

Drying kinetics of black turmeric (*Curcuma caesia*) with optimal controller assisted low cost solar dryer

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Abstract

Solar is abundant, renewable and sustainable energy source that attracted many renowned researchers across the globe. Solar drying is a promising drying technology for fruits and vegetables in developing countries. In this study, a low-cost solar dryer was designed and developed with moisture monitoring and temperature controlling system. The experimental setup consists of modified thermal collector and plenum chamber. Black turmeric (*Curcuma caesia*) slices (2 mm) was carried out for thin layer drying kinetics and results were compared with open sun drying and tray drying. The drying kinetics of the slices was tested by five thin-layer drying models. Among the empirical models investigated, the modified page model satisfactorily described the drying behavior of black turmeric slices with higher R^2 (0.9988) and lower χ^2 (0.0032) values. In addition to that, experiments were also conducted to study the effect of drying conditions on Color, TPC, TFC and Antioxidant activities. The low-cost dryer could be useful in the food industry/farmers/small scale industry as a means of saving time and minimizing product quality damage.

1. Introduction

Curcuma caesia Roxb. (Black turmeric or black zedoary) is a perennial herb with bluish-black rhizome native to North-East and Central India (Devi *et al.*, 2015; Lakshmi *et al.*, 2018). It contains a very good percentage of curcumin which possesses many curative properties among all the *Curcuma* or turmeric species. It is recognized as a medicinal herb to possess with various properties such as anti-fungal activity (Banerjee and Nigam, 1976), anti-asthmatic activity (Arulmozhi *et al.*, 2006), antioxidant activity (Mangla *et al.*, 2010; Lakshmi *et al.*, 2018), anxiolytic and CNS depressant activity (Karmakar *et al.*, 2011) and anti-bacterial activity (Rajamma *et al.*, 2012). The rhizomes of the plant are aromatic in nature. The inner part of the rhizome is bluish-black in color and emits a characteristic sweet smell, due to the presence of essential oil (Pandey and Chowdhury, 2003). The higher moisture content (75-79%) of black turmeric renders them perishable and seasonal availability limits their utilization all-round the year. Hence, suitable preservation techniques should be developed to extend the shelf life of black turmeric.

Many food preservation methods can be adopted for storage like canning, freezing and controlled atmosphere storage but all these methods are expensive (Kalra *et al.*, 1983).

Drying is the most widely employed method for preserving food materials, which is based on the reduction of the water activity values through moisture removal to achieve physicochemical and microbiological stability (Yaldiz *et al.*, 2001; Maskan *et al.*, 2002; Moreira *et al.*, 2008). Sun drying is one of the oldest drying methods followed in many countries, especially by individual households and small-scale enterprises. Though the method of sun drying is inexpensive, the products may be spoiled due to adverse weather conditions and may also get contaminated with dust, insects and their excreta. Further, the process is time-consuming, offers non-uniform drying and requires a larger surface area. The product is also vulnerable to absorb moisture leading to reduced quality (Chavda and Kumar, 2009; Rathore and Panwar, 2011). Open sun drying (OSD) is still widely used in many tropical and subtropical countries as it is the cheapest method. For

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turmeric, the common practice in India is to dry it under open solar drying. However, the quality of the dried products in the open sun drying gets affected due to rodents, sudden rain, improper heating, etc. (Sengar, 2018). This can be overcome by introducing solar drying technology.

In solar drying, solar-energy is used as either the sole source of the required heat or as a supplemental source. The air flow can be generated by either natural or forced convection. The heating procedure could involve the passage of preheated air through the product or by directly exposing the product to solar radiation or a combination of both (Ekechukwu, 1989). Utilization of solar energy for drying is advantageous as it is a free, renewable and abundantly available. It is also an environment-friendly and economically viable source which makes it to be acceptable by the rural farmers (Basunia and Abe, 2001), where the electric supply is either scarce or irregular. Studies conducted on solar drying have proved that it is a good substitute for sun drying for the production of high-quality dried products (Saleh and Badran, 2009). Most of the researcher reported studies on solar drying of various agricultural products such as chilli, cauliflower, grapes, mint, turmeric, pepper, apricot and tomato etc. Black turmeric is largely produce in the north-eastern part of India. Further, it is observed that there is no study reported on the drying kinetics of high-value agriculture products such as black turmeric. For the first time the author reporting the open sun and solar drying models for black turmeric.

2. Materials and methods

The drying chamber and collector were design, developed with the help of locally available, biologically degradable, low-cost materials (plywood, sawdust, thermocol, cotton, stainless steel mesh, wooden skewers, clear glass, galvanized iron sheet) and whole setup was installed in the department of Instrumentation engineering, Central Institute of Technology, Kokrajhar, Assam, India. The trials were carried out in the month of March-April 2017 under the metrological conditions of Central Institute of Technology, Kokrajhar (26°24'N 90° 16'E/26.4°N 90.27°E coordinates and time zone IST (UTC +5:30).

2.1 Sample preparation for drying

Black turmeric was collected from a fruit vendor near the Central Institute of Technology, Kokrajhar, Assam, India. Freshness, Color, size, level of maturity and absence of any mechanical damage were used as selection criteria. The rhizomes were washed thoroughly, and the surface water was wiped with a clean tissue

paper. The samples were spread uniformly on the trays in a single layer. Initial moisture content was measured by hot air oven (IIC, Model: HA-11, Kolkata) method (Rangana, 2005). The samples were then dried in two different drying system i.e., Sun and Solar. In each experiment, a material density of 2.5 kg/m² was used irrespective of the method.

2.2 Experimental set up

The schematic of the indirect type solar dryer is shown in Figure 1. The system consists of a collector (1520 x 760 x 180 mm), a transparent plenum chamber (1220 x 760 x 450 mm) with 4 trays and a blower with a capacity of 20 kg. Flat plate collector is used since it is easy to fabricate and also economical. The collector is made up of GI sheet and copper pipe as it is a good conductor and economical. It was painted black to increase the absorption of heat (Queiroz *et al.*, 2011) and a glass of thickness 5 mm was used (Sukhatme and Sukhatme, 1996). The drying chamber was made of mild steel. Hot air entering from one side and as well as a glass top cover allows the direct sun radiation to pass into the drying chamber. The glass top was provided for an additional drying effect. A centrifugal blower was used for supplying the air. A gate valve was used to control the mass flow rate of air. To prepare drying chamber insulating materials like plywood, sawdust, cotton and thermocol were chosen as it is a good insulator as well as environmentally friendly. In addition, to reduce the heat loss by radiation and to avoid moisture absorption by wood, aluminium foil is wrapped on the inside of the chamber. Food grade stainless steel mesh for the all the four trays was selected for drying of black turmeric. Finally, all these components are fitted in a MS Iron made stand for easy handling and relocating purposes (Lakshmi *et al.*, 2018). The side cover was fixed to the drying chamber using hinges and was lifted up in order to place the samples in the solar dryer.

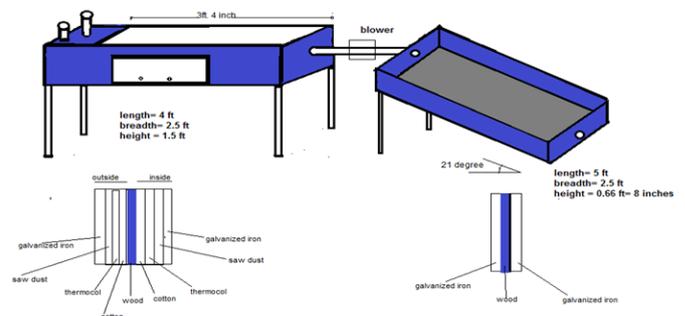


Figure 1. Schematic diagram of solar dryer

The dryer was installed in the top floor of the IE Department as this place was free of shade, particularly for the period of drying from 8 am to 4 pm. A digital weighing balance (Denver, Germany) was used to record

the weight of the sample. Dryer was shut down during the night, and the experimentation was getting resumed the next day at 8 am.

2.2.1 Instrumentation

A Proportional Integral (PI) controller was implemented to the solar dryer to control the air pump (flow rate of 0.5, 1 and 2 m/s) as a manipulated variable to achieve desired value and to reduce the effect of dead time. A PID controller is applied on this kind of the systems time lagging systems, the derivative part is mostly switched off, and only PI control was used (Hägglund, 1996; Yurkevich and Naidu, 2012). Proportional Integral (PI) controllers are fast and very accurate to reach control objectives it combines the advantages of integral control for zero steady-state error and with proportional control to increase the speed of the transient response (O'Dwyer, 2006; Puglisi et al., 2015). So Proportional Integral (PI) controller was implemented to the solar dryer to study its effect on drying chamber temperature.

A moisture removal monitoring system was also introduced in the drying chamber to remove the moisture from the sample (Dai et al., 2015). The measuring of moisture content in materials is of such prominence in so many fields that a varied of devices and analytical methods in use. The traditional method for measuring moisture content in solids and non-volatile liquids is thermal gravimetric. In a thermal gravimetric system, a sample of the material is sensibly weighed and after the material is dried by the application of heat then re-weighed after drying. Any difference in weight generally reduced is indicative of the moisture content removed from the sample (Raisanen et al., 1979). The drying process may be simple exposure to ambient air or in some cases, a hot air driven in solar dryers have been used. The removal of moisture in the testing sample is measured in terms of weight loss, as it is direct and accurate measuring for time-varying parameters. Since the amount of moisture removed from the drying chamber of the solar dryer is not possible to measure directly so it is being measured in terms of weight.

2.3 Drying analysis and evaluation of thin layer drying models

The drying characteristic curves were plotted after analyzing the experimental data. The moisture content was converted to moisture ratio (MR) using the following equation.

$$MR = \frac{(M_t - M_e)}{(M_0 - M_e)} \quad (1)$$

Where, M_0 is the moisture content, kg water/kg dry matter at beginning of the drying; M_e is the moisture content, kg water/kg dry matter when the equilibrium is reached; and M_t is the moisture content, kg water/kg dry matter at time t ,

As the relative humidity of the drying air fluctuated continuously, M_e was assumed to be negligible and the expression was reduced to:

$$MR = \frac{(M_t)}{(M_0)} \quad (2)$$

Mathematical modeling was carried out to describe the drying curve equation of black turmeric and to determine the parameters of the thin layer drying models by fitting experimental data to the model equation. Nine different commonly used models are given in Table 1 and taken into account for specifying the most adequate model in thin layer drying of black turmeric. The nonlinear regression analysis was performed using the statistical analytical tool SAS (Mumbai, India). Although the coefficient of determination (R^2) was one of the principal criteria for selecting the best model to describe thin-layer drying of the turmeric, the reduced chi-square (χ^2) was also included to evaluate the goodness of fit of the models (Equations 3 and 4). The lower chi-square (χ^2) and the higher R^2 values, were chosen as the basis of goodness of fit (Midilli and Kucuk, 2003; Akpınar, 2006).

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

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

Where $MR_{exp,i}$ is the i th experimentally observed moisture ratio; $MR_{pre,i}$ the i th predicted moisture ratio; $MR_{exp, avg}$ is the average experimental moisture ratio; N the number of observations and; n is the number of constants (Sarsavadia et al., 1999). The drying curve for

Table 1. Mathematical models used to describe thin layer drying

SN	Model Name	Model	References
1	Lewis	$MR = \exp(-kt)$	Kabganian et al. (2002)
2	Page	$MR = \exp(-kt^n)$	Page (1949); Kabganian et al. (2002);
3	Modified Page	$MR = \exp[-(kt)^n]$	Yaldyz and Ertekyn, (2001); Midilli et al. (2002)
4	Henderson and Pabis	$MR = a \exp(-kt) + (1 - a) \exp(-kt)$	Demir et al. (2004)
5	Two-term exponential	$MR = a \exp(-kt) + (1 - a) \exp(-kt)$	Sharaf-Eldeen et al. (1980)

each experiment was obtained by plotting the dimensionless moisture ratio of the sample versus the drying time. Modeling the drying of different agricultural products often requires statistical methods of regression and correlation analysis. Linear and non-linear regression models are important tools to find the relationship between different variables, especially, for which no established empirical relationship exists. In this study, the relationships of the constants of the best suitable model with the drying air temperature were also determined by multiple regression technique.

2.4 Quality analysis

2.4.1 Color analysis

Color of fresh and dried black turmeric slices (dried in both solar dryer and in open sun drying) were measured in terms of the L^* , a^* and b^* values using a Hunter lab Colorimeter (D25 LT, Hunter lab, USA) according to the methods followed by Nayak *et al.* (2017).

2.4.2 DPPH radical scavenging activity

Free radical scavenging activity was determined with a DPPH radical assay, performed according to the modified method followed by Babuskin *et al.* (2014). Briefly, 100 μM of DPPH in ethanol was prepared and 1 ml of this solution was added to a test sample (4 mL). The reaction mixture was shaken well and incubated for 30 mins at room temperature. The absorbance of the resulting solution was read at 517 nm using a UV-Vis spectrophotometer (Lambda 25 UV-VIS, Perkin Elmer, Ohio, USA) against a blank and DPPH radical scavenging activity was expressed as μmol of Trolox equivalents (TE) g sample from a standard curve developed with Trolox. All determinations were performed in triplicate. Measurements were performed in triplicate.

2.4.3 Total phenolic content

The Folin-Ciocalteu reagent assay was used to determine the total phenolic content of extracts in accordance with the method followed by Lakshmi *et al.* (2018).

2.4.4 Total flavonoid content

The total flavonoid content of the spice extracts was determined by a method followed by Nayak *et al.* (2017) using quercetin as a standard. All determinations were performed in triplicate.

3. Results and discussion

The moisture of the drying sample is controlled by the heated air flow from the solar collector chamber to

the drying chamber. the sample moisture content and temperature in drying chamber is monitored continuously, and if it is found to be less or greater than the set temperature or sample moisture content, the PI control tracks the stability by varying the air flow by air pump speed Hawlader *et al.* (2008). The three different air flow rates were entered into the collecting chamber. The maximum temperatures achieved with PI controlled pumps are 0.5, 1 and 2 m/s are 63°C, 68°C and 65°C, respectively, with almost similar ambient air temperature for all the velocities. At the end of two days of drying, i.e. 8 hrs/day, the moisture content in the black turmeric in terms of weight loss is 110%, 68% and 85% for 0.5, 1 and 2 m/s, respectively. The moisture removal rate is fastest with the PI controlled air flow rate of 1 m/s, as compared with 0.5, 2 m/s and without pump as seen in Figure 2. The results were also in accordance with the Hegde *et al.* (2015).

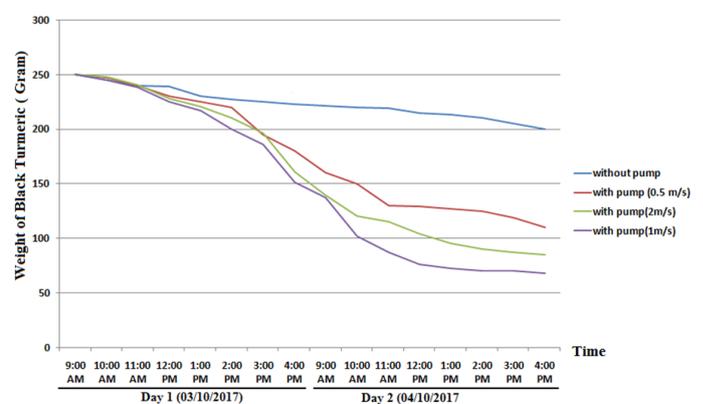


Figure 2. Variation of moisture content (db) kg moisture /kg dry wt. with drying time of black turmeric dried by different air flow rates

3.1 Evaluation of model parameters

The drying data obtained in the experiments were converted to dimensionless moisture ratio (MR). In order to determine the experimental moisture ratio as a function of drying time, five empirical models were used. The estimated parameters and the results of statistical analysis of these models were presented in Table 2. For all drying condition, the models showed the coefficient of determination (R^2) values in the range of 0.9367 to 0.9987. It was indicated that many of the models could satisfactorily describe the drying kinetics of black turmeric slices. Among the thin layer drying models tested (Table 2), Modified page model indicated the highest R^2 values with the lowest χ^2 values.

3.2 Quality analysis

3.2.1 Color of dried slices

The three color parameters (L^* , a^* , b^*) of fresh and dried samples are shown in Table 3. The color of the air-dried black turmeric was found to be dependent on the

Table 2. Comparison of different drying models with drying coefficients (constants)

Model	Model Constants	R ²	χ ²
Lewis	k= 0.01461	0.9652	0.00182
Page	k=0.00413, n=1.28817	0.9743	0.00065
Modified Page	k=0.00666, n= 1.18962	0.9987	0.00041
Henderson and Pabis	k= 0.00434, a= 0.77143	0.9367	0.03652
Two-term exponential	a= 1.71397, k= 0.00983	0.9543	0.00165

Table 3. Quality analysis of black turmeric slices

Slices Parameters	Fresh				Solar dried				Open sun-dried			
	L*	a*	b*	ΔE*	L*	a*	b*	ΔE*	L*	a*	b*	ΔE*
Color	44.22	-1.55	14.58	46.32	40.01	1.94	13.88	42.33	34.15	1.25	11.99	33.12
Antioxidant activity (μ mol of TE per g of sample)			46.62				27.65				21.98	
Total phenolic content (mg GAE per g of sample)			20.11				9.09				7.27	
Total flavonoid content (mg quercetin per g of sample)			11.32				6.66				6.22	

drying air methods. The measured parameters showed that the L* and b* value decreased with both the drying methods and a* values was increased in solar-dried methods compare to open sun drying methods. The ΔE* values for fresh, solar dried and open sun-dried samples are 46.32, 42.33 and 33.12. It is observed that the ΔE* value of the sample dried in solar drying methods is higher than that of the sample dried in open sun drying methods. The photographic views of the black turmeric taken before and after drying are shown in Figure 3.



Figure 3. Photographic views of (A) fresh black turmeric (B) after Solar dried (C) after open sun-dried (Lakshmi et al., 2018)

3.2.2 Effect of drying on antioxidant activity

Antioxidant properties of fresh and dried samples (solar dryer and open sun drying) were investigated through DPPH Assay and their results are depicted in Table 3. The results indicated that the antioxidant activities of the samples were decreasing from fresh (46.62 μ mol of TE per g) to open sun-dried (21.98 μ mol of TE per g).

3.2.3 Effect of drying on TPC and TFC

The total phenolic contents of the powders were decreased from 20.11 to 7.27 mg of GAE/g of extract. The phenolic content estimated in our results was

probably responsible for the free radical-scavenging activity of black turmeric samples and, the levels of total flavonoids varied from 11.32 (fresh) to 6.22 (open sun-dried) mg of quercetin per gram of extract.

4. Conclusion

In the present work, performance analysis of indirect solar dryer has been carried out for drying of 25 kg black turmeric. The experimental results were further analyzed to find the best suitable thin layer drying kinetic model for solar dried samples. It was observed that the modified page model was found to be the best fit for solar dried samples. The results revealed that the optimized design and PI controller gives the significant improvements of the moisture removal in the proposed solar dryer design. It is also observed from the drying kinetics and quality analyses data, the newly developed low-cost solar dryer is definitely a better option for drying the high value medicinal agricultural products like black turmeric.

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