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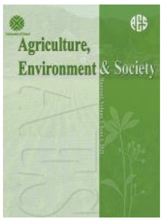

Microwave drying of mallow leaves, drying kinetics and energy analyses

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ABSTRACT

The drying characteristics of mallow (*Malva sylvestris* L.) in a microwave dryer were examined at different microwave power levels. To dry 30 g of mallow leaves, microwave power levels of 360, 450, 540, 720, and 900 W were used. The initial moisture content of samples was 6.31±0.01 g water/ g dry base. To determine the kinetic parameters, which were calculated by comparing the ratio of the difference between the initial and final moisture contents to the equilibrium moisture content, experimental data were fitted to seven distinct models. At various microwave power levels, the moisture diffusivity and energy consumption were measured. Based on the results, increasing microwave power from 360 to 900 W resulted in a drying time reduction between 14 and 5 minutes. A comparison of the proposed models demonstrated that the logarithmic model (MR= a.exp(-k.t)+b) provided the best fit because it had the highest coefficient of determination (R^2), the lowest sum of squared errors (SSE), and the lowest root mean square error (RMSE). This model can therefore be used to estimate the moisture content of mallow leaves during microwave drying. Also, the maximum and minimum energy consumptions for drying with 360 W and 720 W microwaves were 84.0 and 67.5 W.h, respectively. Moreover, the effective diffusivity of mallow leaves varied from 1.098×10^{-10} to 3.532×10^{-10} m^2/s for different microwave powers.

Highlights

- The drying characteristics of mallow in a microwave dryer were investigated.
- The kinetic parameters were calculated by comparing the difference between the initial and final moisture contents to the equilibrium moisture content.
- Increasing microwave power from 360 to 900 W reduced drying time by 14 to 5 minutes.
- The logarithmic model had the best fit, with the highest R^2, lowest SSE, and lowest RMSE.

1. Introduction

Mallow (*Malva sylvestris* L.) is commonly used as a vegetable and medicinal plant in Iran, where it is called Panirak. This plant is usually found near marshes, ditches, oceans, riverbanks, and meadows as well as other moist locations (Razavi et al., 2011). It is used extensively to add a distinctive aroma and flavor to food, such as salads and soups. (Samavati and Manoochehrizade, 2013). This medicinal plant is traditionally used for treating many different infections and diseases, including colds, burns, coughs, tonsillitis, bronchitis, digestive problems, eczema, and cut wounds under different weather conditions. (Pirbalouti et al., 2010).

This plant, like most fruits and vegetables, loses its freshness over time after harvest because of its high moisture content and availability of nutrients to microbes. The use of drying is one of the methods commonly used to restrain microbial growth, inactivate enzymes, and preserve seasonal plants over the course of the year (Lijuan et al., 2005). Furthermore, drying may be used to minimize packaging requirements and to reduce shipping weight (Maroulis and Saravacos, 2003).

Traditional methods for drying agricultural products, such as hot air drying and sun drying, have many disadvantages, including the inability to handle large quantities of agricultural products, inconsistent quality standards, contamination problems, and long drying times (Soysal, 2004). In hot air drying, for instance, the heat transfer to the inner sections of foods is very slow because the thermal conductivity of food materials is low during the falling rate period of the drying process. (Maskan, 2000). Over the past few years, microwaves have become popular as an alternative method of rapidly transferring

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electromagnetic energy (Chen et al., 2001). The drying process can be drastically shortened by replacing hot air with microwave energy (Sharma and Prasad, 2004), and the finished product will be of higher quality, at least in some stages (Yongsawatdigul and Gunasekaran, 1996).

Microwaves are electromagnetic waves with a wavelength of one millimeter to one meter in the frequency range of 300 MHz to 300 GHz. Microwaves are unique in that as they travel through a soft medium, a temperature increase can be observed across the medium (Sadeghi et al., 2019b). Consequently, it has many applications in the food, agricultural, and daily life industries. A typical example is the widespread use of microwaves in the home as food drying devices. Microwave drying reduces the drying time and prevents enzymatic decomposition of the food (Zhang et al., 2006). Additionally, this method of drying is more uniform and energy-efficient than conventional hot air drying (Decareau, 1985).

In a study by Doymaz et al. (2006), they examined microwave drying of dill leaves and presented a mathematical model for it. Alibas (2007) utilized microwaves and other dryers to dry nettle leaves and conducted an analysis of the energy consumption of the leaves under different drying conditions. The mathematical modeling was done for the drying of peppermint leaves by Torki-Harchegani et al. (2016). Zhang et al. (2014) investigated the effects of microwave power on the drying characteristics of *Anoectochilus roxburghii* during drying. Also, several researchers have investigated the spinach drying kinetics (Ozkan et al., 2007; Karaaslan and Tuncer, 2008). The effect of different microwave power levels on chrysanthemum drying was investigated by Wang et al. (2018). Many other studies have been done on the drying kinetic modeling of foods and vegetables such as parsley (Soysal, 2006), apple (Wang et al., 2007), carrot (Stanislawski, 2005), chard leaves (Alibas, 2006), wild cabbage (Yanyang et al., 2004), coriander leaves (Sarimeseli, 2011), basil (Ghasemi Pirbalouti et al., 2013), banana (Pereira et al., 2007), garlic (Figiel, 2009; Sharma and Prasad, 2004) and black tea (Panchariya et al., 2002). However, the literature reviews show there have been no reports regarding the drying kinetics of mallow leaves in microwave ovens. As a result, the main objectives of this study were to investigate the drying behavior of mallow leaves; to investigate the effect of microwave output power levels on drying kinetics and energy consumption; and to compare the experimental data obtained during the drying process with the predicted values obtained using a few thin-layer drying models.

2. Materials and methods

2.1. Materials

The fresh mallow samples were purchased from a local supplier in Zabol (Iran). After washing, they were kept in a refrigerator for 24 hours at 4°C in order to equilibrate their moisture content (Taghinezhad et al., 2021a). Leaf samples were separated from stems and divided into portions of 30 grams each before drying experiments. In order to determine the initial moisture content, four portions were dried in an oven at 105°C for 48 hours. Using the following equation (Mohsenin, 1970), it was determined that mallow leaves had an initial moisture content of 6.31 g water per g dry basis:

$$M_0(\mathrm{d.b}) = \frac{W_0 - W_d}{W_d} \qquad (1)$$

Where W_0 and W_d are the initial mass and the mass of the product after drying, respectively.

2.2. Drying equipment and drying procedure

For drying treatments, a digital microwave oven (GMO 330, GOSONIC, China) with a maximum (100%) output power of 900 W and frequency of 2450 MHz was used. By employing a digital control system, it was possible to select the power level and emittance time of microwaves. The microwave oven contained a rotating glass disk that was powered by an electrical motor. This disc was vital to ensuring homogeneous drying and reducing microwave reflections onto the magnetrons (Sadeghi et al., 2019a). The microwave oven was operated at five different power settings, i.e., 360, 450, 540, 720, and 900 W.

During drying, the mallow leaves were weighed on a digital weight balance (GF-2000 AND, Japan) with a precision of 0.01 g in order to observe and record the moisture loss. Three replications were done for each experiment.

2.3. Mathematical modeling

For the development of thin layer drying models, the changes in moisture content of agricultural products were usually measured and correlated to drying parameters (Midilli et al., 2002). The moisture ratio of mallow leaves was calculated using the following equation (Seyedabadi et al., 2019):

$$MR = \frac{M_t - M_e}{M_0 - M_e} \qquad (2)$$

Where MR is the moisture ratio, M_t is the moisture content at a specific time (g water/g dry base), M_0 is the initial moisture content (g water/g dry base), and M_e is the equilibrium moisture content (g water/g dry base) (Soysal 2004). For microwave drying, the equilibrium moisture content was regarded as zero according to (Maskan, 2000; Alibas, 2006).

The energy consumption of microwave drying was derived from Eq. (3) (Torki-Harchegani, 2016):

$$E_t = P.t \qquad (3)$$

Where E_t is the total amount of energy consumed per drying period (W.h), P is the microwave output power (W) and "t" is the drying time in hours (Hebbar et al., 2004).

There have been several models proposed to predict the moisture loss over time for different food products. In the present study, seven different thin-layer drying models were selected because they are among the most widely employed. In these models, regression analysis was performed by relating the dimensionless moisture ratio (MR) to the drying time for microwave powers of 360, 450, 540, 720, and 900 W. They are described in Table 1 with their names, equations, and references.

Table 1. The mathematical thin-layer models applied to the drying curves of mallow leaves

Model	Equation	Reference
Page’s	$MR = \exp(-k \cdot t^{n})$	Mundada et al. (2010)
Regression	$MR=\exp(-(bt+at^{2}))$	Shi et al. (2008)
Logarithmic	$MR = a \cdot \exp(-k \cdot t) + b$	Ertekin and Yaldiz (2004)
Henderson and Pabis	$MR = a \cdot \exp(-k \cdot t)$	Togrul and Pehlivan (2004)
Lewis	$MR=\exp(-kt)$	Roberts et al. (2008)
Wang and Singh	$MR = 1 + a \cdot t + b \cdot t^{2}$	Ozdemir and Devres (1999)
Midilli	$MR = a \cdot \exp(-k \cdot t^{n})+b.t$	Akar et al. (2019)

For fitting the above models to experimental data, Matlab 2019a (Mathworks Inc., Natick, MA) was used. The coefficient of determination (R^2), root mean square error (RMSE), and sum of squared errors (SSE) were used to compare models, and their mathematical equations are given in Eqs. (4) to (6).The model predicted drying behavior better when SSE and RMSE were close to zero and R^2 was high (Aral and Bese, 2016).

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(MR_{pre,i}-MR_{exp,i})^2}{\sum_{i=1}^{N}(\overline{MR}_{pre,i}-MR_{exp,i})^2} \qquad (4)$$

$$SSE = \sum_{i=1}^{N}(MR_{exp,i} - MR_{pre,i})^2 \qquad (5)$$

$$RMSE = \left(\frac{1}{N}\sum_{i=1}^{N}(MR_{pred,i} - MR_{exp,i})^2\right)^{\frac{1}{2}} \qquad (6)$$

Where $MR_{exp,i}$ and $MR_{pre,i}$ are the experimental and predicted moisture ratios at time i, respectively.

2.4. Determination of the effective moisture diffusivity

Fick's diffusion equation can be used to describe the drying characteristics of agricultural products in the falling rate period. Assuming a uniform initial moisture distribution, Eq. (7) can be used for samples with slab geometry (Taghinezhad et al., 2021b).

$$MR = \frac{8}{\pi^2}\exp\left[-\pi^2 \frac{D_{eff}}{4L^2} \times t\right] \qquad (7)$$

In this formula, t, D_{eff}, and L are the drying time (s), the effective diffusivity (m^2/s), and the half thickness of the slab (m), respectively. A digital caliper was used to measure the mean thickness of mallow leaves and resulted in a value of 0.00028 m

For the purpose of obtaining effective diffusivity, Eq. (7) can be written in the straight-line form as follows (Al-Harahsheh et al., 2009; Dadali et al., 2007; Wang et al., 2007);

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

By plotting experimental drying data in terms of Ln (MR) versus time and then calculating the slope of linear fits, the effective moisture diffusivity was determined (Seyedabadi et al., 2017).

3. Results and discussions

It is possible to investigate the effect of microwave power on drying processes by using the variation of moisture ratio over time. A total of five microwave powers were used in this study: 360, 450, 540, 720, and 900 W. The mass of the samples was 30 g. Figure 1 shows the variation of the moisture ratio (dry basis) over time. As moisture content decreases with time in the drying process, the process is characterized by a progressive reduction in moisture content. At the beginning of the drying process, products have a high moisture content and are losing moisture rapidly. When the moisture content of the product is reduced during the drying process, the natural rate of drying is decreased because the microwave power is absorbed by the product depending on its moisture content. The finding is similar to that of several other studies (Wang et al., 2007; Panchariya et al., 2002; Soysal, 2004).

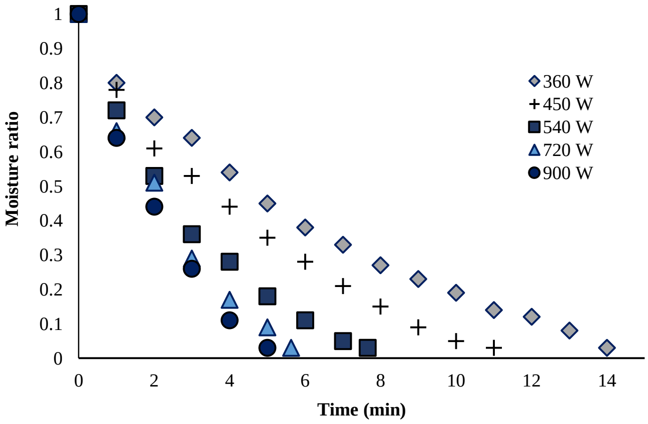

Figure 1. Variation of moisture ratio vs. time during drying of mallow leaves in different microwave powers

Under microwave power levels of 360, 450, 540, 720, and 900 W, the mallow leaves required 35, 19, 14, and 8 minutes to reach the final moisture content, respectively. With the microwave power of 360 W, moisture content decreases gradually, while it decreases dramatically with the microwave power of 900 W. In fact, the microwave power increases the thermal gradient within the sample, thereby increasing the moisture evaporation rate. Thus, the drying time is decreased. There are several authors who have reported similar findings for various foods (Dadali et al., 2007; Al-Harahsheh et al., 2009; Wang et al., 2007).

In addition, it was found that by using 900 W instead of 360 W microwave power, the drying time could be decreased by as much as 64%.

Figure 2 shows the drying energy consumption in Watt-hours (W.h) for different microwave power levels for 30 g mallow leaves.

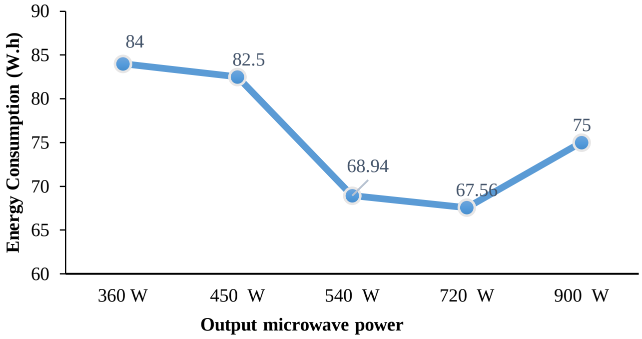

Figure 2. The drying energy consumption (W.h) of mallow leaves in different microwave powers

Table 2. The statistical analysis of fitted models for drying of mallow leaves with various microwave powers.

Power	Model	R^2	RMSE	SSE
360 W	Regression	0.9403	0.0706	0.0649
	Page's	0.9903	0.0284	0.0105
	Henderson and Pabis	0.9896	0.0295	0.0113
	Lewis	0.9803	0.0285	0.0114
	Midilli	0.9976	0.0142	0.0022
	Logarithmic	0.9956	0.0191	0.0044
	Wang and Singh	0.9864	0.0337	0.0148
450 W	Regression	0.9360	0.0775	0.0601
	Page's	0.9889	0.0323	0.0104
	Henderson and Pabis	0.9877	0.0340	0.0115
	Lewis	0.9888	0.0324	0.0115
	Midilli	0.9981	0.0133	0.0014
	Logarithmic	0.9951	0.0214	0.0041
	Wang and Singh	0.9860	0.0363	0.0132
540 W	Regression	0.9366	0.0832	0.0485
	Page's	0.9961	0.0207	0.0030
	Henderson and Pabis	0.9835	0.0297	0.0150
	Lewis	0.9840	0.0256	0.0053
	Midilli	0.9989	0.0110	0.0006
	Logarithmic	0.9987	0.0119	0.0008
	Wang and Singh	0.9923	0.0289	0.0059
720 W	Regression	0.9448	0.0823	0.0339
	Page's	0.9888	0.0370	0.0069
	Henderson and Pabis	0.9817	0.0474	0.0112
	Lewis	0.9843	0.0439	0.0116
	Midilli	0.9854	0.0424	0.0054
	Logarithmic	0.9937	0.0277	0.0031
	Wang and Singh	0.9926	0.0302	0.0046
900 W	Regression	0.9408	0.0883	0.0312
	Page's	0.9908	0.0348	0.0049
	Henderson and Pabis	0.9835	0.0466	0.0087
	Lewis	0.9863	0.0424	0.0090
	Midilli	0.9974	0.0185	0.0007
	Logarithmic	0.9971	0.0194	0.0011
	Wang and Singh	0.9950	0.0256	0.0026

The energy has a minimum value for drying at 720 W. Other microwave powers led to an increase in consumed energy. Based on the assumption that the quality of dried mallow may be negligible, it is recommended that the drying should be done at 720 W of microwave power in order to reduce drying energy consumption.

As shown in Table 2, the parameters R^2, RMSE and SSE are calculated for models fitted to the experimental data of drying mallow leaves with different microwave powers. According to the comparison of these parameters, it was found that, except for the Regression model, all other models were good approximates to predict experiment results, but the logarithmic models were found to have the best fits due to higher R^2 values and lower values of RMSE and SSE.

According to Taheri-Garavand et al. (2011), the Midilli model was capable of illustrating the drying curve of basil leaves under different convective drying conditions. Additionally, another researcher has reported the validity of this microwave-drying model in coriander leaves (Sarimeseli, 2011).

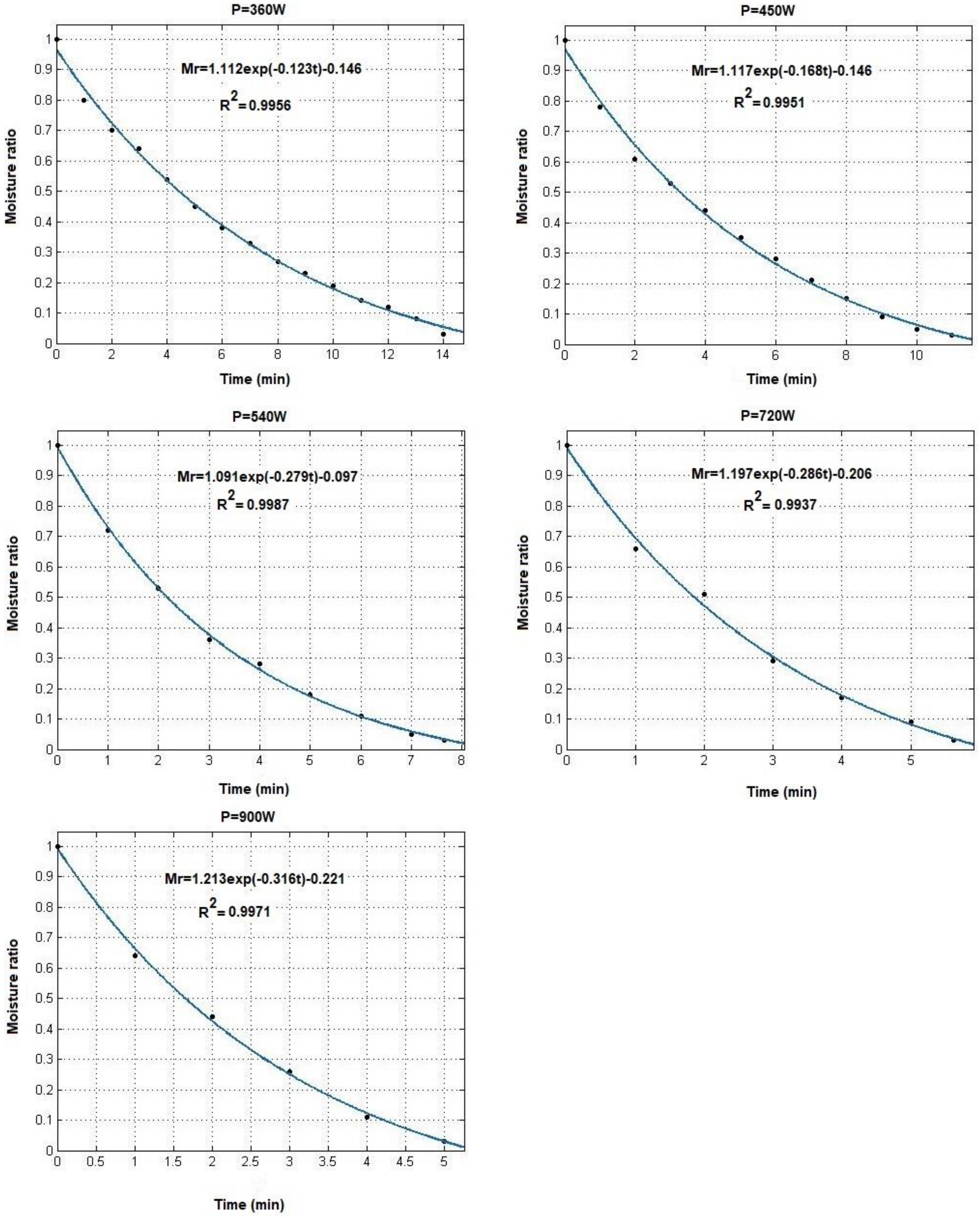

Figure 3. The fitted logarithmic models for drying of mallow leaves in different microwave powers.

Figure 3 shows the logarithmic models that were fitted to the experimental data for different microwave powers. The horizontal axis in the figures has been scaled to facilitate reading. The logarithmic model showed higher coefficient of determination values, which indicate that it is more accurate at predicting drying. Consequently, these models can be used in industrial settings.

Table 3 shows the effective moisture diffusivity values of mallow leaves under 360–900 W microwave powers. These values are found to be within the general range of 10^{-12} to 10^{-6} m^2/s for food materials and agricultural crops (Erbay and Icier, 2010). The minimum and maximum values of the effective moisture diffusivity were 1.098×10^{-10} and 3.532×10^{-10} m^2/s for 360 and 900 W, respectively. This reveals that the moisture diffusivity increases as microwave intensity increases. These findings are in agreement with those of other researchers (Ozbek and Dadali, 2007; Demirhan and Ozbek, 2011).

Table 3. The estimated effective moisture diffusivities for drying of mallow leaves under different microwave powers.

	Microwave power levels				
	360 W	450 W	540 W	720 W	900 W
D_{eff} ($\times10^{-10}$ m^2/s)	1.098	1.582	2.325	3.033	3.532

According to Saramezeli (2011), the effective moisture diffusivity of coriander leaves for microwave powers of 180-360 W ranged from 6.3×10^{-11}-2.19×10^{-10} m^2/s. There have been previously reported results indicating the effective moisture diffusivities of coriander leaves (Sarimesli, 2001) and mint leaves (Ozbek and Dadali, 2007) for microwave drying at 180-900W ranged from 6.3×10^{-11} to 2.19×10^{-10} and 3.982×10^{-11} to 2.073×10^{-10} m^2/s, respectively. Their results are comparable with what we observed in the drying of mallow leaves. Furthermore, microwave drying of foods yielded higher effective diffusivities than convective drying (Erbay and Icer, 2010; Al-Harahsheh et al., 2009).

4. Conclusion

This study investigated a range of microwave power settings for drying mallow leaves. It has been found that the times required to reduce the moisture content of mallow leaves from 6.31 to 0.03 (g water /g dry base) are 14, 11, 7.66, 5.63, and 5 min depending on microwave powers applied of 360, 450, 540, 720, and 900 W. For all microwave powers, the logarithmic model provided the most accurate predictions. Using microwave powers of 720 and 360W, the minimum and maximum values of drying energy were 67.5 and 84.0 watt-hours, respectively. The effective moisture diffusivity was in the range of 1.098×10^{-10} to 3.532×10^{-10} m^2/s for microwave powers of 360 - 900 W.

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