THIN LAYER DRYING CHARACTERISTICS OF CURRY LEAVES (*MURRAYA KOENIGII*) IN AN INDIRECT SOLAR DRYER

by

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In this work, the thin layer drying characteristics of curry leaves (Murraya koenigii) has been studied in an indirect forced convection solar dryer with constant air mass flow rate of 0.0636 kg/s. Twelve thin layer drying models were tested for its suitability to describe the drying characteristics of curry leaves. The dryer has reduced the initial moisture content of curry leaves from 67.3% (wet basis) to the final moisture content of 4.75% (wet basis) in 3.5 hours. The pickup efficiency of indirect solar dryer for drying curry leaves was varied between 4.9% and 23.02%. Based on the statistical parameters, the Modified Henderson and Pabis model and Wang and Singh model were selected for predicting the drying characteristics of curry leaves. The payback period for the solar dryer was evaluated as 8 months, which is found to be much lower when compared with the entire life span of 15 years. The payback evaluation confirms that the solar dryer is economically viable in rural applications.

Key words: *thin-layer drying, curry leaves, indirect solar dryer, drying models, simple payback period*

Introduction

The curry tree is cultivated throughout India, Burma, Australia, the Andaman Islands, Ceylon, China, and Pacific Islands [1]. The curry leaves contain high level of minerals, vitamins, carbohydrates, proteins, antioxidants, plant sterols, amino acids, glycosides, and flavanoids with medical values [2-5]. Drying of curry leaves is considered as an important process as it plays a significant role in preservation and retention of nutritional and sensorial values. In an earlier investigation, Sakhale *et al.* [6] reported that the retention of nutrients like ascorbic acid, calcium, and iron was better in tray drying when compared with sun and shade drying methods. Moreover, the solar drying technology is an attractive energy efficiency option for processing the vegetables and fruits under hygienic conditions to maintain high quality with minimum energy consumption [7]. The indirect forced convection solar dryers have advantageous features such as, consistent drying rate, high thermal efficiency, and producing good quality product compared to other drying modes [8]. Hence, forced convection

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solar dryer was selected to investigate the drying characteristics of curry leaves. The thin layer drying equations are used to describe the drying characteristics of the product. They are used to estimate the drying periods of the products and to generalize drying curves [9]. Several researchers have used the thin layer drying models to explain the drying kinetics of the products such as thymus [10], mint leaves, nettle leaves [11], celery leaves [12], coriander leaves [13], and spinach [14]. No literatures were found on thin layer drying characteristics of curry leaves under indirect solar drying. The main objectives of this work are: (1) to study the drying characteristics of curry leaves in a indirect solar dryer, (2) model the thin layer drying of curry leaves by fitting 12 mathematical drying models and selecting the suitable mathematical model, and (3) economic evaluation using simple payback method.

Materials and methods

The solar dryer is installed at Solar Energy Research Centre in Coimbatore Institute of Engineering and Technology, Coimbatore (latitude of 11.0183° N; longitude of 76.9725° E).

Description of the indirect solar dryer

The experimental set-up consists of a 0.4 kW centrifugal blower, solar air heater with a provision of holding heat storage materials and a drying chamber. The dimension of the solar flat plate collector is 2 m length, 1 m width, and 0.10 m depth with the absorber area of 2 m^2. A tempered glass of 4 mm thickness was placed on the top of the solar flat collector to produce green-house effect. A corrugated absorber plate of 1.2 mm thickness (coated with black paint to increase the absorbsivity) was placed 30 mm below the glass cover for harvesting the solar energy. The bottom surface of the absorber plate was insulated with glass wool of 50 mm thickness to reduce the convective and conductive losses at the bottom side of the absorber plate. The dimensions of the drying chamber are 0.75 × 0.75 m and depth 1.05 m and it has been designed with four trays for placing the products and the distance between each tray is 200 mm. The tray was made of aluminum screen with 90% porosity. A divergent section was provided at the entry of the solar air heater to provide uniform air circulation over the absorber surface. Pebbles of uniform size were filled to height of 60 mm in the air passage to store the thermal energy and to maintain the consistent outlet temperature of air. The schematic arrangement of the solar dryer is shown in fig.1.

Instruments

The experimental set-up, equipped with suitable measuring instruments for the performance study of drying of curry leaves, consists of a blower and a control valve to vary the air flow rate to the collector. Eight calibrated *k* type thermocouples (chromel/alumel) with an accuracy of ±0.5 °C were fixed at various locations of the solar dryer and they were connected with a digital indicator with a resolution of 0.1 °C. The relative humidity of the air is measured using a thermo-hygrometer using a probe with digital display having an accuracy of ±2% and resolution of 0.01%. The mass flow rate of air measured using a U-tube manometer with the accuracy of 0.1%. Solar irradiance of was measured using TES make solar power meter with 0-2000 W/m^2 range and an accuracy of ±10 W/m^2. A digital electronic balance of 1 kg capacity having an accuracy of 0.001 g was used to weigh the samples.

Experimental procedure

Fresh curry leaves (*Murraya koenigii*) were purchased from the local market in Coimbatore, India. The immature and discoloured leaves were discarded. The leaves with

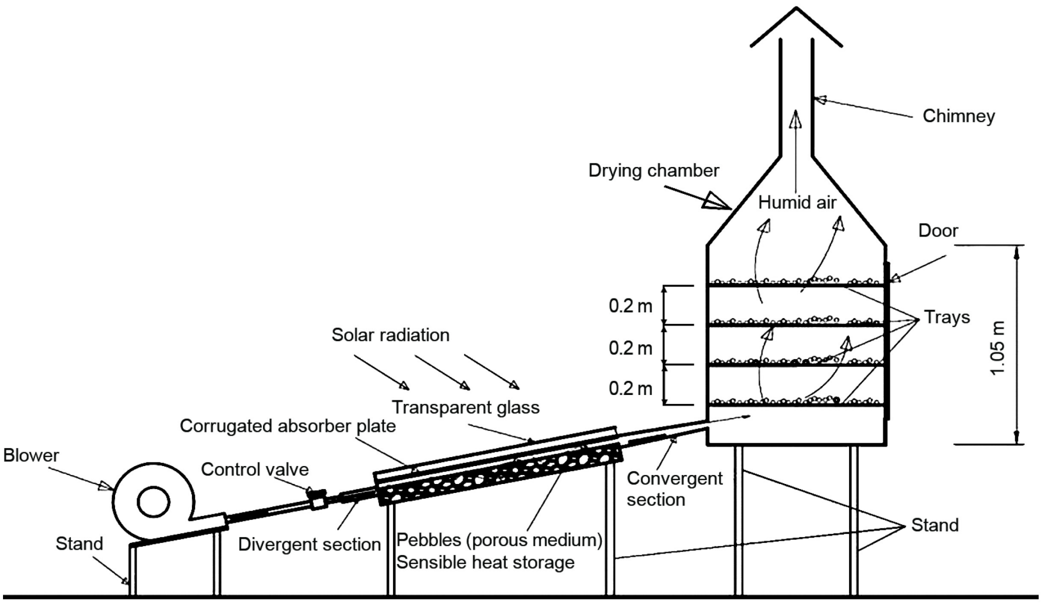

Figure 1. Schematic diagram of the experimental set-up

uniform size and green coloured were only selected for the drying experiments. The air mass flow rate was adjusted for an optimal of 0.0636 kg/s. Five trial experiments were conducted during sunny days (February 20-24, 2016) with minimum fluctuations in sunshine to test the consistency of drying characteristics.

Analysis of drying characteristics

The initial moisture content of vegetables and fruits is usually determined on wet basis (w.b) using eq. (1):

$$M_{\mathrm{i}} = \frac{W_o - W_{\mathrm{d}}}{W_o} \cdot 100 \tag{1}$$

The moisture ratio, MR, is determined:

$$MR = \frac{M_{\mathrm{t}} - M_{\mathrm{e}}}{M_{\mathrm{i}} - M_{\mathrm{e}}} \tag{2}$$

The equilibrium moisture content, M_{e}, is much smaller when compared to initial moisture content M_{i}, the previously mentioned equation can be further reduced:

$$MR = \frac{M_{\mathrm{t}}}{M_{\mathrm{i}}} \tag{3}$$

The drying of curry leaves can be found using:

$$DR = \frac{\mathrm{d}M}{\mathrm{d}t} = \frac{M_{\mathrm{t}+\Delta t} - M_{\mathrm{t}}}{\Delta t} \tag{4}$$

The pick-up efficiency of solar dryer is another important parameter for evaluating the performance of the system. It is a parameter which determines the evaporative capacity of the drying chamber. The pick-up efficiency can be calculated:

$$\eta_{\text{pickup}} = \frac{h_o - h_i}{h_{\text{as}} - h_i} = \frac{W_o - W_{\text{t}}}{m_{\text{a}} t (h_{\text{as}} - h_i)} \tag{5}$$

For selecting the suitable model describing the thin layer drying process of curry leaves twelve commonly used drying models given in tab. 1 were analyzed. The experimental values were fitted to the drying models using non-linear regression analysis in SPSS 20.0 software. In the selection process, the correlation coefficient (R^2) and reduced chi-square χ^2 were used to determine the quality of fit. The criterion for goodness of fit is the higher value of R^2 and the lower value of χ^2.

The reduced chi-square, χ^2, can be calculated:

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

where $MR_{\text{exp,i}}$ is the i^{th} experimental moisture ratio calculated using eq. (3), $MR_{\text{pre,i}}$ – the i^{th} predicted moisture ratio using drying model, N – the number of observations, and n – the number of a model's constants.

Table 1. Drying models [8, 10]

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	$MR = a \exp(-k_0 t) + b \exp(-k_1 t)$
Two term exponential	$MR = a \exp(-kt) + (1 - a) \exp(-kat)$
Diffusion approach	$MR = a \exp(-kt) + (1 - a) \exp(-kbt)$
Modified Henderson and Pabis	$MR = a \exp(-kt) + b \exp(-gt) + c \exp(-ht)$
Verma *et al.*	$MR = a \exp(-kt) + (1 - a) \exp(-gt)$
Wang and Singh	$MR = 1 + at + bt^2$
Midilli and Kucuk	$MR = a \exp(-kt^n) + bt$

Experimental uncertainty

Experimental uncertainty analysis is performed to determine the errors or uncertainty associated with the experimental data, which explains the accuracy of the study. In this experimental study the parameters measured are temperature, relative humidity, solar irradiance, weight of the product and mass flow rate of air. The uncertainty values in measured and calculated parameters can be determined using the equation mentioned by Holman [15]:

$$w_R = \sqrt{\left(\frac{\partial R}{\partial x_1} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \ldots + \left(\frac{\partial R}{\partial x_n} w_n\right)^2} \tag{7}$$

The calculated uncertainty values for the mass flow rate, pick-up efficiency and drying rate are 2.21%, 2.33%, and 4.7%.

Results and discussions

The variation of solar intensity, ambient temperature, collector inlet and outlet temperatures of the day of drying experiments are shown in fig. 2. The solar intensity reaches its maximum value of 918 W/m^2 at 1.30 p. m. and varies in the range from 186 to 918 W/m^2. The average solar intensity records 600 W/m^2. The ambient temperature varies from 29 to 36 °C. The collector inlet temperature was slightly higher than the ambient temperature due to blower work and the temperature varies from 30 to 41 °C. The maximum collector outlet temperature observed was 59 °C at 1.00 p. m. and the corresponding solar intensity was 903 W/m^2. The increase in temperature during morning period observed as very low because of thermal energy storage medium. The energy storage medium plays a significant role in maintaining the consistent temperature by storing the excessive heat in peak sun shine hours and releasing the same in less or no shine hours.

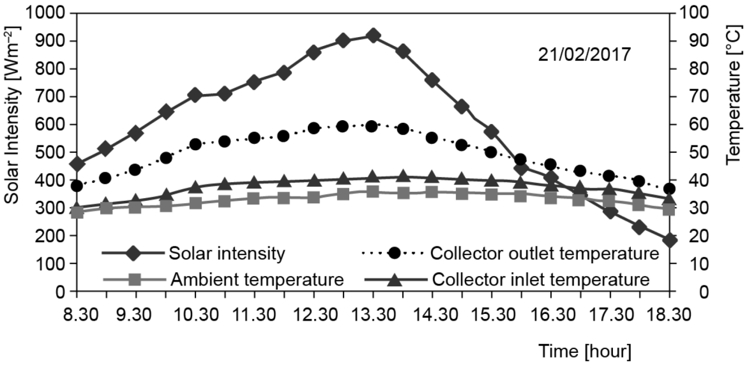

Figure 2. Variation of solar intensity, ambient, collector inlet and outlet temperatures in solar dryer

The initial moisture content of the curry leaves considered in the experimental study was about 67.3% in wet basis. It has been reduced to 4.75% (w.b) and 5.33% in 3.5 hours and 5 hours, respectively, in indirect solar dryer and open sun drying. This moisture content (w.b) was considered as equilibrium moisture content of curry leaves because the drying was continued till 6.30 p. m. but there is no considerable reduction in weight. The variation of moisture content and the moisture ratio of curry leaves during the drying are depicted in figs. 3 and 4 and seen that the moisture content decreases exponentially with the drying time. The drying curve begins with the falling rate period; it means that the constant drying period is not there in drying of curry leaves. The variation of drying rate with the moisture content for solar drying and open sun drying are shown in fig. 5. The graph shows that the rate of drying in solar dryer is faster than open sun drying. It is obvious that the temperature inside the drying chamber is always higher than that of ambient temperature. The drying of open sun drying exhibits fluctuation in drying rate due to the dependency of solar intensity whereas for indirect solar

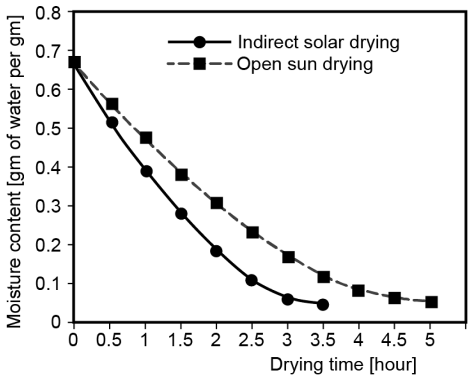

Figure 3. Variation of moisture content (w.b) of curry leaves during drying time

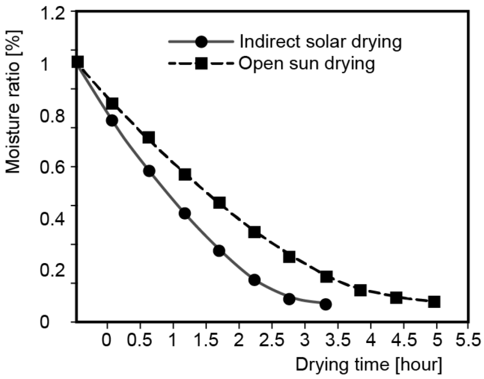

Figure 4. Variation of moisture ratio (*MR*) of curry leaves during drying time

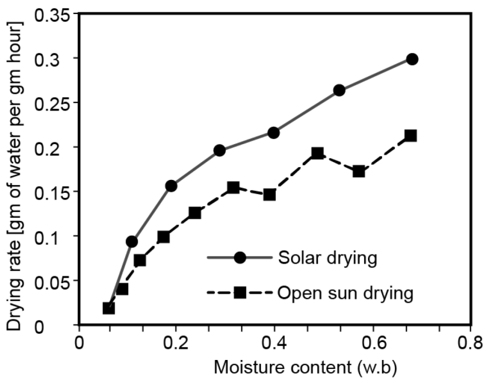

Figure 5. Variation of drying rate of curry leaves with moisture content (w.b)

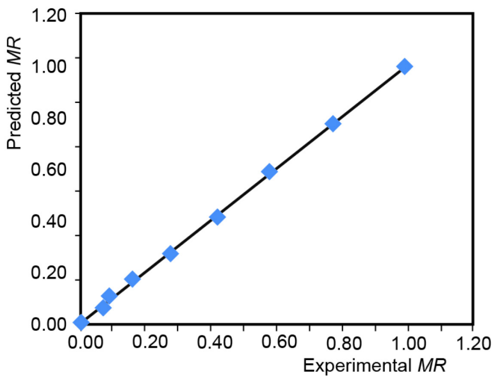

Figure 6. Comparison of experimental and Predicted *MR* for indirect solar drying

dryer, drying rate of curry leaves decreased considerably as the moisture content decreases. It is very clear that the increase in drying rate reduces the duration of drying of curry leaves, but high temperature may spoil the quality of the dried products.

Pick-up efficiency of the solar dryer for drying curry leaves varies from 4.9% to 23.02% and the average pick-up efficiency was observed as 13.34%. During the initial period of drying the pick-up efficiency has the maximum value and over the period it gradually reduces, it is obvious that the content of the product decreases.

The statistical parameters used for selecting the best suitable models are correlation coefficient, R^2, and reduced chi-square, χ^2). All the models considered are satisfactorily describing the thin layer characteristics of curry leaves. Based on the statistical parameters (R^2 = 0.999337, χ^2 = 0.000108) the modified Henderson and Pabis model was selected as best suitable model to describe the thin layer drying characteristics of curry leaves in indirect solar dryer. The statistical results of different drying models for indirect solar drying are indicated in tab. 2.

In order to confirm the selected models, the experimental moisture ratio, *MR*, values are compared with predicted moisture ratio graphically and they are shown in fig. 6. It clearly indicates that the values are banding around 45° inclined line. It means that the selected models are well suitable to describe the thin layer drying behaviour of curry leaves under indirect solar drying.

Table 2. Statistical results of different drying models and their constants and coefficients for indirect solar drying

Model	Model constants	R^2	χ^2
Newton	k = 0.63519	0.982601	0.001994
Page	k = 0.54384, n = 1.28234	0.998022	0.000268
Modified page	k = 0.62189, n = 1.282	0.998021	0.000268
Henderson and Pabis	k = 0.66055, a = 1.04003	0.984369	0.001960
Logarithmic	k = 0.44483, a = 1.23219, c = –0.2200	0.996782	0.000522
Two term	a = –130.610, k_0 = 0.27724, b = 131.6211 k_1 = 0.279212	0.997196	0.000569
Two term exponential	a = 1.82032, k = 0.90855	0.997475	0.000337
Diffusion approach	k = 1.142779, a = 57.158940, b = 1.012799	0.997951	0.000330
Modified Henderson and Pabis	**a = –305.8954, k = 1.650191, g = 1.7100745 b = 192.68815, c = 114.207499, h = 1.540235**	**0.999337**	**0.000108**
Verma *et al.*	a = 76.13808, k = 1.144588, g = 1.155546	0.997951	0.000330
Wang and Singh	a = –0.48465, b = 0.0615	0.999124	0.000117
Midilli and Kucuk	a = 0.99560, k = 0.52433, n = 1.22798 b = –0.0094528	0.998461	0.000312

Economic analysis of solar dryer

Economics of solar dryer is considered as a significant parameter as it directly involves with the financial aspects of commercial applications. The payback period is defined as the minimum period of operation required to recover the capital investment of the system and lesser period is suggested for increasing the acceptability among the rural areas.

The cost of dried products per year, P, can be calculated:

$$\mathrm{P} = \mathrm{C_r} + \mathrm{C_o} + \mathrm{C_m} + \mathrm{L_w} + \mathrm{P_k} \tag{8}$$

The costs involved are cost of the raw material per year, C_r, operational cost, C_o, maintenance cost, C_m, labour cost, L_w, and packaging charge of the dried products, P_k. The operational cost per year or annual running cost is the electricity charges for blower and it is calculated as

$$\mathrm{C_o} = \mathrm{R} \cdot \mathrm{W} \cdot \mathrm{C_e} \tag{9}$$

where R is the number of hours the blower run each year, W – the rated power consumption of blower, and C_e – the unit charge for electricity.

The net profit can be calculated:

$$P_r = P_s - P \tag{10}$$

The simple payback period of solar dryer can be calculated:

$$P_b = \frac{C}{P_r} \tag{11}$$

where P_b is the payback period in years, C – the capital cost of solar dryer in rupees, and P_r – net profit per year.

From the economic analysis, simple payback period obtained is of 8 months which is much lower when compared with the life span of solar dryer. Hence the solar dryer can be economically viable for rural applications (tab. 3).

Table 3. Cost and economic parameters of solar dryer

(a) Fixed capital	C	Rs. 40,000/-
(b) Working capital per year		
1. Raw material cost, Rs 70/kg for 700 kgs	C_r	Rs. 49,000/-
2. Annual running cost, Rs.5/kWh	C_o	Rs. 3,000/-
3. Maintenance and repair cost per year 3% of capital cost	C_m	Rs. 4,000/-
4. Labour and processing cost (Rs. 50/- per day for 250 days)	L_w	Rs. 12,500/-
5. Packaging charge	P_k	Rs. 3,000/-
(c) Dried product selling price (Rs.500/- per kg for 262 kg)	P_s	Rs. 1,31,000/-
(d) Net profit per year	P_r	Rs. 59,500/-
Simple payback period	P_b	8 months
Life of solar dryer		15 years
Loading capacity		2.8 kg per day
Number of working days		250 days

Conclusions

The thin layer drying characteristics of curry leaves in indirect solar dryer has been studied at the mass flow rate of air as 0.0636 kg/s. The initial moisture content of curry leaves was reduced to 4.75% (w.b) from 67.3% (w.b) in 3.5 hours, but in open sun drying it took 5 hours. The drying of curry leaves has only falling rate period. The pickup efficiency of indirect solar dryer for drying curry leaves were estimated as in the range of 4.9% to 23.02%. Based on the statistical parameters, the Modified Henderson and Pabis model was selected as the suitable model to describe the thin layer drying characteristics of curry leaves as it gives the highest R^2, lowest χ^2 values. Simple payback period obtained is of 8 months which is much lower when compared with the life span of solar dryer. Hence the solar dryer can be economically viable for rural applications.

Nomenclature

C – capital cost of dryer, [INR]
C_e – electricity charge per kW, [INR]
C_o – operation cost, [INR]
C_m – maintenance cost, [INR]
C_r – raw material cost, [INR]
DR – drying rate, [gm of water per gm. hour]
h_{as} – adiabatic saturation humidity of air entering the chamber, [kg water per kg dry air]
h_i – absolute humidity of air entering the chamber, [kg water per kg dry air]
h_o – absolute humidity of air leaving the chamber, [kg water per kg dry air]
L_w – labour cost, [INR]
M_e – equilibrium moisture content on wet basis, [%]
M_i – initial moisture content on wet basis, [%]
M_t – moisture content at any time of drying on wet basis, [%]

MR – moisture ratio
MR_{exp} – experimental moisture ratio
MR_{pre} – predicted moisture ratio
m_a – mass flow rate of air, [kgs^{-1}]
N – number of observations
n – number of drying model constants
P – cost of dried product per year, [INR]
P_b – simple payback period
P_k – packing cost, [INR]
P_r – net profit, [INR]
P_s – selling price of dried product, [INR]
R – number blower run hours, [hour]
R^2 – correlation coefficient
t – time [hour]
W_d – weight of dry matter, [kg]
W_o – weight of sample at $t = 0$, [kg]
W_t – weight of sample at any time t, [kg]
W – power consumed by blower, [W]
w_R – uncertainty in result, [%]
$w_1, \dots w_n$ – uncertainty in independent variables $x_1, \dots x_n$

Greek symbols

$\eta_{pick-up}$ – pick-up efficiency, [%]
χ^2 – reduced chi square

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