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Mathematical Modeling of Microwave Drying of Beans (*Vicia faba L.)*, Peas (*Pisum sativum)* and Tomatoes *(Rio grande)* in Thin Layer

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Abstract The main objectives of this paper are firstly to investigate the behavior of the thin layer drying of beans, peas and tomato experimentally in a microwave oven for different power density (1; 2 and 3W/g) and secondly to perform mathematical modeling by using thin layer drying models from literature. The variation of the moisture content of the products studied and four statistical models are tested to validate the experimental result. A non-linear regression analysis is used to evaluate the models constants. The Page and the modified Page models were found to be the most suitable to describe the microwave drying curves of beans, peas and tomato respectively. The effective diffusivity for beans, peas and tomatoes was ranged from 0.326×10^{-9} to 1.609×10^{-9} m²/s, from 0.169×10^{-9} to 1.024×10^{-9}m²/s and from 0.484×10^{-9} to 2.127×10^{-9}m²/s, respectively. The experimental data of the products have been analyzed to obtain the values of the effective diffusivity as a function of power density during the falling drying rate phase.

Keywords Drying, Microwave, Power density, Thin layer, Modeling

1. Introduction

Microwave energy is rapidly absorbed by water molecules which, consequently, results in rapid evaporation of water and thus higher drying rates, therefore microwave drying offers significant energy savings, with a potential reduction in drying times of up 50% in addition to the inhibition of surface temperature of treated [15]. To improve microwave drying a number of studies have been conducted to investigate the effects of different microwave power levels and drying temperatures, and different prediction models have been established [1-7]. The effect of microwave power level and the NaCl concentration on the drying rate of tomato pomace was investigated [8]. It was found that microwave drying could be used effectively for drying of such waste product by shortening of the drying process time.

A microwave drying system, which can automatically and continuously adjust microwave power, control sample temperature and measure sample mass, was developed and used in apple drying [9].

Several thin layer equations available in the literature for explaining drying behavior of agricultural products have been used by Diamente and Munro, 1993 [17] for sweet potato slices, Madamba et al., 1996 [18] for garlic silices, Midilli, 2001 [19] for pistachio, Panchariya et al., 2002 [20] for black tea, Lahsasni et al., 2004 [21] for prickly pear peel, Sacilik et al., 2005 [22] for tomato, Roberts et al., 2008 [23] for grape seeds.

In a typical microwave drying application, a fixed microwave power level is applied throughout the entire drying process, but power density (W/g) not included.

In this study, the thin layer drying behavior of beans, peas and tomatoes in microwave are investigated in order to discover the effect of the power density (W/g) in the drying kinetic and the effective diffusivity.

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2. Materials and Methods

2.1. Materials

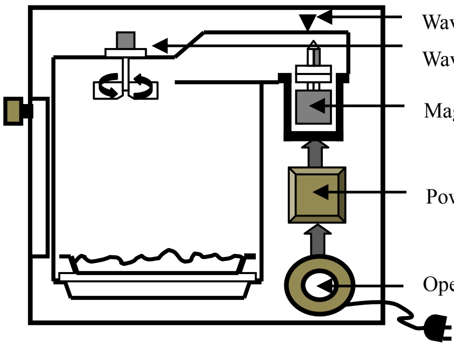
Beans (Vicia faba L.), peas (Pisum sativum) and tomatoes (Rio grande) were collected from experimental parcel Arid Lands Institute (IRA ; Tunisia), washed in water and stored at 4°C for about one day prior to the drying experiment. The average initial moisture content of the samples was determinate by drying representative samples in a convectional oven at 105-110°C for 8-10h [10].

The initial moisture ratio on a dry basis of beans, peas and tomato are 2.15, 3.20 and 11.55 (g/g dried mass) respectively.

2.2. Drying Processes

In microwave process, beans, peas and tomatoes were dried in a programmable domestic microwave oven (HAS-2070M), with maximum output power (700 W) a frequency (2450 MHz) and uncrated weigh (10.5 kg). Samples were subjected to three microwave power densities 1, 2, and 3W/g for 5, 10, 15, 20, 25, 30 and 35 min [16].

The experiment consists in measuring the mass, moisture content and in the following the drying kinetics evolution of the three products to be dried. The mass losses are carried out by using weighting with a type Metter PL 1200 digital display electronic balance of 0.01gr precision.



Microwave oven (HAS-2070M)

2.3. Mathematical Modeling of Drying Curves

The drying curves obtained are processed to find the most convenient expression to describe it. Moisture ratio curves are exponential pace, which is why we chose the 4 models listed in table 1 to be used in this study. Regression analyses are done by using the statistical routine. The coefficient of correlation (r) was one of the primary criteria for selecting the best equation expressing the drying curves of the sample. In addition to r, the various statistical parameters such as; chi-square (χ^2), mean bias error (MBE) and root mean square error (RMSE) were used to determine the consistency of the fit.

These parameters can be calculated as following.

$$\chi^2 = \frac{\sum_{i=1}^{N}(MR_{\exp,i} - MR_{pred,i})^2}{N-n} \quad (1)$$

$$MBE = \frac{1}{N}\sum_{i=1}^{N}(MR_{\exp,i} - MR_{pred,i}) \quad (2)$$

$$MBE = \sqrt{\frac{\sum_{i=1}^{N}(MR_{\exp,i} - MR_{pred,i})^2}{N}} \quad (3)$$

Where $MR_{exp,i}$, stands for the experimental moisture ratio found in any measurement and $MR_{pred,i}$, is the moisture ratio predicted for the measurement. N and n are the number of observation and constants respectively.

Table 1. Mathematical models tested for the moisture ratio values of bean; pea and tomato

Model N°	Name	Model equation	Coefficients of model	Reference
1	Newton	MR= exp(-kt)	k	O'Callaghan, Menzies, and Bailey (1971) and Ayensu (1997)
2	Henderson and Pabis	MR= aexp(-kt)	a ; k	Westerman et al. (1973) and Chhninman (1984)
3	Page	MR= exp(-kt^n)	k ; n	Diamente and Munro (1993)
4	Modified Page	MR= exp(-(kt)^n)	k ; n	White et al. (1981)

2.4. Statistical Analysis

Data were analyzed, using SPSS (Version 17.0) statistical software. SPSS package was used to estimate parameters of models at a 95% confidence level.

2.5. Effective Diffusivity

Analytical solution of Fick's equation for an infinite slab (Eq.(4)) was used in order to estimate effective diffusivity [11].

$$Ln(MR) = Ln(\frac{8}{\pi^2}) - \frac{\pi^2}{(\frac{L}{2})^2} D_{eff}.t \quad (4)$$

Where MR is the moisture ratio, Deff is the effective diffusivity (m²/s), t is the drying time (s) and L is the product leaf thickness (m).

Equation 4 was applied assuming one-dimensional moisture movement without volume change; a constant diffusivity, uniform moisture distribution and negligible external resistance.

3. Results and Discussions

3.1. Drying Curves

The variation of the moisture content dried bases of beans, peas and tomato with the drying time and power density (Pd) are shown in figs. 1-3, respectively. It can be seen that the decrease of MC with power density is remarkable.

Effectively the moisture content of the three products decrease considerably (from 23 to 99%) by microwave drying (3W/g) during the first 20 min.

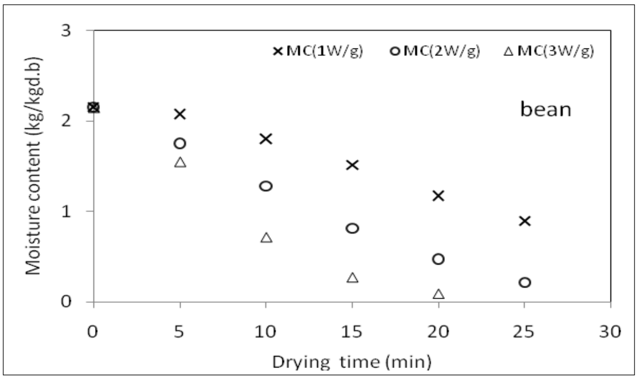


Figure 1. Variation of beans moisture content with drying time and power density

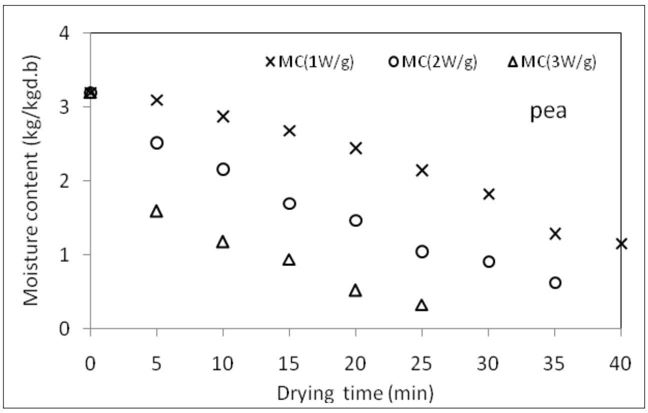


Figure 2. Variation of peas moisture content with drying time and power Density

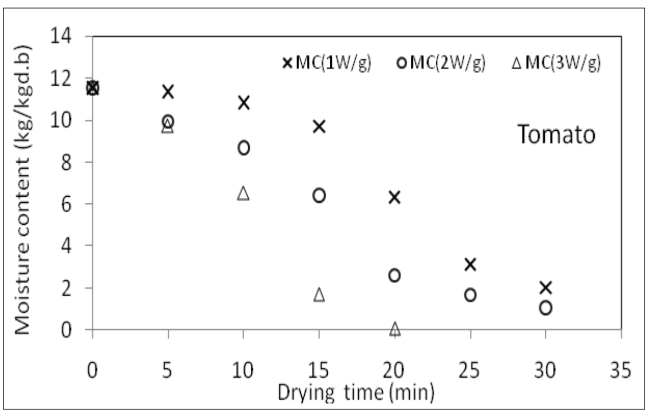


Figure 3. Variation of tomato moisture content with drying time and power density

Figs. 4-6 suggest the variation of drying rate with time and power density for beans peas and tomato in microwave drying process. There is no constant-rate drying period in these curves. The drying rate decreases with decreasing moisture content and increasing drying time. These results were in agreement with the results of [12-14] for some agricultural products.

3.2. Mathematical Modeling of Microwave Drying Curves

3.2.1. Moisture Ratio Modeling

The moisture content data obtained for different products are converted to the moisture ratio expression and then curves fitting computations with the drying time are carried on the four drying models evaluated by the previous workers. The results of statistical analyses undertaken on them are given in tables 2-4.

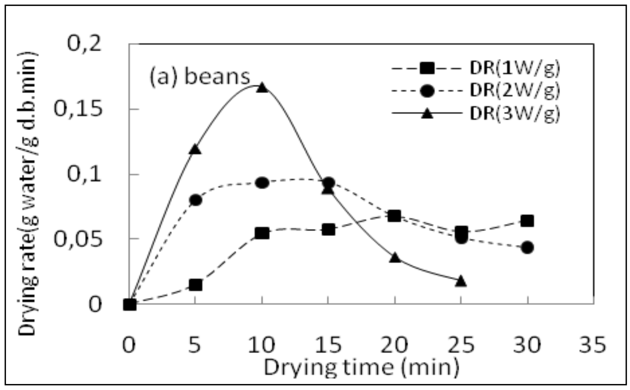


Figure 4. Variation of beans drying rate with drying time and power density

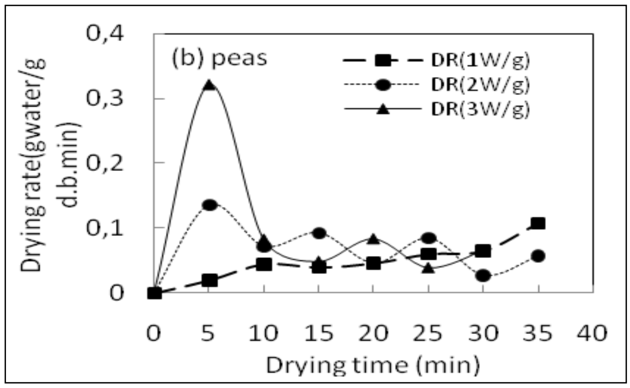


Figure 5. Variation of peas drying rate with drying time and power density

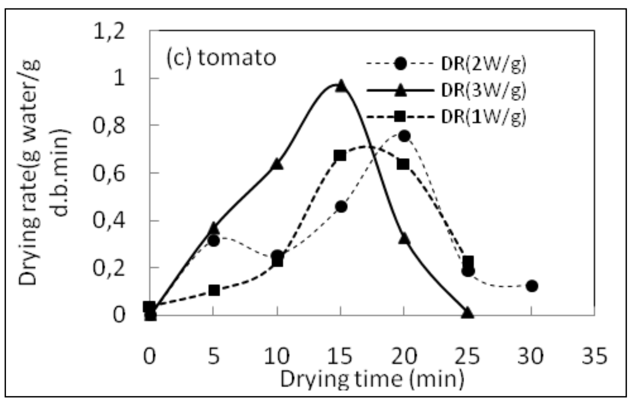


Figure 6. Variation of tomato drying rate with drying time and power density

The results show that the highest values of r and the lowest values of MBE, RMSE and chi² can be obtained with the Page model for beans and peas and modified Page models for tomatoes. These models may be assumed to represent the microwave behavior of bean, pea and tomato in thin layers. The performance of the model is illustrated in figs. 7-9. The predicted data generally band around the straight line representing experimental data, which indicates the suitability of these models in describing drying behavior of beans, peas and tomato.

The effects of microwave power density Pd(W/g) on the coefficient k of Page and modified Page model are also included in the model by multiple regression analysis and the accepted model coefficients for thin layer microwave drying of beans, peas and tomato are as follows (Table 5). The coefficient n of the two models can not be correlated with power density.

Table 2. Modeling of moisture ratio according to drying time for beans

Beans						
Model expression	Power density (W/g)	model coefficients	R²	MBE	RMSE	chi²
exp(-kt)	1	k=0.031	0.874	0.06696050	0.08164681	0.00666620
	2	k=0.065	0.953	0.04480226	0.06040567	0.00364885
	3	k=0.108	0.950	0.04147150	0.06520231	0.00425134
a.exp(-kt)	1	k=0.043; a=1.1841	0.911	0.06597512	0.08548779	0.00730816
	2	k=0.090; a=1.2361	0.929	0.06558505	0.09980461	0.00996096
	3	k=0.162; a=1.3297	0.905	0.07845621	0.13659087	0.01865707
exp(-kt^n)	**1**	**k=0.00164; n=1.971**	**0.997**	**0.00854907**	**0.01216683**	**0.00014803**
	2	**k=0.01802; n=1.484**	**0.998**	**0.00861810**	**0.01100446**	**0.00012110**
	3	**k=0.02373; n=1.645**	**0.999**	**0.00440681**	**0.00734381**	**5.3932E-05**
exp(-(kt)^n)	1	K=0.03863; n=1.971	0.997	0.00854881	0.01216437	0.00014797
	2	K= 0.0668; n=1.484	0.998	0.00866040	0.01105105	0.00012213
	3	K=0.1028; n=1.645	0.999	0.00445722	0.00748727	5.6059E-05

Table 3. Modeling of moisture ratio according to drying time for peas

Peas						
Model expression	Power density (W/g)	model coefficients	R²	MBE	RMSE	chi²
exp(-kt)	1	k=0.019	0.846	0.05075730	0.06031468	0.00363786
	2	k=0.042	0.993	0.01328716	0.01747806	0.00030548
	3	k=0.1	0.964	0.02951434	0.05009481	0.00250949
a.exp(-kt)	1	K=0.018; a=1.0576	0.807	0.01169485	0.12643553	0.01598594
	2	k=0.042; a=1.005	0.993	0.01704165	0.02078322	0.00043194
	3	k=0.085; a=1.105	0.960	0.01503623	0.19060920	0.03633187
exp(-kt^n)	1	k=0.002091; n=1.662	0.984	0.17709823	0.23653637	0.05594945
	2	k=0.2025; n=0.721	0.991	0.01852762	0.02302635	0.00053021
	3	k=0.0443; n=0.988	0.993	0.39988762	0.53247693	0.28353168
exp(-(kt)^n)	**1**	**K=0.0244; n=1.662**	**0.992**	**0.40584748**	**0.01892470**	**0.00035814**
	2	**k=0.0426; n=0.988**	**0.993**	**0.01422116**	**0.01873788**	**0.00035111**
	3	**k=0.1091; n=0.721**	**0.995**	**0.01615219**	**0.02429814**	**0.00059040**

Table 4. Modeling of moisture ratio according to drying time for tomato

Tomato						
Model expression	Power density (W/g)	model coefficients	R²	MBE	RMSE	chi²
exp(-kt)	1	k=0.032	0.539	0.13930479	0.16355692	0.02675087
	2	k=0.054	0.863	0.10144474	0.11182753	0.01250540
	3	k=0.085	0.811	0.09084132	0.12154212	0.01477249
a.exp(-kt)	1	k=0.092 ; a= 1.091	0.706	0.13075137	0.14610838	0.02134766
	2	k=0.059 ; a= 1.094	0.886	0.08658650	0.09730679	0.00946861
	3	k=0.039 ; a= 1.150	0.835	0.09578990	0.11543003	0.01332409
exp(-ktn)	1	k=0.00014 ; n=2.275	0.984	0.04544838	0.06107096	0.00372966
	2	k=0.00287 ; n=2.435	0.991	0.03951462	0.05076819	0.00257741
	3	k=0.00820 ; n=1.664	0.993	0.02359211	0.04279018	0.00183100
exp(-(kt)n)	1	k=0.04014 ; n=2.275	0.961	0.04544838	0.06107096	0.00372966
	2	k=0.05567 ; n=1.664	0.977	0.03951462	0.05076819	0.00257741
	3	k= 0.09042 ; n=2.435	0.984	0.02359211	0.04279018	0.00183100

Table 5. Expressions of the coefficient k of Page and modified Page model as a function of power density P_d

Model	Product	Pd(W/g)	K	expressions of k=f(Pd)	R²
Page	Beans	1	0.00164	K= 0.011xPd-0.007	0.927
		2	0.01802		
		3	0.02373		
Modified Page	Peas	1	0.02440	K= 0.042xPd-0.026	0.902
		2	0.04260		
		3	0.10910		
Page	Tomatoes	1	0.00014	K= 0.004xPd-0.004	0.966
		2	0.00287		
		3	0.00820		

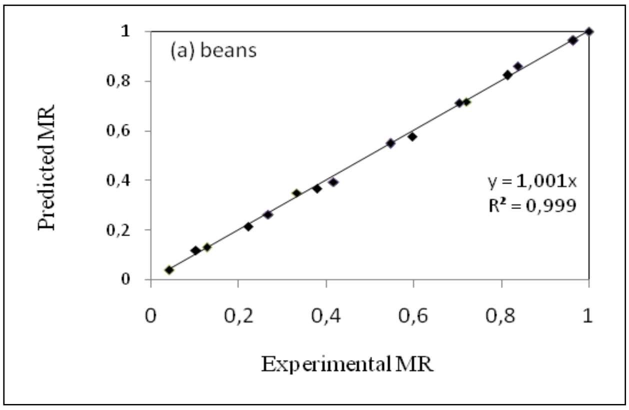


Figure 7. Comparison of experimental and predicted moisture ratio of beans by Page model

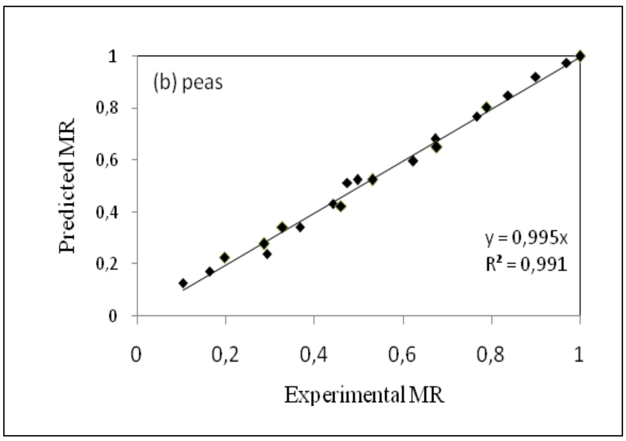


Figure 8. Comparison of experimental and predicted moisture ratio of peas by modified Page model

3.2.2. Effective Diffusivity

The drying during the falling rate is governed by the diffusion of water in the product. The effective diffusivity Deff is typically calculated by graphic method representing the experimental data in terms of the logarithm of moisture ratio (MR) according to the drying time (Figs. 10-12). The result is a straight line which slope allows calculating the effective diffusivity for different powers density (Table 6).

The analysis of table 6 reveals that the effective diffusivity increases with power density due to the increase of temperature and consequent water vapor pressure. The effective diffusivity for beans, peas and tomatoes was ranged from 0.326×10^{-9} to 1.609×10^{-9} m²/s from 0.169×10^{-9} to 1.024×10^{-9}m²/s and from 0.484×10^{-9} to 2.127×10^{-9}m²/s respectively. In all the cases the maximum correspond to the high power density (3W/g) and the effective diffusivity can be expressed as a polynomial equation according to the power density (Table 6).

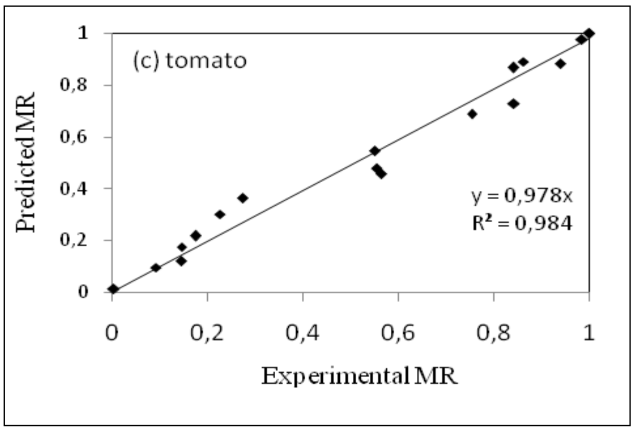


Figure 9. Comparison of experimental and predicted moisture ratio of tomato by Page model

Table 6. Values and expression of effective diffusivity according to power density

Product	Pd(W/g)	Deff (m²/s)	Deff = f(Pd)	R²
Beans	1	$0.326.10^{-9}$	109×Deff = 0.641×Pd - 0.345	0.993
	2	$0.877.10^{-9}$		
	3	$1.609.10^{-9}$		
Peas	1	$0.169.10^{-9}$	109 ×Deff = 0.427×Pd - 0.299	0.972
	2	$0.473.10^{-9}$		
	3	$1.024.10^{-9}$		
Tomato	1	$0.484.10^{-9}$	109×Deff = 0.821×Pd - 5.10	0.883
	2	$0.788.10^{-9}$		
	3	$2.127.10^{-9}$		

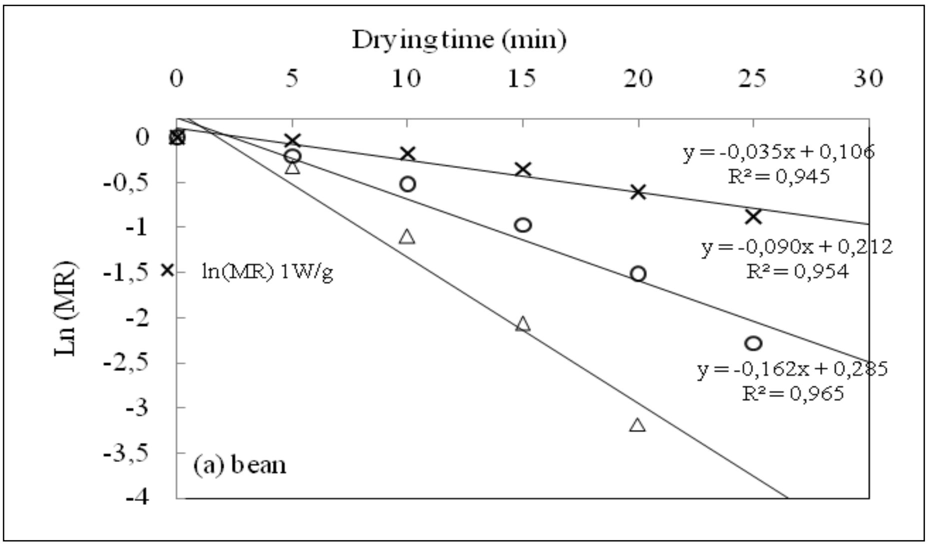


Figure 10. Variation of logarithm of bean moisture ratio with drying time and power density

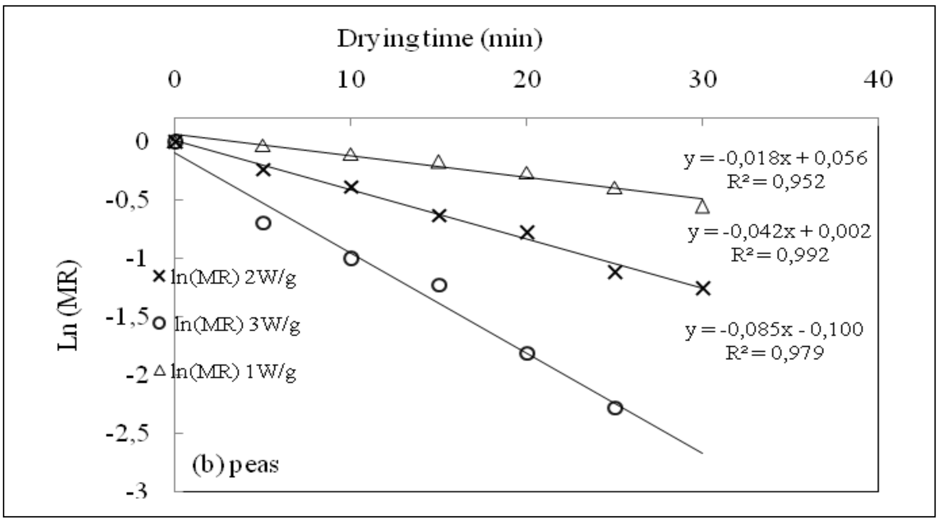


Figure 11. Variation of logarithm of pea moisture ratio with drying time and power density

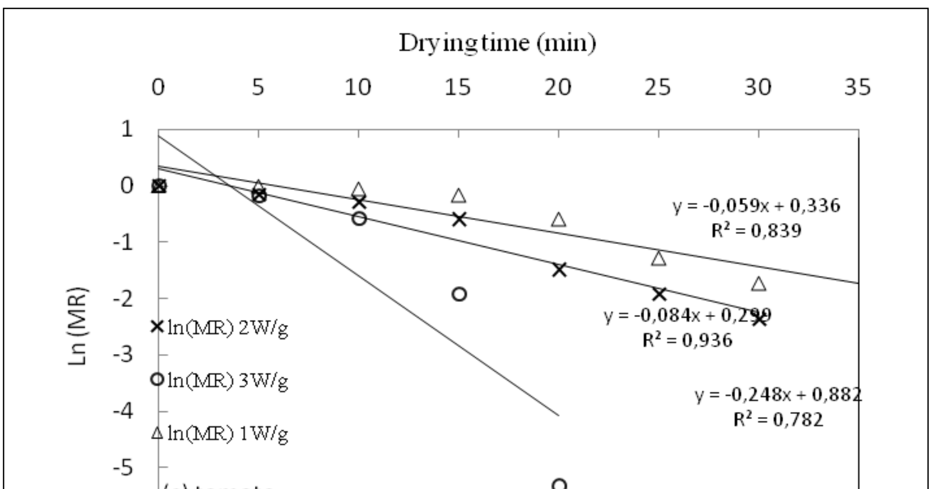


Figure 12. Variation of logarithm of tomato moisture ratio with drying time and power density

4. Conclusions

The following results are drawn from the drying kinetics of beans, peas and tomato in a microwave oven using different power density. No constant drying rate period was observed and all the drying processes occurred in the falling rate period. All the drying models considered in this study are adequately representing the drying behavior of bean, peas and tomatoes. Although the Page and modified Page model were better than others models. The drying parameters k in Page and modified Page models equations can be expressed as a linear function of the power density. The effect of power density on the effective diffusivity D_{eff} was mentioned. The effective diffusivity for beans, peas and tomatoes was ranged from 0.326×10^{-9} to 1.609×10^{-9} m²/s from 0.169×10^{-9} to 1.024×10^{-9} m²/s and from 0.484×10^{-9} to 2.127×10^{-9} m²/s respectively and the correlation of D_{eff} with power density was presented.

Nomenclature

a, b, c, n :	empirical coefficients in drying models
Deff :	effective diffusivity (m²/s)
K :	empirical constant in drying models
L :	half thickness of product (m)
MBE:	mean bias error
MC:	moisture content (g water/g dry basis)
MR:	moisture ratio
MRexp:	experimental moisture ratio
MRpred :	predicted moisture ratio
N:	number of observation
R^2:	coefficient of determination
RMSE:	root mean square error
t:	drying time (min)

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