# Effect of Fruit Thickness on Microwave Drying Characteristics of *Myrtus communis L.*

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**ABSTRACT:** *Myrtus communis L. (Myrtle) is an evergreen shrub and its fruit is used in traditional medicine in hypoglycemic, oral, and stomach diseases therapy. To the best of our knowledge there is no report on microwave drying of it. Therefore, this study is aimed to evaluate the effect of microwave power and fruit thickness on drying kinetics, effective moisture diffusivity, activation energy, specific energy consumption, and quality characteristics of Myrtus communis L.. Thus, four thicknesses (5, 7, 9, and 11 mm) of the fruit were dried at microwave power levels of 450, 600, and 750 W. The kinetics study revealed that the Midilli et al. model exhibited the best microwave drying behavior of the samples. Moreover, increasing microwave power and decreasing fruit thickness resulted in a substantial (P<0.05) reduction in drying time and an increase in drying rate. Fruit thickness also showed a significant effect (P<0.05) on effective moisture diffusivity and specific energy consumption, which ranged from* $0.453\times10^{-7}$ *to* $8.91\times10^{-7}$ *($m^2/s$) and 6.98 to 18.13 (MJ/kg water), respectively. In addition, the less fruit thickness, the more moisture diffusivity, and the less activation energy. The calculated activation energies were in the range of 11.46 to 21.76 (W/g). Moreover, as the thickness of the fruit was reduced and the microwave power was increased, the shrinkage ratio of the samples was reduced and their rehydration abilities were enhanced. Finally, it was determined that a microwave power of 750 W and a fruit thickness of 5 mm made better results in terms of quantity and quality parameters.*

**KEYWORDS:** *Drying kinetics; Energy consumption; Microwave drying; Rehydration; Shrinkage.*

## INTRODUCTION

*Myrtus communis L.* (Myrtle) is an evergreen shrub which belongs to Myrtaceae family [1-3]. It grows in Europe, Africa, America and western parts of Asia [1, 4]. It contains some compounds such as caffeic acid, tannins, and coumarins [1, 5, 6]. Its fruits are in spherical shape with dark red to violet color and contains tannin, anthocyanin glucosides, and flavone glycosides [7-9].

Fruits and vegetables are highly perishable to spoilage, because of their high moisture content (about 80%) [10]. Hence, preservation techniques, such as drying are necessary [11]. Drying is the oldest and the most popular storage and preservation method which reduces the water content, restricts microbiological activity, increases the shelf life of food products [12]. The *Myrtus communis L.* fruits, which is the subject of the present study, grows during mid-autumn in south and north of Iran. Therefore, owning to the mentioned medicinal properties, storing of *Myrtus communis L.* fruit for a long time using drying method is a way to use it in other seasons and extending its consumption period.

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Hot air is the oldest drying method which is based on exposing the sample to direct stream of hot air in order to remove moisture [13]. The non-toxicity and uniformity of the products are features of this method, but it is noted that the products have poor quality characteristics such as nutritional content, shape, and color [14, 15]. Therefore, it is needed to develop some new drying methods, such as microwave method to overcome the problems.

Microwave drying is a comparatively inexpensive process in which water moves onto the surface of product due to dipole heating [16]. In plant processing industry, it is interested to use microwave energy to dry the crops due to reduced time and product quality maintenance [17]. Microwave drying induces an efficient energy and homogeneous distribution of it, in comparison with hot air drying, which leads to enhance efficiency of moisture removal [18]. Other benefits of the microwave method are: causing a puffy structure, being high drying rate [19, 20], saving energy [21], and reducing drying space [18]. Accordingly, the selected method in this paper is microwave drying.

Until now microwave method is widely used for drying different agricultural products such as green peas [22], okra [23], green soybean [24], onion slices [25] parsley [26], brown rice [27], and loquat leaves [28]. For example, *Horuz* and *Maskan* [29] studied microwave and hot air drying of pomegranate arils. They evaluated drying behavior, rehydration, shrinkage, bulk density, and color changes of the products and found that in microwave method, drying rate was higher compared to hot air method. They were also observed that shrinkage and drying time was lower compared to hot air method.

In general, determination of the required time and the impact of different conditions are essential in drying process to design and to select a desired dryer. Therefore, it is important to evaluate kinetics of drying. It is significant for drying process optimization, equipment design, and product quality improvement [30, 31]. To the best of our knowledge, there is no information available on the microwave drying behavior of *Myrtus communis L.* Therefore, this is the selected method for drying process in this work.

Accordingly, this work was aimed to study microwave drying of *Myrtus communis L.* under different condition. Thus, drying curves and its kinetics were evaluated. Moreover, the effect of microwave power and fruit thickness were analyzed on quantity and quality characteristics. The target characteristics were effective moisture diffusivity, activation energy, specific energy consumption of method, and quality characteristic including rehydration and ratio of shrinkage.

## EXPERIMENTAL SECTION

### *Material preparation*

The fresh samples of *Myrtus communis L.* (blue-black variety) was purchased from a local market in Lordegan, Iran. It was harvested during the mid-autumn. The samples were washed before starting experiments in order to remove their impurities and pollutions available on the surface of fruits. Since the *Myrtus communis L.* fruits are spherical, their diameter was considered as thickness of the samples. In order to evaluate effect of fruit thickness, they were separated and grouped in four thickness of 5±0.02, 7±0.04, 9±0.05, and 11±0.07 mm. The thickness of samples were measured by a caliper (Ronix, China). Then, the washed and grouped samples were kept in zippered packets and stored in a refrigerator at a temperature of +4±0.5 °C to reduce chemical and physiological changes and prevent moisture loss. Initial moisture content were specified by keeping the samples in an oven dryer (ATRA, ACE400L, Iran) at 105 °C for 10hr [25, 32]; that is, the time which no weight change was detected. The moisture content of fruits was determined %76±0.5 (*g*/*g d.b.*).

### *Experimental set-up and method*

In this study, a programmable microwave apparatus (Samsung, Sami14, 2450 MHz) was used to supply microwave energy of drying process. It had an inside chamber with dimensions of 0.4×0.22×0.4 $m^3$ and consisted of a rotating glass plate with 0.38 m thickness. The microwave power level was changeable in the range of 100 to 900 W.

Microwave energy, in general, eliminates free moisture from the internal space of material, which is known as volumetric heating. It leads to produce more heat in the object and as a result the inside temperature reaches the highest one (refer to Fig. 1). Therefore, moisture inside the sample will be removed quickly [33]. Microwave drying method was carried out at three levels of output power of 450, 600, and 750 W. These powers were selected based on the initial experiments such a way that burning of samples was not observed. For each test, 10±0.03 g

*Table 1: Frequently used mathematical models describing drying kinetics of food materials*

| Model No. | Model name | Model equation | Reference |
|---|---|---|---|
| 1 | Page | $MR = \exp(-k\ t^n)$ | [35] |
| 2 | Logarithmic | $MR = a \exp(-k\ t) + c$ | [25] |
| 3 | Midilli et al. | $MR = a \exp(-k\ t^n) + b\ t$ | [33] |
| 4 | Newton (Lewis) | $MR = \exp(-k\ t)$ | [36] |
| 5 | Henderson and Pabis | $MR = a \exp(-k\ t)$ | [33] |
| 6 | Two-term | $MR = a \exp(-k_1 t) + b \exp(-k_2 t)$ | [33] |
| 7 | Two term exponential | $MR = a \exp(-k\ t) + (1-a) \exp(-k\ a\ t)$ | [32] |
| 8 | Verma et al. | $MR = a \exp(-kt) + (1-a) \exp(-gt)$ | [32] |

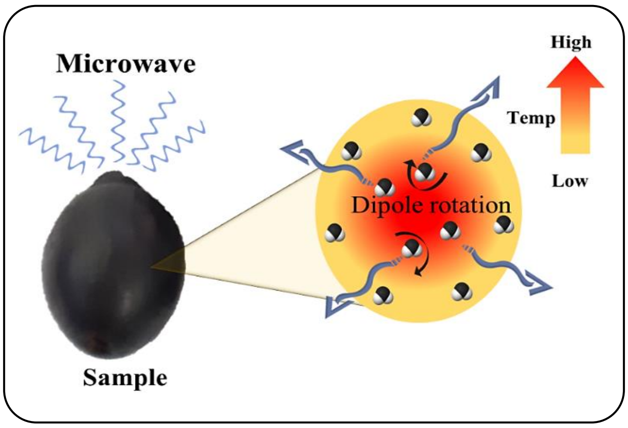


***Fig. 1: Heat and mass transfer direction in Microwave drying Process.***

of the samples with equal thickness was weighted by a digital balance (accuracy 0.001 g, S-ES series, Bell engineering company, Italy) and placed at the center of rotating glass plate of microwave oven. Then, change weight of the fruits was recorded every 30 s by taking out the samples and weighing on a digital balance. The digital balance was located near the microwave device and weighing the samples was done as quickly as possible to avoid weighing errors. Drying process was accomplished until final moisture content of %10±1 (g/g d.b.). All experiments were repeated three times and the mean of data were reported.

### *Mathematical modeling*

To model the drying kinetics behavior of the *Myrtus communis L.* fruits in a mathematical way, 8 widely used thin layer models were investigated. The models are tabulated in Table 1. Here, moisture ratio, *MR*, was defined as [30]:

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

where *M* is moisture content of the fruits (g/g d.b.). The subscripts of *t*, *e*, and *0* denote to at any time, equilibrium, and initial, respectively. Since $M_e << M_t$ and $M_e << M_0$, the value of $M_e$ is negligible [30].

Drying rate, calculated to evaluate drying efficiency, is defined as [34]:

$$\text{Drying rate} = \frac{M_t - M_{t+dt}}{dt} \tag{2}$$

Where $t+dt$ means at time $t+dt$ and $dt$ is time interval (min).

Regression analysis was performed using Sigma Plot (Systat Software, Inc., v.12.3) software to evaluate parameters of the equations. Coefficient of determination ($R^2$) and Root Mean Square Error (RMSE) were measured to find the consistency of models [33]. It is noted, the best model has higher $R^2$-value (closer to one) and lower *RMSE*-value (closer to zero).

### *Effective moisture diffusivity*

Drying process consist of two periods of constant and falling rate [33]. At falling rate period, drying of food material is controlled by internal diffusion phenomenon. Fick's second law of diffusion formulates the phenomenon. It can be used for different geometries including thin layer, cylinder, slab and sphere. The Fick's second law of moisture diffusion is defined as [37]:

$$\frac{\partial MR}{\partial t} = D_{eff} \nabla^2 MR \tag{3}$$

Analytical solution of this equation for spherical geometry of the *Myrtus communis L.* fruits by assuming one dimensional moisture, a uniform moisture distribution, and negligible external resistance is introduced as [37]:

$$MR = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(-n^2\pi^2\frac{D_{eff}\,t}{r^2}\right) \tag{4}$$

Where $r$ is radius of the *Myrtus communis L.* fruits and $D_{eff}$ is effective moisture diffusivity ($m^2/s$). For long time of drying process, only the first term of the series is considered [32, 38]. Hence, a logarithmic form is given as follows:

$$Ln(MR) = Ln\left(\frac{6}{\pi^2}\right) - \frac{\pi^2 D_{eff}\,t}{r^2} \tag{5}$$

Therefore, a straight line can be obtained by plotting ln($MR$) versus $t$ and $D_{eff}$ values calculated using the slope of the line as follows:

$$slope = -\frac{\pi^2 D_{eff}}{r^2} \tag{6}$$

***Activation energy***

Dependence of the effective diffusivity on temperature is described by Arrhenius equation. According to it, activation energy ($E_a$) during falling rate of drying is introduced as follows [32]:

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{RT}\right) \tag{7}$$

Where $E_a$ is the activation energy (kJ/mole), $D_0$ is pre-exponential constant of Arrhenius equation ($m^2/s$), $T$ is the air temperature (K), and $R$ is the universal gas constant (kJ/mole.K). However, in the microwave drying method, the temperature inside the microwave oven chamber cannot be measured exactly. Thus, microwave power level could be applied as an alternative direct parameter instead of temperature [35]. Therefore, *Dadali* and *Özbek* modified this equation and suggested a new formula as [39]:

$$D_{eff} = D_0 \exp\left(-\frac{E_a.m}{P}\right) \tag{8}$$

Where $m$ is the mass of sample (g), $P$ is microwave power (W), and $E_a$ is activation energy (W/g). Its logarithmic form can be written as follows:

$$\ln(D_{eff}) = -E_a\left(\frac{m}{P}\right) + Ln(D_0) \tag{9}$$

Therefore, a straight line can be obtained by plotting $Ln\ (D_{eff})$ versus $\frac{m}{P}$ and activation energy determined by slope of the line.

***Specific Energy consumption***

The specific energy consumption, *SEC*, is expressed as the required energy (kJ) to eliminate 1 kg water from the sample. In this study, it was calculated for different microwave powers and fruit thickness and it defined as follows [40]:

$$SEC = \frac{E_{mec} + E_{th}}{m_w} \tag{10}$$

Where $E_{mec}$ is mechanical energy consumption, $E_{th}$ is thermal energy consumption and $m_w$ is the mass of removed water (kg). It is noted that $E_{mec}$ of microwave oven dryer is negligible compared to $E_{th}$ and $E_{th}$ value can obtained as follows [41]:

$$E_{th} = P \times t \tag{11}$$

Where $P$ is microwave power (W) and $t$ is time ($s$). Therefore, the *SEC* value in microwave drying process can obtained as follows [35]:

$$SEC = \frac{P \times t}{m_w} \tag{12}$$

***Shrinkage ratio***

Volume change of food material upon drying expressed as shrinkage. In this study, it was measured by liquid (toluene in this study) displacement method as reported by *Horuz* and *Maskan* [29]. In order to avoid excessive exposure of samples to solvent uptake, the tests were done as rapidly as possible (less than 15 s). The shrinkage ratio, *S*, was determined as follows [29, 42]:

$$S = \frac{V}{V_0} \times 100 \tag{13}$$

Where $V$ is dried fruit volume (ml) and $V_0$ is the fresh fruit volume (mL).

***Rehydration ratio***

To measure rehydration ratio of dried fruits, a certain amount of the dried *Myrtus communis L.* fruits with the weight of 0.5±0.03 g was immersed in 50 ml of distilled water at 23±0.02 °C and its weight was recorded every 20 min (its weight increases due to the water uptake) until no weight change was observed. The rehydration ratio was calculated by [29, 43]:

$$\text{Rehydration ratio} = \frac{w_t - w_d}{w_d} \times 100 \quad (14)$$

Where $w_d$ and $w_t$ are the fruits weight before and after water uptake (g), respectively.

### *Statistical analysis*

Here, all drying experiments were performed in triplicate and mean of data was reported. The obtained data were analyzed by ANOVA test using software of Minitab v.19 (Minitab, State College, USA). Tukey's comparison test at confidence level of 95% ($P$<0.05) was used to compare the means.

## RESULTS AND DISCUSSION

### *Drying curves*

The fresh *Myrtus communis L.* fruits were dried to an average final moisture ratio, *MR*, of about 0.1 and drying curves were evaluated. Fig. 2 illustrates a typical example of the drying curves for the fruit thickness of 5 mm under different microwave powers. Similar behavior was also observed for all other fruit thickness. Based on the results, the time required to dry the *Myrtus communis L.* fruits with thickness of 5 mm was 9.3, 13.7, and 19.6 min under microwave power of 450, 600, and 750 W, respectively. Statistical analysis showed that at a specific fruit thickness, microwave power had a significant effect ($P$<0.05) on drying time. As indicated in Fig. 2, drying time was reduced significantly by increasing microwave power. It is the results of the more heat absorption due to the higher microwave power which leads to an increase in sample temperature. It also increases heat and mass transfer driving force and drying rate simultaneously, and decreases drying time, as reported in some literature [44, 45]. In terms of the microwave power effect on the drying time, similar behavior were also reported for some food material such as starch [46], purslane leaves [36], hawthorn fruit [47], parsley [26], mango [48], spinach [49] and potato [35].

The main factors affecting the drying time are initial and final moisture contents of the food product, drying

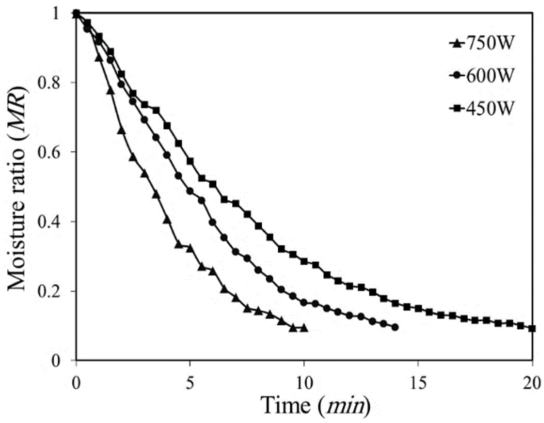


***Fig. 2: Microwave drying curve of Myrtus communis L. fruits at different microwave power and fruit thickness of 5 mm.***

conditions, type of drying system, and inherent characteristics of the food material [35]. Due to existence of the high moisture in fruits and vegetables, water is the major part of dielectric element of the microwave drying and their reaction with microwave energy is very strong [35, 50]. Therefore, as long as the moisture content of these materials is present, the microwave energy is absorbed quickly. Consequently, the microwave energy reduces the drying time in proportion to the amount of moisture remaining in the material [35, 50, 51].

In order to investigate the effect of fruit thickness, the drying curves at a specific power at different thickness are plotted in Fig. 3. Fig. 4 also compares the drying time of all experiments. Maximum drying time was 40.3 min, belonged to the sample with thickness of 11 mm dried at 450 W microwave power. Minimum drying time was 9.3 min, obtained at microwave power of 750 W and fruit thickness of 5 mm which is reduced %79.18 compared to the maximum drying time. Statistical analysis showed that fruit thickness had a significant effect ($P$<0.05) on the drying time and reducing thickness of *Myrtus communis L.* fruits in the range of 5 to 11 mm significantly reduced microwave drying time. This can be justified in this way that the less sample thickness, the less distance of mass transfer from the interior to its surface which causes to reach the moisture to the surface of sample in a short time, resulting in reduce drying time. Several researchers reported similar behavior in terms of the effect of sample thickness on drying time. *Azimi-Nejadian* and *Hoseini* [35] studied effect of potato slices thickness (3.5 to 9 mm) on drying time under microwave drying. They reported that the drying time was decreased with decreasing

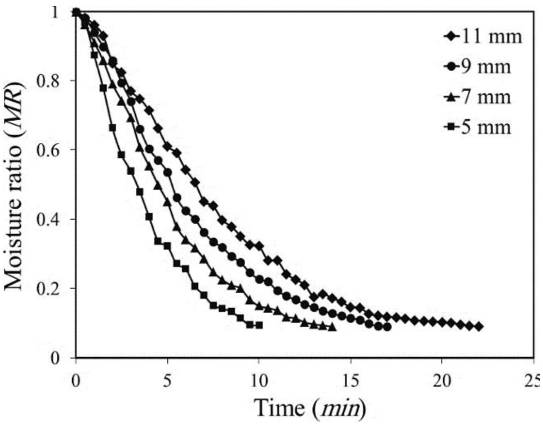


**Fig. 3: Microwave drying curves of *Myrtus communis L.* fruits at different thickness, dried at microwave power of 750 W.**

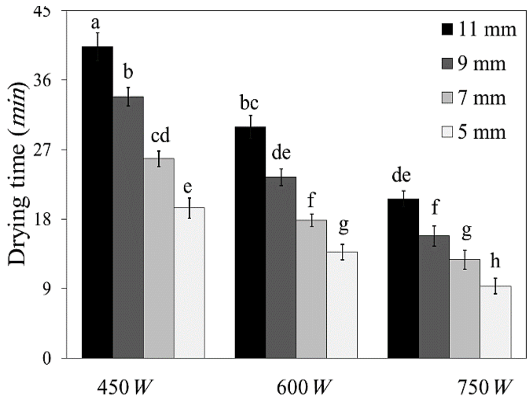


**Fig. 4: Microwave drying time of *Myrtus communis L.* fruits at different thickness and different power levels.**

(a) (b)

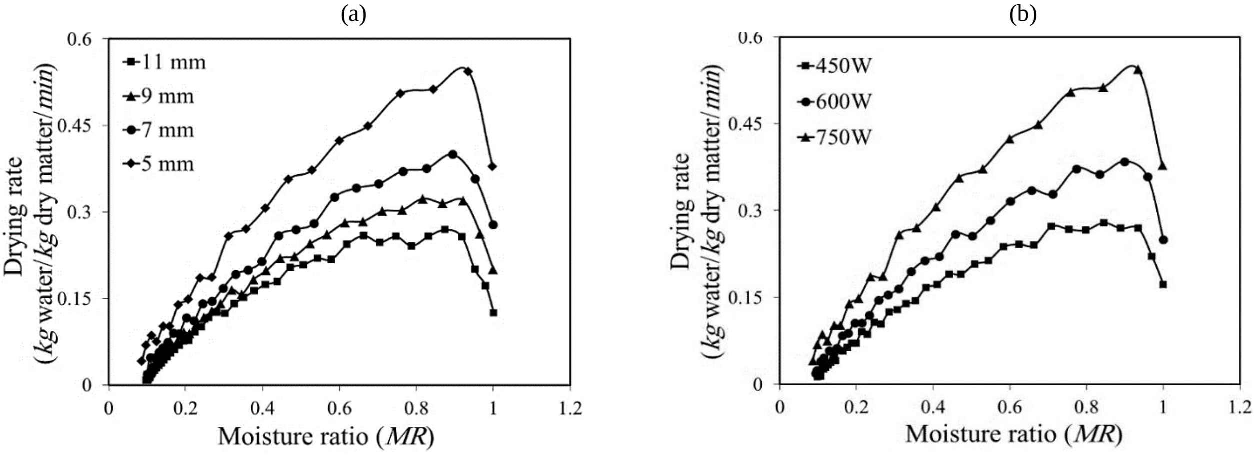


**Fig. 5: Microwave drying rate of *Myrtus communis L.* fruits at a) different thickness under microwave power of 750 W and b) different power levels at fruit thickness of 5 mm.**

thickness in microwave power range of 200-900 W [35]. In another study, *Süfer et al.* [51] examined effect of onion slices thickness (3 to 7 mm) on drying time at microwave power range of 200-900 W. They indicated that the more onion slices thickness, the more drying time [51]. Similar results were also reported for carrot [52], apple slices [53], and elephant foot yam [54].

In addition, drying rates of *Myrtus communis L.* fruit were calculated. A certain number of them are plotted in Fig. 5 against moisture ratio value (*MR*). Similar behavior was also observed for all other operating conditions. As it is obvious, drying rate increased by increasing microwave power and decreasing the fruit thickness. Similar result was also reported for carrot [52]. The maximum drying rate was obtained at highest microwave power level of 750 W and lowest fruit thickness of 5 mm. The amount of microwave energy absorption by food products depends on its moisture content. In the initial stage of the microwave drying, due to high moisture content of samples, the drying rate is high and a great energy is absorbed by the water on the surface of product. This leads to an increase in the temperature of samples. As the process continues, the moisture content of the product decreases and the product surface dries. Subsequently heat penetration inside the samples through dried layer is reduced. It leads to less microwave energy absorption and reduced drying rate. This is in agreement with the results of some researchers [55, 56]. Besides, drying process occurred in falling rate period and it is not observed any constant drying rate period for microwave drying of *Myrtus communis L.* at any of the treatments. This behavior proves that diffusion was dominant mechanism for water removal from samples.

### Mathematical modeling of drying behavior

The Moisture Ratio (MR) values obtained from the experiments were fitted to 8 thin layer drying models listed in Table 1. The results of the fitting are given in Table 2. The suitability of the models was investigated in terms of *RMSE* and $R^2$ values. $R^2$ values were high enough ($R^2$>0.97) for all drying conditions which indicates suitability of all models to describe microwave drying. The average values of *RMSE* and $R^2$ were in the ranges of 0.973-0.999 and 0.013-0.154, respectively. The best model to describe microwave drying behavior of *Myrtus communis L.* fruits was introduced based on the lowest *RMSE* and the highest $R^2$ values.

According to the results, *Midilli et al.* model was the best one to model microwave drying of *Myrtus communis L.* fruits in microwave power range of 450 -750 W and fruit thickness of 5-11 mm. It is expressed as follows:

$$\mathrm{MR} = \mathrm{a}\exp\left(-\mathrm{kt}^{\mathrm{n}}\right)+\mathrm{bt} \quad (15)$$

where the estimated parameters of the model are *n* and *a*, dimensionless drying constants, and *k*, drying constant. These parameters are bolded in Table 2.

*Midilli et al*. model was also successfully applied to dry several other food material under different drying methods such as microwave-hot air drying of oyster mushroom [57] and Gundelia tournefortii L. [33]; and microwave drying of fish, chicken and beef samples [34], pre-gelatinized starch [46], onion slices [51], Gundelia tournefortii L. [58]. The fitted drying curves of samples to *Midilli et al.* model are illustrated in Fig. 6. The result indicates that *Midilli et al.* model is suitable in describing microwave drying characteristics of *Myrtus communis L.* fruits.

### Evolution of effective moisture diffusivity

Effective moisture diffusivity may include vaporization, liquid and vapor diffusion, condensation and other mass transfer phenomena. On the other hand, there is not enough information about the mechanism of moisture transfer within food material during the drying process. Thus, effective moisture diffusivity is introduced to demonstrate the overall transfer coefficient of moisture within food material [23]. In this study, effective moisture diffusivity ($D_{eff}$) values were calculated by slope method using Eq. (6) at different operating conditions. The results are shown in Fig. 7. According to the results, $D_{eff}$ values varied from $0.453\times10^{-7}$ to $8.91\times10^{-7}$ ($m^2/s$) which are within the given overal range of $10^{-11}$ to $10^{-6}$ ($m^2/s$) for food material [54, 59]. Generally, the more microwave power, the more $D_{eff}$ values of *Myrtus communis L.* fruits. The increase was related to heating energy enhancement due to microwave power increment, which leads to an increase in the activity of water molecules. Similar behavior was also reported for some other food material such as potato slices [35], carrot pomace [60], elephant foot yam [54], and okra [23] in term of the effect of microwave power on the effective moisture diffusivity. However, according to statistical analysis, microwave power had no significant effect ($P$>0.05) on $D_{eff}$ at a certain thickness. In addition, $D_{eff}$ values of *Myrtus communis L.* fruits increased with decreasing fruit thickness which is in agreement with the result of *Abano et al.* (2019) for carrot pomace [60]. Moreover, at a certain microwave power, fruit thickness had a significant effect ($P$<0.05) on $D_{eff}$ and it increased significantly with decreasing fruit thickness. The differences between these results can be related to the differences in food characteristics, drying methods, geometric of samples, dryer type, and calculation method [33, 35].

### Evolution of activation energy

The minimum required energy to initiate moisture diffusion is called activation energy ($E_a$). It was calculated for all microwave power levels and fruit thickness. The results showed that $E_a$ values of *Myrtus communis L.* fruits with thickness of 5, 7, 9, and 11 mm were 11.46, 14.58, 18.24, and 21.76 (W/g), respectively. Generally, lower $E_a$ values means higher mass transfer coefficient. According to the results, the less fruit thickness, the more $D_{eff}$ values of *Myrtus communis L.* fruits resulted in decreasing its activation energy. The results are in good agreement with the range of $E_a$ values of some other food product such as elephant foot yam dried by microwave method (9.23 to 23.47 W/g) [54].

### Specific Energy Consumption (SEC)

*SEC* values of *Myrtus communis L.* fruits to reach a final moisture content of about 0.1 were calculated for all experiments and the obtained results are illustrate

***Table 2: The results of fitting of experimental data of Myrtus communis L. fruits to 8 thin layer drying models.***

| Microwave power | Thickness | Page model | | | | Logarithmic model | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | *k* | *n* | $R^2$ | *RMSE* | *k* | *a* | *c* | $R^2$ | *RMSE* |
| 450W | 5.5*mm* | 0.036 | 1.169 | 0.9925 | 0.116 | 0.056 | 1.104 | -0.049 | 0.9915 | 0.141 |
| | 4.5*mm* | 0.047 | 1.038 | 0.9948 | 0.107 | 0.065 | 0.953 | 0.093 | 0.9961 | 0.113 |
| | 3.5*mm* | 0.034 | 1.148 | 0.9916 | 0.092 | 0.061 | 1.023 | 0.039 | 0.9922 | 0.109 |
| | 2.5*mm* | 0.112 | 0.868 | 0.9925 | 0.088 | 0.133 | 0.797 | 0.219 | 0.9963 | 0.098 |
| 600W | 5.5*mm* | 0.094 | 1.068 | 0.986 | 0.129 | 0.137 | 0.977 | 0.086 | 0.9912 | 0.124 |
| | 4.5*mm* | 0.049 | 1.155 | 0.994 | 0.117 | 0.073 | 1.081 | -0.027 | 0.9921 | 0.117 |
| | 3.5*mm* | 0.046 | 1.149 | 0.997 | 0.110 | 0.054 | 1.192 | -0.167 | 0.9912 | 0.112 |
| | 2.5*mm* | 0.118 | 0.945 | 0.981 | 0.093 | 0.174 | 0.828 | 0.217 | 0.9917 | 0.092 |
| 750W | 5.5*mm* | 0.091 | 1.353 | 0.983 | 0.137 | 0.149 | 1.218 | -0.129 | 0.9788 | 0.145 |
| | 4.5*mm* | 0.078 | 1.387 | 0.989 | 0.129 | 0.111 | 1.377 | -0.303 | 0.9825 | 0.138 |
| | 3.5*mm* | 0.092 | 1.226 | 0.974 | 0.143 | 0.158 | 1.068 | 0.0179 | 0.9756 | 0.083 |
| | 2.5*mm* | 0.126 | 1.091 | 0.991 | 0.122 | 0.162 | 1.006 | 0.032 | 0.9923 | 0.092 |

| Microwave power | Thickness | Midilli et al. model | | | | | | Newton (Lewis) model | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | *a* | *k* | *n* | *b* | $R^2$ | *RMSE* | *k* | $R^2$ | *RMSE* |
| 450W | 5.5*mm* | 1.008 | 0.0304 | 1.318 | 0.0022 | 0.9986 | 0.024 | 0.056 | 0.9854 | 0.128 |
| | 4.5*mm* | 1.005 | 0.0362 | 1.309 | 0.0024 | 0.9995 | 0.015 | 0.052 | 0.9919 | 0.118 |
| | 3.5*mm* | 1.002 | 0.0511 | 1.293 | 0.0028 | 0.9993 | 0.016 | 0.051 | 0.9823 | 0.090 |
| | 2.5*mm* | 0.999 | 0.0723 | 1.278 | 0.0031 | 0.9985 | 0.028 | 0.083 | 0.9828 | 0.087 |
| 600W | 5.5*mm* | 1.006 | 0.0401 | 1.311 | 0.0025 | 0.9976 | 0.035 | 0.108 | 0.985 | 0.130 |
| | 4.5*mm* | 1.004 | 0.0557 | 1.291 | 0.0028 | 0.9992 | 0.047 | 0.071 | 0.9867 | 0.128 |
| | 3.5*mm* | 1.001 | 0.0801 | 1.254 | 0.0031 | 0.9985 | 0.058 | 0.065 | 0.9906 | 0.120 |
| | 2.5*mm* | 1 | 0.112 | 1.237 | 0.033 | 0.9994 | 0.015 | 0.106 | 0.9802 | 0.130 |
| 750W | 5.5*mm* | 1.001 | 0.0574 | 1.384 | 0.0036 | 0.9993 | 0.018 | 0.162 | 0.9736 | 0.102 |
| | 4.5*mm* | 0.999 | 0.0871 | 1.277 | 0.035 | 0.9989 | 0.047 | 0.147 | 0.9837 | 0.108 |
| | 3.5*mm* | 1.002 | 0.0118 | 1.231 | 0.0033 | 0.9995 | 0.016 | 0.137 | 0.9789 | 0.123 |
| | 2.5*mm* | 0.998 | 0.171 | 1.219 | 0.0031 | 0.9989 | 0.063 | 0.146 | 0.9889 | 0.125 |

***Table 2 (continue): The results of fitting of experimental data of Myrtus communis L. fruits to 8 thin layer drying models.***

| Microwave power | Thickness | Henderson and Pabis model | | | | Two-term model | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | k | a | $R^2$ | RMSE | a | $k_1$ | b | $k_2$ | $R^2$ | RMSE |
| 450W | 5.5mm | 0.061 | 1.061 | 0.9954 | 0.116 | 0.530 | 0.061 | 0.530 | 0.061 | 0.9954 | 0.116 |
| | 4.5mm | 0.054 | 1.028 | 0.9961 | 0.114 | 0.514 | 0.054 | 0.514 | 0.054 | 0.9941 | 0.114 |
| | 3.5mm | 0.056 | 1.057 | 0.9924 | 0.109 | 0.528 | 0.056 | 0.528 | 0.056 | 0.9924 | 0.120 |
| | 2.5mm | 0.079 | 0.972 | 0.9856 | 0.125 | 0.486 | 0.079 | 0.486 | 0.079 | 0.9856 | 0.126 |
| 600W | 5.5mm | 0.114 | 1.044 | 0.9895 | 0.126 | 1.058 | 0.120 | 1.097 | -0.610 | 0.9943 | 0.102 |
| | 4.5mm | 0.077 | 1.057 | 0.9951 | 0.107 | 0.528 | 0.077 | 0.528 | 0.077 | 0.9951 | 0.107 |
| | 3.5mm | 0.069 | 1.037 | 0.9959 | 0.103 | 0.518 | 0.069 | 0.518 | 0.069 | 0.9959 | 0.094 |
| | 2.5mm | 0.107 | 1.004 | 0.9803 | 0.093 | 0.007 | -0.428 | 1.034 | 0.123 | 0.9961 | 0.113 |
| 750W | 5.5mm | 0.185 | 1.108 | 0.9757 | 0.146 | 0.554 | 0.185 | 0.554 | 0.185 | 0.9757 | 0.149 |
| | 4.5mm | 0.168 | 1.101 | 0.9774 | 0.142 | 0.550 | 0.168 | 0.550 | 0.168 | 0.9774 | 0.145 |
| | 3.5mm | 0.1531 | 1.083 | 0.9754 | 0.132 | 0.542 | 0.153 | 0.542 | 0.153 | 0.9754 | 0.094 |
| | 2.5mm | 0.153 | 1.033 | 0.9923 | 0.081 | 0.516 | 0.153 | 0.516 | 0.153 | 0.9923 | 0.123 |

| Microwave power | Thickness | Two term exponential model | | | | Verma et al. model | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | a | k | $R^2$ | RMSE | a | k | g | $R^2$ | RMSE |
| 450W | 5.5mm | 1.719 | 0.0807 | 0.9941 | 0.114 | 1.089 | 0.063 | 1.179 | 0.9921 | 0.108 |
| | 4.5mm | 1.341 | 0.0578 | 0.9945 | 0.118 | 1.034 | 0.054 | 3.405 | 0.9945 | 0.093 |
| | 3.5mm | 1.691 | 0.0728 | 0.9885 | 0.124 | 1.082 | 0.057 | 1.189 | 0.9951 | 0.086 |
| | 2.5mm | 0.262 | 0.225 | 0.9946 | 0.115 | 0.003 | -0.211 | 0.093 | 0.9966 | 0.098 |
| 600W | 5.5mm | 1.477 | 0.129 | 0.9856 | 0.087 | 1.059 | 0.116 | 5.417 | 0.9909 | 0.124 |
| | 4.5mm | 1.699 | 0.100 | 0.9939 | 0.119 | 1.091 | 0.08 | 1.125 | 0.9968 | 0.091 |
| | 3.5mm | 1.683 | 0.092 | 0.9943 | 0.111 | 1.090 | 0.074 | 0.516 | 0.9981 | 0.109 |
| | 2.5mm | 1 | 0.106 | 0.9802 | 0.131 | 5.768 | 0.105 | 0.105 | 0.9733 | 0.135 |
| 750W | 5.5mm | 1.966 | 0.268 | 0.9873 | 0.093 | 1.275 | 0.215 | 1.391 | 0.9925 | 0.127 |
| | 4.5mm | 1.965 | 0.249 | 0.9918 | 0.085 | 1.283 | 0.199 | 1.158 | 0.9947 | 0.121 |
| | 3.5mm | 1.836 | 0.212 | 0.9742 | 0.154 | 1.160 | 0.166 | 1.980 | 0.9849 | 0.134 |
| | 2.5mm | 1.574 | 0.188 | 0.9909 | 0.123 | 1.055 | 0.158 | 3.510 | 0.9941 | 0.119 |

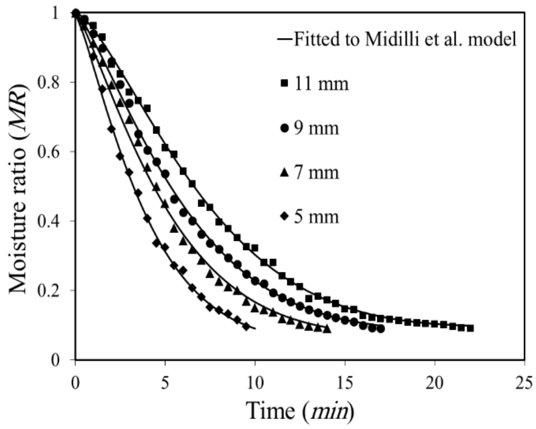


*Fig. 6: Experimental moisture ratio and predicted values by Midilli et al. model for Myrtus communis L. fruits at different thickness and microwave power of 750 W.*

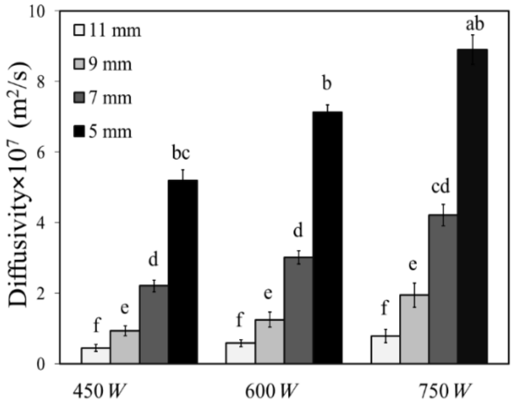


*Fig. 7: Effective moisture diffusivity values ($D_{eff}$) of Myrtus communis L. fruits at different microwave powers and fruit thickness.*

in Fig. 8. They were in the range of 6.98 to 18.13 (MJ/kg water). The minimum value was belonged to samples dried under microwave power level of 750 W with fruit thickness of 5 mm. The maximum value was obtained for the samples dried under microwave power level of 450 W with fruit thickness of 11 mm. According to statistical analysis, at a certain thickness, microwave power had no significant effect ($P$>0.05) on energy consumption. However, as microwave power increased (in the range of 450 to 750 W), energy consumption slightly increased which is due to lower drying time at lower microwave power. It indicates that longer drying time consumes more energy which is in agreement with the results of literature in terms of the effect of microwave power on the specific energy consumption of food material drying [41, 44, 61]. In addition, at a certain microwave power, fruit thickness had a significant effect ($P$<0.05) on specific energy consumption. *SEC* values of *Myrtus communis L.* fruits were significantly decreased with decreasing fruit thickness (in the range of 5 to 11 mm) under a specific microwave power which is due to the lower drying time at lower fruit thickness.

In microwave drying process, the energy of the microwave waves penetrates into the food material. Then it produces a polarity in water molecules of the material and heats it up. As a result, it significantly improves heating rate and uniforms heat distribution of the material. Consequently, it reduces the required time and energy of the process. similar results have also reported by several researchers [50, 62].

### *Shrinkage ratio*

In order to investigate the effect of operating conditions on product quality, shrinkage ratio of fruit samples was calculated. Generally, shrinkage ratio of samples decreased with increasing microwave power levels and decreasing fruit thickness. This might be due to the lower drying time at higher microwave power and lower fruit thickness, which gives the sample less time to shrink. Moreover, steam puffing that occurs in microwave drying method can be another reason to reduce shrinkage under higher microwave power [63]. In addition, at higher microwave power, evaporation of moisture inside the fruits occurs rapidly. The generated internal vapor pressure by the evaporation prevents the sample shrinkage. Similar behavior has also been observed during drying of some other food products such as kiwifruit [64], Chinese jujube [63], and pomegranate arils [29]. The minimum shrinkage ratio of *Myrtus communis L.* fruits was 21.7% at microwave power of 750 W and fruit thickness of 5 mm and maximum value was obtained 47.8% at microwave power of 450 W and fruit thickness of 11 mm. Accordingly the microwave power of 750 W and fruit thickness of 5 mm improved the shrinkage ratio of samples more than the other conditions.

The amount of shrinkage depends on the drying rate. When a single slice of shrinkable material dries at a slower rate, like fruit dried at lower microwave power and higher fruit thickness in this study, the water content differences between its center and surface is higher. Thus, the material shrinkage is more intense. However, if the samples dry

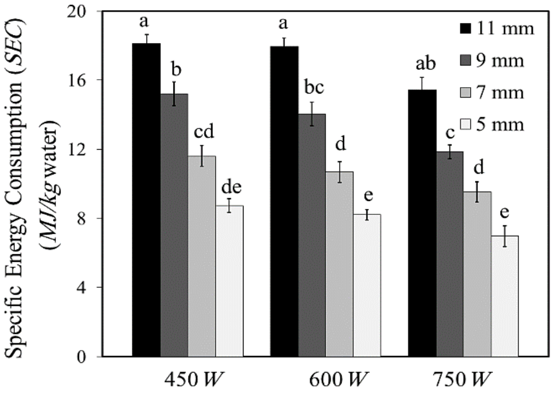


***Fig. 8: Specific Energy Consumption (SEC) of Myrtus communis L. fruits dried at different microwave powers and fruit thickness.***

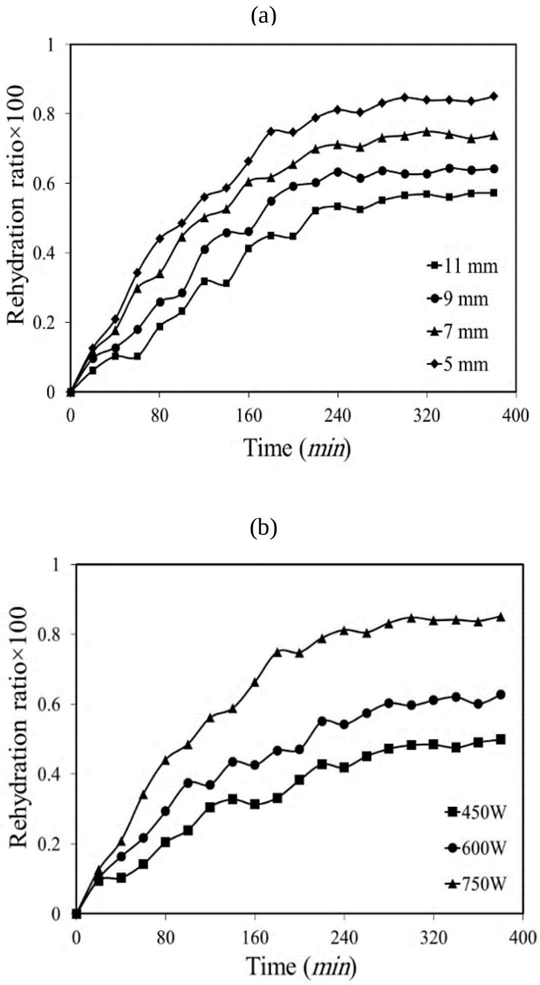


***Fig. 9: Rehydration ratio of Myrtus communis L. fruits at: (a) different fruit thickness under microwave power of 750 W and, (b) different power levels at fruit thickness of 5 mm.***

at higher rate, like fruit dried at higher microwave power and lower fruit thickness in this study, the mentioned differences is lower. Consequently, it cusses to have a dried product with a dimension closer to the one of fresh sample [29]. Therefore, dried samples under higher microwave power and lower fruit thickness (corresponds to higher drying rate) shrunk less than the ones dried at lower microwave power and higher thickness (corresponds to lower drying rate).

***Rehydration ratio***

The study of rehydration ratio is used to obtain food products with much original textural characteristics in the lowest possible time. Two events occur simultaneously during the rehydration process including 1) tumescence of the tissue, and 2) water uptake into the dried material. Since the drying process structurally destructs the food material, and the destruction changes water uptake ability in dried food material [44], therefore, the rehydration ratio of dried food is used as an important quality parameter [65]. It is an index revealing physical and chemical changes and damages caused by drying processes. Rehydration ratios of dried *Myrtus communis L.* fruits were calculated for all experiments. A typical example of them is shown in Fig. 9. Similar behavior was observed for all other experiments. According to Fig. 9 (a) and (b), rehydration ability of the samples was increased by decreasing fruit thickness. It is in agreement with results of carrot [52]. This is because the lower drying time at lower fruit thickness. Moreover, the more microwave power, the more rehydration ability of the dried *Myrtus communis L.* fruits. By exposing the fruits to microwave power for a long time, their internal structure will destruct. It can be attributed to the fact that a lower shrunk structure has greater capacity to water uptake after reconstruction [33].

**CONCLUSIONS**

Effect of microwave power and *Myrtus communis L.* fruit thickness on microwave drying behavior, effective moisture diffusivity, specific energy consumption, and quality characteristics including shrinkage ratio and rehydration were investigated. In the performed kinetics modeling, among eight mathematical models fitted to the experimental moisture ratio data, *Midilli et al.* model had the best fit to show kinetics behavior of *Myrtus communis L.* fruit. The drying time was significantly ($P$<0.05) reduced with increasing microwave power and decreasing fruit thickness. Drying process occurred in falling rate period and there was no constant drying rate period under any of the treatments. Drying rate increased with increasing microwave power and decreasing the fruit thickness. Fruit thickness had a significant effect ($P$<0.05) on effective moisture diffusivity values and increased significantly with decreasing fruit thickness. They varied from $0.453\times10^{-7}$ to $8.91\times10^{-7}$ ($m^2/s$). Energy consumption values were in the range of 6.98 to 18.13 (MJ/kg water) and fruit thickness had a significant effect ($P$<0.05) on energy consumption. Its Minimum value was belonged to samples dried under microwave power level of 750 W and fruit thickness of 5 mm. Generally, shrinkage ratio of samples decreased with increasing microwave power levels and decreasing fruit thickness. Rehydration ability of the samples was increased with decreasing fruit thickness and increasing microwave power. According to the results obtained in this study, it could be concluded that higher microwave power (in the range of 450 to 750 W) and *Myrtus communis L.* fruits with lower thickness (in the range of 5 to 11 mm) results in better results in term of quantity parameters include drying time, drying rate, effective moisture diffusivity, and energy consumption and quality indexes including ratios of rehydration and shrinkage.

**Nomenclature**

| | |
|---|---|
| $D_{eff}$ | Effective moisture diffusivity, $m^2/s$ |
| $D_0$ | Pre-exponential constant of Arrhenius equation, $m^2/s$ |
| $E_a$ | Activation energy, kJ/mol |
| $E_{mec}$ | Mechanical energy consumption |
| $E_{th}$ | Thermal energy consumption |
| k | Drying constant, 1/min |
| m | Sample weight, g |
| MR | Dimensionless moisture ratio |
| $M_t$ | Moisture content (gr water per gr dry matter) at time t |
| $M_{t+dt}$ | Moisture content (gr water per gr dry matter) at time t+dt |
| $M_e$ | Equilibrium moisture content (gr water per gr dry matter) |
| $M_0$ | Initial moisture content (gr water per gr dry matter) |
| n | Dimensionless drying constant |
| P | Microwave power |
| $R^2$ | Coefficient of determination |
| RMSE | Root mean square error |
| R | Universal gas constant, kJ/mol.K |
| S | Shrinkage ratio |
| SEC | Specific energy consumption, kJ/kg |
| T | Air temperature, K |
| t | Time, min |
| V | Dried sample volume, mL |
| $V_0$ | Fresh sample volume, mL |
| $w_d$ | Sample weight before water uptake, g |
| $w_t$ | Sample weight after water uptake, g |

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