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Mathematical modeling for thin layer sun drying of ginger (*Zingiber officinale* Rosc.)

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Abstract

Trials on drying of ginger were conducted during the month of April, 2009 at Agricultural Engineering College and Research Institute, Coimbatore (Tamil Nadu). Ginger rhizomes were mechanically washed, partially peeled, spread in single layer on cemented yard and dried from initial moisture of 594.01% (d.b.) (dry basis) to a final moisture content value of 9.82% (d.b.). Drying of ginger was completed in eight days. Drying characteristics curves, showed no constant rate period and all the drying process occurred in the falling rate period. Thin layer modeling of drying data showed that diffusion approximation model best described the drying process. The effective moisture diffusivity for drying of ginger was calculated as $1.91 \times 10^{-7}\ m^2\ s^{-1}$. Sun dried ginger rhizomes were evaluated for its quality and it was found that the essential oil, oleoresin, moisture and crude fibre contents were 2.0%, 4.6%, 9.82% and 2.5%, respectively.

Keywords: drying, effective moisture diffusivity, ginger, quality, thin layer drying

Introduction

Ginger (*Zingiber officinale* Rosc.) is an under ground rhizome valued as fresh vegetable, dry ginger spice and preserved crystallized ginger. For the preparation of dry ginger, ginger is harvested after eight months of planting when the leaves of the plant turn yellow and starts drying. The harvested clumps of ginger are cleaned manually to remove the dried roots and soil clods. The clumps are then broken to sufficiently large size rhizomes suitable for preparing dry ginger. After cleaning, the rhizomes are subjected to peeling where the fully matured rhizomes are scraped with bamboo splits having pointed ends to remove the outer skin to accelerate the drying process. The peeled rhizomes are washed before drying and spread in open yard for drying. The dry ginger so obtained is valued for its aroma, flavour and pungency (Balakrishnan 2005).

Traditionally ginger is sun dried in a single layer in open yard which takes 7 to 10 days for complete drying. The sun dried ginger is brown in colour, with irregular wrinkled surface and when broken, shows a dark brownish colour. The yield of dry ginger is 19.0–25.0% of fresh ginger depending on the variety and climate (IISR 2005). The major objectives in drying

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ginger are to reduce the moisture content for safe storage over extended period and reduce weight and volume that minimize packaging, storage and transportation costs. Sun drying is practiced in tropical and subtropical regions as energy is abundant, inexhaustive and non-pollutant besides, renewable, cheap and environmental friendly.

Thin layer equations describe the drying phenomena in a united way, regardless of the controlling mechanism. They have been used to estimate drying time of several products and to generalize drying curves. In the development of thin layer drying models for agricultural products, generally the moisture content of the material at any time after it has been subjected to a constant relative humidity and temperature conditions is measured and correlated to the drying parameters (Akpinar 2006). Many mathematical modeling and experimental studies have been conducted on the thin layer drying process of various fruits and vegetables. But thin layer sun drying studies of ginger and its mathematical modeling is not reported. Hence, the present study was conducted to evaluate the sun drying characteristics of ginger, to develop a suitable mathematical model to describe the drying process and to determine the quality of the dried ginger.

Materials and methods

Trials on drying of ginger were conducted at Agricultural Engineering College and Research Institute, Coimbatore, Tamil Nadu during April 2009. Ten kg of freshly harvested mature ginger rhizomes of local variety purchased from Coimbatore market was washed mechanically in a rotary batch type vegetable washer (Punjab Agricultural University model, capacity 60 kg $batch^{-1}$), partially peeled manually using a sharp knife and spread in single layer on cement concrete drying yard. The initial moisture content of fresh ginger used for the experiment was 594.01% (d.b.). The experiments on sun drying were performed between 9:00 h and 17:00 h and the process was continued till a constant mass of dried produce was obtained. The partially dried material at the end of each day was spread on perforated stainless steel tray and kept open the whole night to prevent fungal infection. The loss of mass during drying process was recorded at 9:00 h, 12:00 h and 17:00 h. The experiment was replicated in three batches simultaneously and the mean values were taken.

Weather parameters

Weather parameters like temperature, relative humidity of the ambient air, solar intensity and wind speed were recorded every 1 h interval for eight consecutive days for the month of April 2009 and the mean values were reported. The temperature and relative humidity of ambient air was measured using a digital temperature and relative humidity meter (EQUINOX, EQ-321 S). The velocity of the ambient drying air was measured with an anemometer (PROVA Instrument INC, AVM–05) and the solar radiation was measured using a sunmeter (M/s. Suras Technology, Madurai).

Modeling of drying characteristic curves

The moisture content data at different experimental mode were converted into the moisture ratio (MR) expression and curve fitting with drying time were carried for six drying models as described in Table 1. The

Table 1. Thin layer drying models

Model name	Model	Reference
Newton	$MR = e^{-kt}$	Panchariya *et al.* (2002)
Page	$MR = e^{-kt^n}$	Lopez *et al.* (2000)
Modified Page	$MR = e^{(-kt)^n}$	Ozdemir & Devres (1999)
Diffusion approximation	$MR = e^{(-kt)} + (1 - a)\ e^{(-kbt)}$	Ertekin & Yaldiz (2004)
Two-term exponential	$MR = e^{(-kt)} + (1 - a)\ e^{(-kat)}$	Ertekin & Yaldiz (2004)
Overhults	$MR = e[^{-(kt)^n}]$	Overhults *et al.* (1973)

moisture ratio was determined using the expression,

$$MR = M/M_o \quad (1)$$

where, MR is the moisture ratio; M_0 is the initial moisture content, % d.b; M is the moisture content at time t, % d.b

The drying rate for ginger was determined as follows:

$$R = Q/ t \times W_d \quad (2)$$

where, R is the drying rate, kg of moisture removed h^{-1} kg of dry matter^{-1}; Q is the quantity of moisture removed, kg; t is the drying time, h; W_d is the total bone dry mass of the sample, kg.

Non linear regression procedure was performed on all drying runs to estimate the parameters associated with the six selected drying models. The coefficient of determination R^2 was the primary criterion for selecting the best equation to describe the drying curve. In addition, the reduced chi-square (χ^2), root mean square error (RMSE) and mean bias error (MBE) were calculated to evaluate the efficiency of fitting a model to the experimental data. The highest value of R^2 and the lowest values of χ^2, RMSE and MBE were used to determine the best fit (Togrul & Pehlivan 2002).

The statistical parameters were calculated as follows:

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

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

$$MBE = \frac{1}{N}\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right) \quad (5)$$

where, $MR_{exp,i}$ is the i^{th} experimentally observed moisture ratio, $MR_{pre,i}$ is the i^{th} predicted moisture ratio, N is the number of observations, n is the number of constants in the model.

Effective moisture diffusivity

Fick's second law was used to describe the moisture diffusion during drying of ginger spread in the form of thin slabs as follows (Crank 1975).

$$MR = \frac{8}{\pi^2}\left[\sum_{n=1}^{n=\infty}\frac{1}{(2n+1)^2}\exp\left(\frac{-(2n+1)^2\pi^2}{4}\frac{D_{eff}t}{h^2}\right)\right] \quad (6)$$

Where, MR is the moisture ratio; D_{eff} is the effective moisture diffusivity, $m^2\ h^{-1}$; t is the drying time, hours and h is the thickness of infinite slab dried from top and bottom parallel surfaces, m. For long drying periods, the above equation can be simplified to the following form by taking n = 0 (Geankoplis 2003).

$$MR = \frac{M - M_e}{M_0 - M_e} = \frac{8}{\pi^2}\exp\left(\frac{-\pi^2}{4}\frac{D_{eff}t}{h^2}\right) \quad (7)$$

The value of the equilibrium moisture content, M_e, is relatively small compared to M and M_0. Thus $\frac{M - M_e}{M_0 - M_e}$ is simplified $\frac{M}{M_0}$ and equation 7 can be written as

$$MR = \frac{M}{M_0} = \frac{8}{\pi^2}\exp\left(\frac{-\pi^2}{4}\frac{D_{eff}t}{h^2}\right) \quad (8)$$

The above equation is in the form of

$$MR = \frac{M}{M_0} = Ae^{-kt} \quad (9)$$

where the constants,

$$A = \frac{8}{\pi^2} \text{ and } k = \frac{\pi^2 D_{eff}}{4h^2}.$$

By linearizing equation 9

$$\ln(MR) = \ln\left(\frac{M}{M_0}\right) = \ln A - kt \quad (10)$$

The effective moisture diffusivity of ginger was calculated using the method of slopes. A plot

of ln (M/M_0) versus drying time gives a straight line with a slope (S). Assuming that drying occurs from top and bottom parallel faces, thickness of the slab to be dried from one face is assumed to be half the total thickness h, where h = h/2 in m. Hence the slope is taken as

$$S = \pi^2 D_{eff}/4h^2 \quad (11)$$

From the above expression the effective moisture diffusivity (D_{eff}) can be calculated.

Quality

Essential oil content of dry ginger was estimated as per AOAC (1975) using modified Clevenger apparatus, oleoresin content by the method of ASTA (1968), crude fibre content by the method suggested by Sadasivam & Manickam (1992) and moisture content was analyzed in a fully automatic moisture meter (Sartorius M-50). The total plate count was determined by serial dilution technique as enumerated by Ranganna (1986).

Statistical Analysis

Sigma Plot (ver 6.0) statistical software was used to analyze the data obtained during drying and for mathematical modeling of drying curves.

Results and discussion

Weather parameters

The variations in weather parameters for the month of April 2009 showed that the average day time temperature varied from a minimum of 30.3°C at 9:00 h to a maximum of 38.1°C at 13:00 h (Fig. 1A). The average relative humidity varied from 62.47% at 9:00 h to minimum of 35.09% at 13:00 h, which corresponded to the time when the average solar intensity obtained was maximum (889.38 W m^{-2}) (Fig. 1B). The average wind speed varied from 0.5 m s^{-1} at 9:00 h to a minimum of 0.1 m s^{-1} at 13:00 h and then to a maximum of 1.3 m s^{-1} at 17:00 h (Fig. 1C).

Drying kinetics

The drying characteristic curves of ginger indicated that the moisture content during drying decreased continuously with time. The

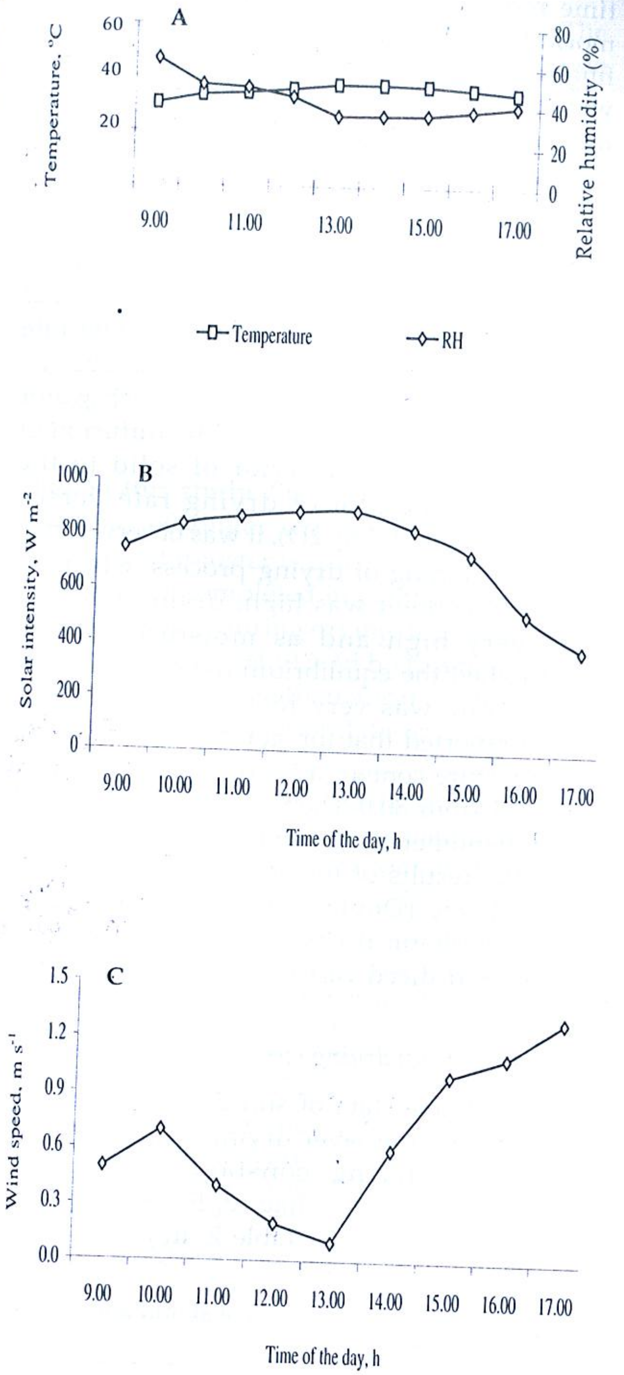

Fig. 1. Variation in weather parameters for a day during the month of April 2009
A. Average daily variation of ambient temperature and relative humidity
B. Average daily variation of solar radiation
C. Average daily variation of wind speed

time required to dry ginger from an initial moisture content of around 594.01% (d.b.) to a final moisture content of around 9.89% (d.b.) was 174 h (8 days) (Fig. 2A). The plot of moisture ratio versus drying time for ginger showed that moisture ratio of ginger reduced exponentially as the drying time increased (Fig. 2B). The plot of drying rate versus drying time, showed no constant rate period during drying of ginger (Fig. 2C) and indicated that the drying process occurred in the falling rate period. In the falling rate period, the material surface was no longer saturated with water and drying rate was controlled by diffusion of moisture from the interior of solid to the surface. In the plot of drying rate versus moisture content (Fig. 2D), it was observed that at the beginning of drying process, when the moisture content was high, drying rate was also very high and as moisture content approached the equilibrium moisture content, drying rate was very low. Sreekumar *et al.* (2002) reported that for safe storage of ginger, the moisture content after harvest needs to be reduced from 80.0-82.0% (w.b.) to 10% (w.b.). The phenomenon of drying is in agreement with the results of the studies on sun drying of mulberry (Doymaz 2004a), fig (Doymaz 2005), mechanical drying of carrot (Doymaz 2004b) and diced cassava roots (Kajuna *et al.* 2001).

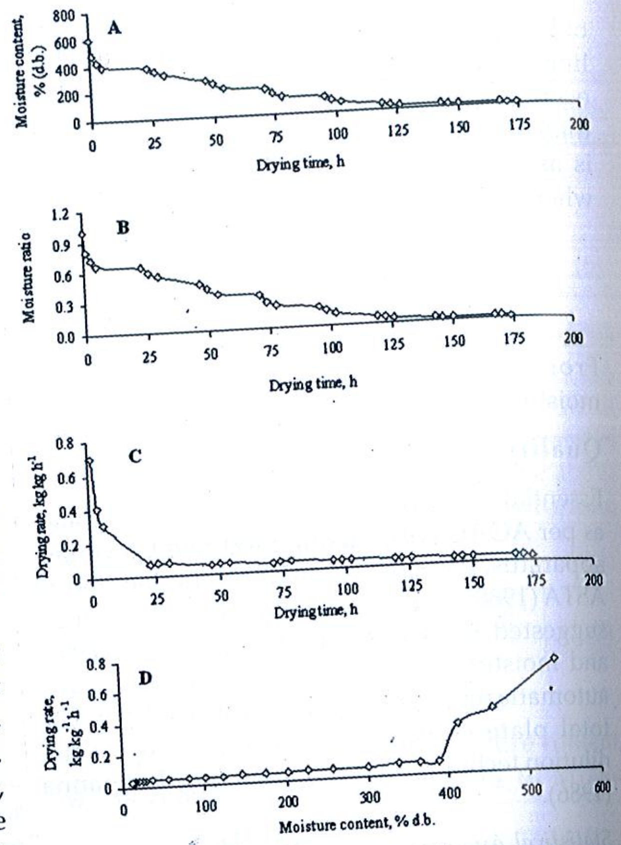

Fig. 2. Drying characteristics of ginger under sun drying
A. Plot of drying time and moisture content
B. Plot of drying time and moisture ratio
C. Plot of drying time and drying rate
D. Plot moisture content and drying rate

Modeling of sun drying curves

Moisture ratio data of sun dried ginger were fitted to six thin layer drying models and the values of drying constants along with statistical parameters like R^2, RMSE, MBE and χ^2 are summarized in Table 2. In all the cases, the values of R^2 were greater than 0.90 indicating a good fit (Erenturk *et al.* 2004), but diffusion approximation model gave comparatively higher R^2 values (0.97) and lower χ^2 (0.003), RMSE (0.05) and MBE (-0.01) values. Hence, diffusion approximation model may be assumed to represent the thin layer drying behaviour

Table 2. Values of drying constants and related statistical parameters for different thin layer drying models

Models	K	n	a	b	R^2	RMSE	MBE	χ^2
Newton	0.02	-	-	-	0.93	0.08	-0.03	0.01
Page	0.05	0.81	-	-	0.93	0.08	-0.02	0.01
Modified Page	0.31	0.06	-	-	0.93	0.08	-0.03	0.01
Diffusion approximation	3.07	-	0.18	0.01	0.97	0.05	-0.01	0.003
Two-term exponential	0.27	-	0.07	-	0.94	0.07	-0.02	0.01
Overhults	0.02	0.81	-	-	0.93	0.08	-0.02	0.01

of ginger for sun drying. The predicted moisture ratios are in good agreement with the observed values (Fig. 3) and therefore it could be concluded that diffusion approximation was relatively better than the other five models. Ebru & Yildiz (2003) compared eleven thin layer drying models to study the drying characteristics of red pepper and found that the drying process was best described by diffusion approximation model.

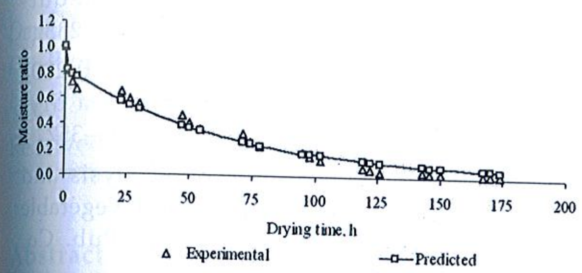

Fig. 3. Experimental and predicted moisture ratios for sun drying of ginger using diffusion approximation model

Effective moisture diffusivity

Effective moisture diffusivity was determined using slopes derived from the plot of ln MR versus drying time (Fig. 4). The effective moisture diffusivity for drying of ginger was

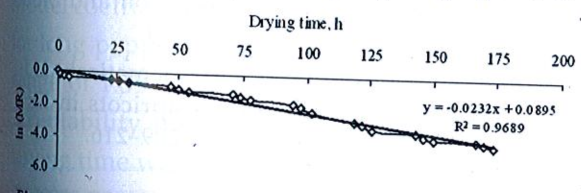

Fig.4. Logarithmic moisture ratio vs drying time

calculated as 1.91×10^{-7} m^2 s^{-1}. Kamruzzaman & Islam (2006) reported the effective moisture diffusivity for *Colocasia esculenta* at 55°C as 4.43×10^{-7} cm^2 s^{-1}. In the drying air temperature of 50°C to 80°C and at constant air velocity of 1.5 m^{2}s^{-1}, the effective moisture diffusivity is, was similar to that obtained for yam by Falade *et al.* (2007) which varied from 9.92×10^{-8} to 1.02×10^{-7} m^2 s^{-1} and 0.829×10^{-6} m^2 s^{-1} to 1.298×10^{-5} m^2 s^{-1} for *Dioscorea alata* and *Dioscorea rotundata*, respectively.

Quality

The important quality parameters of sun dried ginger samples are summarized in Table 3. The essential oil, oleoresin, moisture content, crude fibre and microbial load were 2%, 4.6%, 9.82%, 2.5% and 4.66×10^6 cfu g^{-1}, respectively.

Table 3. Quality parameters of sun dried ginger

Quality parameters	Values
Essential oil content (%)	2.0
Oleoresin content (%)	4.6
Moisture content (%)	9.82
Crude fibre (%)	2.5
Microbial load (x 10^6 cfu g^{-1})	4.66

Thus, in this study, the thin layer sun drying behaviour of ginger with natural convection mode of heat transfer was investigated. Drying of ginger was completed in eight days and the moisture content during drying decreased from an initial value of 594.01% (d.b.) to a final value of 9.82% (d.b.). Six mathematical models were fitted to the experimental data on drying and it was found that the thin layer model which best described the sun drying behaviour of ginger was the diffusion approximation model. Effective moisture diffusivity for sun drying of ginger was calculated as 1.91×10^{-7} m^2 s^{-1}. The quality of sun dried ginger rhizomes was evaluated and it was found that the essential oil, oleoresin, moisture and crude fibre content were 2.0%, 4.6%, 9.82% and 2.5%, respectively.

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