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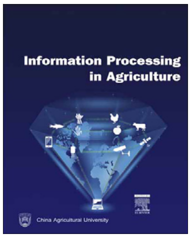

Drying kinetics of whole and sliced turmeric rhizomes (*Curcuma longa* L.) in a solar conduction dryer

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Drying of turmeric was carried out in a solar conduction dryer (SCD). Drying air temperature was achieved around 39–51 °C for an ambient temperature in the range of 25–28 °C. Moisture content from 78.65% (wb), was reduced to 6.36% (wb) and 5.50% (wb) for solid and sliced samples respectively in 12 h effective drying time. Drying curve of sliced samples showed more uniform falling in comparison to that of whole samples. The average effective moisture diffusivity was found to be $1.852 \times 10^{-10}\ \text{m}^2\ \text{s}^{-1}$ for slab samples and $1.456 \times 10^{-10}\ \text{m}^2\ \text{s}^{-1}$ for solid samples. Out of four models tried for simulation, Page model was found as best fitted thin layer drying model when simulation was done for all the drying data. The overall thermal efficiency of the dryer was found to be 55%. Drying of sliced rhizomes showed better drying kinetics and effective drying time could be reduced by slicing instead of drying in whole form.

1. Introduction

India produced about 400,000 tone of turmeric (*Curcuma longa* L.) in fresh weight per year [1] which was about 80% of the world's supply of commercial turmeric. This tonnage was produced in an area of approximately 50,000 acres [2]. The rhizomes are harvested and dried before shipment around the world [3]. Turmeric has been used for preparing traditional Indian curries for hundreds of years for its flavor and color preservatives. Commercially, it is traded as a dye, spice, and source of industrial starch. The characteristic yellow–orange curcuminoids found in rhizomes are used to make a yellow food and textile dye. It also prevents cancer along with inflammation by inducing production of enzymes used to detoxify electrophilic species produced in lipid peroxidation [4]. Curcumin content has been reported to vary from one batch of turmeric powder to another. The percentage has been estimated to be between 1.06% and 5.70% in four different "commercially available" turmeric samples [5]. Significant loss of spice active principles was observed when the spices were subjected to heat processing. Curcumin loss from heat processing of turmeric was 27–53%, with maximum loss in pressure cooking for 10 min [6].

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Nomenclature

A	shape factor	ln	natural logarithm
D_{eff}	effective moisture diffusivity	mm	millimeter
h	hour	N	number of observation
K	slope	R	coefficient of determination
kg	kilogram	t	time
L	linnaeus	wb	wet basis

Drying is the oldest preservation technique of agricultural products and it is an energy intensive process. It is an essential process used all over the world for the preservation of farm produce. It helps in reducing the water activity of the produce to a level below which deterioration does not occur for a definite duration [7]. High prices and shortages of fossil fuels have increased the emphasis on using alternative renewable energy resources [8]. The two oil crises of the early and late 1970s prompted research and development work to have solar dryers to save on energy [9]. Drying of agricultural products using renewable energy such as solar energy is environmental friendly and has less environmental impact. Sun drying is still widely used in many tropical and subtropical countries as it is the cheapest method, but the quality of the dried products is far below the desired standards. The principle of solar crop drying dates back to the advent of civilization. The methods then used were simple and often crude but were reasonably effective. Solar drying can be considered as an elaboration of sun drying and is an efficient system of utilizing solar energy [8,10–12].

As of turmeric is concerned, the common practice in India is to boil the rhizome in alkaline media prior to dehydration [13]. However, there are controversies with respect to the importance of cooking the rhizomes in water or alkaline solution prior to drying and its influence on the levels of curcuminoid pigments and on the color of ground turmeric [14]. Improvement of product quality and reduction of losses can only be achieved by the introduction of suitable drying technologies [15].

Many authors have studied the drying behavior of food materials such as ginger slices [16], eggplant [17], grape [18], grain rice [19], barley [20], sweet potato [21], red chilies [22], apple [23], litchi [24], carrots [25] and several mathematical models have been proposed. Page model of thin layer have been reported to be widely referred for simulation and validation of dryer performances.

A technology developed by a group of innovators based on conduction as mode of heat transfer claimed better efficiency while reducing processing time by 40% [26]. As mode of heat transfer primarily being conduction, the dryer has rightly been named as solar conduction dryer (SCD). The present study was aimed with the following main objectives:

- To observe drying kinetics of turmeric rhizomes in whole as well as in sliced form while drying in a solar conduction dryer (SCD) in typical high humidity and comparatively low solar intensity situation of Assam (India) with geographic coordinates at 26.75° N and 94.22° E.
- To carry out performance evaluation of the dryer through simulation with established model for thin layer drying.

2. Materials and methods

2.1. Drying equipment

The Solar conduction dryer is a solar powered food dehydrator (Fig. 1) developed by a group of innovators known as Science for Society (S4S). The device utilizes solar power in a conductive manner as well as convective way for drying. The structure of solar conductive dryer which comprises of four drying chambers constructed from hollow sections of stainless steel. The dryer has four drying trays, covering a surface area of 1.04 m^2 each. Transparent plastic (PC Multiwall Sheet) is used to cover the trays. The trays are coated with black color special food grade coating, where the products to be dried are placed. A low height air vent to create air current is provided at the middle of the dryer along horizontal direction which also separates the drying chambers in two parts. Each portion contains two drying trays. Atmospheric air enters from the front of the trays and it carries away the moisture of the sample through the chimney. Accesses to the trays are done by sliding the trays out in a designed channel for loading purpose. Engineering drawing of solar conductive dryer is given in Fig. 2.

Fig. 1 – Solar conduction dryer.

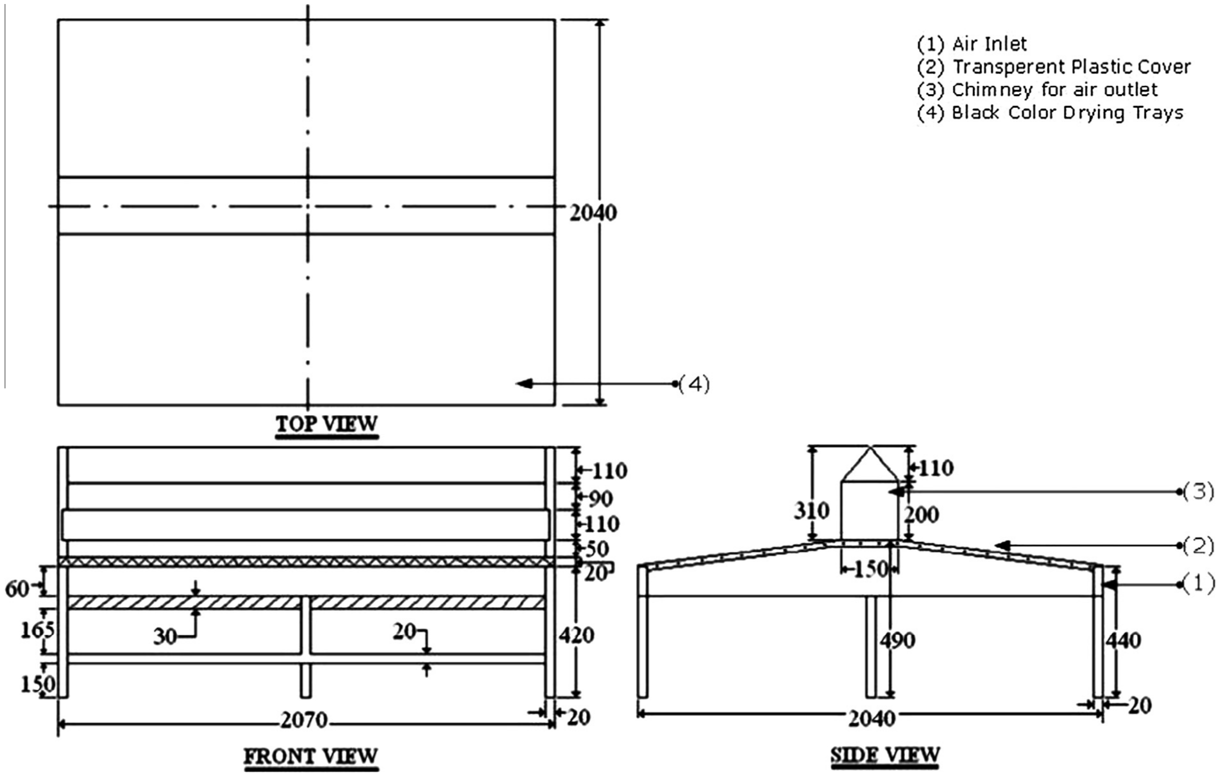

Fig. 2 – Engineering drawing of SCD (all dim. in mm).

2.2. *Instrumentation and observation*

J-type thermocouple (−210 °C to 750 °C) and velocity transmitter (Make-Kimo Instrument, France) were used for measuring temperatures and air velocity at different places respectively. All the measuring instruments were logged into a 16-channnel data logger (Make-R.S. Process System Pvt. Ltd., India). Temperatures and velocities probes were kept at the air inlet of the dryer as well as at the outlet vent of the chimney. Thermocouples were also installed in each tray during drying period. Solar radiation data was obtained from the Department of Agro-Meteorology, Assam Agricultural University, Jorhat for the specified latitude and longitude.

2.3. *Drying experiment*

The sample required for drying was collected from local farmer. The sample preparation protocol consisted of washing the rhizomes in running water and removing the surface water using a basket centrifuge. Prior to drying, the rhizomes pretreated with boiling water for 2 min [7] and sorted out according to their cylindrical shape and size, then cut into pieces of 10–14 mm in thickness and length being 50–70 mm. The whole rhizomes that measured around 10–14 mm in thickness were kept apart for solid drying instead of slicing down. The weights of the two sample lots (sliced and solid) were 12 kg and 4 kg, respectively. Both sliced and solid turmeric were spread over the trays separately covering 70–80% of the area on the trays (Fig. 3). The remaining 20–30% was exposed to solar radiation. Sliced turmeric of 2.72 kg was also dried under open sun drying as control (Fig. 4).

Moisture content of samples was recorded using Contech moisture analyzer at a regular interval of time. Temperature of air in the dryer and weight of the samples were also monitored at preset time interval. As per dryer specification, drying was stopped when the moisture content of the samples reached to 5–6% (wb) for both types.

2.4. *Drying kinetics*

Drying of turmeric rhizomes were observed to be in falling rate. The moisture diffusion of rhizomes can be generalized for moisture ratio (MR) expression, which is given as:

$$MR = \frac{M - M_e}{M_0 - M_e} \tag{1}$$

where M is the material moisture content in % (wb) at time ‘t’, M_e is the equilibrium moisture content % (wb) of the material and M_0 is the initial moisture content of the material % (wb).

2.5. *Effective moisture diffusivity*

From the Fick’s second law of moisture diffusion [27] during drying of thin layer, the Eq. (1) for thin slab could be expressed as:

$$MR = \frac{M - M_e}{M_0 - M_e} = \frac{8}{\pi^2}\left[\sum_{N=1}^{N=\infty} \frac{1}{(2N+1)^2} \exp\left(\frac{-(2N+1)^2 \pi^2 D_{\mathrm{eff}} t}{4h^2}\right)\right] \tag{2}$$

which could be further reduced to:

$$MR = \frac{8}{\pi^2} \exp\left(\frac{-\pi^2 D_{\mathrm{eff}} t}{4h^2}\right) \tag{3}$$

Fig. 3 – Sliced and whole turmeric drying in SCD.

As time t increases, the higher terms approaches zero [28]. For long drying periods, by taking $n = 0$ [29]. The above equation could be rewritten as:

$$MR = Ae^{-kt} \tag{4}$$

where the constants are:

$$A = \frac{8}{\pi^2} \text{ for slab, } \quad = \frac{6}{\pi^2} \text{ for cylinder} \quad \text{ and, } k = \frac{\pi^2 D_{\mathrm{eff}}}{4h^2}$$

Simplifying it into linear form:

$$\ln(MR) = \ln\left(\frac{M - M_e}{M_0 - M_e}\right) = \ln A - kt \tag{5}$$

A plot of ln(MR) versus drying time gave a straight line with a slope 'k'. Assuming drying occurred from top and bottom parallel faces, thickness of the slab to be dried from one face was assumed to be half the total thickness h, where $h = {}^{h}/_{2}$ in 'm'. The effective moisture diffusivity of turmeric was calculated using the slope as,

$$k = \frac{\pi^2 D_{\mathrm{eff}}}{4h^2} \tag{6}$$

2.6. Mathematical modeling

To simulate drying behavior of turmeric rhizomes in the specified SCD, four different established thin layer drying applied are:

$$\text{Lewis, } MR = \exp(-kt) \tag{7}$$

$$\text{Page, } MR = \exp(-kt^n) \tag{8}$$

$$\text{Modified Page, } MR = \exp[-(kt)^n] \tag{9}$$

$$\text{Henderson and Pabis, } MR = a\exp(-kt) \tag{10}$$

Fig. 4 – Open sun drying of turmeric.

Initially moisture content data were converted to moisture ratio expression and curve fitting with drying time for the selected drying model. For analyzing these curve fitting data, Sigma Plot (Version 11.00) software was used in a non-linear regression way.

Coefficient of determination (R^2), and standard error estimate (SEE) were the two statistical parameters chosen for examination of the models. For goodness of fit of the curve to the equation, high value of R^2 and low value of SEE were taken [30]. These parameters could be found as:

$$R^2 = \frac{\sum_{i=1}^{N}(MR_{\exp,i} - MR_{\exp_{\mathrm{mean}},i})^2 - (MR_{\mathrm{pre},i} - MR_{\exp,i})^2}{\sum_{i=1}^{N}(MR_{\exp,i} - MR_{\exp_{\mathrm{mean}},i})^2} \tag{11}$$

where $MR_{\exp,i}$ stands for the experimental moisture ratio found in any measurement, $MR_{\mathrm{pre},i}$ is the predicted moisture ratio for this measurement and N is the total number of observations.

Standard Error of Estimated (SEE) provides information on the long term performance of the correlations by allowing a comparison of the actual deviation between predicted and measured values term by term. The ideal value of SEE is "zero". With n_i as the number of constants, SEE was calculated as:

$$SEE = \sqrt{\frac{\sum_{i=1}^{N}(MR_{\exp,i} - MR_{\mathrm{pre},i})^2}{N - n_i}} \tag{12}$$

2.7. Drier efficiency

The overall thermal efficiency has been evaluated for the drier. The thermal efficiency over an entire drying trial (η) is defined as the ratio of the energy used to evaporate the moisture from the product to the energy supplied to the drier. In this drier, solar radiation falling in the specified surface area is the supplied energy. The overall thermal efficiency of the drier is therefore,

$$\eta = \frac{Mh_{fg}}{IAt} \tag{13}$$

where, M is the mass of water evaporated (kg); h_{fg} is the latent heat of vaporization (MJ/kg); I is the total solar radiation on the dryer (MJ/m^2); A is the solar collection area (m^2) and t is the total time of drying.

3. Result and discussion

3.1. *Drying kinetics of turmeric*

The drying temperature measured in the SCD for both solid and sliced turmeric rhizomes were found to be varied within 39–51 °C when the experiment was in progress. More or less constant temperature was observed after about 0.75 h of initiation. During the trials, this was on an average between 10 and 2 pm.

Drying occurred in falling rate period for both the samples (Fig. 5). It could be seen that, rate of drying was much faster in case of sliced samples in comparison to whole samples up to the end of initial 7 h of drying. At this stage the moisture content were found to be 14.23% and 26.52% (wb) of sliced and whole samples respectively, which was obvious, due to exposure of more porous surface to the drying air in case of sliced samples. It could also be seen that, from the same initial moisture content of 78.65% (wb) and 12 h of effective drying under the same drying condition, the moisture content of sliced sample got reduced to 5.5% (wb) whereas, in case of whole samples it got reduced to 6.36% (wb).

Drying rate was also computed by numerical differentiation of drying data (dMR/dΘ) to obtain drying rate constant, h^{-1} and plotted against moisture content% (wb) (Fig. 6). It was observed that, during initial condition when moisture content was around 60% (wb), drying rates were identical for both samples. Beyond this level, rate of drying was much faster in case of sliced turmeric.

Drying rate constant values (h^{-1}) were also plotted against the drying time for sliced and whole turmeric (Fig. 7). Initially, the drying rates were found to be faster, up to about 6 h. This was due to high amount of free moisture availability, which was easily removed in the initial stage of drying [31]. As the drying progressed, the drying rates increasingly decreased with time. As because of the reduction of moisture was higher in case of sliced than the whole turmeric, the drying rate constant of sliced sample fell down much rapidly for the same interval of time. It is the typical drying behavior for agricultural materials reported by many researchers. Similar results were also observed for the drying of ginger [16], apple [23], litchi [24], carrots [25] etc.

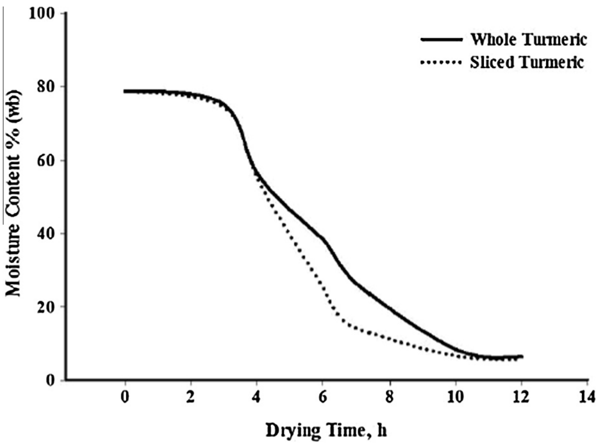

Fig. 5 – Moisture content vs. drying time.

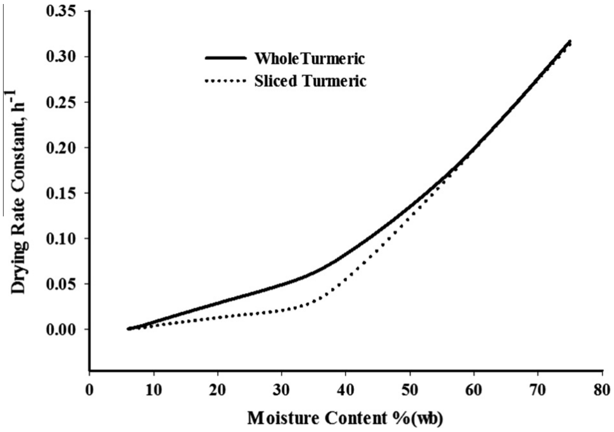

Fig. 6 – Drying rate constant vs. moisture content.

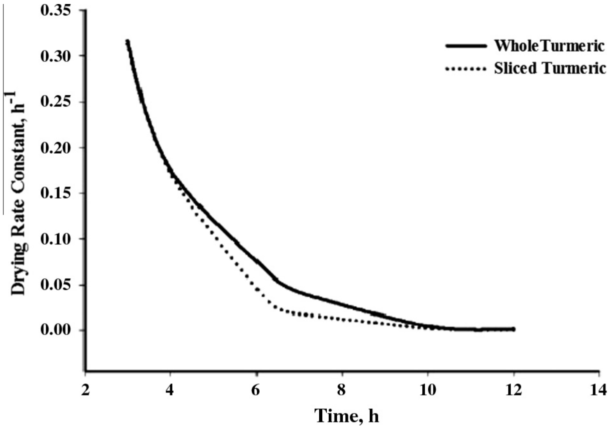

Fig. 7 – Drying rate constant vs. time.

The entire drying process was in falling rate period of drying study during the experiment. It was due to the fact that material surface was no longer saturated with water and drying rate was controlled by diffusion of moisture from interior of solid to the surface. As drying rate became very slow, further reduction of moisture content of whole samples turned out to be impractical. Due to faster removal of moisture from sliced samples during initial high moisture level condition, the possibility of fungal growth also got eliminated and no such events were observed. In case of samples subjected to normal sun drying the effective drying time was found to be 25.5 h, which was more than twice the time required in SCD to reduce moisture nearly to same level. Moreover, in this case white patches of fungal growth were also observed in the sliced samples owing to slow evaporation rate.

3.2. *Calculation of effective moisture diffusivity*

For constant air velocity and temperature condition of drying of sliced and solid turmeric rhizomes, graph was drawn between natural logarithms of moisture ratio (ln *MR*) against time, h (Fig. 8). Effective moisture diffusivity (D_{eff}) calculated for sliced and solid turmeric were $1.852 \times 10^{-10}\,m^2\,s^{-1}$ and $1.456 \times 10^{-10}\,m^2\,s^{-1}$ respectively. In case of sliced

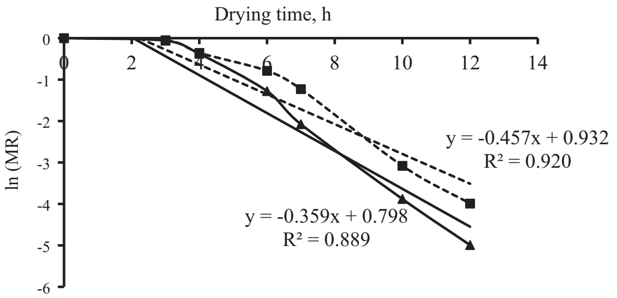

Fig. 8 – ln(*MR*) vs. drying time, h for sliced and solid turmeric.

turmeric samples, the effective moisture diffusivity (D_{eff}) was increased by 21.5% from the whole turmeric. Parveen et al. [32], found moisture diffusivity for drying of turmeric to be varied from 8.43×10^{-11} m^2s^{-1} to 2.51×10^{-10} m^2s^{-1} while drying at air temperature of 50 °C in a tray drier. Falade et al. [33], dried yam at air temperature of 50–80 °C at constant air velocity of 1.5 m s^{-1}. The effective moisture diffusivity obtained was similar to that obtained for *Dioscore alata* and *Dioscorea rotundata*, 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}, respectively.

Due to variation of the outer surface texture for solid and sliced turmeric, sliced turmeric were more porous than solid. As a result, high capillary action was taking place inside the sliced samples. More water diffusion alterations in the capillaries of porous media promoted the difference in moisture diffusivity of sliced and solid turmeric despite being subjected to the same drying conditions.

3.3. Mathematical modeling

Four mathematical models for thin layer drying were selected to simulate the drying characteristics of sliced and solid turmeric. Moisture content data were converted to *MR* and fitted to these four equations. The values of estimated parameters of the equations were listed (Table 1). Among the stated models, the Page model gave highest value of R^2 (0.9946) with low value of SEE (0.0317) for sliced samples in comparison to solid. This indicates that, sliced turmeric drying fits better to Page model. This in turn established good drying behavior of turmeric in sliced form than whole. Nevertheless, the SCD system exhibited satisfactory performance for turmeric drying as evident from R^2 and SEE values obtained irrespective of it being whole or sliced.

Thus, to understand the drying behavior, the predicted values of *MR* from the Page model for sliced and solid turmeric were fitted with respective experimental values against time and represented in Fig. 9 and Fig. 10, respectively. While drying whole turmeric, it was observed that at the initial stage, the predicted values differ significantly from the experimented values. Whereas, during drying of sliced turmeric, predicted moisture ratios were in good agreement with the experimented values. This observation again conforms to the higher effective moisture diffusivity behavior exhibited by sliced turmeric (1.852×10^{-10} m^2 s^{-1}) compared to its whole form (1.456×10^{-10} m^2 s^{-1}) during the initial period of drying.

3.4. Dryer efficiency

An aluminum strip of width 25.4 mm was used for strengthening the boundary of each tray. That apart, the air flow vent at the centre position causes a shadow effect on the trays with change in position of sun during the day. In view of this, an assumptive calculation was done considering 91% of the total area of 4.16 m^2, resulting in 3.854 m^2 effective area available for drying. Average intensity of solar radiation was 345.232 W/m^2 during the days of experimentation. Indirect heat was gained by the turmeric through conduction from the tray surface, of which 20–30% was exposed to solar radiation. Average temperature in the dryer was found to be 45 °C. Therefore, latent heat of vapor at that temperature (from steam table) found to be 2583.2 kJ/kg. The SCD removed 9.28 kg and 3.08 kg of moisture from 12 kg of sliced and 4 kg of whole turmeric rhizomes in 12 h, respectively. From the Eq. (13), the thermal efficiency of the drier was then calculated and found to be 55.6% and 55.36% for sliced and whole turmeric, respectively. Thus, the overall thermal efficiency of the dryer could be inferred as 55% during the experimentation. It has been reported that overall dryer efficiency was 22% for passive solar grain dryer [34], another report stated efficiency as 64% in a village-level solar dryer for tomato drying [35].

Table 1 – Estimated values of parameters for respective models.

Model	Sample type	Estimated parameters			R^2	SEE
		k	*n*	*a*		
Lewis	Slice	0.1727			0.7958	0.1945
	Solid	0.1439			0.8177	0.1722
	Slice	0.0029	3.3947		0.9946	0.0317
Page	Solid	0.0068	2.6685		0.9911	0.0418
	Slice	0.2166	1.0564		0.9831	0.0393
Modified page	Solid	0.1412	1.8833		0.9964	0.0231
	Slice	0.2239		1.023	0.7814	0.213
Henderson and Pabis	Solid	0.1855		1.2623	0.8135	0.1742

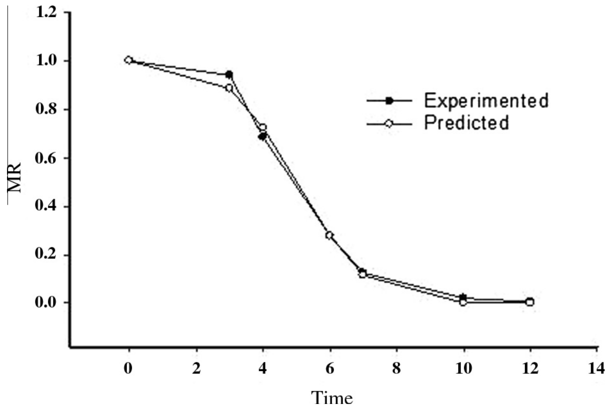

Fig. 9 – Experimented and predicted *MR* of sliced turmeric vs. time, h.

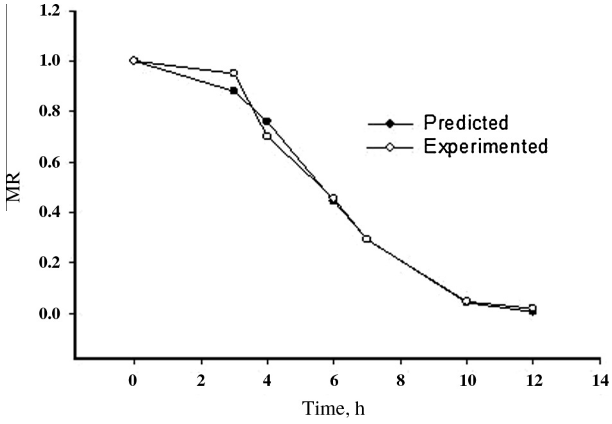

Fig. 10 – Experimented and predicted *MR* of whole turmeric vs. time, h.

4. Conclusion

From the study it could be inferred that, in 12 h of effective drying, initial moisture content of 78.65% (wb) could be reduced to 5.5% (wb) in sliced samples. During the same time, moisture content of whole samples got reduced to 6.36% (wb). In normal practice of open sun drying, effective drying time was 25.5 h. Drying rate was much faster during the initial high moisture period of drying in case of sliced samples. During isothermal drying, the value of effective moisture diffusivity decreased with moisture content. It also depends upon the texture of the product as evident from higher diffusivity in case of sliced samples. Page model for thin layer drying found to be fitted well with the experimental values, establishing suitability of the tested dryer. With overall thermal efficiency of around 55% for turmeric drying, SCD has the potential to completely eliminate possibility of fungal growth in sliced samples which often occurs in high atmospheric humidity areas during normal practice of open sun drying.

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