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A Comparative Study on the Drying Kinetics of Turmeric in a Mixed Mode Solar Dryer with and without a Solar Air Collector

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Abstract: The objective of this research is to experimentally investigate the performance and drying kinetics of turmeric under three different conditions: solar drying with a solar air collector (SAC) in mixed mode, solar drying without a SAC in direct mode, and open sun drying. The study aims to evaluate the moisture reduction and drying time required for each condition. The experimental results demonstrate that a moisture reduction from 86% to 4% (wet basis) can be achieved within 8 hours using a solar dryer with a SAC. The Wang and Singh model exhibited the best fit for the thin-layer drying kinetics, showing the highest coefficient of determination (R2) value and the lowest chi-square (χ2) and root mean square error (RMSE) values. The model constant was determined through regression analysis. Comparing the drying performance, it was observed that drying turmeric in a solar dryer with a SAC resulted in effective drying time and better overall dryer performance compared to drying without the use of a SAC. This research contributes to understanding the drying behavior and performance of turmeric under different drying conditions. The findings highlight the advantages of solar drying with a SAC in terms of drying time and efficiency, offering a sustainable solution for turmeric drying in the region.

Keywords: Turmeric; NER; Direct mode; Mixed mode; Thin layer drying; Solar air collector.

1. INTRODUCTION

In India the use of turmeric is nearly 4000 years old, when it was used as a culinary spice and had some religious significance. India produced about 4 million ton of turmeric (Curcuma longa L.) in fresh weight each year which was about 80% of the world's supply of commercial turmeric (Borah et al., 2015). The North Eastern Region (NER) of India contributes the major production of turmeric. It is considered to have one of the world's best varieties of turmeric with its curcumin content of about 6.8 - 7.5 % (Borah et al., 2015). Commercially, it is used as a spice, source of industrial starch and the characteristic yellow–orange curcuminoids found in rhizomes are used to make a yellow food and textile dye. In this region people are still following the traditional method of drying for preserving the agricultural product from mould, bacteria and fugal attack. Sun drying is considered as the ancient method of drying agricultural product, which is economical, non- polluting but requires large space, exposed to dirt, dust, pest, insects etc. which reduces the quality and economical value of the product(Togrul & Pehlivan, 2002). Drying is a complex heat and mass transfer process and energy intensive process which require latent heat of evaporation to the remove the moisture from the product surface. Solar drying is the advanced technique of sun drying, the products are dried in a closed chamber and under hygienic conditions. The solar dryers are classified as direct type, indirect type and mixed mode the combination of direct and indirect type. In direct solar drying the product is enclosed in a drying chamber with direct exposure to solar radiation from the transparent glass cover. Indirect solar dryers, the product receives indirect heated air from the solar air heaters and mixed solar drying is the combination of direct and indirect solar dryer. The dryers classified may be of passive or active mode(Togrul & Pehlivan, 2002). (Borah et al., 2015) conducted turmeric drying in a solar conduction dryer. The air temperature inside the dryer was around 39–51ºC for an ambient temperature in the range of 25–28ºC. 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. 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%. Most of research studies have been performed for drying of various agricultural products such as chilli, ginger, fig, apricot, grapes, pistachios and medicinal plants using different types of solar dryers in the literature (Fudholi et al., 2014)(Babalis et al., 2006)(Togrul & Pehlivan, 2002)(Midilli, 2003) However, few works were available on the drying of turmeric which is considered as high -value product in the NE region of India. Therefore, the present work is focused on comparing the thin-layer drying characteristics of a local variety of turmeric in a drying chamber with a solar air collector (mixed mode) and without a solar collector (direct mode) under the forced convection mode in the sub-tropical humid climatic condition. To develop a thin layer drying model to best fit the drying kinetic curve for different drying conditions.

2. EXPERIMENTAL SETUP METHODOLOGY

The experimental setup consists of mainly three parts; SAC, blower, and the mixed mode horizontal bed dryer. The SAC consists of two double-pass solar air heaters made up of a wooden frame, an absorbing plate of galvanized steel of thickness 0.85 mm which is painted black to increase the absorptivity of the plate, a bottom plate of the aluminum sheet has been used at the bottom of the heater and the back side of the aluminium is insulated using polyurethane foam sheets to reduce the bottom loss from the heater. A glass cover of 4 mm thickness is used as glazing material to trap the solar radiations and reduces the top losses from SAC. A single-phase blower of 0.56 hp, 2800 RPM has used to draw air from SAH and to blow the hot air into the dryer. At the outlet of the blower a glove valve was used to regulate air mass flow rate. The mixed mode horizontal bed dryer is made up of pine wooden plank of thickness 2.5 cm which provide strength and good insulation to the dryer. The top surface of the dryer was made up of glass cover of 5 mm thickness to allow the solar radiation to enter inside the dryer, the inner side of the dryer was covered by steel plate and painted black to absorber the incidence solar radiation. Six detachable trays made up of wooden frame and metallic wired mesh has placed inside the dryer on which product was loaded. Three trays placed at the top and three at the bottom. A small door was placed on one of the side wall of the dryer for easy mounting and unmounting of the loaded trays into the dryer.

2.1 Sample Preparations

Fresh lakadong variety of turmeric was purchased from local market of Guwahati, India and washed thoroughly to remove surface mud under running water. Fresh turmeric is cured for obtaining dry turmeric. Curing is done by boiling the fresh turmeric in water for 6-8 min. they are then cut into even slice of 2-3 cm thick. Accurately weighted four samples (200 gm) were prepared, one sample placed in oven at 80ºC to know the dry mass of the turmeric. Drying of turmeric was conducted in three different conditions, in mixed mode solar dryer (SAC), direct solar dryer (without SAC) and traditional open sun drying during their harvesting period. Fig. shows the experimental setup for drying of turmeric under the cases considered. During each experiment 10 kg of product was loaded in the dryer. The dryer contains six trays, and all the six trays were equally loaded. Two control samples of 200 g each has taken in a separate small tray, one was placed inside the dryer and other for open sun drying. The amount of moisture reduced was recorded on hourly basis by weighing the control samples. The initial MC of turmeric was 86% (wb) which was reduced to a safe moisture level of 4% (wb) for long shelf life storage. In first condition the dryer was connected with two SAHs which ware connected in series in order to gain high temperature with a compact design. At the outlet of the SAH a blower was connected to force the hot air from the SAH to the dryer. The blower maintains a constant mass flow rate of air 0.062kg/s. In second condition the dryer was not connected to the SAHs in order to make the drying setup cost effective. As the dryer was mixed mode so it was receiving solar radiation from the roof which was made up of glass. So, without connecting the SAHs also the air inside the dryer was getting heated. And the blower was blowing constant mass flow rate of air 0.062kg/s inside the dryer in order to maintain force convection.

2.2 Analysis

The performance of dryer under different drying conditions can be determined on the basis of drying time, moisture content and dryer efficiency.

The moisture content of cluster fig on dry and wet basis is given as;

$$M_{db} = \frac{m_p - m_d}{m_d} \quad (1)$$

$$M_{wb} = \frac{m_p - m_d}{m_p} \quad (2)$$

Where M_{db} = moisture content (db), M_{wb} = moisture content (wb), m_p = mass of wet product and m_d = mass of dry mass.
The mass of moisture removed from the product;

$$W = \frac{m_p(M_{iwb} - M_{fwb})}{100 - M_{fwb}} \quad (3)$$

where m_p (kg) is the mass of wet product dried; M_{iwb} is the initial moisture content (wb) and M_{fwb} is the final moisture content (wb).

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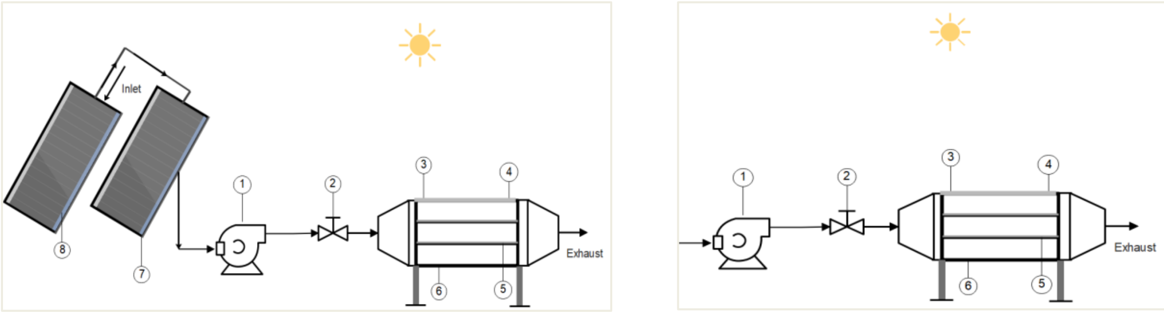

(a) **(b)**

1. **Blower**
2. **Valve**
3. **Glass cover**
4. **Drying chamber**
5. **Drying tray**
6. **Black coating**
7. **Solar air collector 1**
8. **Solar air collector 2**

Figure. 1 (a) Experimental setup of solar drying in mixed mode with solar air collector in series.

3. THIN LAYER DRYING EQUATIONS

It is important to understand the basic idea of modeling the drying kinetics of agricultural product. The drying conditions, type of dryer, and the characteristics of the product (size and shape) to be dried all have significant influence on the drying kinetics. The drying kinetics models are therefore significant in deciding the ideal drying conditions, which are important parameters in terms of equipment design, optimization, and product quality improvement (Onwude et al., 2016). The use of thin layer drying equations have wide applications in solar drying process of various fruits and vegetables due to less data required as compared to the distributed model. The thin layer drying equation may be categorized as theoretical, semi-theoretical and empirical models. The most commonly applied models are semi-theoretical and empirical models, they consider the external resistance to moisture transfer between product and drying air. The main justification of the empirical approach is a satisfactory fit to all experimental data. Thin layer drying equations and experimental data of the drying parameters as a function of drying conditions is required for simulation of the drying systems (Erbay & Icier, 2010).

$$MR = \frac{(M_t - M_e)}{(M_0 - M_e)} \quad (4)$$

$$MR = \frac{M_t}{M_0} \quad (5)$$

The experimental data obtained of moisture ratio (MR) was graphically plotted with drying time and fitted with different drying kinetics models given in (Table.1). The appropriate drying kinetics model can be determined by the statistical methods of regression and correlation analysis to obtain the constant values. The models were validated on the statistical parameter like coefficient of correlation r, Chi-square χ^2 and root means square error RMSE. The coefficient of correlation r given in Eq. (11) is one of the methods for model selection. In addition to R^2, the best-fit curve was determined by various other parameters such as chi-square χ^2 and root mean square error RMSE using Eq.6-8. Therefore, the evaluated best-fit curve has the highest value of R^2 and lowest value of $x^2$and RMSE (Borah et al., 2015). The value of R^2, χ^2 and RMSE given as;

$$x^2 = \frac{\sum_{i=1}^{N} (MR_{exp,i} - MR_{pre,i})^2}{N - n} \quad (6)$$

$$RMSE = \sqrt{\frac{1}{N}\left[\sum_{i=1}^{N} (MR_{exp,i} - MR_{pre,i})^2\right]} \quad (7)$$

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2}{\sum_{i=1}^{N}\left(\overline{MR_{pre}} - MR_{exp,i}\right)^2} \quad (8)$$

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Table 1.
List of drying kinetics models considered in the present study (Erbay & Icier, 2010).

Model name	Model
Newton	$MR = exp\ (-kt)$
Page	$MR = exp\ (-kt^n)$
Modified page	$MR = exp\ (-(kt)^n)$
Henderson and Pabis	$MR = a\ exp\ (-kt)$
Logarithmic	$MR = a\ exp(-kt) + c$
Two-term	$MR = \mathrm{a\ exp(-k_0t) + b\ exp(-k_1t)}$
Two-term exponential	$\mathrm{MR = a\ exp(-kt) + (1-a)exp\ (-kat)}$
Verma	$\mathrm{MR = a\ exp(-kt) + (1-a)exp\ (-gt)}$
Wang and Singh	$\mathrm{MR = 1 + at + bt^2}$

4. RESULTS AND DISCUSSIONS

4.1 Drying curve

The variation in moisture content of turmeric with the drying time in solar dryer with SAC, without SAC and under sun drying was presented in Fig.3. The initial moisture content of turmeric was 86% wb, reduced to final moisture content of 4.3% wb using Eq.2. The drying time observed to achieve a final moisture content of 4.3 % wb in solar dryer with SAC, 11.7% wb without SAC and 26.3 % wb under sun drying was 8 h. As shown in the Fig.3, the moisture content continuously decreases with the increase in the drying time. The drying is considered to be the falling rate period, no constant rate drying period was observed for the drying of turmeric for all the drying conditions. The energy utilized in solar dryer with solar air collector was 850 J/s while in case of solar drying without solar air collector was 485 J/s. The higher amount of heat energy utilized leads to faster moisture removal rate. It is evident from the Fig. 3 that the drying kinetics with solar air collector is little faster and the final moisture content of turmeric is lower than obtained without the use of solar air collector and under open sun drying condition. The performance of dryer was evaluated in terms of dryer efficiency from Eq.4 as 19 % and 12 % in mixed mode solar dryer and direct solar dryer respectively.

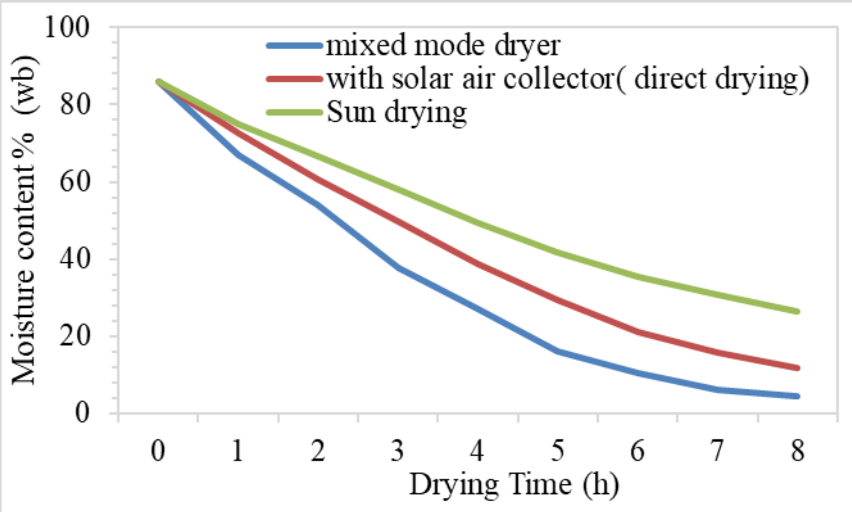

Fig.3 Variation of moisture content with drying time

4.2 Mathematical modelling of solar drying curves

The experimental results of MR data obtained from different drying conditions for drying sliced turmeric (i) without solar air collector (direct drying) and (ii) with solar air collector (mixed mode) were plotted with the drying time and were made to fit with nine different drying kinetics models given in Table 1. The obtained values of drying constants, R^2, x^2 and RMSE obtained from the non-linear regression. The highest value of R^2= 0.9998 and lowest value of x^2= 0.00011 and RMSE= 0.0043 shows that, the Wang and Singh model was found to best fit the drying MR curve of sliced turmeric in dryer with SAC, without SAC and in open sun drying. The model equations for thin layer drying of sliced turmeric in terms of moisture ratio are given as:

$\mathrm{MR = 1 + at + bt^2}$ (Wang and Singh model)
a= -0.168; b= 0.0073
where MR is the moisture ratio; t is the drying time (h); a and b are the experimental drying constants

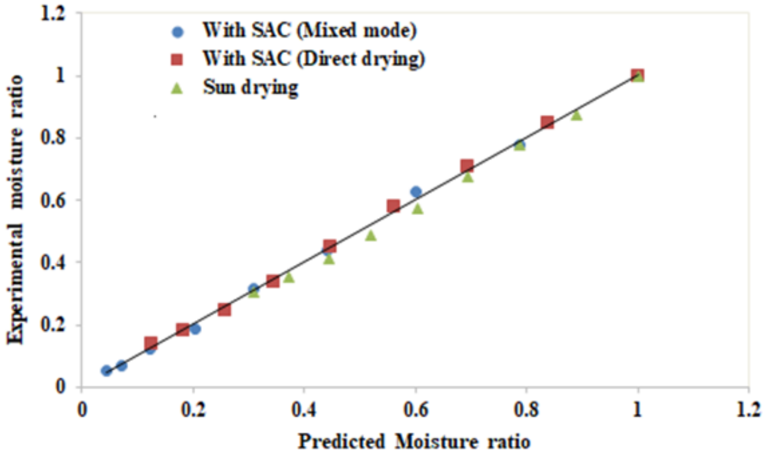

Fig.4 Comparison of experimental and predicted moisture ratio by Wang and Singh model.

The validation of predicted drying curve model and the experimental data is given in Fig. 4 for solar drying in mixed mode, direct solar drying and drying under open sun. All the MR data points of experimental and predicted models are close to the straight line.

5. CONCLUSION

Drying of local variety of turmeric was carried out using solar dryer with SAC, without SAC and under sun drying for comparing the different drying techniques. The moisture removal from the turmeric in the drying process occurs in the falling rate period, no constant rate drying period was observed for all drying conditions. The initial moisture content of turmeric on wet basis was reduced from 86 to 4.3% in 8 h for solar drying with SAC, while solar drying without SAC and open sun drying attain final moisture content of 11.7% wb and 26.3 % wb 8 h. The Wang and Singh model is the best fitted model for describing the drying kinetic curve of turmeric for all the drying conditions based on the statistical regression analysis. The dryer efficiency was calculated as 19% and 12% in solar dryer with and without the SAC respectively. the use of solar dryer with SAC has the potential to dry high-grade turmeric available in the NE region, with less drying time and reduce the possibility of mould and fungal growth due to high humidity in the ambient in the region.

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