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# Drying of pistachios by using a microwave assisted dryer

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**ABSTRACT.** In this study, the drying kinetics of two varieties of Turkey pistachios (Antep- Moisture content (MC) 32.01% (db) and Siirt-MC 41.92% (db)) were investigated by using a temperature and power controlled microwave dryer. The drying experiments were carried out at different temperatures (36, 40 and 48°C), air flow rates (FRs) (0.2, 0.4 and 0.7 $m^3\ h^{-1}$) and microwave power (250, 500 and 750 W). Six mathematical models in the literature were selected to the determination of the goodness of fit based on the experimental data. Among the selected models, the Modified Henderson and Pabis model was found to be the optimum model for describing the drying behavior of Antep pistachios (APs) and Siirt pistachios (SPs). It was found that $R^2$ values for both APs and SPs were found between 0.992 and 0.9999.

**Keywords:** microwave, drying, pistachios, heating velocity.

## Secagem de pistache em secador por microondas

**RESUMO.** Neste estudo, as cinéticas de secagem de duas variedades da pistaches de Turquia (Antep- Teor de Umidade (MC) 32.01% (bs) e Siirt - MC 41.92% (bs) foram investigados usando um secador microondas com temperatura e potência controlada. As experiências de secagem foram executadas em temperaturas diferentes (36, 40 e 48°C), fluxo de massa de ar (FRs) (0.2, 0.4 e 0.7 $m^3\ h^{-1}$) e potência de microondas (250, 500 e 750 W). Seis modelos matemáticos da literatura foram selecionados para a determinação da precisão do ajuste baseado nos dados experimentais. Entre os modelos selecionados, o modelo de Henderson e Pabis Modificado mostrou-se ser o modelo ótimo para descrever o comportamento da secagem de pistaches Antep (APs) e pistaches Siirt (SPs). Valores de R2 entre 0.992 e 0.9999 foram obtidos tanto para APs como para SPs.

**Palavras-chave:** microondas, secagem, pistachios, velocidade de aquecimento.

## Introduction

Microwave heating has been in use in a great deal of industrial sectors such as drying industry, textile industry. Also, it is important to be aware of the latest developments in industrial drying technologies with rising energy cost and to meet consumer demands for higher quality of dried products with less energy cost (BALBAY et al., 2011). In drying industry, microwave heating is a fast, high impact, and economical technique to reduce the moisture content of materials (WANG et al., 2008), which provides uniform distribution of the thermal energy and rapid heat transfer, so MC removes from foods more effectively and faster. High temperature with low relative humidity is preferable for rapid drying process. However, rapid drying process not only reduces the water content, but also affects physical, chemical and biological properties like enzymatic activity, microbial spoilage, hardness, aroma, flavor, color and odor (BARBOSA-CANAVAS; VECA-MERCADO, 1996). Therefore, safe and controllable drying methods are required.

In the literature, several researchers in the developed and developing countries have applied studies on microwave assisted drying of various fruits/vegetables and woods; rapeseeds (LUPINSKA et al., 2009), spinach (DADALI et al., 2007a), potato (ZANG et al., 2006), mushroom (RODRIGUES et al., 2005), okra (DADALI et al., 2007b) and woods (JIA; AFZAL, 2007; LI et al., 2008) and reported that the drying by microwave assisted convective and microwave vacuum methods are more efficient than conventional drying techniques. Kouchakzadeh and Shafeei (2010) studied modeling of microwave-convective drying of two varieties of Iranian Pistachios (Khany-53.8%(db) and Abasaliy-61.2%(db)). MC (Antep- MC 32.01% (db) and Siirt-MC 41.92%(db)) of Pistachios growing in Siirt and Antep, Turkey is found to be different from that of pistachios growing in Iranian Khany and Abasaliy. So, Antep and Siirt pistachios have been dried by microwave oven in different temperatures, and also microwave power, heating velocity and air FRs by experimental study to which we applied the six mathematical models (Table 1).

The pistachio production is mostly seen in countries having a dry climate and arid soil. Iran, United States, Turkey, Italy and Syria are the leaders of pistachio production. Turkey is one of the most pistachio-producer countries with 120113 tons, which makes Turkey the third largest pistachio-producer after Iran (192269 tons) and USA (126100 tons) (FAOSTAT, 2008). Turkish pistachio is primarily exported to six countries: Italy, Greece, Hong Kong, Egypt, Saudi Arabia, and Germany, which represent both the leading export pistachio markets. Pistachio cultivars of Antep and Siirt are the major pistachio varieties that are grown in Turkey. Antep is located 38°28'E and 36°38'N and Siirt is located at 37°56'N and 41°57'E in the southern East part of the Anatolia, Turkey.

The objective of the present study is to investigate the microwave drying characteristics (depending on temperature, microwave power, heating velocity and air FRs) of APs and SPs which are grown in Turkey and to fit the experimental data to different mathematical models available in the literature. Also, it is to investigate the analysis of drying rates for APs and SPs in microwave drying. There is scarce data on drying of pistachios at different temperatures, microwave power, heating velocity and air FRs by using microwave type dryer in the literature.

## Material and methods

### Experimental set-up

Two major varieties of pistachio cultivars, namely Antep and Siirt were used in the experimental study (Figure 1). The initial MCs of pistachios were determined by oven drying at temperature of 130°C for 6h according to standard method ASAE (2005). About 100 g of both APs and SPs was placed in an oven, its final weight was taken, and the difference in weight was taken as water loss and expressed as grams water per gram dry matter. The initial MC for APs was 32.01% (db) and SPs 41.92% (db).

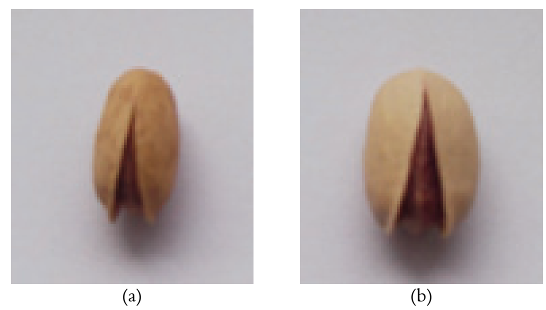


**Figure 1.** The Pistachio varieties; a. Antep, b. Siirt.

The experimental set-up designed and fabricated in the laboratory in order to dry some matter was used in the experiments as seen a solid three dimensional drawing of it in Figure 2. An experimental microwave oven having a maximum power output of 1200 W was used for the drying experiment. A controller is connected to the oven in order to adjust the microwave output power and the time schedule. The dimensions of the inner cavity are 370 mm (W) × 345 mm (D) × 335 mm (H) which makes a volume of about 43 L.

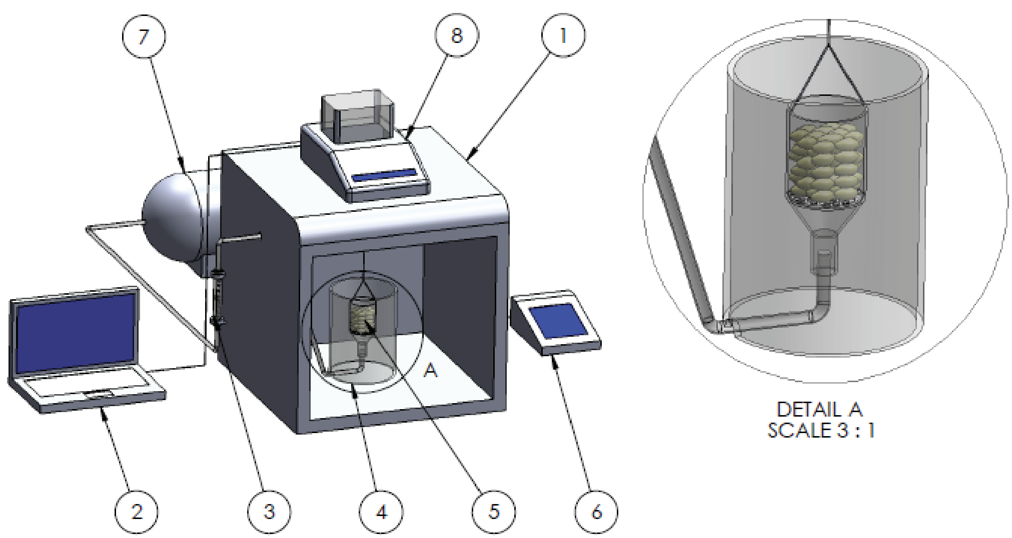


**Figure 2.** The schematic view of experimental set-up: 1. Microwave oven, 2. Notebook, 3. Flow meter, 4. Glass tube, 5. Drying cap, 6. Data input unit, 7. Air compressor, 8.Digital scale.

The system was performed for about some minutes by an electrical heater fan to reach thermal steady state in the absence of pistachios, before each experiment. Air supplied from the compressor was adjusted to the desired FR by a calibrated inlet flow meter according to outlet flow rate before the beginning experiments and fed to the drying cap after being filtered by inlet and outlet filters, respectively. Moisture loss was recorded at 1 or 2 minutes intervals during drying by weighing the pistachios samples inside the drying cap connected to a digital balance having an accuracy of 0.001 g and determined the tare of the drying cap out of pistachios by a rope after turning off flow meter, microwave power and fan. The microwave was applied until the weight of the sample reduced to a moisture content level about 0.01 g. The experiments were conducted to obtain data for moisture content as a function of time. Three microwave power intensities of 250, 500 and 750 W, three temperatures of 36, 40 and 48°C and three air FRs 0.2, 0.4 and 0.7 $m^3$ $h^{-1}$ were studied in microwave drying. The drying was carried out according to the desired power and temperature level, and time interval. The drying experiments were carried out in a laboratory where room temperature and air relative humidity were in the range of 24 ± 1°C and 20 ± 10%, respectively

### Modeling of drying curves

The moisture ratio of pistachios was calculated using the following equation.

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (1)$$

where:

MR is the basis moisture ratio;

$M_e$ equilibrium moisture content (g water $g^{-1}$ dry matter);

Mt, is the moisture content at time t, (g water $g^{-1}$ dry matter);

$M_0$ is initial moisture content (g water $g^{-1}$ dry matter).

The analysis for non-linear regression was performed using MATLAB (version 2009a). In order to select a suitable drying curve, six models in Table 1 were fitted to the experimental MR data. Every one of the drying runs for models were performed at the air FR of 0.4 $m^3$ $h^{-1}$. The correlation coefficient ($R^2$) is one of the primary criteria to select the goodness of fit of these models (MIDILLI; KUCUK, 2003), which has a range from 0 to 1. In addition to $R^2$, sum square error(SSE) and root mean square error (RMSE) are used to determine the quality of the fit (MEZIANE, 2011). The SSE and RMSE can be calculated as follows:

$$SSE = \frac{1}{N}\sum_{i=1}^{N}(MR_{ei} - MR_{pi})^2 \quad (2)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(MR_{ei} - MR_{pi})^2\right]^{1/2} \quad (3)$$

where:

$MR_{ei}$ is the ith experimental moisture ratio;

$MR_{pi}$ is the ith predicted moisture ratio;

N is the number of observations in the model.

The higher $R^2$ values and RMSE values, the better are goodness of fit (BALBAY, 2012; HII et al., 2009; MEZIANE, 2011).

## Results and discussion

### Analysis of drying curves

The variations of MC (db) as a function of drying time (DT) at temperatures of 36, 40 and 48°C with the introduced constant FRs of air of 0.4 $m^3$ $h^{-1}$ are shown in Figures 3 and 4. The figures express behavior of APs and SPs, respectively. The rate of microwave drying is much faster than traditional hot air drying. The most moisture removal takes place at the beginning of the process. Since, the heat generation is the most intense. This is chiefly due to high initially moisture content of pistachios and large latent heat of vaporization of water. Water physically and chemically held in the pistachio matrix requires more energy for its removal compared to liquid water at the same temperature and pressure conditions. High temperature drying accelerates moisture removal compared to low temperature drying. Increasing the temperature gradually increases the MR of samples for the same period of DT and decreases the total DT since heat transfer is increased. At the temperature of 36ºC, the longest drying time is required, while at the temperature of 48ºC the shortest drying time is required. The temperatures have more significant effect on the drying of SPs compared to APs. The MC of the pistachios during drying is very an important parameter in drying technology. A high-quality drying for pistachio is provided with MC 5-7% (db) (BALBAY et al., 2011; KOUCHAKZADEH; SHAFEEI, 2010). This theory is required to the desired level without substantial loss of flavor, color, taste, and nutrients during drying of APs and SPs.

**Table 1.** Mathematical models applied to drying curves.

| No. | Model Name | Model | References |
|---|---|---|---|
| 1 | Newton | $MR = \exp(-kt)$ | (AYENSU, 1997) |
| 2 | Page | $MR = \exp(-kt^n)$ | (DOYMAZ, 2006) |
| 3 | Modified Page | $MR = \exp\left[-(kt)^n\right]$ | (OZDEMIR; DEVRES, 1999) |
| 4 | Henderson and Pabis | $MR = a\exp(-kt)$ | (HENDERSON; PABIS, 1961) |
| 5 | Logarithmic | $MR = a\exp(-kt) + c$ | (TOGRUL, 2005) |
| 6 | Modified Henderson and Pabis | $MR = a\exp(-kt) + b\exp(-gt) + c\exp(-ht)$ | (KARATHANOS, 1999) |

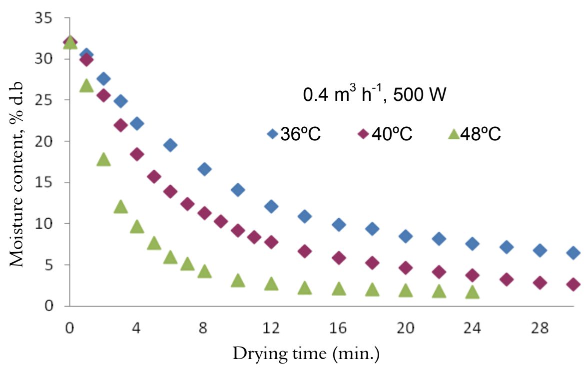


**Figure 3.** Moisture content versus drying time of APs at different temperatures.

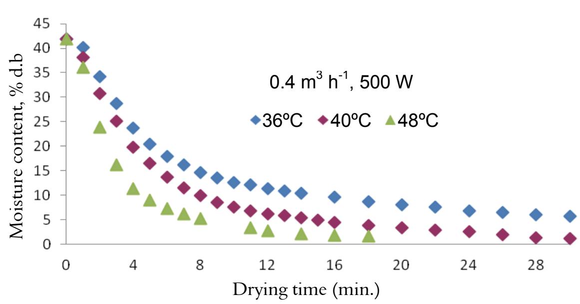


**Figure 4.** Moisture content versus drying time of SPs at different temperatures.

Increasing the microwave power from 250 W to 500 W and then to 750 W has a little impact on the MC level (i.e. 2-3%) during the 5-6 minutes. Figure 5 represents MC change versus time during the drying process of SPs in different air FR(i.e., 0.2, 0.4 and 0.7 $m^3$ $h^{-1}$). Air FRs ranging from 0.2 and 0.4 $m^3$ $h^{-1}$ have more effect on MR decrease in pistachios than those between 0.4 and 0.7 $m^3$ $h^{-1}$. The reason for this is due to the fast drying of SPs by microwave which doesn't let water remove from inside dryer cap seperated from SPs. The FR of air does not have effect on the increase of MR as much as temperature.

Changes in SPs MR when exposed to different heating rates (0.5 and 1°C min.$^{-1}$ respectively) during microwave drying with time-dependent changes are presented in Figure 6. As shown, although moisture ratio decreases with 0.5°C min.$^{-1}$ heating rate in the first 15 minutes in a linear manner, it does not drop linearly with heating rate at 1°C min.$^{-1}$ Moisture ratio for both heating rate (0.5 and 1°C min.$^{-1}$) about 30th minute of microwave drying is found to be between 0-0.2.

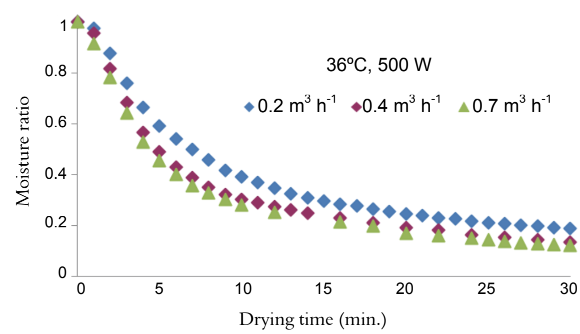


**Figure 5.** Moisture ratio versus drying time of SPs at different air FRs.

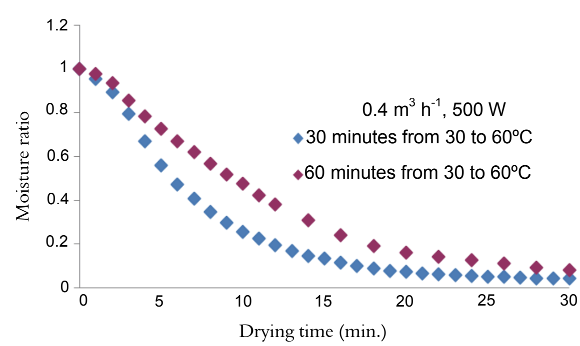


**Figure 6.** Moisture ratio versus drying time of SPs at different heating velocities.

## Modelling of drying curves

The data (MC) obtained from the drying experiments were analyzed using MATLAB software to the 6 mathematical models listed in Table 1. The models were fitted to observed data, and this was performed using goodness of statistical parameters. The values of $R^2$, SSE and RMSE for different temperatures (36, 40 and 48°C) for APs and SPs are presented in Tables 2 and 3, respectively. As can be seen in Table 2, the $R^2$, SSE and RMSE values range from 0.7672 to 0.999, 0.0002003 to 0.04384 and 0.0108 to 0.1396, respectively. At the same time, as Table 3 can be seen values range from 0.7749 to 0.9996, 0.0005422 to 0.3939 and 0.006722 to 0.1483, respectively. Moreover, a good fit observed based on the highest coefficient of determination ($R^2$) and the lowest RMSE values in all cases. The highest $R^2$ values and RMSE values were found by Modified Henderson and Pabis model for APs and SPs. These models have a good agreement with experimental data. The $R^2$ values of the Modified Henderson and Pabis (1961) model for APs varies between 0.9929 and 0.999 and the $R^2$ values of the Modified Henderson and Pabis (1961) model for SPs varies 0.994 and 0.9996.

### Analysis of drying rates

The drying rates of APs and SPs were calculated by the following equation:

$$DR = \frac{M_{t+dt} - M_t}{dt} \quad (4)$$

where:

$M_t$ is the moisture content at time t (g water $g^{-1}$ dry matter);

$M_{t+dt}$: moisture content at t+dt (g water $g^{-1}$ dry matter);

t: drying time (minute).

Drying rates versus drying time of pistachios at the different temperatures are showed in Figures 7-8. As can be seen in figures, during the period of decreasing drying rate, moisture content continuously decreases. The maximum drying rate is observed at the beginning of the process. Towards end of the process, when the drying rate value is completely controlled by internal diffusion, the air FR no longer any effect (LENIGER, 1975). DR increases with the increase in temperature. Because of increasing potential in heat transfer between air and pistachios, evaporation of water inside the pistachios accelerates.

**Table 2.** Statical results of 6 mathematical models at different drying conditions (APs-0.4 $m^3 h^{-1}$, 500 W).

| General model | T °C | Coefficients | $R^2$ | SSE | RMSE |
|---|---|---|---|---|---|
| | 36 | k = 0.07036 | 0.9705 | 0.03716 | 0.04676 |
| Newton | 40 | k =0.1204 | 0.9767 | 0.03743 | 0.04222 |
| | 48 | k =0.2741 | 0.9752 | 0.03252 | 0.04508 |
| | 36 | k = 0.1138, n = 0.8165 | 0.9878 | 0.01534 | 0.03097 |
| Page | 40 | k = 0.1653, n = 0.8508 | 0.9859 | 0.02263 | 0.03364 |
| | 48 | k = 0.3101, n = 0.9076 | 0.9767 | 0.03054 | 0.04513 |
| | 36 | k = 0.06982, n = 0.8165 | 0.9878 | 0.01534 | 0.03097 |
| Modified Page | 40 | k = 0.1205, n = 0.8507 | 0.9859 | 0.02263 | 0.03364 |
| | 48 | k = 0.2752, n = 0.9076 | 0.9767 | 0.03054 | 0.04513 |
| | 36 | a = 0.905, k = 0.06662 | 0.9744 | 0.03228 | 0.9744 |
| Henderson and Pabis | 40 | a = 0.9801, k = 0.1173 | 0.9772 | 0.03654 | 0.04274 |
| | 48 | a = 1.01, k = 0.2773 | 0.9753 | 0.03237 | 0.04646 |
| | 36 | a = 0.8425, c = 0.1802, k=0.1153 | 0.9984 | 0.002015 | 0.01159 |
| Logarithmic | 40 | a = 0.9365, c = 0.09493, k=0.1595 | 0.996 | 0.00647 | 0.01845 |
| | 48 | a = 0.9779, c = 0.05887, k=0.3343 | 0.9927 | 0.009594 | 0.02618 |
| | 36 | a=0.1457, b=-0.2175, c=1.092, g=0.1043, h=0.1088, k=-0.006492 | 0.9984 | 0.002011 | 0.01295 |
| Modified Henderson and Pabis | 40 | a=-1.845, b=0.4236, c=2.467, g=0.3152, h=0.07604, k=0.07556 | 0.9929 | 0.01139 | 0.02668 |
| | 48 | a=0.1788, b=1.089, c=-0.2682, g=0.4962, h=21.69, k=0.05795 | 0.999 | 0.001284 | 0.0108 |

**Table 3.** Statical results of 6 mathematical models at different drying conditions (SPs-0.4 $m^3 h^{-1}$, 500W).

| General model | T °C | Coefficients | $R^2$ | SSE | RMSE |
|---|---|---|---|---|---|
| Newton | 36 | k = 0.1105 | 0.9304 | 0.1011 | 0.06778 |
| | 40 | k =0.1681 | 0.9853 | 0.02602 | 0.03363 |
| | 48 | k =0.2825 | 0.9818 | 0.02669 | 0.03962 |
| Page | 36 | k = 0.1904, n = 0.7526 | 0.9643 | 0.05181 | 0.04967 |
| | 40 | k = 0.1932 , n =0.9267 | 0.9869 | 0.02324 | 0.0325 |
| | 48 | k = 0.2705, n = 1.033 | 0.982 | 0.02645 | 0.04066 |
| Modified Page | 36 | k = 0.1104, n = 0.7526 | 0.9643 | 0.05181 | 0.04967 |
| | 40 | k = 0.1696, n = 0.9267 | 0.9869 | 0.02324 | 0.0325 |
| | 48 | k = 0.2821, n = 1.033 | 0.982 | 0.02645 | 0.04066 |
| Henderson and Pabis | 36 | a = 0.9489, k = 0.1031 | 0.9346 | 0.09498 | 0.06725 |
| | 40 | a = 0.1.009, k = 0.1697 | 0.9854 | 0.02587 | 0.03429 |
| | 48 | a = 1.033, k = 0.2927 | 0.9829 | 0.02514 | 0.03964 |
| Logarithmic | 36 | a = 0.8908, c = 0.1573, k=0.1817 | 0.9909 | 0.01317 | 0.02566 |
| | 40 | a = 0.9878, c = 0.05251, k=0.2028 | 0.9948 | 0.009281 | 0.02102 |
| | 48 | a = 1.013, c = 0.03505, k=0.3251 | 0.9893 | 0.01563 | 0.03228 |
| Modified Henderson and Pabis | 36 | a=0.3644, b=-0.8336, c=-0.198, g=0.2997, h=21.09, k=-0.03272 | 0.9993 | 0.001068 | 0.007925 |
| | 40 | a=0.4071, b=5.5, c=-4.852, g=0.2509, h=0.2454, k=0.09088 | 0.994 | 0.01071 | 0.02439 |
| | 48 | a=0.2613, b=-0.4485, c=1.187, g=2.962, h=0.6017, k=0.1049 | 0.9996 | 0.0005422 | 0.006722 |

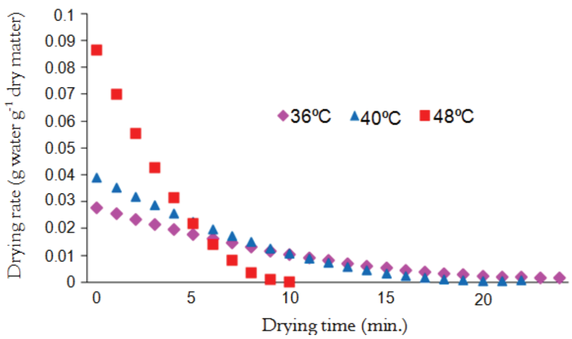


**Figure 7.** Drying rate versus drying time of APs at different temperatures and constant microwave power level (500 W).

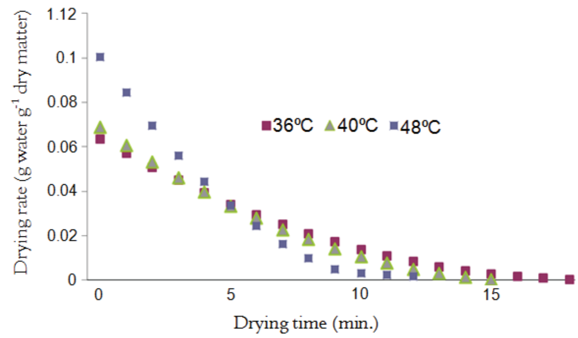


**Figure 8.** Drying rate versus drying time of SPs at different temperatures and constant microwave power level (500 W).

## Conclusion

In this study, mathematical modeling of APs and SPs with initial moisture content of 32.01% (db) and 41.92% (db) was investigated as a function drying conditions in microwave-assisted dryer. The drying experiments were carried out at different temperatures (36, 40 and 48°C), microwave power (250, 500 and 750 W) and air FRs (0.2, 0.4 and 0.7 $m^3$ $h^{-1}$). In order to select a suitable drying curve, six models were fitted to the experimental MR data. Among the mathematical models investigated, the Modified Henderson and Pabis model showed a good agreement with the experimental data. The $R^2$ values of the Modified Henderson and Pabis model for APs and SPs ranges from 0.9929 to 0.999 and 0.994 to 0.9996, respectively. The SSE and RMSE values for APs and APs range from 0.0002003 to 0.3939 and 0.006722 to 0.1483, respectively.

## Nomenclature

db = dry basis
DR = drying rate (g water $g^{-1}$ dry matter min)
DT = drying time
$M_t$ = moisture content at time t (g water $g^{-1}$ dry matter)
$M_0$ = initial moisture content (g water $g^{-1}$ dry matter)
$M_e$ = equilibrium moisture content (g water $g^{-1}$ dry matter)
MC = moisture content
MR = moisture ratio (dimensionless)
$MR_{ei}$ = $i^{th}$ experimental moisture ratio (dimensionless)
$MR_{pi}$ = $i^{th}$ predicted moisture ratio (dimensionless)
min. = minute
N = number of observations
RMSE = root mean square error
$R^2$ = coefficient of determination
SSE = sum square error
t = time (min.)

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