Research Article

Mathematical modelling of microwave assisted dehydration of osmotically pretreated yellow sweet pepper (*Capsicum annum L*)

Abstract

Drying kinetics modeling and effective moisture diffusivity (D_{eff}) of osmotically dehydrated yellow sweet pepper (*Capsicum annum L.*) during microwave assisted convective drying at power levels of 70, 140, 210 and 280W, air temperature of 35, 45 and 60°C and constant air velocity of 1.5m/s were investigated. Among the 11 proposed models, Page model gave a better fit for all drying conditions used. Deff decreased from 1.21×10^{-7} to 8.91×10^{-8} m²/s with decrease of drying temperature from 60 to 35°C which is 102 to103times reported earlier. The frequency factor (D_0) values decreased from 9.7564×10^{-5} to 0.8806×10^{-5} m²/s while the activation energy of diffusion (E_a) decreased from 21.8741 to 10.7167KJ/mole with the increase in microwave power from 0.35 to 1.4W/g. So, pretreatment can be used as criteria for faster drying thereby maintaining final product quality. These mathematical models have much more practical utility as far as process design of food industry is concerned.

Keywords: microwave drying, drying kinetics, moisture diffusivity, activation energy

Sachidananda Swain,[1] Samuel DVK,[2] Kar A,[3] Bal LM,[4] Sahoo GP[5]
[1]Division of Natural Resource Management, Central Agricultural Research Institute, India
[2]Division of Agricultural Engineering, Indian Agricultural Research Institute, India
[3]Division of Post Harvest Technology, Indian Agricultural Research Institute, India
[4]College of Agriculture, Jawaharlal Nehru Agricultural University, India
[5]Gandhi Institute of Excellent Technocrats, BBSR, India

Correspondence: Sachidananda Swain, Division of Natural Resource Management, Central Agricultural Research Institute, Port Blair-744101, India, Tel 919531868394, Email sachi9463@gmail.com

Introduction

Fruits and vegetables play a significant role in human nutrition as they provide many essential vitamins and minerals.[1] However, they are usually in shortage during off-seasons because of high perishability. A very common method of preservation for these agricultural corps is to dry them in order to reduce storage volume, minimizing packaging, storage, transportation costs and makes possible storage of the product under ambient temperatures and thereby extend their shelf life.[2–4] Conventional drying involves exposure of food and agricultural products to high temperature and for long times, which can result in serious damage to flavor, color, rehydration capacity and nutrients of the treated material as well as low energy efficiency.[5–8] However, in recentyears, microwave drying has gained popularity as an alternative drying method to overcome above problems for a wide variety of food products.[9–11] It has several advantages over conventional hot air drying, such as higher drying rate, minimal heating at locations with less water, thus reducing overheating of atmosphere.[12] In microwave heating, as the temperature inside the material approaches the boiling point of water, pressure development becomes significant. This increase in vapour pressure facilitates the transfer of water to the outside[13] and generates higher drying rates than conventional drying, where heat is transferred from the surface to the inside of the solids.[10,14–16]

Microwave drying system is widely used in combination with air drying system during drying via microwave energy.[17] These combined drying systems not only increase the drying rate of the product, but also increase the quality of the dry product.[18] Numerous studies were carried out with microwave-air combined dryers and many agricultural products have been dried successfully. Crops such as carrots,[19] apple and mushroom[17,20] could be dried successfully using combined drying technique.

Peppers are an important source of nutrients in the human diet, and an excellent source of vitamin A and C as well as neutral and acidic phenolic compounds, which are important antioxidants for a variety of plant defense responses. However, heating causes losses of sensorial (texture, taste, flavor and color) and nutritional quality attributes, such as reduction of ascorbic acid content.[21] Thus, to minimize the above losses, a study was conducted for the effect of the microwave-assisted drying on the characteristics of yellow sweet pepper. The overall goal of modeling a drying process is to understand and predict the influence of extrinsic factors such as temperature, contact time and pressure (vacuum) and intrinsic factors such as the nature of the food material, size and shape, on the mass transfer phenomena of moisture loss, color degradation, losses of bio-chemical parameters etc which influence the characteristics of the final product and hence its quality. Therefore, objectives of the present study are to compare the developed mathematical models for predicting the kinetics of drying, to investigate the drying rates and also the moisture diffusivity of yellow sweet pepper during combined microwave-convective drying as a function of the microwave power and air temperature.

Practical applications

The research findings of the study would give an innovative facet for food preservation and drying of yellow sweet pepper for enhancing the commercial potential of these commodities and open new avenues for food Industry. Modelling to application of microwave drying to food products which is part of a continuous from fresh foods to value added products manufacturing line helps to, calculate the residual moisture content of products as well as determination of diffusion rate and activation energy which saved the drying time on the basis of continuously generated data from univariate sensors. Next to monitoring, the application of continuous processes demands also real-time adjustment of critical input variables to ensure that the process stays within the design Space. Mechanistic models are very useful for this purpose as, once validated, several tools can be applied to gain further process knowledge, for example uncertainty and sensitivity analysis in large scale. Further, this article will help the researchers

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and academicians working in drying of agricultural commodities in general and yellow sweet pepper in particular.

Materials and methods

Material

Fresh yellow sweet pepper samples were procured from the Center of Protected Cultivation Technology, Indian Agricultural Research Institute, New Delhi. The samples were washed and stored at 7±0.5°C in the cold storage until analysis. Before the drying experiments, the samples were taken out of the cold storage and sliced with a knife. At least 10 measurements of length, breadth and thickness were made at different points of the sliced pepper with a vernier caliper (M$_i$tutoyo, Japan) having an accuracy of 0.02mm; only slices that fell within a 5% range of the average dimensions (length, breadth and thickness) were used. The average value of length (60±1.5mm) breadth (6±0.5mm) and thickness (4±0.41mm) were calculated. Initial moisture content was measured by taking 30g samples, dried in an oven at 70°C for 24h which was calculated as 89.01±0.45% (w.b.).[22]

Pretreatment (osmotic dehydration)

The samples were osmotically dehydrated as a pretreatment using parameters, such as salt, sucrose, RPM, solution to sample ratio (SSR) and time, inside the incubator shaker by using Central Composite Rotatable Design (CCRD) given elsewhere.[23] These were optimized based on the objective requirements of weight loss, moisture loss and solid gain, and optimized dehydrated samples containing 71.29±0.65% (w.b.) moisture were taken for microwave drying.

Drying equipment and drying method

Drying experiments were performed in a laboratory scale microwave-convective dryer consists of four subsystems: air supply unit, heating unit, drying unit, and control unit, available in the Division of Post Harvest Technology, Indian Agricultural Research Institute, New Delhi. The blower (model: 0.24HP, 50Hz, continuous single phase) blows the air to the heating section to maintain the temperature up to desire level, regulated by thermostat from where it passes to the microwave oven. A thermostat (Multispan, MDC2901) was mounted over the blower to detect the change in the air temperature, which can be varied by manually using the regulator unit. The microwave oven (WP700L17.3 MW Oven, LG make, 17L Capacity) with technical features of ~230V, 50Hz, and 700W with a frequency of 2450MHz has the dimensions of 295, 458 and 370mm and consisted of a turn table of 270mm diameter at the base of the oven and it also operates in pulsed mode. The microwave oven has the capability of operating at ten different microwave output powers between 70 and 700W measured using the IMPI-2L test.[24] The adjustment of microwave power level and processing time was done with the aid of an analogue control facility located on the microwave oven. The dryer was run without the sample placed in, for about 30min to set the desired drying conditions before each drying experiment. Air velocity was measured with an hot wire anemometer (Model No: AM-4204; Make: LT Lutron, Taipei, Taiwan) having a least count of 0.1m/s. Preliminary experiments of microwave-hot air drying of yellow sweet pepper resulted in charring of the product towards the end of drying at power level higher than 280W. The combined microwave-hot air drying experiments were thus conducted with continuous microwave power of 280Wand step down intervals of 70W, in conjunction with hot air at 30, 45 and 60°C temperatures at constant air velocity of 1.5m/s.

Two hundred (200) grams of osmotically-dehydrated yellow sweet pepper was arranged in a single layer on the rotating glass plate and placed in the centre of the oven and the drying process was started for different combinations of microwave power and air temperature. Then, the samples were removed from the oven periodically and moisture loss was measured by weighing on the digital balance (Panacea GX 4000, Germany) with 0.01g precision. Three replications of each experiment were performed according to preset conditions and the data given are an average of these results. The reproducibility of the experiments was within the range of ±5%. Drying process continued until the moisture content of samples fell down to about 6% (w.b.). All weighing processes were completed in <10s during the drying process.

Theoretical consideration

Mathematical modeling of the drying curves: To determine the most suitable drying model, the drying cures were fitted to experimental data using eleven different thin layer drying models (Table 1). The moisture ratio and drying rate of yellow sweet pepper were calculated using the following equations:

$$MR = \frac{M - M_e}{M_i - M_e} \tag{1}$$

Where, MR is the moisture ratio, M is the moisture content at a specific time (kg/kg d.b.), M_i is the initial moisture content (kg/kg d.b.), and M_e is the equilibrium moisture content (kg/kg d.b.). The equilibrium moisture content was assumed to be zero for microwave drying as stated by Doymaz.[25] The MR, however, was simplified to M/M_i:

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

Where, M_t and M_{t+dt} are the moisture content (kg/kg d.b.) at drying time t and t+dt (min), respectively.

Table 1 Thin layer drying models used

Model No.	Model Name	Model Equation	References
1	Newton	MR= e^{-kt}	Ayensu[45]
2	Page	MR =	Agrawal and Singh[46]
3	Modified Page	MR =	White et al.[47]
4	Henderson and Pabis	MR = a e^{-kt}	Akpinar et al.[48]
5	Logarithmic	MR = a e^{-kt} +c	Yaldiz et al.[49]
6	Wang and Singh	MR = 1+at+bt^2	Wang and Singh[50]
7	Diffusion approach	MR = a e^{-kt} + (1–a) e^{-kbt}	Togrul and Pehlivan[51]
8	Verma	MR = a e^{-kt} + (1–a) e^{-gt}	Verma et al.[52]
9	Two-term exponential	MR = a e^{-kt} + (1–a) e^{-kat}	Sharaf-Elden et al.[53]
10	Simplified Fick's diffusion equation	MR =	Togrul and Pehlivan[51]
11	M$_i$dilli–Kucuk equation	MR =	Sacilik and Elicin [54]

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Effective moisture diffusivity

Generally, drying of foods takes place in two periods, a constant rate and falling rate period. After a short heating period, a constant rate period followed by a falling rate period which is a dominating period during drying process. The mechanism of moisture movement within a hygroscopic solid during the falling-rate period could be represented by effective moisture diffusion phenomenon (liquid diffusion, vapour diffusion, vaporization-condensation, hydrodynamic flow and other possible mass transfer mechanisms) is used and represents an overall mass transport property of water in the material. During drying, it can be assumed that diffusivity, explained with Fick's diffusion equation, is the only physical mechanism to transfer the water to surface.[26] Effective moisture diffusivity, which is affected by composition, moisture content, temperature and porosity of the material, is used due to the limited information on the mechanism of moisture movement during drying and complexity of the process.[27] The effective moisture diffusivity D_{eff}, at any given moisture content can be determined using 'methods of slopes' technique.[28] Several researchers have utilized this technique for estimating the moisture diffusivity of food materials.[29–31] So, Fick's second law equation for non steady-state diffusion, assuming that the samples used can be approximated to cylinders, the diffusion is expressed by Crank.[32]

$$\frac{\partial M}{\partial t} = \frac{1}{r}\left\{\frac{\partial}{\partial r}\left(D_{eff} r \frac{\partial M}{\partial r}\right) + \frac{\partial}{\partial Z}\left(D_{eff} r \frac{\partial M}{\partial Z}\right)\right\} \qquad (3)$$

For the solution of Fick's diffusion equation, the yellow sweet pepper slices were assumed as an infinite slab because of the thickness of the sample (4±0.4mm) was much less than its diameter. The effective moisture diffusivity for infinite slab was therefore calculated by the following solution.[32]

$$MR = \frac{M - M_e}{M_0 - M_e} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2} \times \exp\left(-\frac{(2n+1)^2 \pi^2 D_{eff}}{4L^2}t\right) \qquad (4)$$

Where, D_{eff} is the effective diffusivity (m²/s); L_0 is the half thickness of slab (m). For long drying times; n=1, then Eq. (4) can be reduced to the following form:

$$MR = \frac{8}{\pi^2}\exp\left(\frac{-\pi^2 D_{eff}}{4L^2}t\right) \qquad (5)$$

Diffusivities are typically determined by plotting experimental drying data in terms of ln MR versus drying time t in Eq. (5), because the plot gives a straight line with a slope as follows:

$$\ln MR = In\frac{8}{\pi^2} - \frac{\pi^2 D_{eff}}{4L^2}t \qquad (6)$$

$$Slope = \frac{\pi^2 D_{eff}}{4L^2} \qquad (7)$$

Calculation of activation energy

The temperature dependence of the effective diffusivity may be described by an Arrhenius-type relationship[33–35] as follows:

$$D_{eff} = D_0 \exp\left(\frac{E_a}{RT}\right) \qquad (8)$$

$$\ln D_{eff} = \ln D_0 - \frac{Ea}{RT} \qquad (9)$$

Plotting ln D_{eff} vs 1/T gives the slope of E_a/R to calculate the activation energy. Where, D_0 is the pre-exponential/Frequency factor of the Arrhenius equation (m²/s), E_a is the activation energy (J/mol), R is the universal gas constant (J/mol K), and T is the absolute temperature (K). From the slope of the straight line of ln D_{eff} versus reciprocal of T, described by the Arrhenius equation, the activation energy, E_a, could be calculated. The model described by equations (4) and (9) can be expressed in the simplified form:

$$MR = f(T,t,L,D_0,E_a)$$

Where, t and T are variables and L, D_0 and E are the model parameters.

Statistical test

The non-linear regression procedure was used to obtain the drying parameters of the above equations using the MATLAB 7.1 (R2008a) software package. The coefficient of determination (R^2) root mean square error (RSME) and residual sum of square (RSS) were used as primary criteria to select the best fit of the tested mathematical model to the experimental data. The higher the value of R^2 and lower the value of RSS and RSME, the better the model was taken to fit. By definition:

$$RSS = \frac{\sum_{i=1}^{N}\left(C_{exp,i} - C_{pre,i}\right)}{N - P} \qquad (10)$$

$$RMSE = \sqrt{\frac{\sum_{i}^{N}\left(C_{exp,i} - C_{pre,i}\right)^2}{N}} \qquad (11)$$

Where, $C_{exp,i}$ is the ith experimental value, $C_{pre,i}$ is the ith predicted value, N is the total number of observations, p is the number of constants in a particular model.

Results and discussion

Drying kinetics

The moisture ratio versus drying time curves for microwave-convective drying of the osmotically dehydrated yellow sweet pepper samples (moisture content: 71.29±0.65%, w.b.) at different microwave output power levels (70, 140, 210 and 280W) and temperatures (30, 45 and 60°C) are shown in Figure 1. When the microwave power increased, the time needed to achieve a certain moisture ratio decreased being highest (122min) for 0.35W/g at 30°C and lowest (30min) for 1.4 W/g at 60 °C, which indicated that high power level saved 76% of the drying time for yellow sweet pepper to approximately 6% (w.b.) moisture content. Thus, it is obvious that the moisture ratio decreased more rapidly when the microwave power is increased. It was due to high electric field for high power, so that the rate of orientation of water molecules inside the heterogeneous food matrix were more causing more friction to be changed into heat for the evaporation of water molecules. Hence, the drying times were inversely proportional to applied microwave power levels applied. Similar observations were

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reported by Soysal[36] for parsley, Wang and Xi[37] for carrot slices, Giri and Prasad[38] for mushroom and Karaaslan and Tuncer[39] for spinach. However, Student's t-test revealed that, keeping the power level constant, the moisture ratio had non- significant effect (p<0.05) with increase in air temperature from 30 to 60°C.
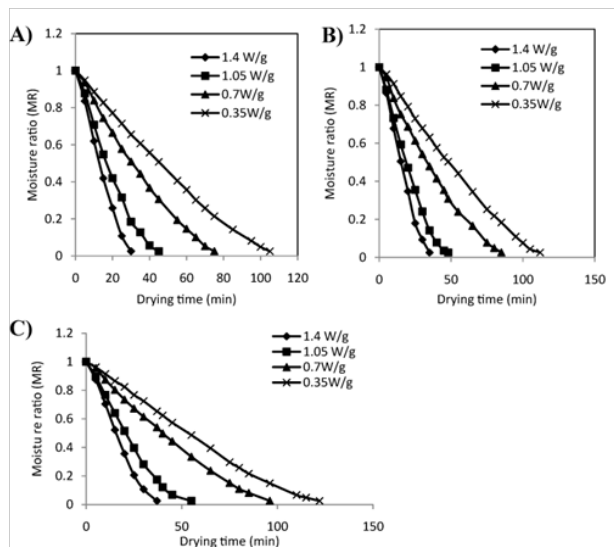

Figure 1 Effect of moisture ratio on drying time at different levels of power at air temperature of 60, 45 & 30 °C.

The relations between drying rate with drying time are shown in Figure 2. It was observed that with the increase in drying time the drying rate increased up to certain level with the increase in microwave power and air temperature and then gradually decreased. It was due to the fact that, after certain period, a small amount of water was present which required more time to drive out from the samples causing less drying rate. The maximum drying rate was 0.096 and 0.088 (g. water g. solid^{-1}.min^{-1}) for the samples. The initial moisture content of yellow sweet pepper was relatively constant (2.48g. water g. solid^{-1}), but the difference in the drying time requirements were mainly due to difference in the drying rate. The higher the power level, the greater the increase in drying rates. Nevertheless, a limit for power application was established on the basis of retaining the color stability of the product, otherwise browning may be detected due to sugar caramelisation by excessive local heating. Drying rate showed a fast increase at the beginning of the process due to microwave heating and a subsequent decrease, showing two differentiated periods: the first, where drying rate decreases slowly to reach a plateau with a practically constant value, and the second with a gradually decreasing drying rate from a given critical moisture content (Figure 3). So, drying rate curves showed a sigmoid shape, where the influence of microwave power can be observed practically in the entire range of sample moisture content. Nevertheless, at a higher power level, the initial rates are more greatly enhanced. The constant rate periods were more prominent at lower power level, being maximum at 0.7W/g and 30°C which gradually decreased with the increase in the power levels, being almost absent in 1.4W/g. It was because of thin layer of arrangement of samples and too rapid heating by high power, providing instant drying. The constant rate period ranged from 0.011 to 0.096g. Water g.solid^{-1}.min^{-1} for the microwave output powers between 0.35 to 1.4W/g. After a short heating period, the time requirements during constant rate period varied with microwave output powers. The constant rate period was changed nearly from 1.84 to about 0.46g water g dry base^{-1}, nearly from 1.84 to about 0.56,

nearly from 2.22 to about 0.28, nearly from 2.48 to about 0.21g water g dry base^{-1} for the microwave output powers between 0.35 to 1.4W/g. A constant rate period was followed by a falling rate period in which moisture content decreased to 0.063g water g dry base^{-1} for all drying conditions. These results were in agreement with the study of parsley leaves by Soysal[36] and spinach by Dadali et al.,[26] dried in a domestic microwave oven who reported that after a short heating period, a long constant rate period and a falling rate period was observed.
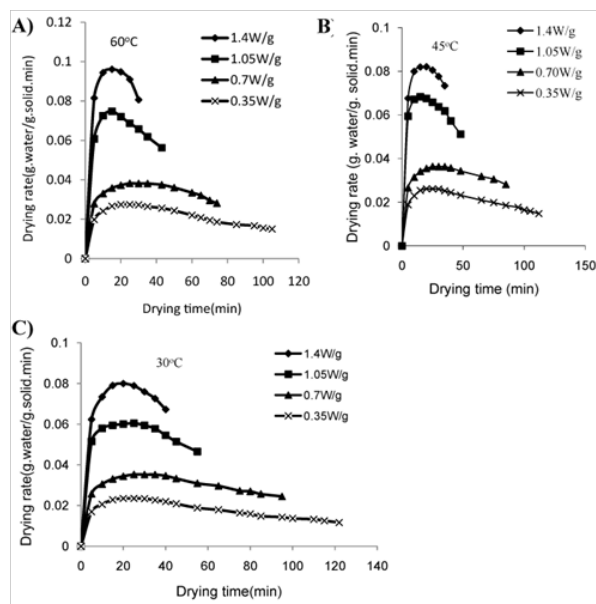
Figure 2 Effect of drying rate on drying time at different levels of power at air temperature of 60, 45 & 30 °C.
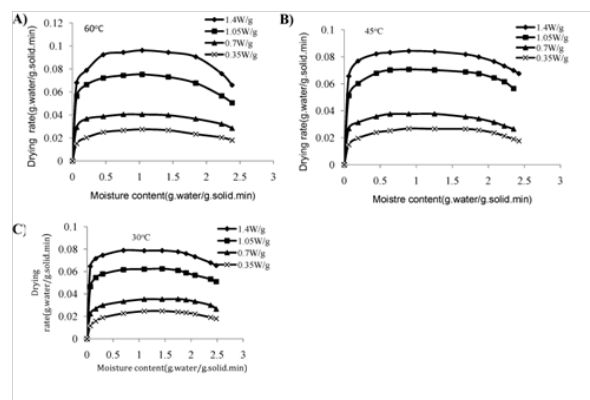
Figure 3 Effect of drying rate on moisture content at different levels of power at air temperature of 60, 45 & 30 °C.

Modeling the thin layer drying data

The moisture content data obtained at different microwave powers and air temperatures were converted to the moisture ratio and then the curve-fitting procedure was performed for eleven well-known semi-empirical models in Table 1, among which Page model (Eq. 12) gave better fit for all drying data under all conditions tested with a higher R^2, less root mean square error (RMSE) and residual sum of square (RSS), shown in Table 2. The equation for Page model is,

$$MR(k,n) = \frac{M - M_e}{M_o - M_e} = \exp(-kt^n) \qquad (12)$$

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Where, k and n are empirical constant, t is the temperature.

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A good agreement was found between experimental and fitted values for yellow sweet pepper under all conditions. The parameters k and n of semi-empirical Page's equation (Eq. 12) were estimated using nonlinear regression technique (Table 3) and the fitness is illustrated in Figure 1. From Table 3, the k value increases as the microwave

output power increases during the drying process. Its values ranged from 0.016 to 0.102min^{-1} and the model gave a better fit for all the experimental data points with R^2 greater than 0.98. As high R^2 and low RMSE and RSS values (<0.006) predicted for the sample, it is best suited for Page model. The best R^2 is 0.9992 for 1.4W/g microwave power at 30°C among all drying conditions. Based on the multiple regression analysis, the temperature dependence of the coefficients (k and n) was fitted to second order polynomial equation shown in Table 4.

Table 2 Results of statistical analyses on the modeling of yellow sweet pepper

Model no.	Model name	Power, W/g	Temp,°C	R^2	RMSE	RSS
1	Newton's model		60	0.9438	0.0872	0.0456
		1.4	45	0.9938	0.0889	0.0553
			30	0.9384	0.0896	0.0563
			60	0.9596	0.0697	0.0438
		1.05	45	0.9523	0.0760	0.0579
			30	0.9531	0.0744	0.0554
			60	0.9573	0.0673	0.0634
		0.70	45	0.9634	0.0607	0.0552
			30	0.9550	0.0685	0.0704
			60	0.9514	0.0697	0.0875
		0.35	45	0.9464	0.0747	0.1063
			30	0.9424	0.0792	0.1132
2	Page's model		60	0.9965	0.0240	0.0028
		1.4	45	0.9959	0.0232	0.0032
			30	0.9992	0.0169	0.0017
			60	0.9974	0.0188	0.0028
		1.05	45	0.9961	0.0229	0.0027
			30	0.9978	0.0170	0.0026
			60	0.9948	0.0244	0.0031
		0.70	45	0.9945	0.0243	0.0032
			30	0.9941	0.0256	0.0042
			60	0.9982	0.0187	0.0140
		0.35	45	0.9934	0.0269	0.0130
			30	0.9945	0.0251	0.0107
3	Modified Page's model		60	0.9438	0.0955	0.0456
		1.4	45	0.9398	0.0960	0.0553
			30	0.9384	0.0968	0.0563
			60	0.9596	0.0740	0.0438
		1.05	45	0.9523	0.0802	0.0579
			30	0.9531	0.0785	0.0554
			60	0.9573	0.0698	0.0634
		0.70	45	0.9608	0.0828	0.0552
			30	0.9550	0.0709	0.0704
			60	0.9514	0.1717	0.0875
		0.35	45	0.9464	0.0768	0.1060
			30	0.9424	0.0815	0.1132

Table continued..

Model no.	Model name	Power, W/g	Temp,°C	R^2	RMSE	RSS
4	Handerson and Pabis	1.4	60	0.9530	0.0874	0.0382
			45	0.9510	0.0866	0.0450
			30	0.9508	0.0865	0.0449
		1.05	60	0.9689	0.0649	0.0337
			45	0.9627	0.0709	0.0452
			30	0.9647	0.0681	0.0418
		0.70	60	0.9690	0.0595	0.0460
			45	0.9734	0.0536	0.0402
			30	0.9677	0.0600	0.0505
		0.35	60	0.9639	0.0619	0.0651
			45	0.9625	0.0642	0.0743
			30	0.9597	0.0682	0.0792
5	Logarithmic	1.4	60	0.9963	0.0258	0.0030
			45	0.9945	0.0317	0.0050
			30	0.9901	0.0380	0.0072
		1.05	60	0.9960	0.0247	0.0042
			45	0.9960	0.0245	0.0048
			30	0.9929	0.0323	0.0083
		0.70	60	0.9963	0.0090	0.0011
			45	0.9989	0.0114	0.0076
			30	0.9890	0.0111	0.0096
		0.35	60	0.9992	0.0093	0.0214
			45	0.9891	0.0293	0.0317
			30	0.9878	0.0365	0.0243
6	Wang and Singh	1.4	60	0.9960	0.0254	0.0032
			45	0.9941	0.0301	0.0054
			30	0.9912	0.0365	0.0080
		1.05	60	0.9966	0.0215	0.0037
			45	0.9966	0.0215	0.0041
			30	0.9938	0.0284	0.0072
		0.70	60	0.9991	0.0100	0.0013
			45	0.9989	0.0107	0.0016
			30	0.9989	0.0113	0.0017
		0.35	60	0.9993	0.0088	0.0013
			45	0.9987	0.0118	0.0025
			30	0.9971	0.0181	0.0056

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Table continued..

No.	Model					
		1.4	60	0.9925	0.0391	0.0061
			45	0.9398	0.1052	0.0553
			30	0.9386	0.1060	0.0561
		1.05	60	0.9951	0.0275	0.0052
			45	0.9952	0.0268	0.0057
7	Diffusion approach		30	0.9915	0.0354	0.0100
		0.70	60	0.9574	0.0726	0.0633
			45	0.9634	0.0652	0.0552
			30	0.9550	0.0736	0.0704
		0.35	60	0.9514	0.0739	0.0875
			45	0.9464	0.0790	0.1063
			30	0.6402	0.0804	0.1123
		1.4	60	0.9926	0.0388	0.0060
			45	0.9780	0.0635	0.0201
			30	0.9792	0.0616	0.0190
		1.05	60	0.9859	0.0467	0.0153
			45	0.9792	0.0561	0.0252
8	Verma		30	0.9894	0.0354	0.0100
		0.70	60	0.9783	0.0517	0.0231
			45	0.9805	0.0476	0.0294
			30	0.9921	0.0308	0.0123
		0.35	60	0.9702	0.0579	0.0536
			45	0.9702	0.0589	0.0591
			30	0.9968	0.0197	0.0062
		1.4	60	0.9437	0.0956	0.0457
			45	0.9397	0.0960	0.0553
			30	0.9281	0.0969	0.0563
		1.05	60	0.9595	0.0740	0.0438
			45	0.9525	0.0802	0.0579
9	Two-term exponential		30	0.9531	0.0785	0.0555
		0.70	60	0.9914	0.0313	0.0127
			45	0.9919	0.0295	0.0122
			30	0.9906	0.0324	0.0147
		0.35	60	0.9880	0.0356	0.0215
			45	0.9887	0.0352	0.0223
			30	0.9891	0.0355	0.0214
		1.4	60	0.9525	0.0977	0.0382
			45	0.9510	0.0948	0.0450
			30	0.9508	0.0948	0.0449
		1.05	60	0.9689	0.0693	0.0337
			45	0.9627	0.0752	0.0452
10	Simplified Fick's diffusion equation		30	0.9647	0.0723	0.0418
		0.70	60	0.9522	0.0769	0.0709
			45	0.9552	0.0722	0.0678
			30	0.9677	0.0623	0.0506
		0.35	60	0.9573	0.0693	0.0770
			45	0.9453	0.0755	0.0970
			30	0.9505	0.0779	0.0972

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Table continued..

			60	0.9998	0.0068	0.0001
		1.4	45	0.9958	0.0140	0.0007
			30	0.9996	0.0095	0.0003
			60	0.9992	0.0117	0.0008
		1.05	45	0.1548	0.3830	1.0270
			30	0.1217	0.3853	1.0390
11	M,dilli–Kucuk equation		60	0.3138	0.3044	1.0190
		0.70	45	0.3186	0.2931	1.0310
			30	0.3489	0.2912	1.0180
			60	0.4369	0.2602	1.0150
		0.35	45	0.4874	0.2521	1.0170
			30	0.4817	0.2606	1.0190

Table 3 Parameters of page's model

Power(W/g)	Temp,°C	k	n	R^2
	60	0.0102	1.659	0.9963
1.4	45	0.0082	1.649	0.9945
	30	0.0072	1.671	0.9992
	60	0.0113	1.460	0.9963
1.05	45	0.0082	1.529	0.9961
	30	0.0070	1.529	0.9929
	60	0.0052	1.440	0.9963
0.70	45	0.0056	1.388	0.9989
	30	0.0036	1.440	0.9891
	60	0.0028	1.455	0.9982
0.35	45	0.0022	1.493	0.9891
	30	0.0016	1.536	0.9878

Table 4 Second order polynomial fittings of page's model coefficients

Power (W/g)	
1.4	$k = 0.01118 - 1.457 \times 10^{-4}T + 4.28610^{-7}T^2$ $n = 1.697 - 9.298 \times 10^{-4}T + 2.452 \times 10^{-6}T^2$
1.05	$k = 0.01325 - 2.84 \times 10^{-4}T + 6.683 \times 10^{-7}T^2$ $n = 1.384 + 5.283 \times 10^{-3}T - 1.518 \times 10^{-5}T^2$
0.70	$k = 0.00233 + 4.555 \times 10^{-5}T - 1.109 \times 10^{-7}T^2$ $n = 1.56 - 4.369 \times 10^{-4}T + 1.204 \times 10^{-5}T^2$
0.35	$K = 0.002731 - 4.416 \times 10^{-5}T + 1.251 \times 10^{-5}T^2$ $n = 1.465 + 2.589 \times 10^{-3}T - 7.868 \times 10^{-6}T^2$

Moisture diffusivity and activation energy

The results have shown that internal mass transfer resistance controls the drying time due to the presence of a falling rate drying period. Therefore, the values of effective diffusivity at different drying temperatures could be obtained by using Eq. 8. The average values of effective diffusivities in the drying process varied in the range of $1.21 \times 10^{-7} - 8.91 \times 10^{-8} m^2/s$. As it is expected, the values of D_{eff} increased with the increase of drying temperature. Its values reached a maximum and then decreased as drying progresses. Diffusivity was not identifiable for moisture content values below 2.07kg/kg db for all conditions of microwave power and air temperature, is due to the hypotheses which impose equilibrium moisture content at the boundary on one hand and consider the migration of humidity depends on the parameters of drying air at the beginning of the process on the other hand.[40] However, the effective moisture diffusivities were 10^2 to 10^3 times more than the previous investigations for food materials which lie in range of 10^{-11} to $10^{-9} m^2/s$.[33] The reason may be due to the effect of pretreatment (osmotic dehydration) where the texture and chemical constituents of the food were altered.[41] during rotation inside the incubator-shaker which created different channeling paths for the water molecules to migrate outward resulting greater diffusivity by subsequent microwave drying. Hence, the pretreatment helped in enhancing the diffusion coefficient by which the drying time got

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reduced by faster removal the moisture and thereby the final product quality could be maintained. Effect of temperature on effective diffusivity is generally described using Arrhenius-type relationship (Eq. 8) to obtain better agreement of the predicted curve with experimental data. The frequency factor (D_0) and activation energy are shown in Table 5. The frequency factor (D_0) values decreased from 9.7564×10^{-5} to $0.8806 \times 10^{-5} m^2/s$ while the activation energy decreased from 21.8741 to 10.7167KJ/mole with the increase in microwave power from 0.35 to 1.4W/g. The activation energy barrier must be overcome to activate moisture diffusion, and although it would be beneficial to use high temperatures so as to increase the drying rates by increasing moisture diffusion,[42] it is advisable to dry yellow sweet pepper at optimum temperatures to maintain quality. The values of ln D_{eff} with inverse of temperatures are plotted (Figure 4), the slope of which gives the activation energy (Table 5). This activation energy is in reasonable agreement with the data presented by several other authors, for example 20.00KJ/mol for potato,[43] 27.61KJ/mol for corn,[44] 28.36KJ/mol for carrot.[25]

Table 5 Calculated values of diffusion coefficient and activation energy

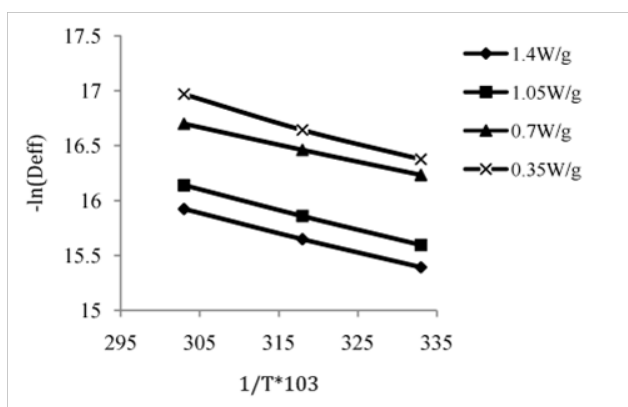| Power(W/g)	$D_o(\times 10^{-5})$ m²/s	E_a(KJ/mole)
1.4	0.8806	10.7167
1.05	1.670	12.5541
0.7	8.4479	18.7896
0.35	9.7564	21.8741

Figure 4 Arrhenius type relationship between effective moisture diffusivity and reciprocal of absolute temperature.

Conclusion

In order to explain the drying behaviour during microwave assisted convective drying of yellow sweet pepper, 11 different thin layer drying models were compared according to their R^2, RMSE and RSS. The relationships between the model parameters and the drying conditions for the computation of the moisture ratio in relation to drying time were determined and reported. According to the results of thin layer microwave drying of yellow sweet pepper, Page model could be used to predict the moisture content of the product at any time of drying process with high ability between drying air temperatures of 30 and 60°C at constant air velocity of 1.5m/s. The drying rate increased remarkably with the power output and temperature of the microwave-convective dryer where drying takes place in the falling rate period. The coefficients of this model and the apparent diffusion coefficient are the most important parameters in the moisture transfer, and they were found to be dependent on the temperature of the drying air. D_{eff} decreased from 1.21×10^{-7} to $8.91 \times 10^{-8} m^2/s$ with decrease of drying temperature from 60 to 35°C which is 10^2 to10^3 times more than the previous investigations for food materials (range of 10-11 to 10-9m²/s) can be better explained by the effect of pretreatment (osmotic dehydration) where the texture and chemical constituents of the food were altered during rotation inside the incubator-shaker which created different channeling paths for the water molecules to migrate outward resulting greater diffusivity by subsequent microwave drying. Hence, the pretreatment helped in enhancing the diffusion coefficient by which the drying time got reduced by faster removal the moisture and thereby the final product quality could be maintained. These mathematical models can be used for online quality prediction at any time having much more practical significance and can be recommended to food industry for process design. Therefore the above research findings would be very useful for drying of yellow sweet peppers which have special nutraceutical and pharmaceutical potential. However, quality of end product using this drying system needs to be studied.

Conflict of interest

Author declares that there is no conflict of interest.

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