A New Approach for Modeling of Hot Air-microwave Thin Layer Drying of Soybean

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Introduction

- Soybean is one of the most important sources of human and animal nutrition.
- In food industry, soybean is widely used to produce fat products such as refined edible soybean oil.

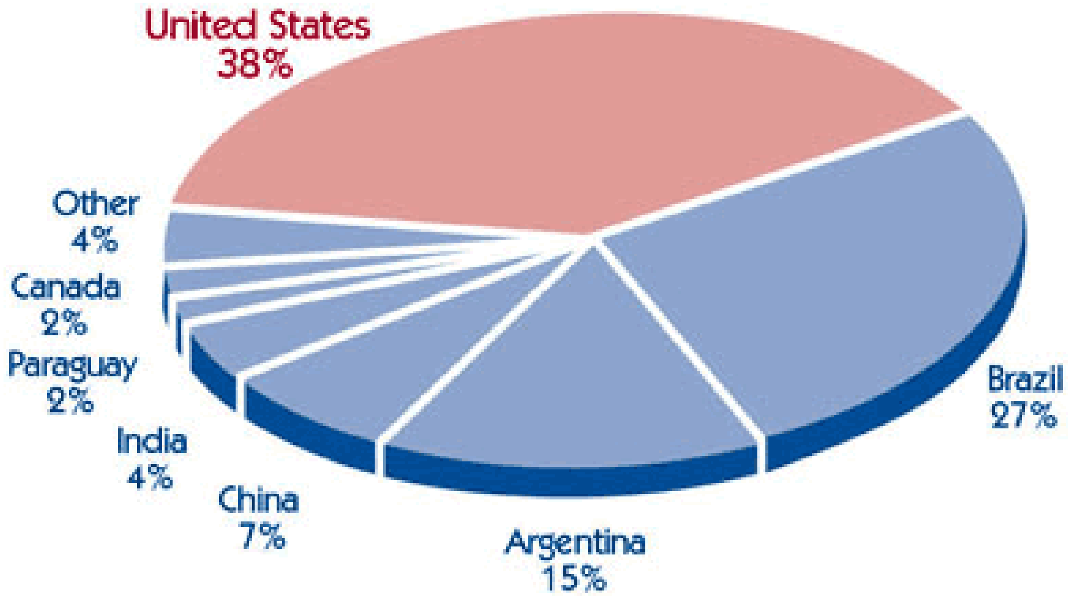
Introduction

- **Soybean oil is the leading vegetable oil traded in the international markets, next only to palm. Soya bean oil constitutes 22.85% of global edible oil .**

- **Soybean accounts for more than 50% of the world's oilseeds production.**

Top Soybean Producing Countries
(million metric tons)

USA	91.42
Brazil	68
Argentina	54
China	14.5
India	75
Paraguay	7.2
Canada	3.5
...	…
Iran	0.14
World total	211



Introduction

- Soybean can be harvested at the moisture content of about 22% (d.b) content.

- For oil extracting or storage of this product the moisture content level should be decreased to 12% (d.b).

Literature review

- Several researchers have worked on the conventional hot air drying of food materials such as
  - Rough rice (Hacıhafızog et al., 2008)
  - Green beans (Doymaz, 2005)
  - Soybeans (Hutchinson & Otten, 1983), Canola (Kitic and Viollaz, 1984)

- All studies show that the application of the conventional drying methods consumes long drying time and high amount of energy.

- Application of microwave heating in conjunction with the hot air drying would lead to a great reduction in drying time and energy.

- By adding microwave heating which leads to uniform generation of heat through the volume of each grain, the drying time would be decreased greatly and the air temperature can be applied to a lower degree.

- This can be seen in the operation of the **microwave-assisted fluidized bed dryers**.

- For mathematical modeling of such dryers, one needs to be aware of the kinetics of hot air-microwave drying of a single kernel which plays the role of an element for bulk grains.

Objectives of the study

- To study the effect of the air temperature and microwave power on the drying kinetics of soybeans.

- Determination of a thin layer drying equation for soybeans undergoing hot air-microwave drying.

- Determination of the effective moisture diffusivity for several drying conditions.

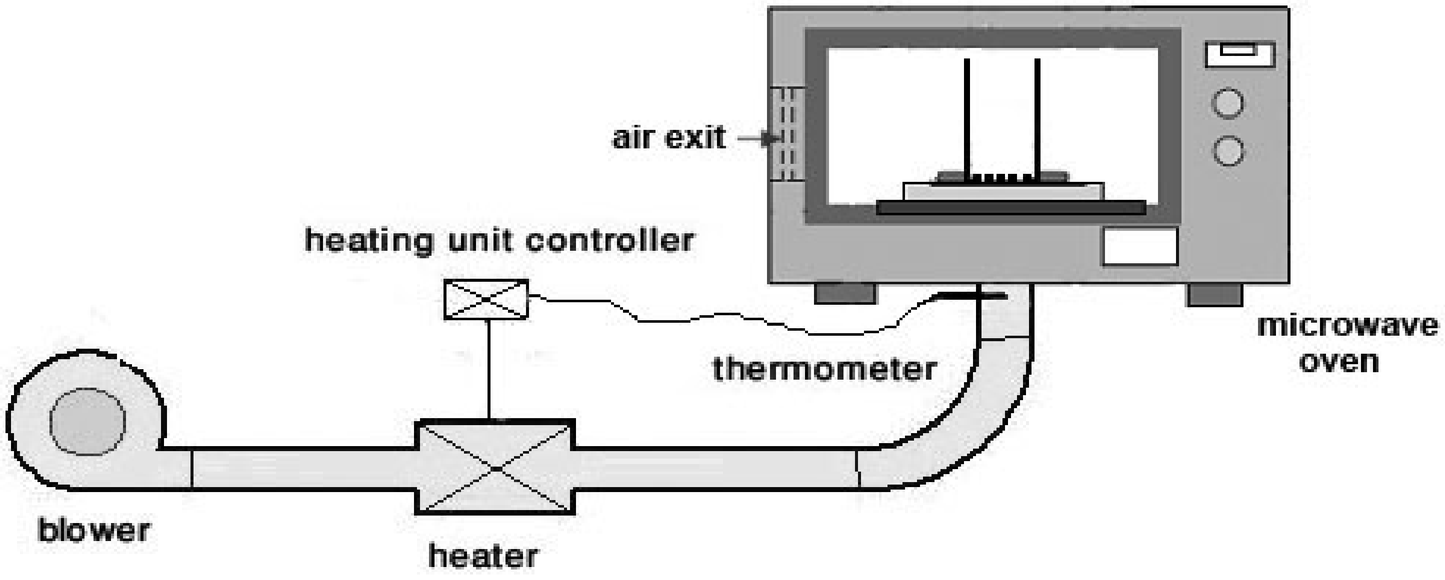
Previous studies

Thin layer drying equation → *The microwave power of magnetron (W).* **?**

Present study

Thin layer drying equation → *The microwave power density (W/g) at the surface of food material*

Material & Methods



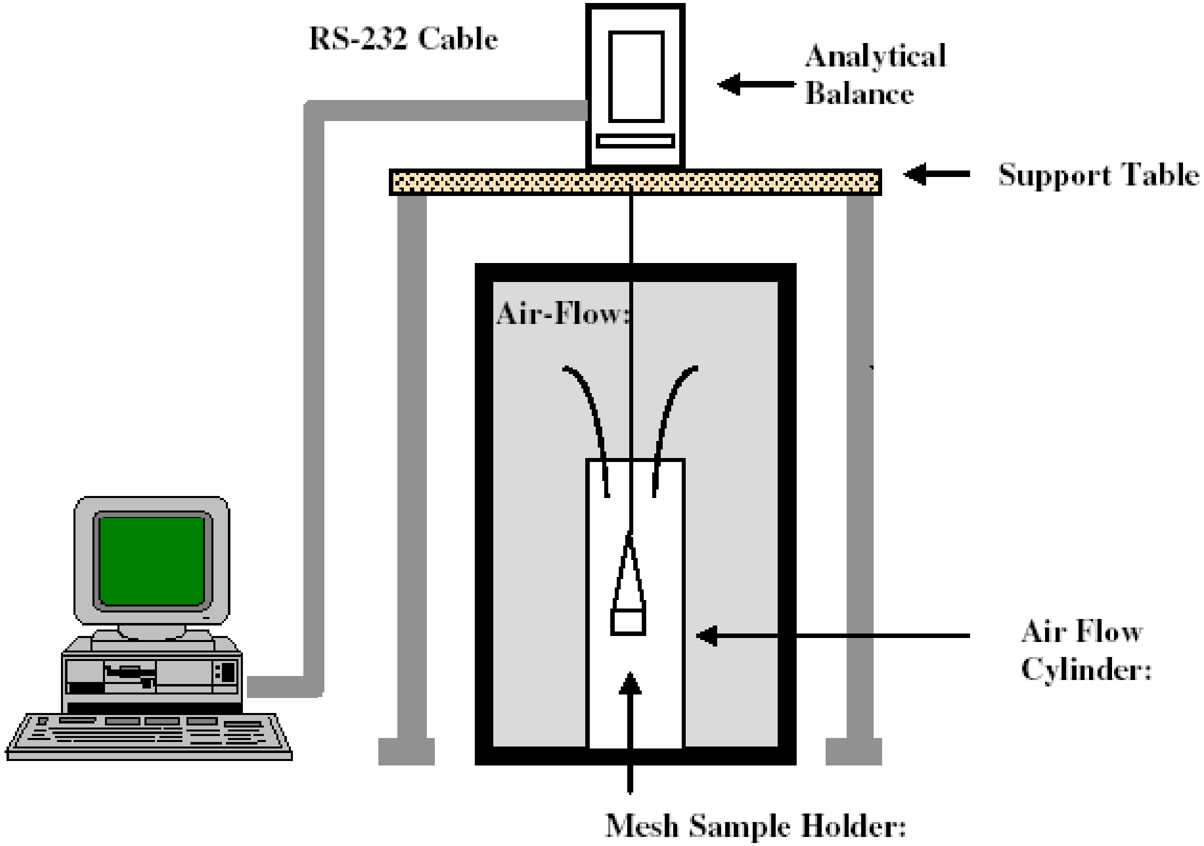
The dryer consists of a **domestic microwave oven** (Type: LG, CC-4284TCR) capable of producing five different output powers with the frequency of 2450 MHz and wavelength of 12.24 cm.

Variable speed fan controlled by an inverter (Type: N50-007SF)

Two **electrical pre-heaters** of 1 kW as well as three 0.5 kW

A **temperature controller** (Type: SAMWON ENG, SU-105IP)

- **7±0.5g of soybean**
  Initial moisture content of 20-21% d.b.



Convective hot-air drying apparatus.

- **using GF-600 having the accuracy of 0.001g**

Measuring instruments

- “Testo 625” with accuracy of ±0.5°C in span of -10-60°C in measuring the temperature and accuracy of ±2.5% RH in span of 0-100% in measuring the relative humidity

- “Testo 425” hotwire air velocity meter with accuracy of 0.03 m/s.

- Throughout all experiments the air velocity try to keep constant at 0.4± 0.1m/s.

Treatments of the experiment

- Temprature: 30, 40, 50 and 60 °C
- Microwave power: 180, 360, 540, 720 and 900 W

Modeling of the Moisture Ratio

$$MR = \frac{M(t) - M_e}{M_0 - M_e}$$

Equilibrium moisture content, M_e, was estimated using Henderson

$$1 - RH = \exp\left(-0.000032\,(492 + 1.8\,T)\,M_e^{1.52}\right)$$

Mathematical models applied to the moisture ratio values

No.	Model Name	Model Eq.	References
1.	Newton	$MR = \exp(-kt)$	Hacıhafizog *et al.* (2008)
2.	Page	$MR = \exp(-kt^n)$	Hacıhafizog *et al.* (2008)
3.	Henderson & Pabis	$MR = a\exp(-kt)$	Chhinman (1984)
4.	Logarithmic	$MR = a\exp(-kt) + c$	Hacıhafizog *et al.* (2008)
5.	Two term	$MR = a\exp(-k_0 t) + b\exp(-k_1 t)$	Henderson (1974)
6.	Modified Two term	$MR = a\exp(-k_0 t) + b\exp(-k_1 t) + c$	Present Study
7.	Verma *et al.*	$MR = a\exp(-kt) + (1-a)\exp(-gt)$	Verma *et al.* (1985)
8.	Midilli *et al.*	$MR = a\exp(-kt^n) + bt$	Midilli *et al.* (2002)

Determination of the Effective Moisture Diffusivity

Fick's law of diffusion:

$$\frac{\partial M}{\partial t} = \nabla^2 (D_{eff} M)$$

where M is the moisture content of grain (kg/kg), t is time (s)
D_{eff} is the effective moisture diffusivity (m^2/s).

Using spherical coordinates, for a constant value of D_{eff} :

$$\frac{\partial M}{\partial t} = \left(D_{eff} \frac{\partial^2 M}{\partial r^2} + \frac{2}{r} \frac{\partial M}{\partial r} \right)$$

The following initials and boundary conditions are usually applied to solve the above Eq.

$$M(r, 0) = M_0 \quad for \quad r < R$$

$$M(r_0, t) = M_e \quad for \quad t > 0$$

The analytical solution →

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

The first term of the series solution →

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

The above Eq. can be written in a linearized form

↓

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

Estimation of the Microwave Power Density

The microwave power density at the surface of grains was determined experimentally using calorimetric method:

$$p_0 = \frac{\rho_w v_w C_w \Delta T_{abs} + h_{fg} \Delta m}{t}$$

The microwave power densities were calculated to be 0.89, 1.6, 3.2, 4.3 and 5.3 W/g

Analysis

- The constants in the models were determined and correlated with drying air temperature and microwave power density.
- non-linear regression analysis were run using SPSS 16 software.

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

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

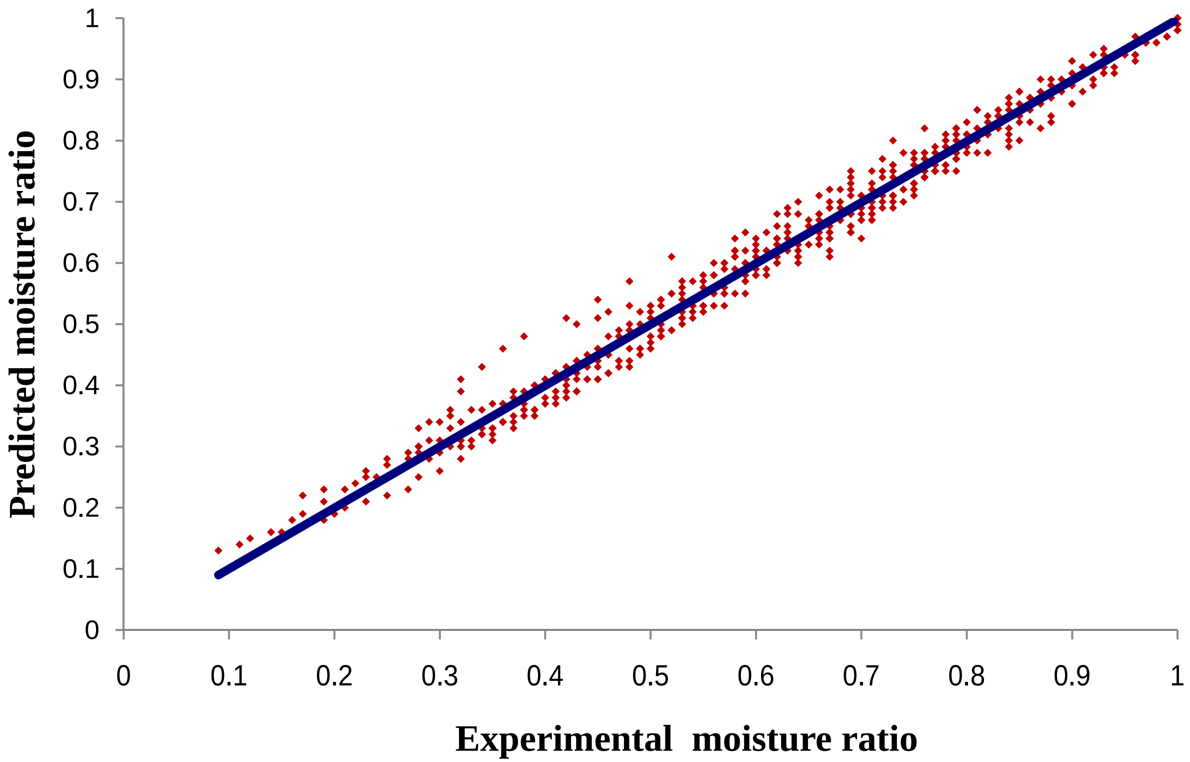
$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{\exp} - MR_{pre}\right)^2\right]^{\frac{1}{2}}$$

Results & Discussion

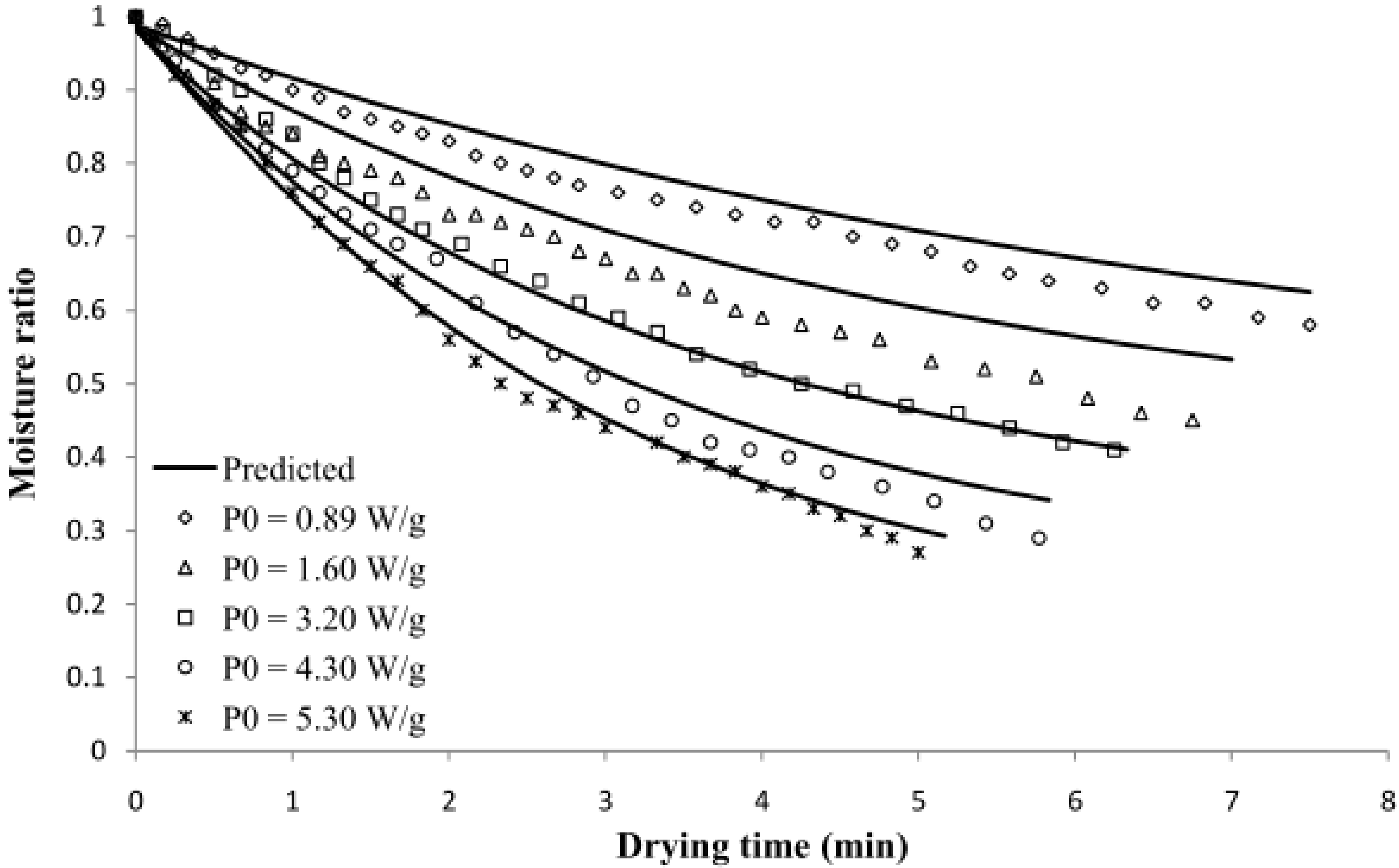
Statistical results of mathematical modeling

No.	Model Name	Model Constants	R^2 (%)	X^2	MBE	RMSE
1.	Newton	$k = 0.002\,T + 0.042\,P_0 - 0.042$	97.0	0.00146	0.00363	0.03813
2.	Page	$k = 0.002\,T + 0.047\,P_0 - 0.005$ $n = 0.004\,T + 0.003\,P_0 + 0.683$	97.9	0.00105	0.00134	0.03217
3.	Henderson & Pebis	$a = 0.000012\,T - 0.001P_0 + 0.975$ $k = 0.002\,T + 0.041\,P_0 - 0.046$	97.3	0.00133	0.00085	0.03634
4.	Logarithmic	$a = 0.004\,T + 0.022\,P_0 + 0.536$ $k = 0.002\,T + 0.063\,P_0 - 0.022$ $c = -0.004\,T - 0.015\,P_0 + 0.418$	98.0	0.00099	0.00008	0.03122
5.	Two term	$a = 0.015\,T - 0.021\,P_0 + 0.062$ $k_0 = 0.0000707\,T + 0.069\,P_0 + 0.101$ $b = -0.014\,T + 0.025\,P_0 + 0.904$ $k_1 = -0.003\,T + 0.034\,P_0 + 0.070$	98.3	0.00085	0.00020	0.02883
6.	Modified Two term	$a = -0.014\,T + 0.202\,P_0 + 0.457$ $k_0 = -0.007\,T + 0.076\,P_0 + 0.248$ $b = 0.021\,T - 0.145\,P_0 - 0.166$ $k_1 = -0.002\,T + 0.159\,P_0 + 0.079$ $c = -0.006\,T - 0.050\,P_0 + 0.665$	98.6	0.00070	0.00025	0.02610
7.	Verma *et al.*	$a = 0.010\,T + 0.044\,P_0 - 0.296$ $k = 0.008\,T + 0.043\,P_0 - 0.442$ $g = 0.004\,T + 0.066\,P_0 - 0.072$	98.1	0.00090	0.00043	0.02978
8.	Midilli *et al.*	$a = -0.001\,T + 0.008\,P_0 + 1.017$ $k = 0.001\,T + 0.005\,P_0 + 0.016$ $n = 0.004\,T - 0.006\,P_0 + 0.720$ $b = 0.011$	97.9	0.00102	0.00027	0.03155

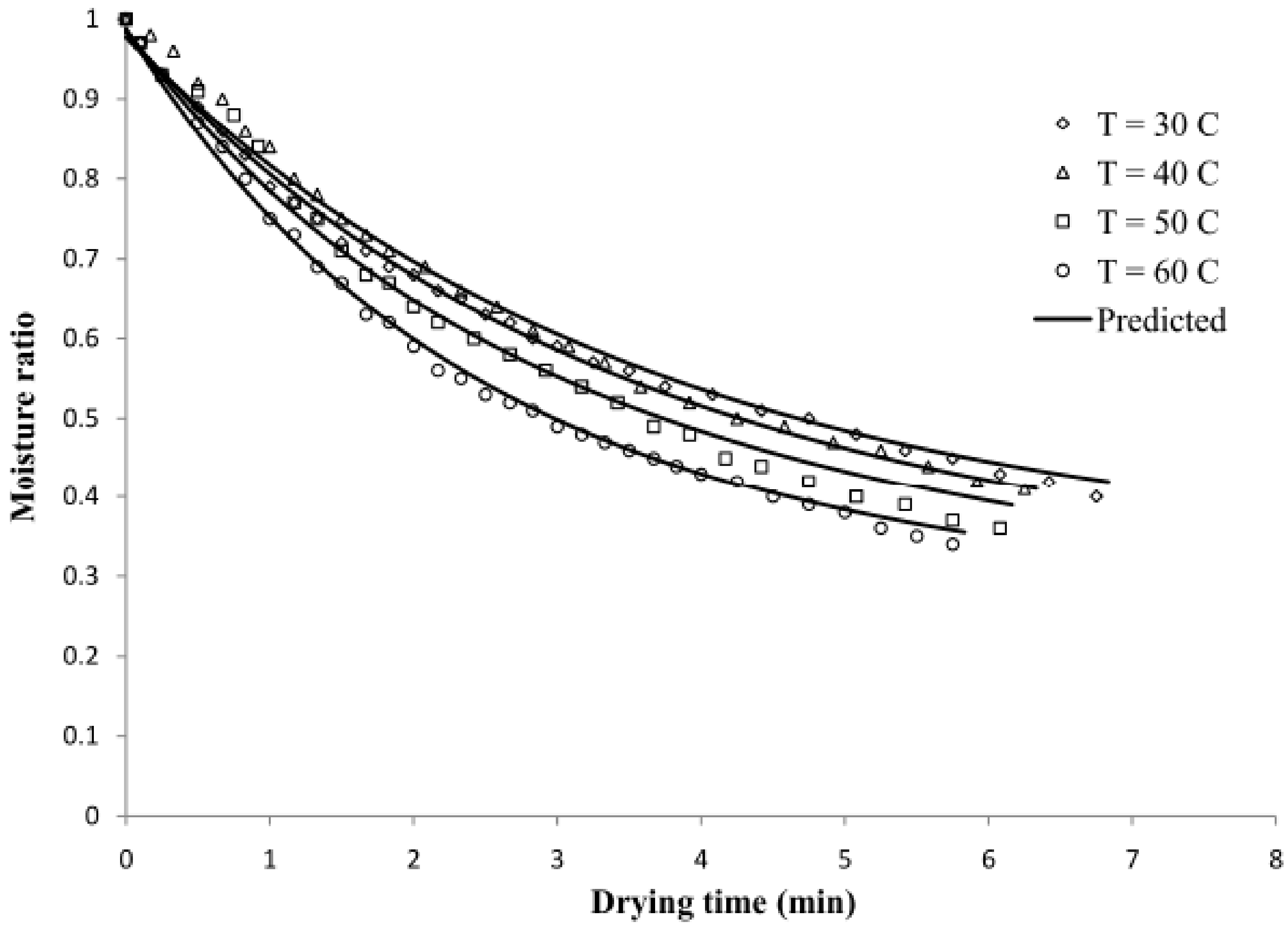
The experimental data versus predicted data for Modified Two-Term Exponential model



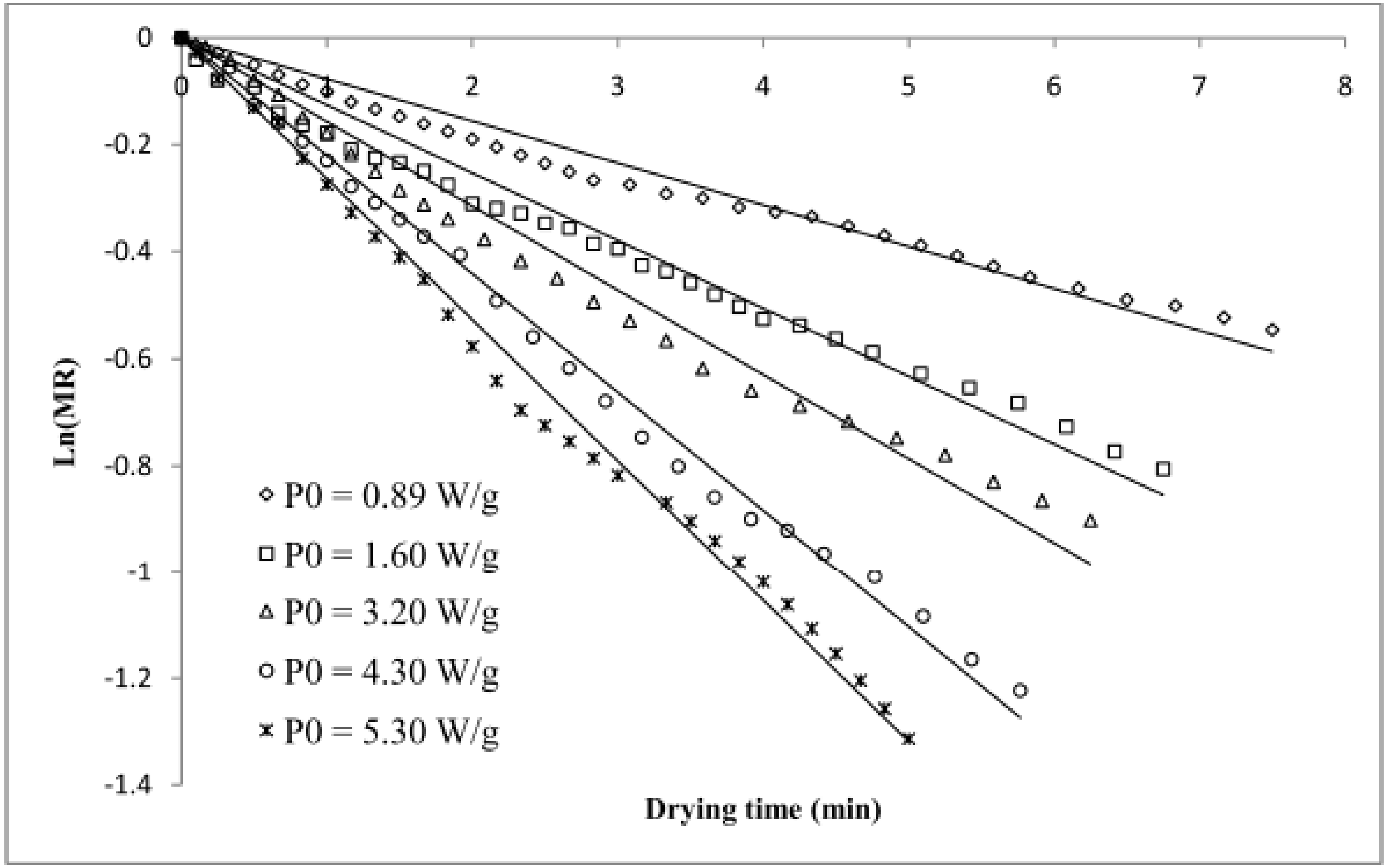
The effect of microwave power on the drying kinetics at T=40^{o}C



The Effect of Air Temperature on the Drying Kinetics at microwave power density of 3.2 w/g

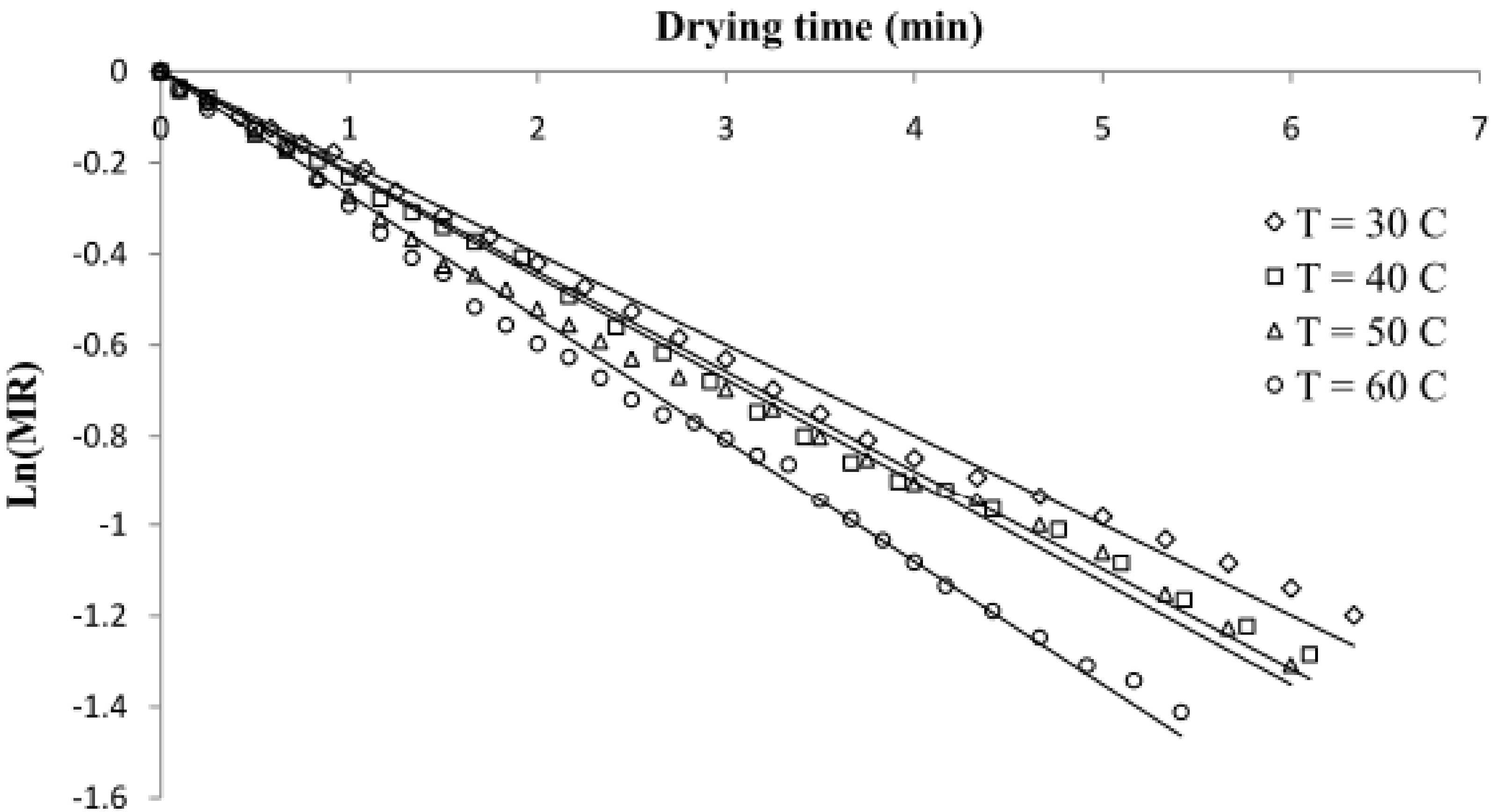


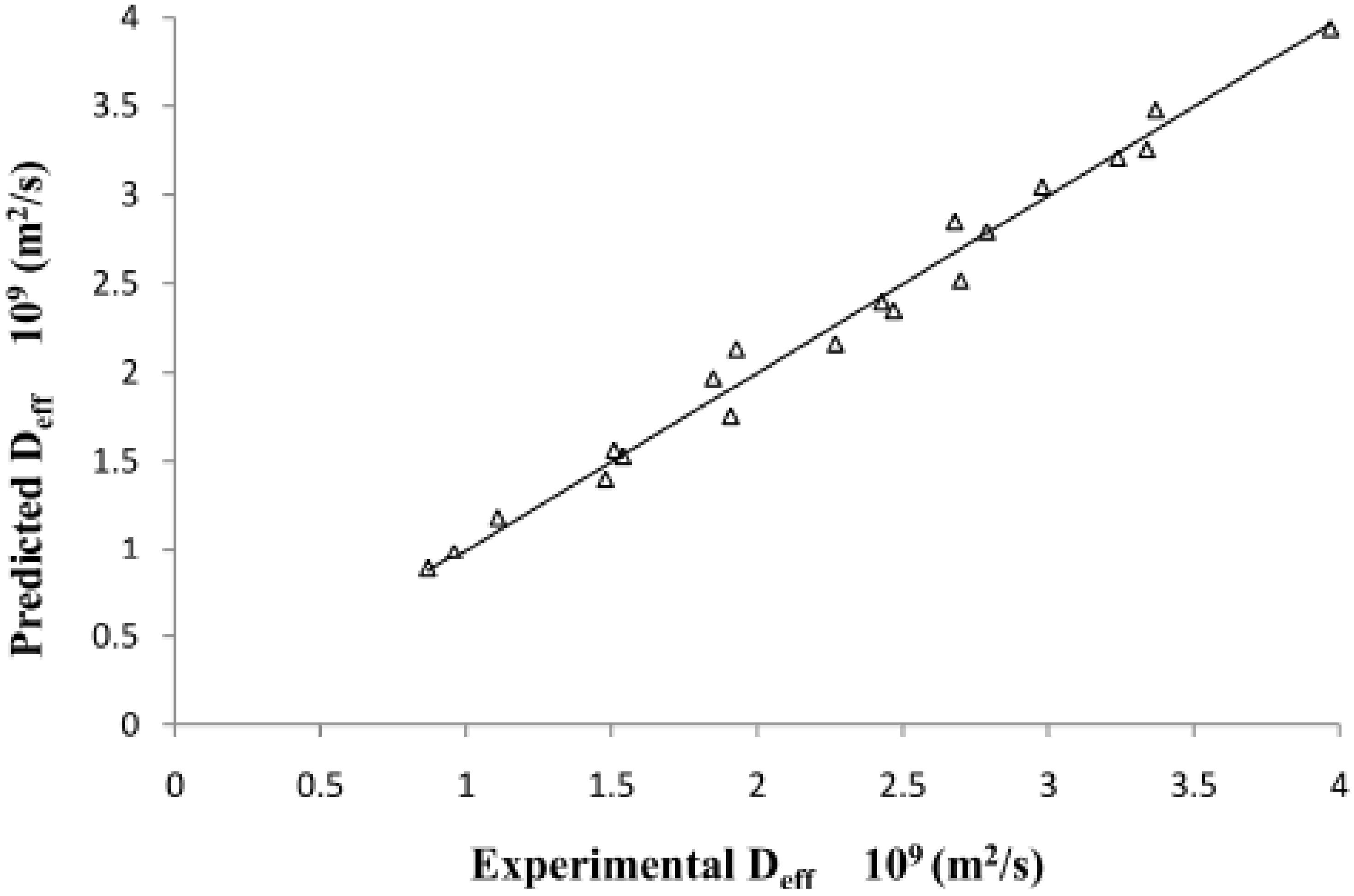
Determination of the Effective Moisture Diffusivity



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

Determination of the Effective Moisture Diffusivity





Predicted D_{eff} 10^9 (m^2/s)
Experimental D_{eff} 10^9 (m^2/s)
0
0.5
1
1.5
2
2.5
3
3.5
4

Determination of the Effective Moisture Diffusivity

T (°C)	P_0 (w/g)	Slope (1/min)	$D_{eff}\times10^9$ (m^2/s)	R^2 (%)
30	0.89	0.071	0.8740	98.1
40	0.89	0.078	0.9602	97.2
50	0.89	0.090	1.1080	99.0
60	0.89	0.123	1.5142	94.3
30	1.60	0.120	1.4773	97.6
40	1.60	0.125	1.5388	97.2
50	1.60	0.155	1.9081	96.7
60	1.60	0.184	2.2651	97.6
30	3.20	0.150	1.8466	93.1
40	3.20	0.157	1.9327	97.7
50	3.20	0.197	2.4252	99.3
60	3.20	0.218	2.6837	97.2
30	4.30	0.201	2.4744	99.2
40	4.30	0.219	2.6960	99.4
50	4.30	0.227	2.7945	97.8
60	4.30	0.271	3.3362	99.5
30	5.30	0.242	2.9792	97.6
40	5.30	0.263	3.2367	99.2
50	5.30	0.274	3.3731	97.9
60	5.30	0.322	3.9664	98.7

The following empirical equation was obtained to estimate effective moisture diffusivity as a function of drying constants of the Modified Two Term model (k_0 and k_1), air temperature (°C) and microwave power density (W/g):

$$D_{eff} \times 10^9 = a_0\, K_0^2 + a_1\, K_1^2 + a_2$$

where,

$$a_0 = -0.143\, T + 2.005\, P_0 + 23.215$$

$$a_1 = 0.194\, T + 1.634\, P_0 - 30.526$$

$$a_2 = 0.010\, T + 1.808\, P_0 - 0.665$$

The values of R^2 and χ^2 are 98.2 % and 2.6102×10^{-11}, respectively.

Conclusion

- The results show that the drying time would decrease for about 92-97 % in comparison with conventional drying, due to application of microwave power.

- The most appropriate model was the Modified Two Term model with the values of 98.6 %, 0.00070, 0.00025 and 0.02610 for R^2, χ^2, *MBE* and *RMSE*, respectively.

- Applying microwave power in conjunction with hot air drying led to higher drying rate in comparison with the conventional hot air drying.

- The effective moisture diffusivity for several drying conditions was calculated in the range from 0.8740×10^{-9} m^2/s to 3.9664×10^{-9} m^2/s.


Thank You