N}\left(MR_{pre,i}\right)\left(MR_{\exp,i}\right)-\left(\sum_{i=1}^{N}MR_{pre,i}\right)\left(\sum_{i=1}^{N}MR_{\exp,i}\right)}{\sqrt{\left(N\sum_{i=1}^{N}MR_{pre,i}^{2}-\left(\sum_{i=1}^{N}MR_{pre,i}\right)^{2}\right)\left(N\sum_{i=1}^{N}MR_{\exp,i}^{2}-\left(\sum_{i=1}^{N}MR_{\exp,i}\right)^{2}\right)}}$	(24)
2	Total sum of squares	$SST=\sum_{1}^{n}\left(MR_{\exp,i}-MR_{avg}\right)^{2}$	(25)
3	Error (residual) sum of squares	$SSE=\sum_{i=1}^{N}\left(MR_{\exp,i}-MR_{pre,i}\right)^{2}$	(26)
4	Residual sum of squares	$RSS=\sum_{i=1}^{N}\left(MR_{\exp,i}-MR_{pre,i}\right)^{2}$	(27)
5	Coefficient of determination	$R^{2}=\frac{SSR}{SST}=1-\frac{SSE}{SST}$	(28)
6	Adjusted R^2	$\overline{R}^{2}=1-\left(1-R^{2}\right)\frac{N-1}{N-k-1}$	(29)
7	Reduced chi-square	$\chi^{2}=\frac{\sum_{i=1}^{N}\left(MR_{\exp,i}-MR_{pre,i}\right)^{2}}{N-n}$	(30)
8	Root mean square error	$RMSE=\sqrt{\frac{\sum_{i=1}^{N}\left(MR_{pre,i}-MR_{\exp,i}\right)^{2}}{N}}$	(31)
9	Residuals	$residuals=\sum_{i=1}^{N}\left(MR_{\exp,i}-MR_{pre,i}\right)$	(32)
10	Modeling efficiency	$EF=\frac{\sum_{i=1}^{N}\left(MR_{\exp,i}-MR_{\exp,ave}\right)^{2}-\sum_{i=1}^{N}\left(MR_{pre,i}-MR_{\exp,i}\right)^{2}}{\sum_{i=1}^{N}\left(MR_{\exp,i}-MR_{\exp,ave}\right)^{2}}$	(33)
11	Standard error of estimate	$SEE=\sqrt{\frac{\sum_{i=1}^{N}\left(MR_{\exp,i}-MR_{cal,i}\right)^{2}}{N-n_{p}}}$	(34)
12	Reduced sum square error	$RSSE=\frac{\sum_{i=1}^{N}\left(MR_{\exp,i}-MR_{cal,i}\right)^{2}}{N}$	(35)
13	Mean bias error	$MBE=\frac{\sum_{i=1}^{N}\left(MR_{pre,i}-MR_{\exp,i}\right)}{N}$	(36)
14	Mean relative percentage error	$P=\frac{100}{N}\sum_{i=1}^{N}\frac{\left\|MR_{\exp,i}-MR_{pre,i}\right\|}{MR_{\exp,i}}$	(37)

2.3.3. Basic Drying Calculations

Dimensionless mass ratio, moisture content, mass shrinkage ratio and drying rate are described in Equations (38), (39), (40) and (41), respectively, (Midilli et al., 1999; Alibaş, 2012).

Dimensionless mass ratio

$$MR = \frac{M_t - M_e}{M_i - M_e} \quad (38)$$

Moisture content

$$MC(\%) = \frac{M_t - M_e}{M_i} \quad (39)$$

Mass shrinkage ratio

$$S_{mr} = \frac{M_t}{M_i} \quad (40)$$

Drying rate

$$DR = -\frac{dM}{dt} = -\frac{M_{t+dt} - M_t}{dt} \quad (41)$$

2.3.4. Experimental Errors and Uncertainty Analysis

In experimental studies, the accuracy of the measured values is as important as the results. The most important variable affecting accuracy is errors that may arise due to different reasons during the experimental. These errors can occur in two different ways. One of them is the errors caused by the structure of the experiment set and the measurement tools and the other is the errors caused by the operator. Errors and uncertainties in experiments may occure some variables such as device selection, environmental impact, observation, reading data, and test planning (Midilli et al., 1999; Doğru et al., 2002).

Total error rate in a measurement with n independent variables:

$$W_R = \left[\left(\frac{\partial R}{\partial x_1} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \left(\frac{\partial R}{\partial x_3} w_3\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n} w_n\right)^2\right]^{1/2} \quad (42)$$

or

$$\frac{W_R}{R} = \left[\left(\frac{w_1}{x_1}\right)^2 + \left(\frac{w_2}{x_2}\right)^2 + \left(\frac{w_3}{x_3}\right)^2 + \cdots + \left(\frac{w_n}{x_n}\right)^2\right]^{1/2} \quad (43)$$

(a_1) Error due to mass, power and time measurements during experiments = ± 1 g, $\pm$ 0,5W, $\pm$ 0.001min.

(a_2) Error caused by reading of mass, power and time = $\pm$ 0.01g, $\pm$ 0.005W, $\pm$ 0.00001min.

$$W_R = [(a_1)^2 + (a_2)^2 + ..]^{1/2} = \%1.5 \quad (44)$$

3. Results and Discussion

3.1. Apricot Samples

Drying experiments of apricot are performed at 100W, 300W, 450W, 600W, 700W and 800W microwave powers. The dimensionless mass ratios obtained by using 23 thin or thin layer drying curve equations are estimated for each experiment and the five best model obtained depending on 14 evaluation criteria are given in Figure 3. Also, drying curve equations for 300W microwave power for which the most suitable drying is obtained for apricots are evaluated based on 14 evaluation criteria and the results are presented in Table 4. During the determination of the best suitable model when any of correlation coefficient (r), coefficient of determination (R^2), adjusted R^2 and modeling efficiency (EF) are higher than 1 for each experiment, these models are not taken into consideration.

The best models are obtained as Wibull, Modified Page, Aghbashlo et al., Aghbashlo et al., Aghbashlo et al., and Modified Page II for 100W, 300W, 450W, 600W, 700W and 800W, respectively, and drying curve equations are given in Equations (45-51) for each best model.

$$MR = \exp\left(-\left(\frac{t}{81.86}\right)^{2.007}\right) \quad (45)$$

$$MR = \exp\left(-(0.693\,t)^{1.875}\right) \quad (46)$$

$$MR = \exp\left(-\frac{0.043543t}{1-0.038517t}\right) \quad (47)$$

$$MR = \exp\left(-\frac{0.061575t}{1-0.050239t}\right) \quad (48)$$

$$MR = \exp\left(-\frac{0.062151t}{1-0.070597t}\right) \quad (49)$$

$$MR = \exp\left(-1.4706\left(\frac{t}{-2.2137^2}\right)^{1.9751}\right) \quad (50)$$

$$MR = \exp\left(-\left(\frac{t}{4.0311}\right)^{1.9751}\right) \quad (51)$$

Drying experiments of apricot are performed for 800W, 700W, 600W, 450W, 300W and 100W microwave powers. As seen in Figure 3, drying times are determined as 7, 12, 19, 20, 25 and 125 minutes for 800W, 700W, 600W, 450W, 300W and 100W power values, respectively. It is seen that the dimensionless mass ratio almost linearly decreases with increasing of time.

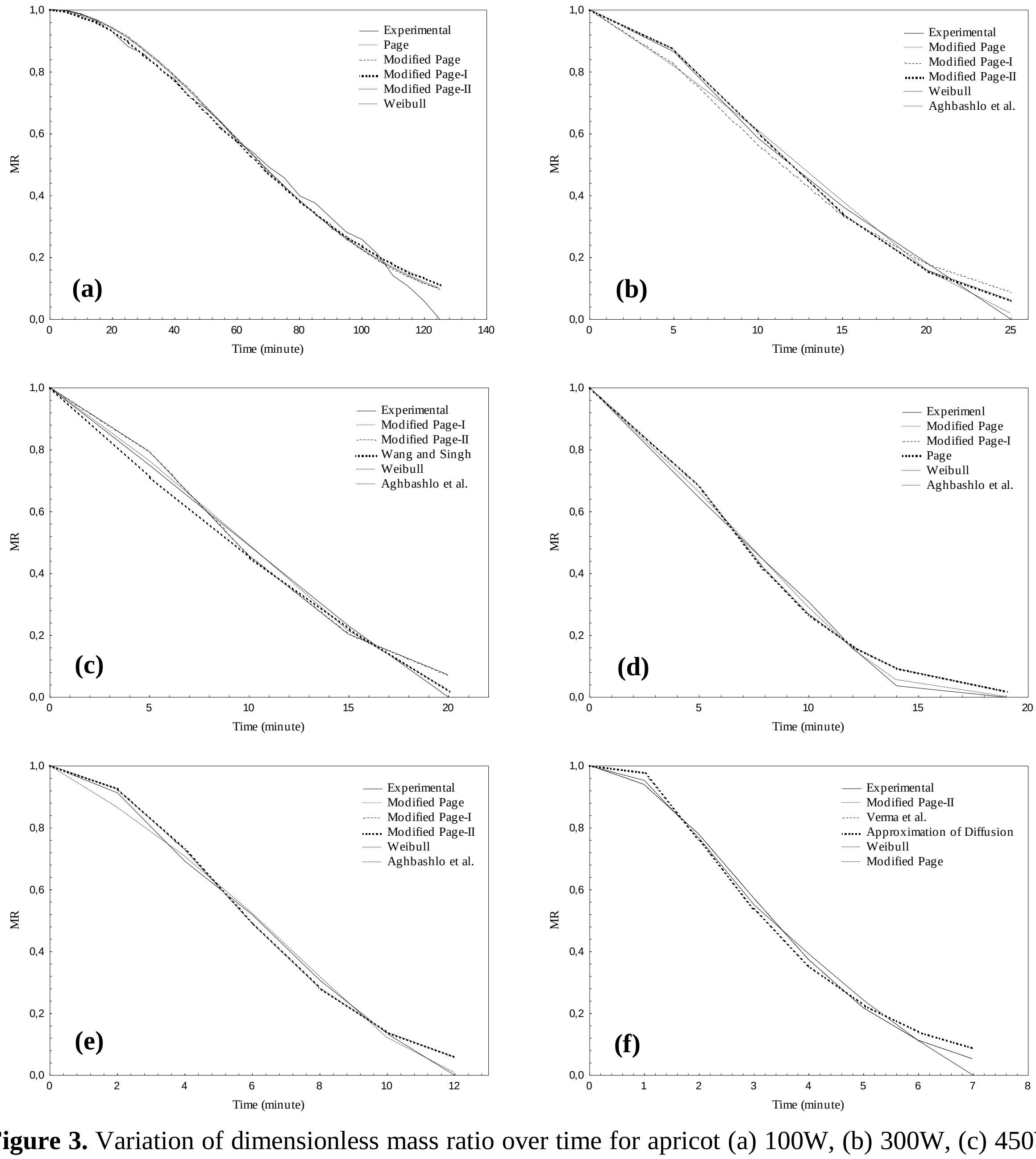

Figure 3. Variation of dimensionless mass ratio over time for apricot (a) 100W, (b) 300W, (c) 450W, (d) 450W, (e) 600W, (f) 700W, (g) 800W

Table 4. Evaluation criteria of apricot for 300W

Model Name	R	RSS	SST	SSE	R2	χ2	$\bar{R}^2$	RMSE	residuals	EF
Newton, Lewis	0.96923	0.06836	1.56921	0.06836	0.95644	0.01367	0.94555	0.10674	0.02412	0.9
Page	0.99495	0.01074	1.56921	0.01074	0.99315	0.00269	0.98859	0.04231	0.00999	0.9
Modified Page	0.99671	0.00532	1.56921	0.00532	0.99661	0.00133	0.99435	0.02977	-0.03440	0.9
Modified Page-I	0.99495	0.01074	1.56921	0.01074	0.99315	0.00269	0.98859	0.04231	0.00999	0.9
Modified Page-II	0.99671	0.00532	1.56921	0.00532	0.99661	0.00177	0.99153	0.02977	-0.03440	0.9
Henderson and Pabis	0.96433	0.05827	1.56921	0.05827	0.96287	0.01457	0.93811	0.09855	-0.09143	0.9
Logarithmic	0.99687	0.00475	1.56921	0.00475	0.99697	0.00158	0.99243	0.02813	-0.00112	0.9
Midilli-Kucuk	0.99711	0.00447	1.56921	0.00447	0.99715	0.00223	0.98576	0.02729	-0.01046	0.9
Demir et al.	0.99687	0.00474	1.56921	0.00474	0.99698	0.00237	0.98489	0.02811	0.00000	0.9
Two-Term	0.99687	0.00475	1.56921	0.00475	0.99697	0.00237	0.98487	0.02814	-0.00091	0.9
Two-Term Exponential	0.99292	0.01219	1.56921	0.01219	0.99223	0.00305	0.98705	0.04508	-0.05462	0.9
Verma et al.	0.99403	0.01012	1.56921	0.01012	0.99355	0.00337	0.98387	0.04108	-0.05018	0.9
Approximation of Diffusion	0.99405	0.01012	1.56921	0.01012	0.99355	0.00337	0.98388	0.04107	-0.05057	0.9
Modified Henderson and Pabis	0.94913	0.05827	1.44619	0.05827	0.95971	-0.05827	1.08058	0.10795	-0.09143	0.9
Thompson										
Wang and Singh	0.00576	1.44619	0.00576	0.99601	0.00192	0.99203	0.03396	0.04655	0.99601	0.0
Hii et al.	0.99506	0.00527	1.44619	0.00527	0.99636	-	1.01457	0.03246	-0.02624	0.9
Simplified Fick’s diffusion (SFFD)	0.94913	0.05827	1.44619	0.05827	0.95971	0.02913	0.83883	0.10795	-0.09143	0.9
Weibull	0.99491	0.00532	1.44619	0.00532	0.99632	0.00177	0.99264	0.03261	-0.03440	0.9
Aghbashlo et al.	0.99611	0.00401	1.44619	0.00401	0.99723	0.00134	0.99446	0.02831	0.01240	0.9
Parabolic	0.98705	0.01232	1.44619	0.01232	0.99148	0.00616	0.96593	0.04964	-0.00348	0.9
Balbay and Şahin	0.99869	0.00120	1.44619	0.00120	0.99917	0.00120	-	0.01550	-0.00001	0.9
Alibas (Modified Midilli-Kucuk)	0.99483	0.00481	1.44619	0.00481	0.99668	-	1.01329	0.03101	0.00006	0.9

(a) **(b)** **(c)**

Figure 4. Photographs of apricot during drying (a) initial stage, (b) mid stage, (c) last stage (Şimşek, 2018)

At 800W, 700W and 600W microwave powers, slight wrinkling and shape change occur on the outer part of the product during the initial stage of drying. It is observed that the apricot inner center began to burn perceptibly in the following stage. While the wrinkling and shape change on the outer surface continued, bruises in apricot-colored began to appear. In the last stage of drying, while the burning situation starting from the inner center increases, on the outer surfaces, burns occur on the adjacent inner surfaces of apricot in the dish and signs of charring are observed. In these microwave powers, while the product is drying in a short time it is observed that the burning occurred had a negative effect on the product quality.

At 450W and 300W power values, a stable and slight shape change and wrinkling is observed in the product in the initial stage of drying. However, at 100W microwave power, it is observed that there is little loss of mass in the product, the product is stable and there is no change in freshness (see Figure 4a). In the following stage, the drying starting from the inner center of the apricot steadily continues towards the outer surface of the product. While the wrinkling and shape change on the outer surface continue, bruises in apricot-colored appear (see Figure 4b). In the last stage of drying, the drying starting from the inner center is completed with the change of shape and color towards the outer wall (see Figure 4c). While the product is stable and preserving substance specificity no burning is observed (see Figure 4). The drying time of the product increases, natural appearance and color change is observed in the product (see Figure 4). It was observed that the drying performed at 450W, 300W and 100W powers has a positive effect on the product quality compared to the drying at 800W, 700W and 600W powers.

Apricot is adversely affected by microwave drying process due to its chemical structure containing high sugar. If microwave drying is performed, it should be determined whether the product is suitable for microwave drying or not by examining the dielectric loss factor (Wang et al., 2003). In the microwave drying method, uniform heating is provided at each point product that absorbs the microwave, while in other drying methods, the heat is transferred from the outside to the inside. Also, since all of the energy given is used in drying the product, it is efficient. In addition, not all products are suitable for microwave drying, since the depth of microwave penetration into the product is limited and some products burn as a result of energy accumulation at certain points (Drouzas et al., 1999; Won et al., 2004). Despite the increased evaporation, all the moisture cannot pass through the apricot peel and is kept inside, causing the product to be cooked or scalded or even burned at high powers.

3.2. Kiwi Samples

Drying experiments of kiwi are performed at 100W, 300W, 450W, 600W, 700W and 800W microwave powers. The dimensionless mass ratios determined for the five best model are presented in Figure 5. Also, drying curve equations for 600W microwave power for which the most suitable drying is obtained for kiwi are presented in Table 5.

Drying times are determined as 7, 12, 13, 22, 30 and 110 minutes for 800W, 700W, 600W, 450W, 300W and 100W power values, respectively. It is seen that the dimensionless mass ratio almost linearly decreases with increasing of time.

The best models are obtained as Alibaş (Modified Midilli–Kucuk), Aghbashlo et al., Midilli–Kucuk, Midilli–Kucuk, Alibaş (Modified Midilli–Kucuk), and Modified Page for 100W, 300W, 450W, 600W, 700W and 800W, respectively, and drying curve equations are given in Equations (52-57) for each best model.

$$MR = 0.27811\exp\left(-0.00185t^{2.18479}\right) - 0.00656t + 0.71709 \quad (52)$$

$$MR = \exp\left(-\frac{0.02841t}{1-0.02630t}\right) \quad (53)$$

$$MR = 0.99986\exp\left(0.05861t^{0.0000008}\right) - 0.049716t \quad (54)$$

$$MR = 0.98466\exp\left(0.003166t^{1.18693}\right) - 0.077114t \quad (55)$$

$$MR = 4.76926\exp\left(-0.35410t^{1.178834}\right) + 0.108842t - 3.76936 \quad (56)$$

$$MR = \exp\left(-\left(0.25485t\right)^{1.77583}\right) \quad (57)$$

There is no noticeable change in the product in the initial stage of the drying process for 800W, 700W microwave power values. In the following stage, it is observed that color change occure in the kiwi sample and redness determine in the core part of the product center. In the last stage of drying, the shape and color change in the product gradually increased, and burning on the inner surfaces and firing towards the outer Wall occur. While drying is observed in the product in a short time, it was observed that the burning occurred had a negative effect on the product quality.

In the initial stage at 600W, 450W, 300W, 100W microwave power values, wrinkling and a little shape and color occurred in the product (see Figure 6a).

In the following drying stage, it is seen that redness observed in the core part of the middle part of the product and color and shape change occur in the kiwi samples (see Figure 6b). In the last drying stage, the shape and color change in the product gradually increased and redness occurred on the inner surfaces (see Figure 6c). It is observed that the product tends to dry naturally. The fact that the structure of the inner core part of the kiwi samples is different from the other parts has a negative effect on the drying of the product. While rednesses and even burns are observed in the central part of the samples, it is determined that the drying showed different characteristics as it moved away from the center and non-uniform drying occur.

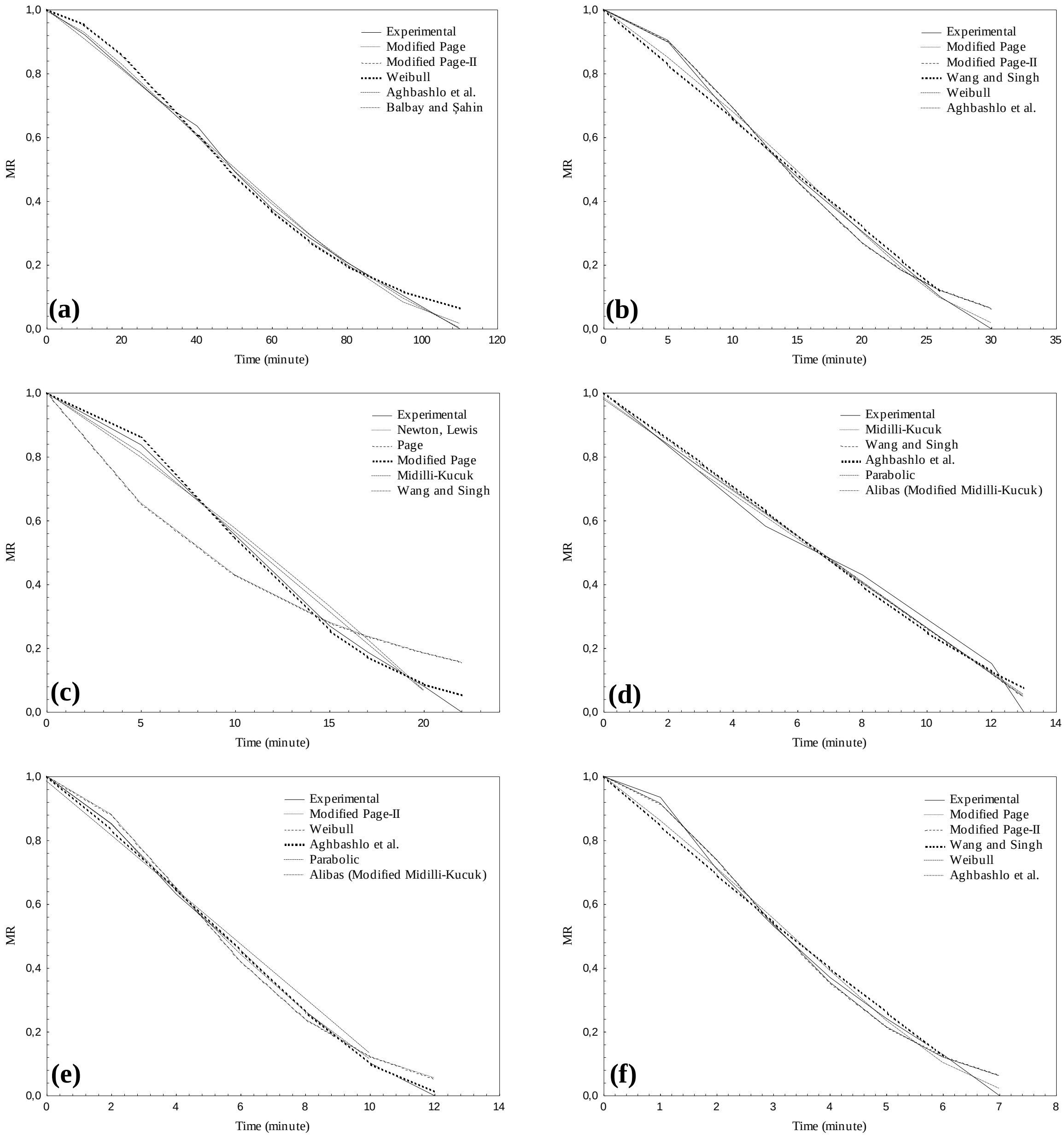

Figure 5. Variation of dimensionless mass ratio over time for kiwi (a) 100W, (b) 300W, (c) 450W, (d) 450W, (e) 600W, (f) 700W, (g) 800W

Table 5. Evaluation criteria of kiwi for 600W

Model Name	r	RSS	SST	SSE	R2	χ2	$\bar{R}^2$	RMSE	residuals	EF
Newton Lewis	0.97014	0.05272	1.61380	0.05272	0.96733	0.00879	0.96080	0.08679	-0.00822	0.9673
Page	0.97014	0.05272	1.61380	0.05272	0.96733	0.01054	0.95099	0.08679	-0.00822	0.9673
Modifiye Page	0.98351	0.02426	1.61380	0.02426	0.98497	0.00485	0.97745	0.05887	-0.05759	0.9849
Modifiye Page-I	1.23245	2.77990	1.61380	2.77990	-0.72258	0.55598	-1.58386	0.63018	-3.79167	-0.722
Modifiye Page-II	0.98351	0.02426	1.61380	0.02426	0.98497	0.00606	0.96994	0.05887	-0.05759	0.9849
Henderson and Pabis	0.96764	0.04906	1.61380	0.04906	0.96960	0.00981	0.95440	0.08372	-0.07477	0.9696
Logarithmic	0.99516	0.00701	1.61380	0.00701	0.99566	0.00175	0.99132	0.03164	-0.00230	0.9956
Midilli-Kucuk	0.99529	0.00683	1.61380	0.00683	0.99577	0.00228	0.98730	0.03124	-0.00001	0.9957
Demir et al.	0.99020	0.01423	1.61380	0.01423	0.99118	0.00474	0.97355	0.04508	-0.00294	0.9911
Two-Term	0.96764	0.04906	1.61380	0.04906	0.96960	0.01635	0.90880	0.08372	-0.07478	0.9696
Two-Term Exponential	0.98087	0.02855	1.61380	0.02855	0.98231	0.00571	0.97346	0.06387	-0.05337	0.9823
Verma et al.	0.98178	0.02708	1.61380	0.02708	0.98322	0.00677	0.96644	0.06219	-0.05278	0.9832
Approximation of Diffusion	0.98178	0.02708	1.61380	0.02708	0.98322	0.00677	0.96644	0.06219	-0.05293	0.9832
Modifiye Henderson and Pabis	0.96764	0.04906	1.61380	0.04906	0.96960	0.04906	-	0.08372	-0.07477	0.9696
Thompson										
Wang and Singh	0.99514	0.00734	1.61380	0.00734	0.99545	0.00147	0.99318	0.03239	-0.02370	0.9954
Hii et al.	0.98391	0.02376	1.61380	0.02376	0.98528	0.01188	0.91167	0.05826	-0.03537	0.9852
Simplified Fick's diffusion (SFFD)	0.96764	0.04906	1.61380	0.04906	0.96960	0.01227	0.93920	0.08372	-0.07477	0.9696
Weibull	0.98351	0.02426	1.61380	0.02426	0.98497	0.00485	0.97745	0.05887	-0.05759	0.9849
Aghbashlo et al.	0.99152	0.01270	1.61380	0.01270	0.99213	0.00254	0.98819	0.04260	-0.04956	0.9921
Parabolic	0.99526	0.00686	1.61380	0.00686	0.99575	0.00172	0.99149	0.03131	0.00000	0.9957
Balbay and Şahin	0.99530	0.00681	1.61380	0.00681	0.99578	0.00227	0.98735	0.03118	-0.00135	0.9957
Alibas (Modifiye Midilli-Kucuk)	0.99575	0.00616	1.61380	0.00616	0.99618	0.00308	0.97709	0.02967	0.00000	0.9961

(a) **(b)** **(c)**

Figure 6. Photographs taken during the experiments for kiwi (a) initial stage, (b) mid stage, (c) last stage (Şimşek, 2018)

3.3. Mint Samples

Drying experiments of mint are done at 100W, 300W, 450W, 600W, 700W and 800W microwave powers. The dimensionless mass ratios obtained for the five best model are presented in Figure 7. Also, drying curve equations for 700W microwave power for which the most suitable drying is obtained for kiwi are presented in Table 6.

Drying times are determined as 5, 8, 10, 10, 15 and 65 minutes for 800W, 700 W, 600W, 450W, 300W and 100W power values, respectively. It is seen that the dimensionless mass ratio almost linearly decreases for higher microwave powers (700W, 800W) and nonlinearly decreases for lower microwave powers (100W, 300W, 450W, 600W) with increasing of time.

The best models are obtained as Aghbashlo et al., Aghbashlo et al., Aghbashlo et al., Hii et al., Midilli–Kucuk, Aghbashlo et al. for 100W, 300W, 450W, 600W, 700W and 800W, respectively, and drying curve equations are given in Equations (58-63) for each best model.

$$MR = \exp\left(-\frac{0.013633t}{1-0.013896t}\right) \tag{58}$$

$$MR = \exp\left(-\frac{0.051884t}{1-0.060599t}\right) \tag{59}$$

$$MR = \exp\left(-\frac{0.072717t}{1-0.093828t}\right) \tag{60}$$

$$MR = 0.7714\exp\left(-0.0136t^{2.8727}\right)+0.2285\exp\left(-6.6419t^{2.8727}\right) \tag{61}$$

$$MR = 0.998522\exp\left(-0.088416t^{1.977331}\right)-0.001532t \tag{62}$$

$$MR = \exp\left(-\frac{0.232215t}{1-0.197517t}\right) \tag{63}$$

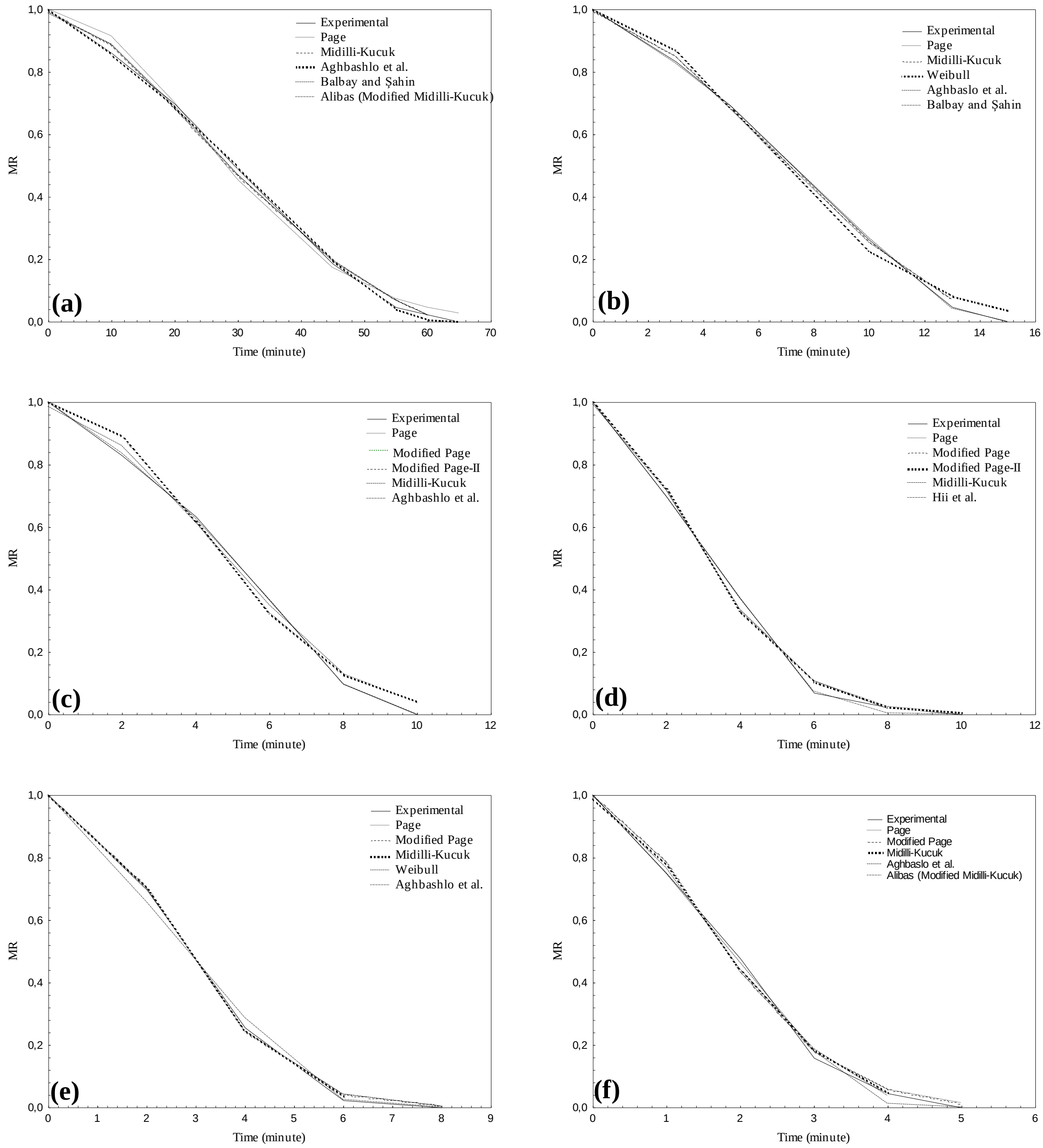

Figure 7. Variation of dimensionless mass ratio over time for mint (a) 100W, (b) 300W, (c) 450W, (d) 450W, (e) 600W, (f) 700W, (g) 800W

Table 6. Evaluation criteria of mint for 700W

Model Name	r	RSS	SST	SSE	R^2	χ^2	$\bar{R}^2$	RMSE	residuals	EF
Newton, Lewis	0.97470	0.05072	0.99375	0.05072	0.94897	0.01268	0.93195	0.10071	-0.05134	0.94897
Page	0.99971	0.00052	0.99375	0.00052	0.99947	0.00017	0.99895	0.01023	-0.01633	0.99947
Modified Page	0.99971	0.00052	0.99375	0.00052	0.99947	0.00017	0.99895	0.01023	-0.01633	0.99947
Modified Page-I	-	2.59924	0.99375	2.59924	-1.61560	0.86641	-4.23119	0.72101	-3.02326	-1.6156
Modified Page-II	0.99971	0.00052	0.99375	0.00052	0.99947	0.00026	0.99789	0.01023	-0.01633	0.99947
Henderson and Pabis	0.97264	0.04752	0.99375	0.04752	0.95218	0.01584	0.90436	0.09749	-0.11134	0.95218
Logarithmic	0.98697	0.01996	0.99375	0.01996	0.97991	0.00998	0.91965	0.06319	0.00000	0.97991
Midilli-Kucuk	0.99977	0.00036	0.99375	0.00036	0.99964	0.00036	-	0.00851	-0.00109	0.99964
Demir et al.	0.98697	0.01996	0.99375	0.01996	0.97991	0.01996	-	0.06319	0.00000	0.97991
Two-Term	0.97264	0.04752	0.99375	0.04752	0.95218	0.04752	-	0.09749	-0.11134	0.95218
Two-Term Exponential	0.97446	0.05115	0.99375	0.05115	0.94853	0.01705	0.89706	0.10114	-0.05183	0.94853
Verma et al.	0.98749	0.02014	0.99375	0.02014	0.97973	0.01007	0.91893	0.06347	0.03677	0.97973
Approximation of Diffusion	0.98748	0.02014	0.99375	0.02014	0.97974	0.01007	0.91894	0.06346	0.03675	0.97974
Modified Henderson and Pabis	0.97264	0.04752	0.99375	0.04752	0.95218	-0.04752	1.09564	0.09749	-0.11134	0.95218
Thompson										
Wang and Singh	0.99075	0.01570	0.99375	0.01570	0.98420	0.00523	0.96840	0.05604	0.04501	0.98420
Hii et al.	0.99972	0.00052	0.99375	0.00052	0.99948	-	1.00209	0.01018	-0.01401	0.99948
Simplified Fick's diffusion (SFFD)	0.97264	0.04752	0.99375	0.04752	0.95218	0.02376	0.80873	0.09749	-0.11134	0.95218
Weibull	0.99971	0.00052	0.99375	0.00052	0.99947	0.00017	0.99895	0.01023	-0.01633	0.99947
Aghbashlo et al.	0.99855	0.00251	0.99375	0.00251	0.99748	0.00084	0.99495	0.02240	0.00607	0.99748
Parabolic	0.99094	0.01391	0.99375	0.01391	0.98601	0.00695	0.94402	0.05274	0.00000	0.98601
Balbay and Şahin	0.99978	0.00034	0.99375	0.00034	0.99966	0.00034	-	0.00819	0.00000	0.99966
Alibas (Modified Midilli-Kucuk)	1.00000	0.00000	0.99375	0.00000	1.00000	-	1.00000	0.00000	0.00000	1.00000

(a) (b) (c)

Figure 8. Photographs taken during the experiments for mint a) initial stage, (b) mid stage, (c) last stage (Şimşek, 2018)

During the drying period for 800W, 700W, 600W, 450W, 300W and 100W microwave powers, it is observed that the color and shape change in the product is natural-looking and no adverse situation such as burning and redness occur (see Figure 8). The negative effects of drying apricot and kiwi with microwave are not observed in microwave drying of mint. Consequently, it is seen that drying with microwave reduces the drying time and also energy costs.

3.4. Basic Comparison of Dried Samples

Figures 9 (a), (b) and (c) present the variation of moisture content depending on time for apricot, kiwi and mint, respectively.

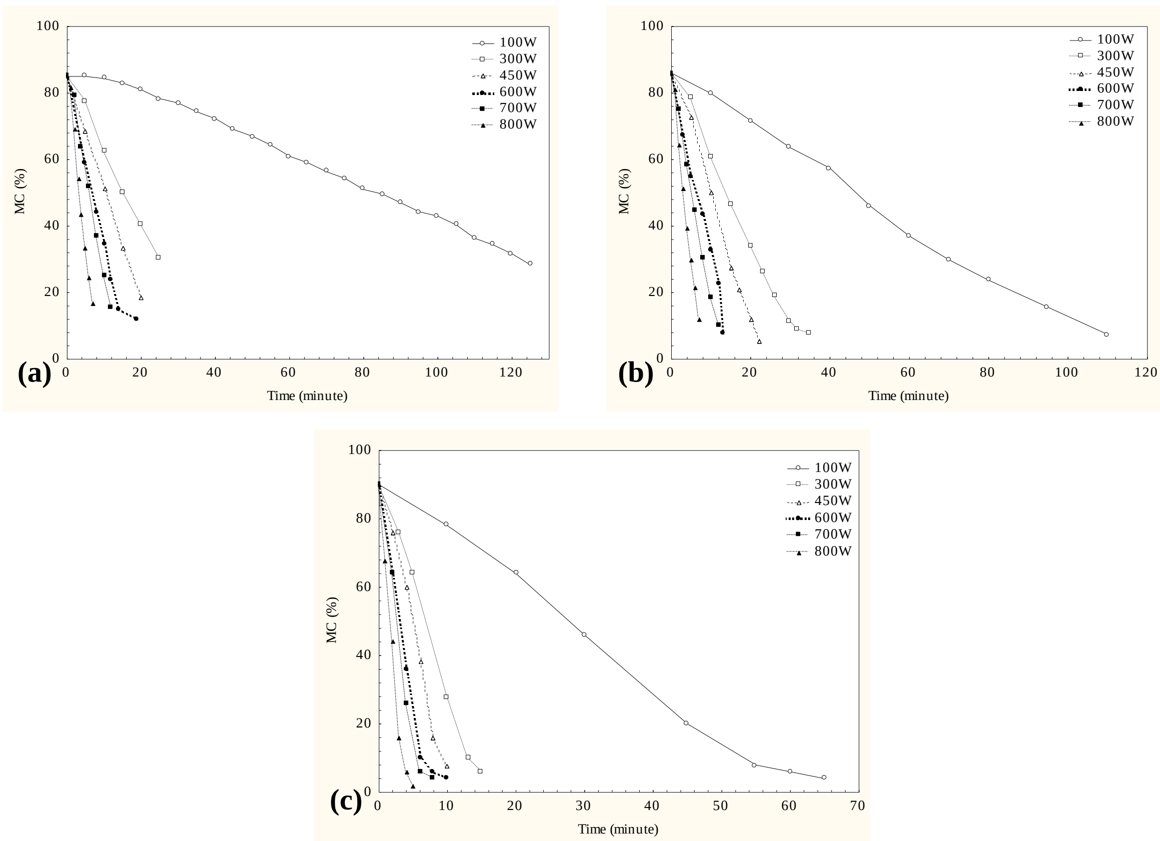

Figure 9. The variation of moisture content over time (a) apricot, (b) kiwi, (c) mint

The initial moisture content are determined as 85%, 86% and 90% for apricot, kiwi and mint, respectively. The moisture content almost linearly decreases with increasing of time for each product. Also, it is observed that when the microwave power rises the moisture transfer time highly decrease for each product. However, it is seen that the fastest decrease in moisture content occurred in mint, kiwi and apricot samples, respectively, for each microwave power.

Figures 10 (a), (b) and (c) present the variation of mass shrinkage ratio ovet time for apricot, kiwi and mint, respectively. The mass shrinkage ratio almost linearly reduces with rising of time for each product. Also, it is observed that when the microwave power increases the mass shrinkage ratio time highly decrease for apricot, kiwi and mint samples. Furthermore, it seems that the fastest decrease in mass shrinkage ratio occurred in mint, kiwi and apricot for each microwave power, respectively.

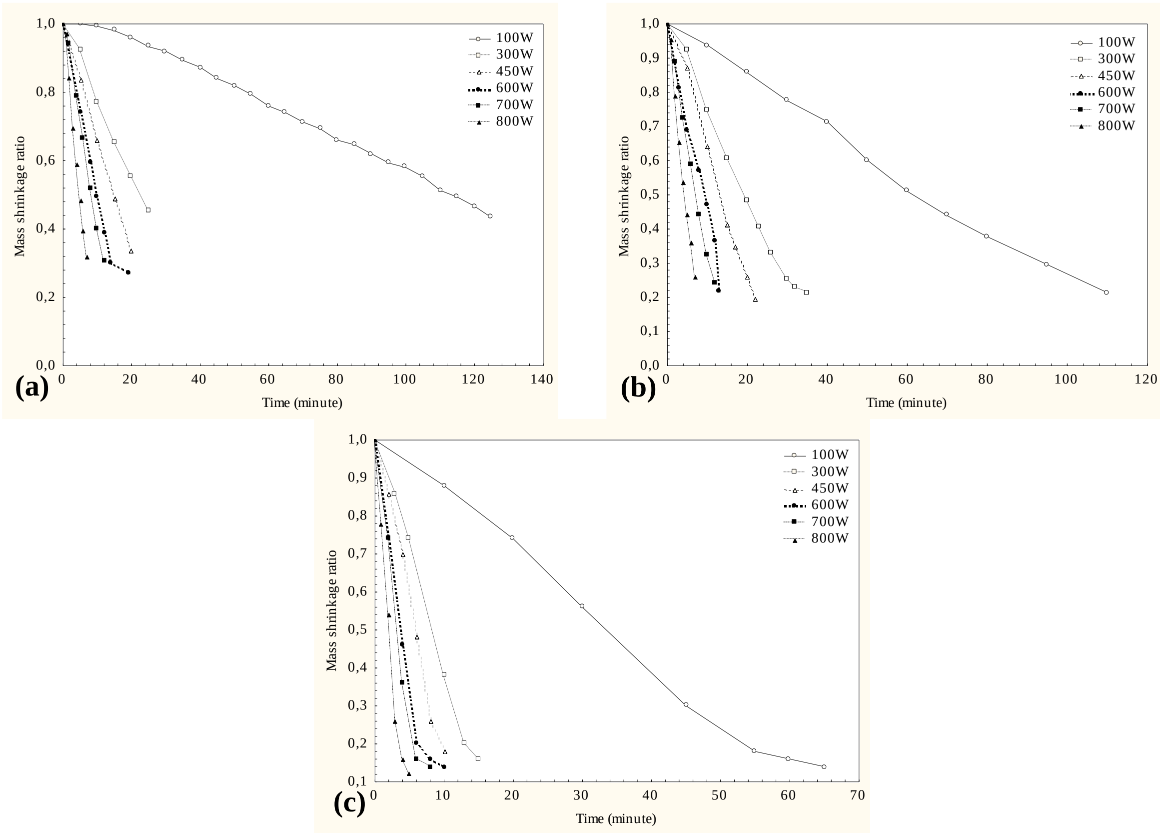

Figure 10. The variation of mass shrinkage ratio over time (a) apricot, (b) kiwi, (c) mint

Figures 11 (a), (b) and (c) present the change of drying rate over time at different microwave powers for apricots, kiwi and mint, respectively. It is observed that the drying rate increases with increasing of microwave power. Maximum drying rates of apricots estimated as 23 gwater/min at 3rd minute, 11.5 gwater/min at 4th minute, 8 gwater /min at 12th minute, 5.2 gwater/min at 10-15th minute, 4.6 gwater/min at 10th minute and 1.2 gwater/min at 110th minute for 800W, 700W, 600W, 450W, 300W, and 100W, respectively. Drying times for the same power values are determined 7, 12, 19, 20, 25 and 125 minutes, respectively.

For kiwi samples maximum drying rates estimated as 14 gwater/min at 2nd minute, 7.5 gwater/min at 4th minute, 14 gwater /min at 13th minute, 4.2 gwater/min at 10-15th minute, 2.8 gwater/min at 10th minute and 1.1 gwater/min at 50th minute for 800W, 700W, 600W, 450W, 300W, and 100W, respectively. Drying times for the same power values are determined 7, 12, 13, 22, 30 and 110 minutes, respectively.

Maximum drying rates of mint samples estimated as 14 gwater/min at 3rd minute, 9.5 gwater/min at 4th minute, 7 gwater /min at 4th minute, 5.5 gwater/min at 6-8th minute, 3.6 gwater/min at 10th minute and 0.9 gwater/min at 30th minute for 800W, 700W, 600W, 450W, 300W, and 100W, respectively. Drying times for the same power values are determined 5, 8, 10, 10, 15 and 65 minutes, respectively.

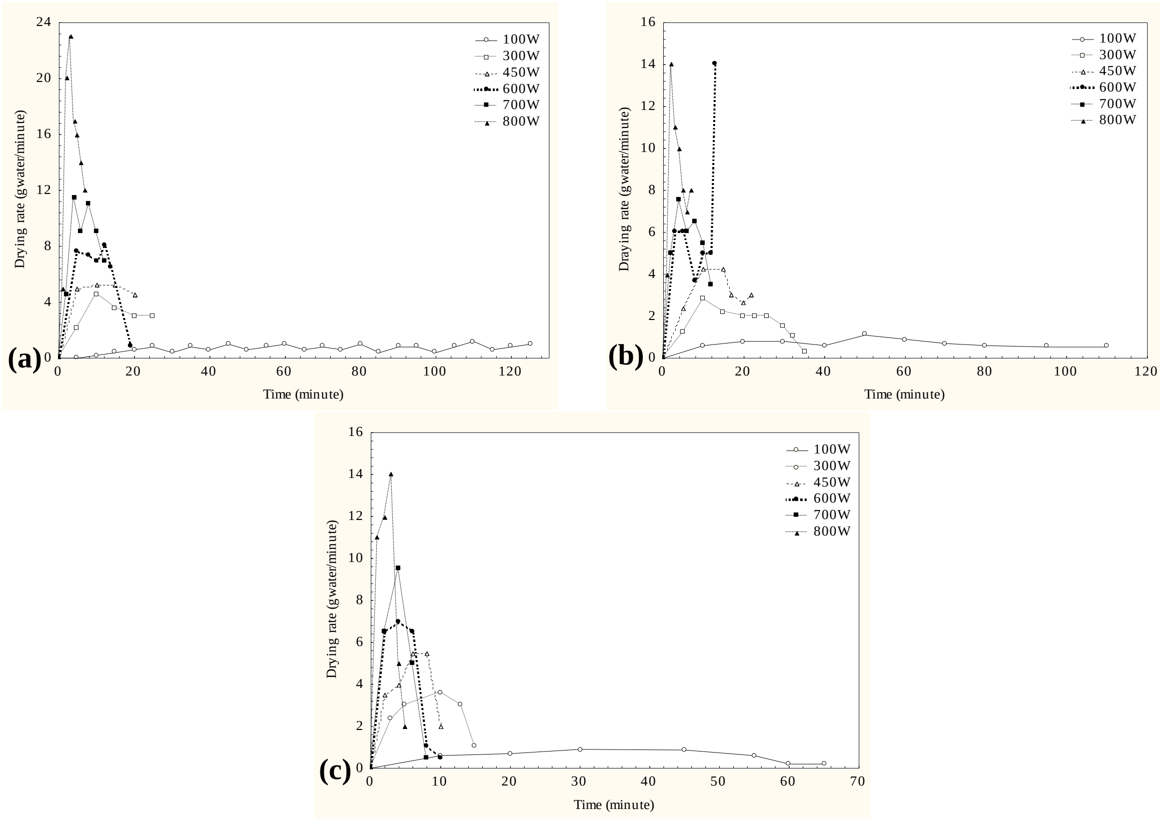

Figure 11. The variation of drying rate over time (a) apricot, (b) kiwi, (c) mint.

5. Conclusions

In this study, microwave drying behaviors of apricot, kiwi and mint leaves are experimentally investigated for different microwave powers (100W, 300W, 450W, 600W, 700W, and 800W). Some important concluding remarks are given as follows:

- ✓ The most suitable microwave power is 300W for thin layer microwave apricot drying.
- ✓ The most suitable model is Modified Page model for thin layer microwave apricot drying
- ✓ The most suitable microwave power is 600W for thin layer microwave kivi drying.
- ✓ The most suitable model is Midilli-Kucuk model for thin layer microwave kiwi drying
- ✓ The most suitable microwave power is 700W for thin layer microwave mint drying.
- ✓ The most suitable model is Midilli-Kucuk model for thin layer microwave mint drying.
- ✓ Drying time significantly decreases as microwave drying power increases.
- ✓ The fastest decrease in moisture content and mass shrinkage ratio occurred in mint, kiwi and apricot for each microwave power, respectively.
- ✓ Drying rate increases with increasing of microwave power for each product sample.
- ✓ Microwave drying method is not suitable for drying apricots especially at high microwave powers.

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Nomenclature

a, b, c, g	Empirical constants in models
c, g, h, k, k_0, k_1, k_2	Drying constants (min^{-1})
DR	Drying rate (g water/minute)
EF	Modeling efficiency
MBE	Mean bias error
MC	Moisture content
MR	Dimensionless mass ratio
S_{mr}	Mass shrinkage ratio
M_t	Product moisture on dry basis at "t" (g water/g dry solid
M_{t+dt}	Product moisture on dry basis at "t+dt" (g water/g dry solid
M_i	Initial product moisture on dry basis (g water/g dry solid)
M_e	Equilibrium or final product moisture on dry basis (g water/g dry solid)
N	Number of observations
n	Number of constants
P	Mean relative percentage error
r	Correlation coefficient
R^2	Coefficient of determination
$\bar{R}^2$	Adjusted R^2
RMSE	Root mean square error
RSS	Residual sum of squares
RSSE	Reduced sum square error
SEE	Standard error of estimate
SST	Total sum of squares
t	Time (minute)
W_R	Total error
$x_1, x_2, x_3, .., x_n$	Variables affecting the measurement
$w_1, w_2, w_3, .., w_n$	Error rate related to independent variables

Greek symbols

χ^2	Reduced chi-square

Subscripts

avg	Average
exp	Experimental
pre	Predicted