Hot air drying characteristics of mango ginger: Prediction of drying kinetics by mathematical modeling and artificial neural network

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Abstract Mango ginger (*Curcuma amada*) was dried in a through-flow dryer system at different temperatures (40–70 °C) and air velocities (0.84 – 2.25 m/s) to determine the effect of drying on drying rate and effective diffusivity. As the temperature and air velocity increased, drying time significantly decreased. Among the ten different thin layer drying models considered to determine the kinetic drying parameters, semi empirical Midilli et al., model gave the best fit for all drying conditions. Effective moisture diffusivity varied from $3.7 \times 10^{-10} \text{ m}^2/\text{s}$ to $12.5 \times 10^{-10} \text{ m}^2/\text{s}$ over the temperature and air velocity range of study. Effective moisture diffusivity regressed well with Arrhenius model and activation energy of the model was found to be 32.6 kJ/mol. Artificial neural network modeling was also employed to predict the drying behaviour and found suitable to describe the drying kinetics with very high correlation coefficient of 0.998.

Keywords Mango ginger · Through-flow dryer · Diffusion · Artificial neural network · Thin layer drying

Introduction

Curcuma amada popularly known as mango ginger is a perennial, rhizomatous herb and unique species belonging to Zingiberace family which resembles Zinger but imparts raw mango flavor. *C.amada* originated in the Indo-Malayan

region, widely distributed and cultivated in different parts of India. Due to its exotic flavor of raw unripe mango, it is used in pickles, candies, curries, salads, etc. in Indian subcontinent (Sasikumar 2005; Policegoudra et al. 2011). The volatile oils of the mango ginger contain the mixtures of compounds present in both raw mango and turmeric (Golap and Bandyopadhyaya 1984; Rao et al. 1989). The spice is credited for applications in traditional Ayurveda and Unani medicine system as appetizer, antipyretic, laxative, diuretic, emollient etc. It also has biological properties like antioxidant (Prakash et al. 2007; Policegoudra 2007a), antimicrobial (Policegoudra et al. 2007b), antifungal (Singh et al. 2002), anti-inflammatory (Mujumdar et al. 2000) activity etc. Mango ginger is also an unconventional source of starch having potential functional properties (Policegoudra and Aradhya 2008). Conventional drying of mango ginger involves washing of rhizomes to remove dirt, slicing and sun drying. Artificial drying of mango ginger will solve many problems associated with conventional process. Drying is a complicated unit operation process involving simultaneous, coupled heat and mass transfer, particularly under transient conditions (Diamante et al. 2010). It is one of the oldest methods of preservation and one of the most important in post-harvest processing of fruits, vegetables and other agricultural products to reduce the moisture content which increases the self-life by decreasing the enzyme activity and microbial activity and spoilage of food products (Mujumdar and Law 2010; Guine et al. 2012). Also, it brings about substantial reduction in weight and volume thereby minimizing packaging, storage and transportation costs (Okos et al. 1992). The most common method of drying is natural drying (sun drying or shade drying) and hot air drying because of their low cost. The disadvantages of natural drying are: contamination with dust, insects etc. in drying environment, extremely weather dependent and longer drying time. Therefore, hot air drying is a cost effective

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method of drying which provides uniformity and hygiene, and is inevitable for food drying process (Diamante and Munro 1993; Doymaz and Pala 2002). Several studies have been carried out by researchers to investigate the convective hot air drying characteristics of the fruits and vegetables: apple (Sacilik and Elicin 2006), carrot (Doymaz 2004), red pepper (Doymaz and Pala 2002), banana (Karim and Hawlader 2005), kiwi fruit (Simal et al. 2005), black grapes (Togrul 2010), eggplant (Ertekin and Yaldiz 2004), figs (Babalís et al. 2006) and sweet potato (Diamante and Munro 1993). There is no literature available on hot air drying behavior of mango ginger in spite of its high medicinal and food value even though research work has been reported on microwave drying of mango ginger by the present authors (Krishna Murthy and Manohar 2012). Dried mango ginger find applications in imparting flavor of mango and ginger in food preparations of ready mixes and extraction of volatiles.

Mathematical modeling of the drying process and equipment is an important aspect of drying technology in post-harvest processing of agricultural materials. Numerous mathematical equations can be found in literatures that describe drying phenomena of agricultural products. Some of the models frequently used by researchers for application in drying studies are listed in Table 1. Among them, thin layer drying models have found wide application due to their ease of use. Thin layer drying means to dry the sample as a single layer. These models can be categorized as theoretical, semi-theoretical and empirical model (Akpınar 2006; Midilli et al. 2002; Park et al. 2002). The theoretical models suggest that the moisture transport is controlled mainly by internal moisture mechanism and needs assumption of geometry of the food material, mass diffusivity and heat conductivity. The most widely investigated theoretical drying model is Fick's second law of diffusion (Babalís et al. 2006). Semi theoretical models and empirical models consider only the external resistance to the moisture transport and are valid only in the specific range of temperature, air velocity and humidity for which they were developed (Ozdemir and Devres 1999). Semi-theoretical models are derived from the general solutions of Fick's second law of diffusion. Some commonly used semi-theoretical models are Page model, Handerson and Pabis model, Lewis model, Two term model, Approximation of diffusion model, Midilli et al., model. Empirical models derive a direct relationship between average moisture content and drying time. They neglect fundamentals of the drying process and their parameters have no physical meaning. Therefore, they cannot give clear and accurate view of the important processes occurring during drying although they may describe the drying curve for the conditions of the experiments. Among them, Wang and Singh model and Thompson model have found applications in the literature (Hii et al. 2009). These

models are easily applied to drying simulations as they depend on the experimental data.

Artificial Neural Network (ANN) is an alternative approach to mathematical modeling for prediction of drying kinetics. They have the ability to learn by experience and do not require parameters of physical models. ANN is capable of handling complex systems with nonlinearities and interactions between decision variables (Lertworasirikul 2008). Many authors successfully used ANN to describe the drying characteristics of many agricultural products; carrots (Erenturk and Erenturk 2007), ginseng (Martynenko and Yang 2006), tomato (Movagharnjad and Nikzad 2007), cassava and mango (Hernández-Pérez et al. 2004), grain (Liu et al. 2007), *Echinacea angustifolia* (Erenturk et al. 2004).

The objective of the present investigation is (a) to observe the effect of temperature and air velocity on drying characteristics of mango ginger (b) to select the best model among several thin layer drying models which explains the moisture removal behavior of mango ginger (c) to calculate effective moisture diffusivity and the activation energy and (d) to predict the moisture content at different temperatures and air velocities during the course of drying using Artificial Neural Network methodology.

Materials and methods

Experimental material

The fresh mango ginger rhizomes were procured from local market, Mysore, India. Rhizomes were washed in running tap water to remove adhered soil and stored in cold room at 4 ± 1 °C until they were taken for drying studies. Moisture content was determined by toluene distillation method as per ASTA (1985) and average initial moisture was found to be 9 ± 0.25 kg water. kg db⁻¹. Before each drying experiment, the thin slices of rhizome were obtained using slicing machine (M/s Robot coupe, USA, Model: CL 50 Gourmet). At least 20 slices were measured for the thickness using Vernier caliper and the average thickness was 1.77 ± 0.02 mm. The slices were circular with diameters ranging between 10 to 15 ± 0.02 mm.

Hot air dryer

The hot air drying experiments were conducted in laboratory microwave-convective dryer (Heindl GmbH, Mainburg, Germany) without operating the microwave component of the dryer (Fig. 1). The dryer consists of ventilator (600 m³/h), electrical heating coils (2.25 kW/ 400 V/ 50 Hz), single tray ($400 \times 200 \times 40$ mm) with holes having diameter of 5 mm. The ambient air passes through heating coils and gets heated up to the required temperature and enters the drying

Table 1 Thin layer drying models used to describe drying kinetics

Model	Equation	Reference
1. Lewis model	$MR = -kt$	Falade and Solademi 2010
2. Page Model	$MR = \exp(-kt^n)$	Doymaz 2005
3. Modified Page	$MR = \exp(-kt)^n$	Wang et.al. 2007
4. Handerson and Pabis	$MR = a \cdot \exp(-kt)$	Ertekin and Yaldiz 2004
5. Midilli et.al model	$MR = a \cdot \exp(-kt^n) + bt$	Ozbek and Dadali 2007
6. Simplified Fick's Diffusion Equation	$MR = a \cdot \exp(-k(t/L^2))$	Diamante and Munro 1993
7. Diffusion approximation	$MR = a \exp(-kt) + (1-a) \exp(-b \cdot kt)$	McMinn 2006
8. Logistic Model	$MR = b/(1 + a \cdot \exp(kt))$	Jain and Pathare 2004
9. Two Term Model	$MR = a \exp(-k_1 t) + b \exp(-k_2 t)$	Hii et al. 2009
10. Thompson model	$t = a \cdot \ln MR + b \cdot (\ln MR)^2$	Ozdemir and Devres 1999

MR Moisture ratio; *t* drying time; *a*, *b*, *k*, *k₁*, *k₂*, *n* are parameters of the models; *L* half thickness of the slice

chamber in through flow mode and escapes via ventilator. The hot air was not circulated back to the system. Temperature and velocity of the hot air were measured by means of transducers provided in the control panel.

Drying procedure

The dryer was allowed to run for some time prior to loading of material to allow the air to reach the desired temperature. The sliced rhizome of 150 g were placed on the tray in the drying cabinet and arranged in a single layer. To study the effect of temperature and air velocity on drying kinetics of moisture removal during hot air drying, the experiment was performed at four different temperatures 40, 50, 60, 70 °C with a constant air velocity of 0.84 ± 0.02 m/s. To study the effect of air velocity on drying, studies were carried out at four different air velocities 0.84, 1.36, 1.84, 2.25 m/s under constant air temperature of 60 °C. The moisture loss was recorded at regular intervals of time using the digital weighing balance (OHAUS-Adventure,

USA, Model: ARB120) with the measurement precision of ± 0.01 g. Each drying experiment was conducted in triplicate and average values are reported with standard deviation. The drying experiments were carried out until there was no further change in the three consecutive weights.

Mathematical modeling

The experimental moisture content (kg water. kg db⁻¹) data of mango ginger during hot air drying process were converted to dimensionless moisture ratio (*MR*) number using the equation:

$$MR = \frac{X_t - X_e}{X_o - X_e} \quad (1)$$

Where *X_o* is the initial moisture content, *X_t* is the moisture content at time *t* and *X_e* is the equilibrium moisture content (Shittu and Raji 2011; Ertekin and Yaldiz 2004; Wang et al. 2007). Equation 1 can be further simplified to $MR = X_t/X_o$ as the values of *X_e* is relatively small compared to *X_o* and *X_t* for long drying time (Diamante and Munro 1993; Esturk 2012; Wang et al. 2007).

The drying rate (*dx/dt*) during the experiments was calculated using the following equation:

$$dx/dt = (x_t - x_{t+dt}) / dt \quad (2)$$

Where *X_{t+dt}* is the moisture content at time *t+dt* and *X_t* is the moisture content at time *t* is the drying time measured in minutes (Ozbek and Dadali 2007). The experimental data of dimensionless moisture ratio Vs drying time were fitted to 10 different thin layer drying models listed in Table 1.

Statistical analysis and evaluation of drying models

Nonlinear least square method using the SOLVER tool based on the Generalized Reduced Gradient (GRG) method

Fig. 1 Schematic diagram of Hot air drier used for drying experiments

of iteration available in Microsoft Excel (Microsoft Office 2010, USA) was used to fit the experimental data to selected models. For evaluating the goodness of fit, four statistical parameters such as residual sum square (RSS), root mean square error (RMSE), chi square (CS) and Relative percentage deviation (RPD) were used in addition to coefficient of determination (R^2) as primary criterion. The values of R^2 were one of the primary criterions for selecting the best model and can be used to test linear relationship between experimental and model predicted values (Gunhan et al. 2005). High R^2 (closer to 1) value represents the best fit. Statistical parameters may be computed from the following mathematical equations.

$$RSS = \sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})^2 \quad (3)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})^2}{N}} \quad (4)$$

$$CS = \frac{1}{N-p} \sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})^2 \quad (5)$$

$$RPD = \frac{100}{N} \sum_{i=1}^N \frac{|MR_{exp,i} - MR_{pre,i}|}{MR_{exp,i}} \quad (6)$$

Where N is the total number of observations, p is number of factors in the mathematical model, $MR_{exp,i}$ and $MR_{pre,i}$ are the experimental and predicted moisture ratio at any observation i . In nonlinear regression RSS is the important parameter and ideal value is zero (Sun and Byrne 1998). Relative percentage deviation compares the absolute differences between the predicted moisture content with the experimental moisture content throughout the drying process. The relative percent errors below 10 % indicate very good fit (Roberts et al. 2008; Ozdemir and Devres 1999). RMSE and CS compare the differences between the model predicted values of moisture ratios to the experimental moisture ratios. The values of the RMSE and CS are always positive. Lower values indicate the closeness of experimental value with predicted value and goodness of fit (Midilli and Kucuk 2003).

Estimation of effective moisture diffusivity

Drying phenomenon of biological products takes place in the falling rate period after a short heating period (Ozbek and Dadali 2007; Falade and Solademi 2010). It is generally accepted that liquid diffusion is the only physical mechanism to transfer water to surface to be evaporated. Fick's second law given in Eq. 7 can be used to describe the drying

process of the mango ginger. It is a unidirectional diffusion equation and can be used for various regularly shaped bodies such as rectangular, cylindrical and spherical products.

$$\frac{\partial x}{\partial t} = D_{eff} \frac{\partial^2 x}{\partial z^2} \quad (7)$$

Where X is the moisture content (kg.water.kg db⁻¹), t is the time (s), z is the diffusion path (m), D_{eff} is the moisture dependent diffusivity (m²/s) (Akpınar 2006; Doymaz 2004; Wang et al. 2007). Analytical solution to Eq. 7 was developed by Crank (1975) and following assumptions were made in arriving the solution: uniform distribution of initial moisture throughout the sample, negligible internal resistance to mass transfer, moisture transport/mass transfer by diffusion mechanism, Constant diffusion coefficient, negligible product shrinkage during drying, surface moisture content of the sample instantaneously reaches equilibrium with the condition of surrounding air (Ozbek and Dadali 2007; Doymaz 2004). Appropriate initial and boundary conditions for solving the Eq. 7 are given below (Akpınar 2006):

$$\begin{aligned} t = 0, 0 < z < L, X &= X_0 \\ t > 0, z = 0, dx/dt &= 0 \\ t > 0, z = L, X &= X_e \end{aligned}$$

The solution of the Eq. 7 for infinite slab of thickness $2L$ is:

$$MR = \frac{x_t - x_e}{x_0 - x_e} = \frac{8}{\pi} \sum_{n=0}^{\infty} \frac{1}{(2n+1)} \cdot \exp\left(-\frac{(2n+1)^2 \pi^2 D_{eff} t}{4L^2}\right) \quad (8)$$

For long drying period, Eq. 8 can be further simplified to only the first term of the series (Tutuncu and Labuza 1996):

$$MR = \frac{x_t - x_e}{x_0 - x_e} = \frac{8}{\pi} \exp\left(-\frac{\pi^2 D_{eff} t}{4L^2}\right) \quad (9)$$

The Eq. 9 could be further simplified to a straight line equation as given below:

$$\ln(MR) = \ln\left(\frac{8}{\pi}\right) - \left(\frac{D_{eff} \pi^2}{4L^2} t\right) \quad (10)$$

Effective moisture diffusivity was typically determined by plotting experimental drying data in terms of $\ln(MR)$ Vs drying time and found from the slope ($\pi^2 D_{eff}/4L^2$) according to Eq. 10.

Analysis of drying data by artificial neural network

Configuration of ANN used in the present study shown in Fig. 2 is a multilayer perceptron (MLP) feed-forward network with one input layer, one hidden layer and one output

Fig. 2 ANN Configuration

layer. The input variables in the input layer are temperature of hot air, air velocity and drying time and the only output variable in the output layer is the moisture content of mango ginger at any time. The software program written as a Macro in Microsoft-Excel uses feed-forward back-propagation algorithm for training and testing (Tiberius version 7.0.3, <http://www.tiberius.biz/>). The activation function used in the algorithm is hyperbolic tangent. The software allows varying the parameters of ANN process like learning rate, weights, number of nodes in the hidden layer between the ranges of values. These are varied progressively to arrive at the maximum coefficient of determination for the training data as the number of epochs (learning cycles) increased. Eighty percent of experimental data points were randomly selected for training purpose while the remaining data were set for testing purpose.

Results and discussion

Effect of temperature on drying kinetics of mango ginger

Drying curves of moisture ratio Vs drying time reflecting the effect of temperatures at constant air velocity of 0.84 m/s is shown in Fig. 3a. The drying process was assumed to be finished when changes in moisture loss were negligible. Drying time to reduce the initial moisture content of 9 kg water. kg db⁻¹ to 0.1 kg water. kg db⁻¹ decreased substantially as the temperature increased. When drying is carried out at a constant air velocity of 0.84 m/s, drying time decreased about 2.6 times when drying temperature increased from 40 to 70 °C.

Drying rates calculated from Eq. 2 against drying time at different temperatures at constant air velocity of 0.84 m/s are shown in Fig. 3b. Constant drying rate period was not observed in any of the experiments. Drying process of mango ginger presented a typical falling rate period with a shorter accelerating phase at the start. Entire drying took place in the falling rate period like most food products. Drying rate was predominantly in the falling rate period,

Fig. 3 Effect of drying temperature at constant air velocity of 0.84 m/s (a) moisture ratio Vs time (b) drying rate Vs time (c) Drying rate Vs moisture content

indicating that diffusion is the mechanism governing the moisture removal during hot air drying of mango ginger. Drying rate is directly proportional to the temperature and as the temperature increased, drying rate also increased significantly and resulted in shorter drying time. Figure 3c shows the drying rate as a function of moisture content. As the moisture content decreases drying rate also decreased. The average drying rates varied from $0.045 \text{ kg water. kg.db}^{-1}.\text{s}^{-1}$ (at 40°C) to $0.089 \text{ kg water. kg.db}^{-1}.\text{s}^{-1}$ (at 70°C).

Dimensionless moisture ratio was regressed against the drying time according to the thin layer drying models presented in Table 1. All the proposed models showed higher values of R^2 and lower values of RSS, RMSE and CS. But the Relative Percentage Deviation, another statistical test selected to evaluate the performance of selected models, varied significantly. Comparing the various statistical parameters of various models, Midilli et al. model was selected as the best model to predict the drying characteristics of mango ginger undergoing hot air drying as the values of RPD were found to be less than 10 % except at 40°C temperature (air velocity of 0.84 m/s). The RPD values for other models were found to be greater than 10 % indicating comparatively poorer fit to experimental data. The estimated value of statistical parameters and constant parameters of Midilli et al. model were presented in Table 2 and the regression of the model to experimental drying data was illustrated in Fig. 3.

Effect of air velocity on drying kinetics of mango ginger

Figure 4a shows the effect of air velocity on progress of moisture ratio with drying time at constant air temperature of 60°C . Drying time of the sample decreased from 120 min. to 95 min. as the air velocity increased from 0.84 m/s to 2.25 m/s for the same reduction moisture content from the initial moisture content of $9 \text{ kg water. kg db}^{-1}$ to

$0.1 \text{ kg water. kg db}^{-1}$. Effect of air velocity on drying rate as a function of drying time is plotted in Fig. 4b. Effect of air velocity on drying rate as a function of moisture content is also shown in Fig. 4c. As the moisture content decreased, drying rate also decreased at all air velocities. Highest drying rate of about $0.45 \text{ kg water kg}^{-1} \text{ d.b.s}^{-1}$ was observed while employing air velocity of 2.25 m/s (Fig. 4c). It can be seen that at moisture content of about $7 \text{ kg water. kg db}^{-1}$, drying rate at air velocity of 2.25 m/s is almost double that of drying rate when air velocity is at 0.84 m/s .

Effect of temperature and velocity on effective moisture diffusivity

The method of slope was used to calculate the effective moisture diffusivities of mango ginger. According to Eq. 10, a plot of $\ln(\text{MR})$ vs drying time gives a straight line with the slope $(\pi^2 D_{\text{eff}}/4L^2)$. The effective moisture diffusivities and corresponding coefficient of determination (R^2) values are presented in Table 3 for various temperatures and air velocities. Variation of effective diffusivity with temperature is illustrated in Fig. 5a. During hot air drying at various temperatures, the effective moisture diffusivities of mango ginger varied from $3.7 \times 10^{-10} \text{ m}^2/\text{s}$ to $12.5 \times 10^{-10} \text{ m}^2/\text{s}$ as the temperature increased from 40°C to 70°C indicating an increase of 225 % in diffusivities. On the other hand, the effective moisture diffusivities varied from $8.34 \times 10^{-10} \text{ m}^2/\text{s}$ to $9.32 \times 10^{-10} \text{ m}^2/\text{s}$ as the air velocity increased from 0.84 m/s to 2.25 m/s . While velocity increased by 2.7 times, effective diffusivity increased only by 12 %. The temperature effect has been more pronounced than the effect of air velocity on moisture diffusivity. Similar trend has also been reported by other researchers related to agricultural materials undergoing analogous drying conditions. For example $2.25 - 7.29 \times 10^{-10} \text{ m}^2/\text{s}$ for Pepino (Uribe et al. 2011), $1.47 \times 10^{-10} - 2.19 \times 10^{-9} \text{ m}^2/\text{s}$ for black grapes

Table 2 The estimated values of statistical parameters and model constants of Midilli et.al model at various drying conditions

Temperature (°C)	Air Velocity (m/s)	Statistical values					Model Constants			
		R^2	RSS	RMSE	CS	RPD	k	n	a	b
40	0.84	0.999	1.33E-03	8.16E-03	8.33E-05	9.30	0.007	1.244	0.994	4.58E-05
50	0.84	0.996	5.50E-04	5.86E-03	4.59E-05	4.094	0.009	1.274	0.993	1.98E-05
60	0.84	0.999	3.17E-04	4.94E-03	3.52E-05	5.132	0.017	1.190	0.997	8.69E-05
60	1.36	0.999	2.81E-04	4.48E-03	2.34E-05	5.897	0.036	1.082	0.998	2.22E-04
60	1.84	0.999	4.25E-04	5.33E-03	3.27E-05	8.054	0.048	1.035	1.001	2.64E-04
60	2.25	0.999	4.43E-04	5.26E-03	3.17E-05	7.206	0.054	1.022	0.999	2.81E-04
70	0.84	0.999	8.12E-05	2.72E-03	1.16E-05	4.807	0.019	1.239	0.999	5.52E-05

R^2 coefficient of determination; RSS residual sum square; RMSE root mean square error; CS chi square; RPD Relative percentage deviation

Fig. 4 Effect of air velocity at constant temperature of 60 °C. (a) Moisture Ratio versus drying time (b) drying rate versus time (c) drying rate versus moisture content

(Togrul 2010), $0.776\text{--}9.335 \times 10^{-9} \text{ m}^2/\text{s}$ for Carrot (Doymaz 2004), 7.46×10^{-11} to $1.87 \times 10^{-10} \text{ m}^2/\text{s}$ for cocoa (Hii et al. 2009), 8.4×10^{-10} – $1.13 \times 10^{-9} \text{ m}^2/\text{s}$ for figs (Babalís et al. 2006), $1.7\text{--}3.31 \times 10^{-11} \text{ m}^2/\text{s}$ (Duc et al. 2011). The values of effective diffusivities estimated in the present work lie within the general range of 10^{-11} – $10^{-9} \text{ m}^2/\text{s}$ for food materials.

Calculation of activation energy

The effect of temperature on the effective moisture diffusivity is often described using Arrhenius type simple exponential relationship (Eq. 11 below) to obtain better agreement of the predicted curve with experimental data (Ozdemir and Devres 1999; Doymaz 2004; Falade and Solademi 2010; Uribe et al. 2011).

$$D_{\text{eff}} = D_0 \exp\left(-\frac{E_{\text{aD}}}{R(T_{\text{abs}})}\right) \quad (11)$$

Where D_{eff} (m^2/s) is the effective moisture diffusivity, D_0 (m^2/s) is pre-exponential factor, E_{aD} is activation energy (kJ mol^{-1}), R is ideal gas constant ($8.314 \times 10^{-3} \text{ kJ mol}^{-1} \text{ K}$) and T_{abs} (K) is the absolute temperature ($T_{\text{abs}} = T^{\circ}\text{C} + 273.15$). The fitness of the data with the model is illustrated in Fig. 5a. The calculated values of D_0 and E_{aD} were found to be 0.0001 and $32.55 \text{ kJ mol}^{-1}$ with coefficient of determination (R^2) of 0.97.

The Arrhenius type of exponential equation was also used to represent the dependence of the drying rate constant on the temperature (Eq. 11).

$$k = k_0 \exp\left(-\frac{E_{\text{ak}}}{R(T_{\text{abs}})}\right) \quad (12)$$

where k (min^{-1}) is the drying rate constant obtained by using Midilli et al. model, k_0 is the pre-exponential factor (min^{-1}), E_{ak} is activation energy (kJ mol^{-1}), R is ideal gas constant ($8.314 \times 10^{-3} \text{ kJ mol}^{-1} \text{ K}$) and T_{abs} is the absolute temperature (K). The values of k vs $1/T_{\text{abs}}$ shown in the Fig. 5b accurately fit to Eq. 12 with coefficient of determination (R^2) of 0.93. The k_0 and the E_{ak} values were estimated to be 1318 s^{-1} and $31.66 \text{ kJ mol}^{-1}$ respectively. The value of E_{aD} estimated from Eq. 11 is quite similar to the value of E_{ak} estimated from Eq. 12.

The activation energy obtained in the present investigation is compared with other high moisture agricultural materials such as carrot, $28.39 \text{ kJ mol}^{-1}$ (Doymaz 2004), mint leaves, $82.93 \text{ kJ mol}^{-1}$ (Park et al. 2002), okra, $51.26 \text{ kJ mol}^{-1}$ (Doymaz 2005), pumpkin, $32.26 \text{ kJ mol}^{-1}$ (Guine et al. 2012) and low moisture rapeseed, $28.47 \text{ kJ mol}^{-1}$ (Duc et al. 2011). It can be seen that there is wide variation in reported values of activation energies in view of the complex structure of food materials.

Table 3 Effective moisture diffusivities of mango ginger at different temperatures and air velocities

	Temperature (°C) at 0.8 m/s air velocity				Air velocity (m/s) at 60 °C			
	40	50	60	70	0.84	1.36	1.84	2.25
R^2	0.972	0.996	0.996	0.990	0.996	0.981	0.979	0.969
$D_{eff} \times 10^{-10} \text{ m}^2/\text{s}$	3.771	6.799	8.346	12.265	8.346	8.452	8.812	9.321

D_{eff} Effective diffusivity; R^2 coefficient of determination

The relationship between drying rate constant and effective moisture diffusivity

The relationship between drying rate and effective moisture diffusivity using Eqs. 11 and 12 with the assumption that activation energy values are quite similar as reported in previous section (Ozbek and Dadalli 2007) was derived as below:

$$k_{th} = \alpha \cdot (D_{eff})_{th} \quad (13)$$

The theoretical values of drying rate constant (k_{th}) are obtained from Eq. 12 and the theoretical values of effective

moisture diffusivity ($(D_{eff})_{the}$) are obtained from Eq. 11 for the present work. The k_{th} values were regressed against the effective moisture diffusivity values according to the Eq. 13 with coefficient of determination (R^2) and reduced chi square values of 0.999 and 1.99×10^{-8} respectively. The estimated value of constant (α) was $1.67 \times 10^7 \text{ min}^{-1} \text{ m}^{-2} \text{ s}$.

Fig. 5 Effect of drying temperature (a) on effective moisture diffusivities (b) on drying rate constants **Fig. 6** ANN prediction of moisture content (a) at different temperatures (constant air velocity of 0.84 m/s) (b) at different air velocities (constant temperature of 60 °C)

Prediction of drying kinetics by ANN

ANN can predict the drying kinetics as a function of time and velocity at all the temperatures in range of study very well since the experimental drying data was fed as per the configuration shown in Fig. 2. A learning rate of 0.001 with 10 hidden nodes in the hidden layer predicted the drying behavior well in the entire range of study. Prediction of moisture content by ANN is poor at the end of drying as the absolute relative error was very high. Relative percentage deviation of moisture content predicted by ANN is 15.3 %. The prediction by ANN towards the end of drying is higher by nearly 100 % compared to actual values at some experimental points. But, statistical significance for prediction of moisture content by ANN for the entire data set is very high as denoted by high R^2 of 0.998. ANN prediction of moisture content at different temperatures and air velocities are illustrated in Fig. 6a and b respectively. There are few studies in literature on application of ANN to drying of food materials. Erenturk and Erenturk (2007) found ANN better suited to air drying of carrot (R^2 of 0.999) compared to mathematical models (R^2 of 0.998). Ramesh et al. (1996) successfully applied the ANN approach to air drying of cooked rice in predicting the moisture content of rehydrated cooked rice. The present study does not come as a surprise, as an earlier study by the authors on microwave drying of mango ginger indicated the satisfactory application of ANN to predict the moisture content as a function of microwave power and drying time (Krishna Murthy and Manohar 2012).

Conclusion

Hot air drying kinetics of mango ginger was studied in a through-flow dryer system at drying temperatures 40–70 °C at constant air velocity of 0.84 m/s and effect of air velocity (0.84–2.25 m/s) at 60 °C was also studied. Among various empirical and theoretical thin layer models regressed to experimental drying data, semi-empirical Midilli et al., model fitted best based on statistical comparison parameters. To understand the mass transfer mechanism, effective moisture diffusivity was calculated at different temperatures and air velocities and calculated values ranged from $3.7 \times 10^{-10} \text{ m}^2/\text{s}$ to $12.5 \times 10^{-10} \text{ m}^2/\text{s}$ at the temperature 40 °C to 70 °C and $8.34 \times 10^{-10} \text{ m}^2/\text{s}$ to $9.32 \times 10^{-10} \text{ m}^2/\text{s}$ as the air velocity increased from 0.84 m/s to 2.25 m/s. There was increase in effective moisture diffusivity with increase in temperature and air velocity. Activation energy which describes the effect of temperature on moisture diffusivity was found to be 32.6 kJ/mol. The relationship between the effective moisture diffusivity and drying rate constant was also evaluated and showed a linear relationship. It was also established that

artificial neural network modeling could also be employed as alternative effective tool to describe the drying phenomena.

References

- Akpınar EK (2006) Determination of suitable thin layer drying curve model for some vegetables and fruits. *J Food Eng* 73:75–84
- Babalís SJ, Papanicolaou E, Kyriakis N, Belessiotis VG (2006) Evaluation of thin layer drying models for describing drying kinetics of figs (*Ficus carica*). *J Food Eng* 75:205–214
- Crank J (1975) *Mathematic of diffusion*, 2nd edn. Oxford University Press, London, pp 267–268
- Diamante LM, Munro PA (1993) Mathematical modeling of the thin layer solar drying of sweet potato slices. *Sol Energy* 51:271–276
- Diamante LM, Ihns R, Savage GP, Vanhanen L (2010) A new mathematical model for thin layer drying of fruits. *Int J Food Sci Technol* 45:1956–1962
- Doymaz I (2004) Convective air drying characteristics of thin layer carrots. *J Food Eng* 61:359–364
- Doymaz I (2005) Drying characteristics and kinetics of okra. *J Food Eng* 69:275–279
- Doymaz I, Pala M (2002) Hot air drying characteristics of red pepper. *J Food Eng* 55:331–335
- Duc LA, Han JW, Keum HD (2011) Thin layer drying characteristics of rapeseed. *J Stored Prod Res* 47:32–38
- Erenturk S, Erenturk K (2007) Comparison of genetic algorithm and neural network approaches for the drying process of carrot. *J Food Eng* 78:905–912
- Erenturk K, Erenturk S, Tabil LG (2004) A comparative study for the estimation of dynamical drying behavior of *Echinacea angustifolia*: regression analysis and neural network. *Comput Electron Agr* 45:71–90
- Ertekin C, Yaldiz E (2004) Drying of eggplant and selection of a suitable thin layer drying model. *J Food Eng* 63:349–359
- Esturk O (2012) Intermittent and Continuous microwave-convective air drying characteristics of sage (*Salvia officinalis*) leaves. *Food Bioprocess Technol* 5:1664–1673
- Falade KO, Solademi OJ (2010) Modeling of air drying of fresh and blanched sweet potato slices. *Int J Food Sci Technol* 45:278–288
- Golap SG, Bandyopadhyaya C (1984) Characterization of mango-like aroma in *Curcuma amada* Roxb. *J Agr Food Chem* 32:57–59
- Guine RPF, Francisca H, Barroca MJ (2012) Mass transfer coefficients for the drying of pumpkin (*Cucurbita moschata*) and dried product quality. *Food Bioprocess Technol* 5:176–183
- Gunhan T, Demir V, Hancioglu E, Hepbasli A (2005) Mathematical modeling of drying of bay leaves. *Energy Convers Manag* 46:1667–1679
- Hernandez-Perez JA, Garcia-Alvarado MA, Trystram G, Heyd B (2004) Neural networks for heat and mass transfer prediction during drying of cassava and mango. *Innov Food Sci Emerg Technol* 5:57–64
- Hii CL, Law CL, Cloke M (2009) Modelling using a new thin layer drying model and product quality of cocoa. *J Food Eng* 90:191–198
- Jain D, Pathare PB (2004) Selection and evaluation of thin layer drying models for infrared radiative and convection drying of onion slices. *Biosyst Eng* 89:289–296
- Karim A, Hawlader MNA (2005) Drying characteristics of banana: theoretical modeling and experimental validation. *J Food Eng* 70:35–45
- Krishna Murthy TP, Manohar B (2012) Microwave drying of mango ginger (*Curcuma amada* roxb): prediction of drying kinetics by

- mathematical modelling and artificial neural network. *Int J Food Sci Technol* 47:1229–1236
- Lertworasirikul S (2008) Drying kinetics of semi-finished cassava crackers: a comparative study. *LWT-Food Sci Technol* 41:1360–1371
- Liu X, Chen X, Wu W, Peng G (2007) A neural network for predicting moisture content of grain drying process using genetic algorithm. *Food Control* 18:928–933
- Martynenko AI, Yang SX (2006) Biologically inspired neural computation for ginseng drying rate. *Biosyst Eng* 95:385–396
- McMinn WAM (2006) Thin-Layer modelling of the convective, microwave, microwave-convective and microwave-vacuum drying of lactose powder. *J Food Eng* 72:113–123
- Midilli A, Kucuk H (2003) Mathematical modelling of thin layer drying of pistachio by using solar energy. *Energy Convers Manag* 44:1111–1122
- Midilli A, Kucuk H, Yapar ZA (2002) New model for single layer drying. *Dry Technol* 20:1503–1513
- Movagharnajad K, Nikzad M (2007) Modeling of tomato drying using artificial neural network. *Comput Electron Agr* 59:78–85
- Mujumdar AS, Law CL (2010) Drying technology: trends and applications in post-harvest processing. *Food Bioprocess Technol* 3:843–852
- Mujumdar AM, Naik DG, Dandge CN, Puntambekar HM (2000) Anti-inflammatory activity of *Curcuma amada* Roxb. in albino rats. *Indian J Pharmacol* 32:375–377
- Okos MR, Narsimhan G, Singh RK, Witnauer AC (1992) Food dehydration. In: Heldman DR, Lund DB (eds) *Handbook of food engineering*. Marcel Dekker, New York
- Ozbek B, Dadalli G (2007) Thin-layer drying characteristics and modelling of mint leaves undergoing microwave treatment. *J Food Eng* 83:541–549
- Ozdemir M, Devres YO (1999) The thin layer drying characteristics of hazelnuts during roasting. *J Food Eng* 42:225–233
- Park KJ, Vohnikova Z, Bord FPR (2002) Evaluation of drying parameters and desorption isotherms of garden mint leaves. *J Food Eng* 51:193–199
- Policegoudra RS, Aradhya SM (2008) Structure and biochemical properties of starch from an unconventional source - a mango ginger (*Curcuma amada* Roxb.) rhizome. *Food Hydrocoll* 22:513–519
- Policegoudra RS, Abiraj K, Channe Gowda D, Aradhya SM (2007a) Isolation and characterization of antioxidant and antibacterial compound from mango ginger (*Curcuma amada* Roxb.) rhizome. *J Chromatogr B* 852:40–48
- Policegoudra RS, Divakar S, Aradhya SM (2007b) Identification of Difurocumenonol, a new antimicrobial compound isolated from mango ginger (*Curcuma amada* Roxb.) rhizome. *J Appl Microbiol* 102:1594–1602
- Policegoudra RS, Aradhya SM, Singh L (2011) Mango ginger (*Curcuma amada* Roxb.) – A promising spice for phytochemicals and biological activities. *J Biosci* 36:739–748
- Prakash D, Suri S, Upadhyay G, Singh B (2007) Total phenol, antioxidant and free radical scavenging activities of some medicinal plants. *Int J Food Sci Nutr* 58:18–28
- Ramesh MN, Kumar MA, rao Srinivasa PN (1996) Application of artificial neural networks to investigate the drying of cooked rice. *J Food Process Eng* 19(3):321–329
- Rao AS, Rajanikanth B, Seshadri R (1989) Volatile aroma components of *Curcuma amada* Roxb. *J Agr Food Chem* 37:740–743
- Roberts JS, Kidd DR, Padilla-Zakour O (2008) Drying kinetics of grape seeds. *J Food Eng* 89:460–465
- Sacilik K, Elicin AK (2006) The thin layer drying characteristics of organic apple slices. *J Food Eng* 73:281–289
- Sasikumar B (2005) Genetic resources of curcuma: diversity, characterization and utilization. *Plant Genet Resour* 3:230–251
- Shittu TA, Raji AO (2011) Thin layer drying of African breadfruit (*Treculia Africana*) seeds: modeling and rehydration capacity. *Food Bioprocess Technol* 4:224–231
- Simal S, Femenia A, Garau M, Crosello C (2005) Use of exponential Page's and diffusional models to simulate the drying kinetics of kiwi fruit. *J Food Eng* 66:323–328
- Singh G, Singh OP, Maurya S (2002) Chemical and biocidal investigations on essential oils of some Indian *Curcuma* species. *Prog Cryst Growth Charact Mater* 45:75–81
- ASTA (American Spice Trade Association) (1985) Official analytical method of the American Spice Trade Association. New Jersey
- Sun DW, Byrne C (1998) Selection of EMC/ERH isotherm equations for rapeseed. *J Agr Eng Res* 69:307–315
- Togrul IT (2010) Modelling of heat and moisture transport during drying black grapes. *Int J Food Sci Technol* 45:1146–1152
- Tutuncu MA, Labuza TP (1996) Effect of geometry on the effective moisture transfer diffusion coefficient. *J Food Eng* 30:433–447
- Uribe E, Vega-Galvez A, Scala KD, Oyanadel R, Torrico JS, Miranda M (2011) Characteristics of convective drying of pepino fruit (*Solanum Muricatum* Ait): application of Weibull distribution. *Food Bioprocess Technol* 4:1349–1356
- Wang Z, Sun J, Liao X, Chen F, Zhao G, Wu J, Hu X (2007) Mathematical modelling on hot air drying of thin layer apple pomace. *Food Res Int* 40:39–46