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THE THIN LAYER DRYING CHARACTERSTICS OF CHILLY LEAF UNDER OPEN SUN AND IN A SOLAR DRYER

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ABSTRACT

In bio-oil production by fast pyrolysis of agricultural residues, controlled drying of feedstock to appropriate moisture content is very important since higher moisture content in biomass generally causes operational problems of biomass combustors and higher CO emissions. Chilly plants form an abundant biomass after harvesting of fresh chillies. In this paper, experimental investigation of the thin-layer drying of chilly (*Capsicum annuum*) leaves was conducted under open sun and solar drying methods. Solar drying was realized through a solar air heater in a drying chamber. It was completed by both forced (collector with and without fins) and natural convection methods. The experiments were done to attain less than 10% residual moisture content. The experiments were done at an average ambient temperature of 37.74°C and an average irradiance of 653.8 W/m^2. The calculated values were tailored to four different mathematical drying models available in literatures. The appraisal between models was done by the application of regression coefficients, Root mean square error and sum squared errors. The logarithmic model with the highest R^2 and lower SSE value best fits the open air drying (natural convection) and solar drying (forced convection) of chilly leaves best.

Keywords: chilly leaves, open drying, solar drying, forced convection, thin layer drying, drying models.

INTRODUCTION

India, the largest producer of chillies, has an annual chilly production of around 14 lakh tonnes, according to Ministry of Agriculture. The chilly plant is a popular kitchen plant in every household in India. It belongs to the genus *Capsicum*. The fruit amassed can be used directly for the day to day household cooking endeavours or can be dried to reduce moisture content to less than 10% and then, exported. At the same time, the leaves and stalk do not have any direct use and hence can be gathered to produce valuable biomass. The leaf of the *Capsicum annum* is low in initial moisture content with high roughage and lignocelluloses and hence, can be used for decent quality biomass production which can be used for pyrolysis reactions for the production of bio-oil. Drying is one of the aged practices in the World [1]. It has been in use since time immemorial for various aims. Processing of food is the most common one. The primary target for drying is the reduction of moisture content. Materials with high moisture content can lead to various adverse concerns when stored for later use like bacteria, dust, pests and viruses. Drying also makes it easier to wrap up, store and ship the materials [2]. In biomass production, the moisture content of the materials has to be maintained at the least for best results. The southern states of India stretched out close to the equator and is blessed through the year with a sunny and relatively dry climate especially, Tamil Nadu and hence it is suitable for the use of solar energy in drying. The use of solar energy reduces the capital investment for any industry set up and it is non-polluting, renewable and infinite.

Biomass can be produced from dead or recently dead matter or organisms. It mostly refers to lingo-cellulosic biomass. As energy source, it can be used either directly through combustion or by renovating into various biofuels [3]. When burned, the energy stored in biomass is released to produce heat or electricity. The solid biomass like agricultural waste, forestry waste and crops etc are used to produce the bio oil products but it has high moisture content. Drying biomass fuel improves combustion efficiency, increases steam production, reduces net air emissions, and improves boiler operation [4]. The first step in any pyrolysis reaction is evaporating or drying the feed stock to required moisture content which otherwise may reduce the efficiency of the overall process. In biomass pyrolysis, drying of feed stock is important since the included water content may get distilled in pyrolysis oil lowering the heating value and flame temperature of the oil. It can also cause a decrease in combustion rate and increase in ignition delay as compared with diesel fuels. The presence of high moisture content in biomass materials makes its transportation and storage difficult and more energy is required to evaporate the high water content in these materials. The efficiency of transportation and storage of these high moisture biomass materials is very less. In addition it can create other problems like the risk of composting during storage. Whenever the water content of bio oil is more than 30%, phase separation will happen soon which hinders its use as a fuel. Therefore it is most essential to dry the biomass which is used as feed stock for pyrolysis reactions to less than 10% moisture content [3]. Forced convection removes moisture from the biomass materials at a faster rate than natural convection. This will definitely help to ensure safe and optimum operation of pyrolysis reactors and will improve the quality of pyrolysis oil. The liquid pyrolysis product called 'bio-oil' is a carbon dioxide neutral compound, can be used as an energy source as well as a feed stock for chemical production

Modelling using various thin-layer models is approximate way of predicting the moisture content at the given time. It is useful for the design engineers to choose

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the appropriate technique to be used for the drying and designing of the drying setup [5]. The main intention of mathematical modelling is the approximation of various process considerations as a function of time. Many researches on mathematical modelling and experimental studies have been conducted on thin layer drying processes of red chilly [1], long green pepper [6], coriander leaf and stem [7], mint leaves [8], date palm [9], tomatoes [10] and Roselle [11].

This paper aims to study the thin layer drying characteristics of red chilly leaves using both open air and solar drying. The experimental data is fitted to four different mathematical models and most suitable model is found out using regression analysis.

MATERIALS AND METHODS

Chilly leaves, after harvesting of fresh chillies were collected from fields for experimentation. Almost similar sized leaves were collected. Solar drying experiments were conducted in the month of August in Vellore, Tamil Nadu located at 12.8 °N latitude and 78°E longitude. Experiments were conducted in thin layer under open sun and in forced convection solar dryer simultaneously. Previously weighed quantity of chilly leaves were spread in two equal area aluminium wire net trays and was placed one in open sun and another inside two adjacent forced convection solar chimney dryers Figure-1 (one with finned and other with flat plate collector) simultaneously. The ambient velocity of air was at an average of 1.2 m/s and inside the solar dryer air velocity was kept constant at 18.7 m/s. In the experiments, weight loss of the sample, the inlet-outlet temperatures in the solar collector, absorber temperature, humidity, ambient temperature, wind speeds, the amount of solar insolation were recorded at 1 hour interval. The solar dryer was devised such that, the incident sunbeam falls directly on a collector surface area of 0.43 m^2. The plate is made of aluminium and is inclined at 17° to the floor. To improve the heating capacity of the equipment, the lower part of the plate is treated with black paint. Solar drying is done using two solar dryers, one having flat plate collector and other having collector with fins to increase area of absorption of solar radiation. The experimental values are tabularized, plotted and fitted using various mathematical models. The objectives of this paper is to study the drying kinetics of chilly leaves as a biomass in open air drying and in a forced convection solar dryer and to select the mathematical model which best fits its drying behaviour.

Figure 1. Forced convection solar dryer.

For performing mathematical modelling, the drying models available in Table-1 are fitted to obtain the most appropriate drying curve equation for chilly leaf drying.
The moisture ratio was calculated using Equation (1)

Moisture ratio, $MR = \frac{(Mt - Me)}{(Mo - Me)}$ (1)

Which can be approximated to $MR = \frac{Mt}{Mo}$, due to fluctuation of relative humidity of surrounding air.
The Drying Rate was computed using Equation (2).

Drying Rate, $DR = \frac{(Mt+dt - Mt)}{(dt)}$ (2)

Where, M_{t+dt} and M_t gives moisture content in two consecutive time interval dt. For mathematical modelling, the theoretical drying equations in Table-1 were tested using statistical parameters to present the optimum model for illustrating the drying curve equation of chilly leaves during drying by the solar dryer and under open sun [6, 12].

The best model to explain the thin-layer drying of Chilly leaves is realized using certain Statistical Parameters. The curve fitting was done using MATLAB R2010a. The primary comparison was grounded on the regression coefficient (R^2) [12]. Also, various other parameters like Root Mean Square Error (RMSE), Sum Squared Error (SSE) and adjusted R^2 values were studied. These parameters can be calculated using equations (3), (4) and (5).

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Table-1. Mathematical models used to describe drying kinetics.

Model name	Model equation
Henderson and Pabis	MR=a*exp(-kt)
Logarithmic	MR=a*exp(-kt)+c
Two term	MR=a*exp(-k_0t)+b*exp(k_1t)
Wang and Singh	MR=1+at+bt^2

Root Mean Square Error,

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,i})^2\right]^{1/2} \quad (3)$$

Sum Squared Error,

$$SSE = \frac{1}{N}\sum_{i=1}^{N}(MR_{exp} - MR_{pred})^2 \quad (4)$$

Regression coefficient,

$$R^2 = \frac{\sum_{i=1}^{n}(MR_i - MR_{pre,i}) - \sum_{i=1}^{n}(MR_i - MR_{exp,i})}{\sqrt{\left[\sum_{i=1}^{n}(MR_i - MR_{pre,i})^2\right]\left[\sum_{i=1}^{n}(MR_i - MR_{exp,i})^2\right]}} \quad (5)$$

Where, MR stands for moisture ratio, t stands for the temperature, a, b, c, k_0 and k_1 are constants, $MR_{exp,i}$ is the i^{th} experimentally observed moisture ratio, $MR_{pre,i}$ the i^{th} predicted moisture ratio, n the number constants. The values of these parameters are discussed in the following sections. The selection of adequate mathematical model is done based on the closeness of experimental values to the theoretical ones.

RESULTS AND DISCUSSIONS

The drying experiments conducted were aimed at reducing the moisture content of chilly leaf from an initial value of more than 75% to final value of less than 10% by heating during the midday to attain maximum efficiency. To augment the efficiency of the results, the procedure was repeated and a variation of only 5% was observed. An hourly calculation of the ambient temperature ranged widely between 32.7 and 44°C during the duration of the experimental procedure for open air drying and between 24.6 and 34.8°C for solar drying as shown in Figure-2. During the trials, the maximum solar insolation reached 984.12 W/m² at 12 noon as in Figure-3. The inlet air temperature of the solar dryer was 40.5°C and the outlet temperature of air from solar dryer reached 48.5°C. Air velocity was kept constant to be 1.21 m/s. Figure-2 and Figure-3 depict the variation of ambient temperature and solar insolation with time, respectively.

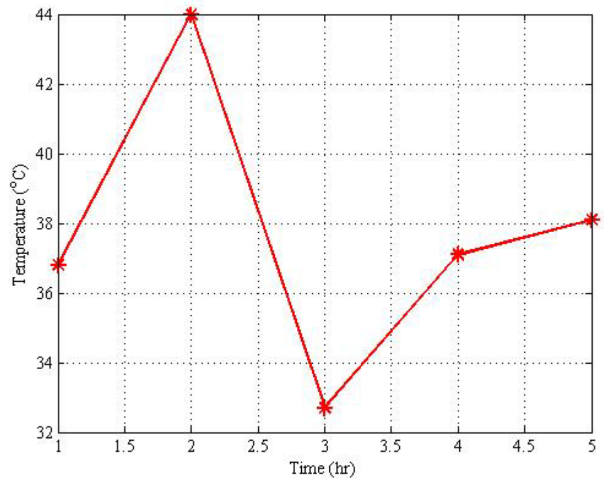

Figure-2. Variation of ambient temperature with time.

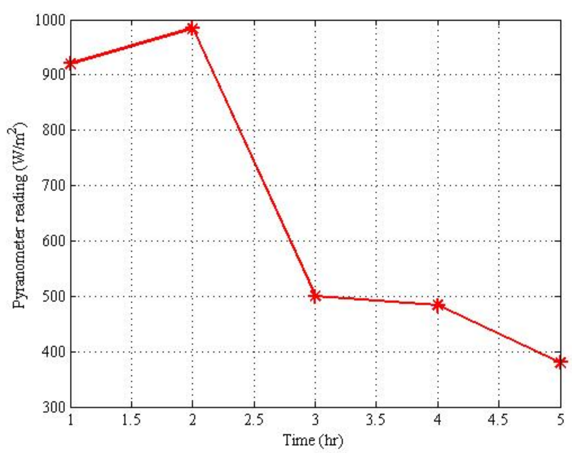

Figure-3. Variation of solar insolation with time.

Drying curves

Drying curves, showing the variation of moisture content and drying rate with time both for open air drying and forced convective solar drying having collector with fins and without fins is shown in graphs below. The instantaneous solar radiation received during the operation of the instrument was at maximum during noon. A single run of the experiment took 4 hours to complete and was done during the daytime. Both for open air drying and solar drying, the net weight and moisture content were found to decrease with time as according to common expected outcomes. The decrease is not strictly linear. There is moisture throughout the leaf but, the evaporation of moisture form the surface of the leaf is faster and quicker (free moisture) than for those inside the leaf, hence the expected decrease in rate of weight and moisture content reduction with time. There is a difference in the rates when the internal moisture is considered due to the diffusion rates that affect the movement of the moisture to the surface from inside, from where it evaporates as shown in Figure-4 and Figure-5. Finned collectors increase the surface area of absorption of solar radiation and hence drying effect of finned

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collectors will be more than that of flat plate collectors. The chilly leaves having 78% db average moisture content were dried to 9% db moisture content in 3 hours for open air drying as in Figure-4. Constant rate period was absent from the drying curves and drying took place mostly in the falling rate period. For open air drying, drying rate reached maximum value of 30.92 g/hr at a moisture content of 25% db as in Figure-5.

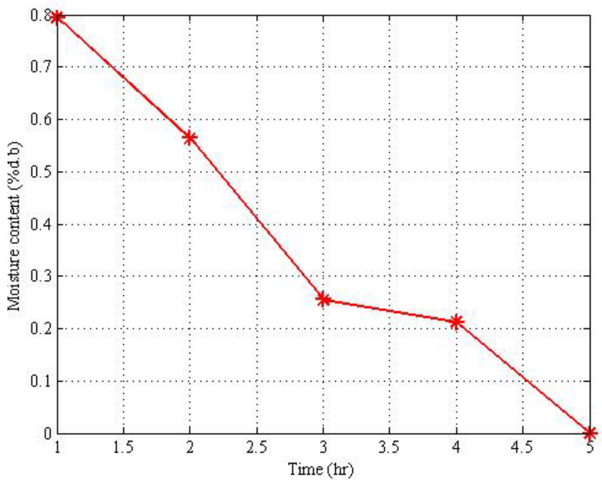

Figure-4. Variation of moisture content and time for open air drying.

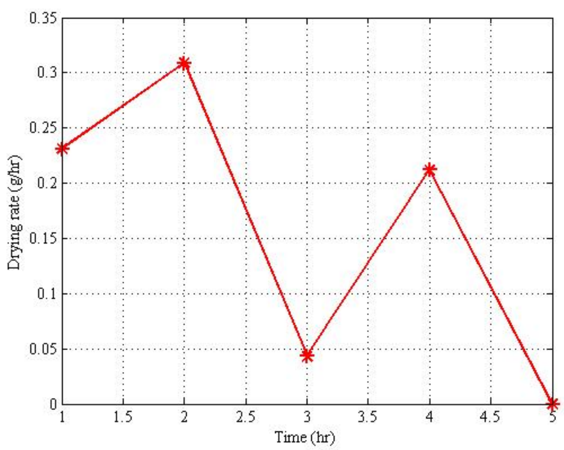

Figure-5. Variation of drying rate and time for open air drying.

In case of solar drying with finned solar collector, drying rate was continuously dropping after reaching a maximum value of 29.86 g/hr while for drying using flat plate collector drying rate was maximum of 26 g/hr and after a small drop it stood at a value of 10 g/hr as in Figure-6 and Figure-7.

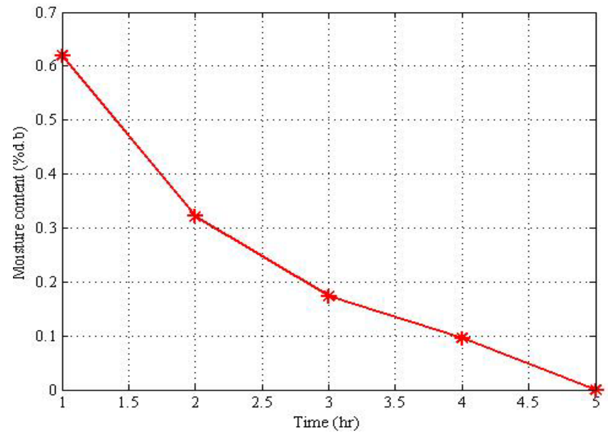

Figure-6. Variation of moisture content and time for solar drying using finned plate collector.

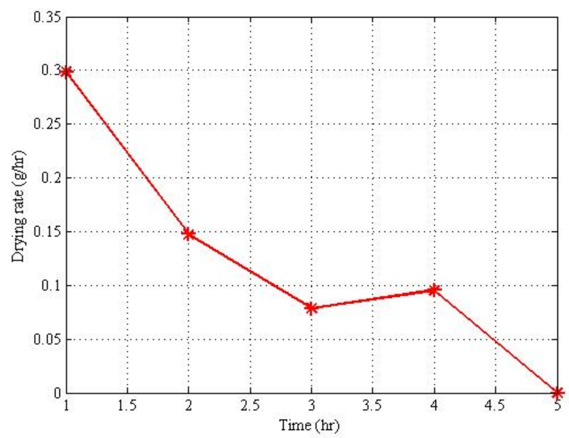

Figure-7. Variation of drying rate and time for solar drying using finned plate collector.

Comparing the drying curves it is clear that drying rate was maximum in open air drying and finned solar collector has a comparable good drying rate than flat plate solar collectors as in Figure-8 and Figure-9.

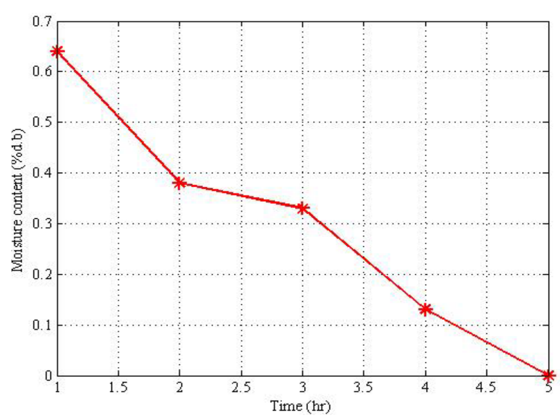

Figure-8. Variation of moisture content and time for solar drying using flat plate collector

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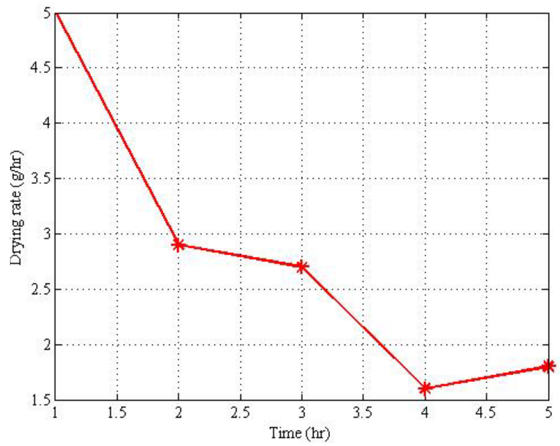

Figure-9. Variation of drying rate vs. time for solar drying using flat plate collector

Fitting of drying curves using mathematical models

The moisture contents are converted to corresponding moisture ratios and drying curves are fitted with respect to time using four standard mathematical models. These were computed using MATLAB software and the results of curve fitting are analyzed using statistical parameters R^2, RMSE and SSE values. Highest R^2 and lowest RMSE and SSE values indicates good fit of the model. The Logarithmic model best explained the Open air drying with R^2 of 0.9702, RMSE of 0.3854 and SSE of 0.29703. The Wang and Singh model best explained the natural convection solar drying with R^2 of 0.9997, RMSE of 0.00788 and SSE of 0.0001. The Henderson and Pabis model best explained the solar drying using finned plate collector with R^2 of 0.9911, RMSE of 0.04245 and SSE of 0.005406. The logarithmic model best explained the solar drying using flat plate collector with R^2 of 0.9706, RMSE of 0.0935 and SSE of 0.01748. The experimental data is banded around the straight line representing data found by computation, which indicates the suitability of the mathematical models in describing the drying behavior of red chilly leaves.

The results of the curve fitting under different drying conditions are shown in Tables 2, 3 and 4.

Table-2. Modelling of moisture ratio according to drying time for thin layer open air drying of chilly leaves.

Model name	Model equation	R^2	SSE	RMSE	Constants
Henderson and Pabis	MR= a*exp(-kt)	0.9316	0.68366	0.4774	a=4.191, k= 2.066
Logarithmic	MR= a*exp(kt)+c	0.9702	0.29703	0.3854	a=7.497, c=3.483, k=0.7565
Two term	MR=a*exp(k_0t)+b*exp(-k_1t)	0.9611	0.38827	0.38827	a=3.76, k_0= 3.908, b=3.944, k_1= 0.372
Wang and Singh	MR=1+at+bt^2	0.9622	0.33042	0.5853	a=6.139, b= 7.412

Table-3. Modelling of moisture ratio according to drying time for thin layer forced convection solar drying with finned collector.

Model Name	Model equation	R^2	SSE	RMSE	Constants
Henderson and Pabis	MR= a*exp(-kt)	0.9911	0.005406	0.4774	a=4.191, k=2.066
Logarithmic	MR= a*exp(kt)+c	0.9959	0.002487	0.3854	a=7.497, c=3.483, k=0.7565
Two term	MR=a*exp(k_0t)+b*exp(-k_1t)	0.9911	0.005406	0.38827	a=3.76, k_0=3.908, b=3.944, k_1= 0.372
Wang and Singh	MR=1+at+bt^2	0.9866	0.008109	0.5853	a=6.139, b= 7.412

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Table-4. Modelling of moisture ratio according to drying time for thin layer forced convection solar drying with flat plate collector.

Model name	Model equation	R^2	SSE	RMSE	Constants
Henderson and Pabis	MR= a*exp(-kt)	0.9287	0.04238	0.1189	a= 1.015, k= 0.5003
Logarithmic	MR= a*exp(kt)+c	0.9706	0.01748	0.0935	a=2.643, c=1.674 k= 0.1129
Two term	MR=a*exp(-k_0t)+b*exp(-k_1t)	0.9407	0.03522	0.1877	a= 26.04, k_0= 0.876, b=0.9013, k_1= 25.06
Wang and Singh	MR=1+at+bt^2	0.9679	0.01904	0.07967	a= 0.3183, b=0.0176

CONCLUSIONS

Drying characteristics of chilly leaf in open air in a solar dryer was investigated. Constant rate period was absent in the drying curves and most of the drying occurred during the falling rate period. Drying rate was more and moisture content was less as the temperature of the drying air increased. Drying data obtained were fitted to four drying models and goodness of fit is determined using different statistical parameters. Due to random variation of atmospheric conditions experimental data was subjected to fine errors.

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