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

**Abstract**

Drying kinetics modeling and effective moisture diffusivity (*D_e*) 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 1.21x10^-7 to 8.91x10^-10m/s with decrease of drying temperature from 60 to 35°C which is 102 to 103 times reported earlier. The frequency factor (*D_0*) values decreased from 9.7564x10^-7 to 0.8806x10^-10/s while the activation energy of diffusion (*E_d*) 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

**Introduction**

Fruits and vegetables play a significant role in human nutrition as they provide many essential vitamins and minerals. 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. Convontional 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. However, in recent years, microwave drying has gained popularity as an alternative drying method to overcome above problems for a wide variety of food products. 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. In microwave heating, as the temperature inside the material approaches the boiling point of water, pressure development becomes significant. Heating, as the temperature inside the material approaches the boiling point of water, pressure development becomes significant. 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. Chaotic 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...
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 ±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 Tutoyo, Japan) having an accuracy of 0.02mm; only slices that fell within a 5% range of the average dimensions (length, breadth, 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.).

**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. 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 up 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 specific time (kg/kg d.b.), M is the moisture content at a drying time t and t+dt (min), respectively. Moisture ratio and drying rate of yellow sweet pepper were calculated using the following equations:

\[ \text{MR} = \frac{M - M_e}{M_i - M_e} \]

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 Doyma. The MR, however, was simplified to \( M/M_i \).

Drying rate = \( \frac{M_{t+dt} - M_t}{dt} \)

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

| Model No. | Model Name          | Model Equation                                      | References         |
|-----------|---------------------|------------------------------------------------------|--------------------|
| 1         | Newton              | MR = e^{-kt}                                        | Ayensu            |
| 2         | Page                | MR =                                                | Agrawal and Singh  |
| 3         | Modified Page       | MR =                                                | White et al.       |
| 4         | Henderson and Pabis | MR = a \cdot e^{kt}                                 | Akpinar et al.    |
| 5         | Logarithmic         | MR = a \cdot e^{kt} + c                             | Yalidi et al.     |
| 6         | Wang and Singh      | MR = a \cdot e^{kt} + (1-a) \cdot e^{-kt}           | Wang and Singh    |
| 7         | Diffusion approach  | MR = a \cdot e^{kt} + (1-a) \cdot e^{-kt}           | Togrul and Pehlivan|
| 8         | Verma               | MR =                                                | Verma et al.       |
| 9         | Two-term exponential| MR = a \cdot e^{kt} + (1-a) \cdot e^{kt}            | Sharaf-Elden et al.|
| 10        | Simplified Fick's diffusion equation | MR =                                                | Togrul and Pehlivan|
| 11        | Mdiili-Kucuk equation | MR =                                                | Sacilik and Elicin |

**Table 1 Thin layer drying models used**

**Theoretical consideration**

Mathematical modeling of the drying curves: To determine the most suitable drying model, the drying curves 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:

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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

\[
\frac{\partial M}{\partial t} = \frac{1}{r} \left( \frac{\partial}{\partial r} \left( D_{eff} \frac{\partial M}{\partial r} \right) + \frac{\partial}{\partial Z} \left( D_{eff} \frac{\partial M}{\partial Z} \right) \right)
\]

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

\[
MR = \frac{M-M_{eq}}{M_0-M_{eq}} = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp \left( -\frac{\pi^2 D_{eff} t}{4L^2} \right) \tag{4}
\]

Where, \( D_{eff} \) is the effective diffusivity (m\(^2\)/s); \( L_s \) is the half thickness of slab (m). For long drying times; \( n=1 \), then Eq. (4) can be reduced to the following form:

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

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:

\[
\ln MR = \ln \left( \frac{8}{\pi^2} \exp \left( -\frac{\pi^2 D_{eff} t}{4L^2} \right) \right) \tag{6}
\]

\[
\text{Slope} = \frac{\pi^2 D_{eff}}{4L^2} \tag{7}
\]

Calculation of activation energy

The temperature dependence of the effective diffusivity may be described by an Arrhenius-type relationship33–35 as follows:

\[
D_{eff} = D_0 \exp \left( \frac{E_a}{RT} \right) \tag{8}
\]

\[
\ln D_{eff} = \ln D_0 - \frac{E_a}{RT} \tag{9}
\]

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 (m\(^2\)/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 \( E_a \) 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:

\[
\text{RSS} = \sum_{i=1}^{N} (C_{exp,i} - C_{pre,i})^2 \tag{10}
\]

\[
\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N} (C_{exp,i} - C_{pre,i})^2}{N}} \tag{11}
\]

Where, \( C_{exp,i} \) is the \( i^{th} \) experimental value, \( C_{pre,i} \) is the \( i^{th} \) 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...
reported by Soysal for parsley, Wang and Xi for carrot slices, Giri and Prasad for mushroom and Karaaslan and Tuncer 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. 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 R², less root mean square error (RMSE) and residual sum of square (RSS), shown in Table 2. The equation for Page model is,

\[
MR(k, n) = \frac{M - M_e}{M_o - M_e} = \exp\left(-kt^n\right)
\] (12)
Where, $k$ and $n$ are empirical constant, $t$ is the temperature.

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

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 0.102 min$^{-1}$ 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 1.4 W/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.

| Model no. | Model name     | Power, W/g | Temp, °C | $R^2$ | RMSE  | RSS   |
|-----------|----------------|------------|----------|-------|-------|-------|
| 1         | Newton’s model | 1.4        | 60       | 0.9438| 0.0872| 0.0456|
|           |                | 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|
| 2         | Page’s model   | 1.4        | 60       | 0.9573| 0.0673| 0.0634|
|           |                | 45         | 0.9634   | 0.0607| 0.0552|
|           |                | 30         | 0.9514   | 0.0697| 0.0875|
|           |                | 0.35       | 45       | 0.9464| 0.0747| 0.1063|
|           |                | 30         | 0.9424   | 0.0792| 0.1132|
|           |                | 60         | 0.9965   | 0.0240| 0.0028|
|           |                | 1.05       | 45       | 0.9959| 0.0232| 0.0032|
|           |                | 30         | 0.9992   | 0.0169| 0.0017|
|           |                | 60         | 0.9974   | 0.0188| 0.0028|
| 3         | Modified Page’s model | 1.4 | 45       | 0.9916 | 0.0229 | 0.0027 |
|           |                | 30         | 0.9978   | 0.0170 | 0.0026 |
|           |                | 0.35       | 45       | 0.9948 | 0.0244 | 0.0031 |
|           |                | 60         | 0.9945   | 0.0243 | 0.0032 |
|           |                | 30         | 0.9941   | 0.0256 | 0.0042 |
|           |                | 60         | 0.9982   | 0.0187 | 0.0140 |
|           |                | 1.4        | 45       | 0.9934 | 0.0269 | 0.0130 |
|           |                | 30         | 0.9945   | 0.0251 | 0.0107 |
|           |                | 60         | 0.9438   | 0.0955 | 0.0456 |
|           |                | 1.05       | 45       | 0.9398 | 0.0960 | 0.0553 |
|           |                | 60         | 0.9596   | 0.0740 | 0.0438 |
|           |                | 0.35       | 45       | 0.9523 | 0.0802 | 0.0579 |
|           |                | 30         | 0.9531   | 0.0785 | 0.0554 |
|           |                | 0.70       | 60       | 0.9573 | 0.0698 | 0.0634 |
|           |                | 45         | 0.9608   | 0.0828 | 0.0552 |
|           |                | 30         | 0.9550   | 0.0709 | 0.0704 |
|           |                | 0.35       | 45       | 0.9464 | 0.0768 | 0.1060 |
|           |                | 30         | 0.9424   | 0.0815 | 0.1132 |
### Mathematical modelling of microwave assisted dehydration of osmotically pretreated yellow sweet pepper (Capsicum annum L)

Table continued...

| Model no. | Model name       | Power, W/g | Temp, °C | $R^2$  | RMSE  | RSS   |
|-----------|------------------|------------|----------|--------|--------|-------|
|           |                  |            |          |        |        |       |
| 4         | Henderson 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 |
| 5         | Logarithmic      | 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 |
| 6         | Wang and Singh   | 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 |
|           |                  | 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 |
| 6         | Wang and Singh   | 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...

|   |   |   |   |   |
|---|---|---|---|---|
|  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 |
|  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 |
|  1.05 | 60 | 0.9926 | 0.0388 | 0.0060 |
|  45 | 0.9780 | 0.0635 | 0.0201 |
|  30 | 0.9792 | 0.0616 | 0.0190 |
|  0.70 | 60 | 0.9859 | 0.0467 | 0.0153 |
|  45 | 0.9792 | 0.0561 | 0.0252 |
|  30 | 0.9894 | 0.0354 | 0.0100 |
|  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 |
|  0.70 | 60 | 0.9595 | 0.0740 | 0.0438 |
|  45 | 0.9525 | 0.0802 | 0.0579 |
|  30 | 0.9531 | 0.0785 | 0.0555 |
|  0.35 | 60 | 0.9880 | 0.0356 | 0.0215 |
|  45 | 0.9887 | 0.0352 | 0.0223 |
|  30 | 0.9891 | 0.0355 | 0.0214 |
|  1.05 | 60 | 0.9525 | 0.0977 | 0.0382 |
|  45 | 0.9510 | 0.0948 | 0.0450 |
|  30 | 0.9508 | 0.0948 | 0.0449 |
|  0.70 | 60 | 0.9689 | 0.0693 | 0.0337 |
|  45 | 0.9627 | 0.0752 | 0.0452 |
|  30 | 0.9647 | 0.0723 | 0.0418 |

### Diffusion approach

|   |   |   |   |   |
|---|---|---|---|---|
|  0.05 | 60 | 0.9915 | 0.0354 | 0.0100 |
|  45 | 0.9915 | 0.0354 | 0.0100 |
|  30 | 0.9915 | 0.0354 | 0.0100 |

### Two-term exponential

|   |   |   |   |   |
|---|---|---|---|---|
|  1.4 | 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 |
|  0.70 | 60 | 0.9510 | 0.0948 | 0.0450 |
|  45 | 0.9508 | 0.0948 | 0.0449 |
|  30 | 0.9689 | 0.0693 | 0.0337 |
|  1.05 | 60 | 0.9627 | 0.0752 | 0.0452 |
|  45 | 0.9647 | 0.0723 | 0.0418 |
|  30 | 0.9522 | 0.0769 | 0.0709 |
|  0.70 | 60 | 0.9552 | 0.0722 | 0.0678 |
|  45 | 0.9677 | 0.0623 | 0.0506 |
|  30 | 0.9573 | 0.0693 | 0.0770 |
|  0.35 | 60 | 0.9453 | 0.0755 | 0.0970 |
|  45 | 0.9505 | 0.0779 | 0.0972 |
|  30 | 0.9505 | 0.0779 | 0.0972 |

### Simplified Fick's diffusion equation

|   |   |   |   |
|---|---|---|---|
|  1.4 | 60 | 0.9926 | 0.0388 |
|  45 | 0.9780 | 0.0635 |
|  30 | 0.9792 | 0.0616 |
|  0.70 | 60 | 0.9859 | 0.0467 |
|  45 | 0.9792 | 0.0561 |
|  30 | 0.9894 | 0.0354 |
|  0.35 | 60 | 0.9702 | 0.0579 |
|  45 | 0.9702 | 0.0589 |
|  30 | 0.9968 | 0.0197 |
|  1.4 | 60 | 0.9437 | 0.0956 |
|  45 | 0.9397 | 0.0960 |
|  30 | 0.9281 | 0.0969 |
|  0.70 | 60 | 0.9595 | 0.0740 |
|  45 | 0.9525 | 0.0802 |
|  30 | 0.9531 | 0.0785 |
|  0.35 | 60 | 0.9880 | 0.0356 |
|  45 | 0.9887 | 0.0352 |
|  30 | 0.9891 | 0.0355 |
|  1.05 | 60 | 0.9525 | 0.0977 |
|  45 | 0.9510 | 0.0948 |
|  30 | 0.9508 | 0.0948 |
|  0.70 | 60 | 0.9689 | 0.0693 |
|  45 | 0.9627 | 0.0752 |
|  30 | 0.9647 | 0.0723 |
|  0.35 | 60 | 0.9552 | 0.0722 |
|  45 | 0.9677 | 0.0623 |
|  30 | 0.9573 | 0.0693 |
|  0.70 | 60 | 0.9522 | 0.0769 |
|  45 | 0.9552 | 0.0722 |
|  30 | 0.9677 | 0.0623 |
|  0.35 | 60 | 0.9453 | 0.0755 |
|  45 | 0.9505 | 0.0779 |
|  30 | 0.9505 | 0.0779 |

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

Table 3 Parameters of page's model

| Power (W/g) | Temp, °C | k    | n    | R²   |
|-------------|----------|------|------|------|
| 1.4         | 60       | 0.0102 | 1.659 | 0.9963 |
|             | 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) | k                       | n                       |
|-------------|-------------------------|-------------------------|
| 1.4         | k = 0.01118-1.457x10⁻⁷T+4.286x10⁻¹⁰T² | n = 1.697-9.298x10⁻¹⁰T+2.452x10⁻¹³T² |
| 1.05        | k = 0.01325-2.84x10⁻⁷T+6.683x10⁻¹⁰T³ | n = 1.384+5.283x10⁻¹⁰T⁻1.518x10⁻¹³T³ |
| 0.70        | k = 0.00233+4.555x10⁻⁸T⁻1.109x10⁻¹⁰T⁷ | n = 1.56-4.369x10⁻¹⁰T+1.204x10⁻¹³T³ |
| 0.35        | k = 0.002731-4.416x10⁻⁸T+1.251x10⁻¹⁰T² | n = 1.465+2.589x10⁻¹⁰T⁻7.868x10⁻¹³T² |

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 1.21×10⁻⁷-8.91×10⁻⁸m²/s. As it is expected, the values of effective diffusivity 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 10² to 10³ times more than the previous investigations for food materials which lie in range of 10⁻¹¹ to 10⁻⁹m²/s.13 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_e) and activation energy are shown in Table 5. The frequency factor (D_e) values decreased from 9.7564 × 10⁻⁷ to 0.8806 × 10⁻⁸ m²/s while the activation energy decreased from 21.8741 to 10.7167 KJ/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, it is advisable to dry yellow sweet pepper at optimum temperatures to maintain quality. The values of ln D_e 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 authors, for example 20.00 KJ/mol for potato, 27.61 KJ/mol for corn, 28.36 KJ/mol for carrot.

Table 5 Calculated values of diffusion coefficient and activation energy

| Power(W/g) | D_e (x10⁻⁷) m²/s | E (KJ/mole) |
|-----------|------------------|-------------|
| 1.4       | 0.8006           | 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 R², 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_e decreased from 1.21x10⁻¹⁷ to 8.91x10⁻⁹ m²/s with decrease of drying temperature from 60 to 35°C which is 10⁻¹ to 10⁻¹⁰ times more than the previous investigations for food materials (range of 10⁻¹¹ to 10⁻¹⁸m²/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.

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Conflict of interest

Author declares that there is no conflict of interest.

References

1. Craig W, Beck L. Phytochemicals: health protective effects. Can J Diet Pract Res. 1999;60(2):78–84.
2. Bayas T, Icier F, Ersus S, et al. Effects of microwave and infrared drying on the quality of carrot and garlic. Eur Food Res Technol. 2003;218:68–73.
3. Kordylas JM. Processing and preservation of tropical and subtropical foods. London: Macmillan Education Ltd; 1991.
4. Nicotelli JF, Telis-Romero J, Telis VNR. Air-drying of fresh and osmotically pre-treated pineapple slices: fixed air temperature versus fixed temperature drying kinetics. Drying Technol. 2001;19(9):2175–2191.
5. Drouzas AE, Tsami E, Saravacos GD. Microwave/vacuum drying of model fruit gels. J Food Eng. 1999;39(2):117–122.
6. Lin TM, Durance TD, Scaman CH. Characterization of vacuum microwave, air and freeze dried carrot slices. Food Res Int. 1998;31(2):111–117.
7. Vadivambal R, Jayas DS. Changes in quality of microwave-treated agricultural products-a review. Biosys Eng. 2007;98(1):1–16.
8. Yongsawatdigul J, Gunasekaran S. Microwave vacuum drying of cranberries, part I. energy use and efficiency. J Food Process Pres. 1996;20(2):121–143.
9. Bouraoui M, Richard P, Durance T. Microwave and convective drying of potato slices. J Food Process Eng. 1994;17(3):353–363.
10. Feng H, Tang J. Microwave finish drying of diced apples in a spouted bed. J Food Sci. 1998;63(4):679–683.
11. Tulasidas TN, RagHAVan GSV, Mujumdar AS. Microwave drying of grapes in a single mode cavity at 2450 MHz: drying kinetics. Drying Technol. 1995;13(8&9):1549–1972.
12. Sharma GP, Prasad S. Effective moisture diffusivity of garlic cloves undergoing microwave-convective drying. J Food Eng. 2004;65(4):609–617.
13. Goksu EI, Sumnu G, Esin A. Effect of microwave on fluidized bed drying of macaroni beads. J Food Eng. 2005;66(4):463–468.
14. Bal LM, Kar A, Satya S, et al. Drying kinetics and effective moisture diffusivity of bamboo shoot slices undergoing microwave drying. Int J Food Sci Technol. 2010;45(11):2321–2328.

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