Comparative study of solar drying characteristics and thin-layer mathematical modelling of mango and cluster beans in two types of solar driers

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Abstract: A solar drier is designed and developed using evacuated tube collector. The performance of the drier is investigated using mango slices and cluster beans in Thanjavur, Tamilnadu, India. A comparison is also done with another solar drier assisted with flat plate collector. The time taken by solar driers assisted with evacuated tube collector and flat plate collector are 5 hours and 12 hours respectively to reduce the moisture content of mango slices from 78% (wb) to 8.5% (wb). Similarly, the time taken by solar driers assisted with evacuated tube collector and flat plate collector are 9 hours and 13 hours respectively to reduce the moisture content of cluster beans from 85.8% (wb) to 8.9% (wb). The efficiency of the solar drier assisted with evacuated tube collector is observed to be 51.45% and 41.9% for mango and cluster beans respectively. The efficiency of the solar drier assisted with flat plate collector is found to be 30.68% and 32.26% for mango and cluster beans respectively. Eight thin-layer mathematical models are applied to investigate the most suitable model that could explain the drying kinetics of mango slices and cluster beans separately for both the solar driers using IBM SPSS 20 statistical package. From the results it is observed that model developed by Midilli et al having highest correlation coefficient (R^2), lowest reduced chi-square (χ^2) value and lowest root mean square error (RMSE) value shows a good fit for both the driers for mango slices and for cluster beans.

Keywords: efficiency, evacuated tube collector, flat plate collector, mathematical model, moisture content, solar drier

1. INTRODUCTION

Food processing and preservation plays an important role in stimulating the economic growth of a country like India as agriculture is considered to be the main source of Indian economy.

Most of the agricultural products grown are seasonal [1]. Agricultural products, if left as such will biologically degrade [2]. Preservation plays a vital role as it can minimize the loss of the produce. Though there are different types of preservation techniques, drying is found to be the most efficient method that can yield more profit to the farmers. Drying is an important post harvest preservation technique which brings the produce to desire moisture content and increase the shelf-life for a long longer duration [3]. The produce is thus made available throughout the year and yield high market value during demand [4].

The different types of drying techniques are sun drying, mechanical drying, solar drying and solar hybrid drying [5-10]. Sun drying is the conventional and traditional method used in sub-tropical countries like India [11]. But, the quality of the produce is very poor due to contamination resulting from infestation with dust, insect and pathogenic bacteria as well as uncontrolled drying [12, 13]. The sun dried produce could not meet the basic quality standards required for export. On the other hand, mechanical driers mainly depend on electricity. But energy reserves are depleting at a rapid rate [14]. Also the driers are not economical. Hence, solar driers are considered to be the best way to eliminate these problems and help the farmers to secure a great economic return.

Solar driers require solar collectors to trap solar radiation. From the literature it is observed that most of the available solar driers make use of Flat Plate Collector (FPC) [15-17]. But the performance of Evacuated Tube Collector (ETC) is better as compared to FPC in terms of efficiency [18]. It is also observed that only very few studies have been carried out on solar driers with ETC [19-21].

Research studies on drying characteristics of agricultural products such as grapes [22-25], ginger [26], pork strips [27], tomato [28], rice [29], cassava [30], chilli pepper [31], onion [32] and prickly pear cladode [33] have been reported in literature. It is observed that no study has been reported so far on drying characteristics of mango and cluster beans in solar driers assisted with ETC.

In the present study, we have made an attempt to design a novel solar drier assisted with ETC and compare its performance with the available solar drier assisted with FPC using mango and cluster beans in

Thanjavur District, Tamilnadu, India. Also, the dying characteristics of mango and cluster beans are studied by employing thin-layer drying equations and the suitable mathematical model is chosen for both the solar driers (ETC assisted and FPC assisted).

2. MATERIALS AND METHOD

Two solar driers are used in the present study. One solar drier makes use of ETC as air heater while the other solar drier makes use of FPC as air heater. The performance of both the driers is investigated with the help of mango slices and cluster beans. The experiment was performed in the month of June and July, 2013 in Thanjavur District, Tamilnadu, India between 9.00 a.m. to 5.00 p.m. According to the latitude of Thanjavur District (10º45'N), the collectors (ETC & FPC) are oriented South to 25º45' with respect to horizontal to make certain that it transmits maximum solar radiation into the collector. The initial moisture content of mango slices and cluster beans are determined using hot-air oven, keeping the sample at 105ºC for 24 hours.

2.1 Evacuated Tube Collector (ETC) Assisted Solar Drier

This drier basically consists of ETC to heat the air, an electric driven motor to force the air into the collector, drying chamber with aluminium perforated trays to place the sample to be dried and a vent to escape the moist air present in the chamber into the surrounding. The schematic diagram of the drier is shown in Fig. 1 [34].

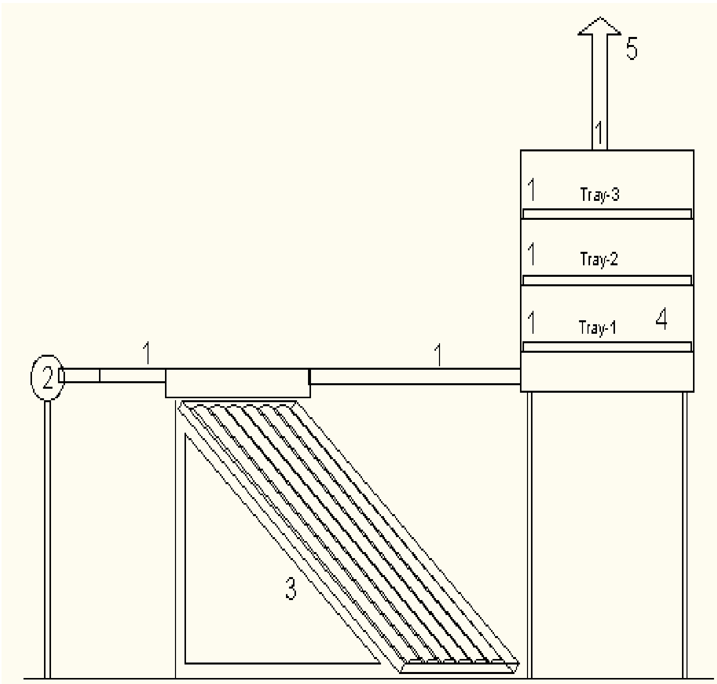

Fig. 1 Design of the solar drier with ETC (1, temperature sensor; 2, electric driven motor 3, ETC - evacuated tube collector; 4, drying chamber; 5, vent) [34]

Six ETCs are used in this drier. ETC has two tubes made of borosilicate glass. The inner tube is coated with absorbent material. The space between the twin glasses in ETC is evacuated which enables to cut the heat loss to a maximum level. This collector makes use of sun's light energy to convert into heat. So the performance of ETC is better even during cloudy days. An electrical driven centrifugal motor is used to force air into the collector. A regulator fitted in the motor helps to control and adjust the flow of air. Stainless steel framed chamber is shielded with rock wool insulation on all the sides to avoid heat loss. As the chamber is insulated on all the sides solar radiation cannot fall on the sample directly. This helps in enriching the quality of the dried sample. Based on the convective principle that warm air always move up, a vent is fitted on the top of the drying chamber which enhances the air flow inside the drier.

2.2 Flat Plate Collector (FPC) Assisted Solar Drier

This drier basically consists of a chamber with aluminium meshed drying tray, an electric motor driven fan and FPC. The schematic diagram of the drier is shown in Fig. 2.

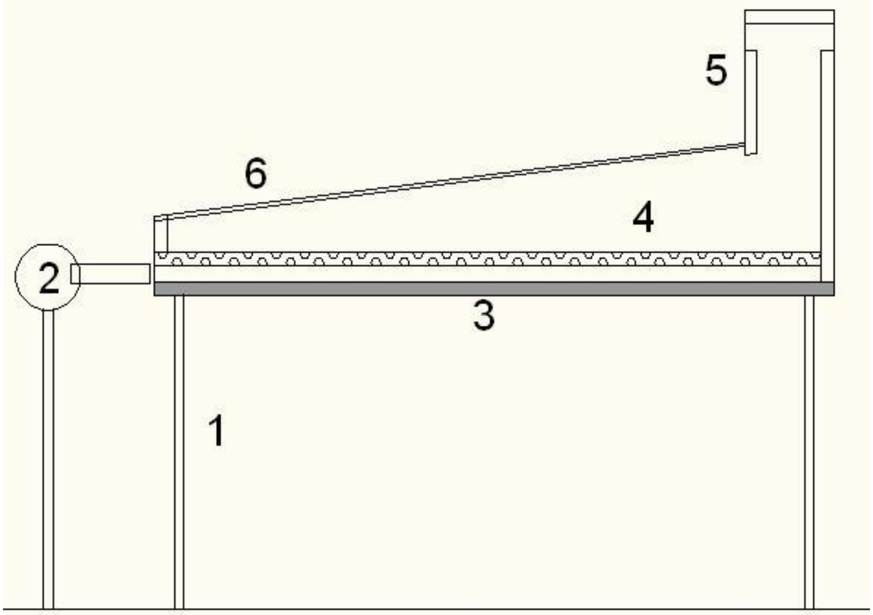

Fig. 2 Design of the solar drier with FPC (1, elevated stand; 2, electric motor driven fan; 3, absorber plate of FPC; 4, drying tray; 5, air vent; 6, transparent glass cover)

The interior of flat plate collector is painted black to absorb the incoming solar radiation. The frame is made of metal. The drying tray is placed above the absorber plate with air gap between the absorber plate and the drying tray. It is insulated on all the sides except top with fibre to reduce heat loss. It is covered with a transparent glass sheet on the top through which the sunlight falls on the product directly. Also the short-wave radiation received from the sun is absorbed by the absorber plate and gets converted to long-wave radiation which cannot escape through the transparent glass sheet. Air flow inside the collector is increased with the help of electric motor driven fan connected to one side of the collector. The sample placed on the tray utilizes the heat to remove the moisture present in it and gets dried. The moist air is removed with the help of the vent in the chamber.

2.3 Measuring Devices

A digital electronic balance (D-sonic make; $\pm$0.1g accuracy) is utilized to find out the mass of the sample. MASTECH MS6252B digital anemometer is utilized to find the wind velocity, relative humidity and ambient temperature. Temperature at various locations is measured using ordinary mercury thermometer (110ºC) and Resistance Temperature Detector Platinum 100 (RTD Pt100) sensors connected to a temperature controller and digital display unit. The solar radiation at the place where the drier is located is noted using a sun meter (TES 1333) [34].

2.4 Experimental Procedure

In both the driers equal quantity of fresh samples (mango slices and cluster beans) are uniformly spread on the trays present inside the chamber. The hot air from the collector removes the moisture in the sample and hence the mass of the samples reduces as time increases. During the experimental period the mass of the sample, relative humidity, wind velocity and temperature at various locations such as collector inlet, collector outlet, inside the chamber and chimney outlet are measured every hour. The experiment is performed from 9.00 a.m. to 5.00 p.m. every day. Drying of the sample is done until it reaches the equilibrium moisture content which is considered as safe moisture content for long shelf-life. The samples are stored in air-tight packets to avoid adsorption of moisture from the surroundings during night hours (5.00 p.m. to next day 9.00 a.m.)

2.5 Drying Kinetics

To learn the drying kinetics of the samples (mango slice and cluster bean) thin-layer mathematical model equations are used and the most suitable model is chosen for both the driers (ETC assisted and FPC assisted).

Moisture content present in the sample (wet basis) is evaluated using [31]

$$M_{wb} = \frac{m_i - m_f}{m_i} \quad (1)$$

Where, m_i and m_f are the initial and final mass of the sample, respectively.
The moisture ratio (MR) of the sample is computed using the equation [8], [21], [27], [28], [31], [33]

$$MR = \frac{M - M_e}{M_0 - M_e} \quad (2)$$

Where, M_e, M_0 and M are equilibrium moisture content of the sample, initial moisture content of the sample and moisture content of the sample at any time, respectively. As equilibrium moisture content M_e is negligible, the expression for moisture ratio is simplified as [8], [21]

$$MR = \frac{M}{M_0} \quad (3)$$

Mathematical models used in the present study to observe the drying kinetics of mango slices and cluster beans are given in Table1.

Table1. Different mathematical models applied for solar drying of mango slices and cluster beans. [8], [21], [23], [27], [28], [31-33]

Model Name	Model Equation
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 exponential	MR = a exp (-kt) + (1- a) exp (-kat)
Wang and Singh	MR = 1 + at + bt^2
Midilli et al	MR = a exp ($-kt^n$) + bt

Where k, n, a, c and b are drying constants and t is the drying time. Using equation (3) the experimental moisture ratio (MR) is determined and is fitted to the above eight mathematical models. The various constants and coefficients of the model are predicted by non-linear regression analysis using IBM SPSS 20 statistical package. The correlation coefficient (R^2), reduced chi-square (χ^2) and root mean square error (RMSE) are evaluated using the following expressions [8], [27], [28], [31-33].

$$R^2 = \frac{\sum_{i=1}^{N}(MR_{exp,i} - \overline{MR}_{\exp})(MR_{pre,i} - \overline{MR}_{pre})}{\sqrt{\sum_{i=1}^{N}(MR_{exp,i} - \overline{MR}_{\exp})^2 \sum_{i=1}^{N}(MR_{pre,i} - \overline{MR}_{pre})^2}} \quad (4)$$

$$\chi 2 = \frac{\sum_{i=1}^{N}(MR_{exp,i} - MR_{pre,i})^2}{N - n} \quad (5)$$

$$RMSE = \left[\frac{1}{N}\left(\Sigma_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2\right)\right]^{\frac{1}{2}} \quad (6)$$

Where, N and n are the number of observations and number of constants in the equation respectively, $MR_{exp,i}$ and $MR_{pre,i}$ are the ith experimental and predicted moisture ratio respectively, $\overline{MR}_{\exp}$ and $\overline{MR}_{pre}$ are the mean of sum of $MR_{exp,i}$ and $MR_{pre,i}$ respectively.

The most relevant model for drying is considered to have highest correlation coefficient (R^2), lowest root mean square error (RMSE) and lowest reduced chi-square (χ^2) and is chosen accordingly for solar drying of mango slices and cluster beans **[**10], [19], [25-30].

3. RESULTS AND DISCUSSIONS

A novel solar drier is designed and developed using ETC and the performance of the drier is studied using mango slices and cluster beans. The performance of the drier is also compared with the available FPC assisted solar drier for which a series of drying experiment was performed in the month of June and July 2013 from 9.00 a.m. to 5.00 p.m. in Thanjavur district, Tamilnadu, India.

During the experimental period, solar insolation varied from 101.5W/m^2 to 818.8W/m^2 and 180.5W/m^2 to 726.2W/m^2 for mango and cluster bean drying experiments respectively. For mango and cluster bean drying experiments, the ambient temperature varied from 30.5ºC to 35.7ºC and 31ºC to 35.2ºC respectively whereas the temperature inside the drying chamber of ETC assisted solar drier varied from 61ºC to 104ºC and 62ºC to 103ºC respectively & the temperature of the drying chamber of FPC assisted solar drier varied from 42ºC to 81ºC and 40ºC to 72ºC respectively. The temperature inside the drying chamber is found to be very high than the corresponding ambient temperature in ETC assisted solar drier as compared to FPC assisted solar drier. Also the drying rate is rapid in ETC assisted solar drier than the FPC assisted solar drier.

A comparison of variation of moisture content with respect to drying time in the two driers is shown in Fig. 3 and Fig. 4 for mango slices and cluster beans respectively. It is also evident from the graph that rate of drying is faster initially and is found to decrease with increase in moisture removal.

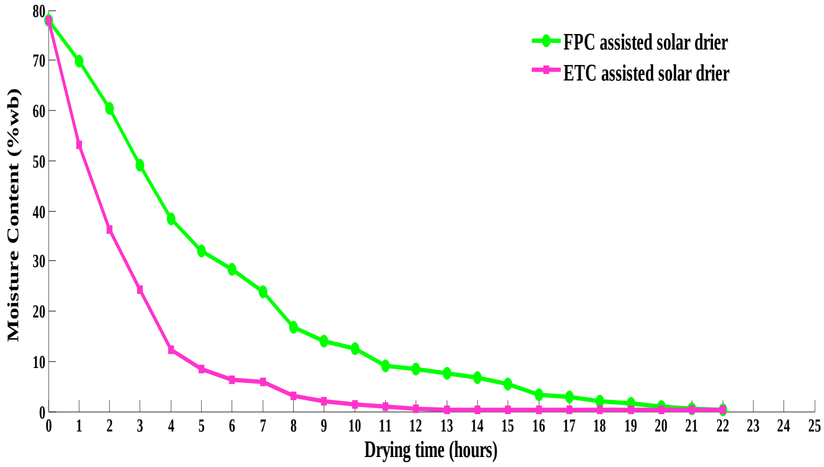

Fig. 3 Comparison of variation of moisture content (wb) of mango slices with respect to drying time in ETC assisted solar drier and FPC assisted solar drier

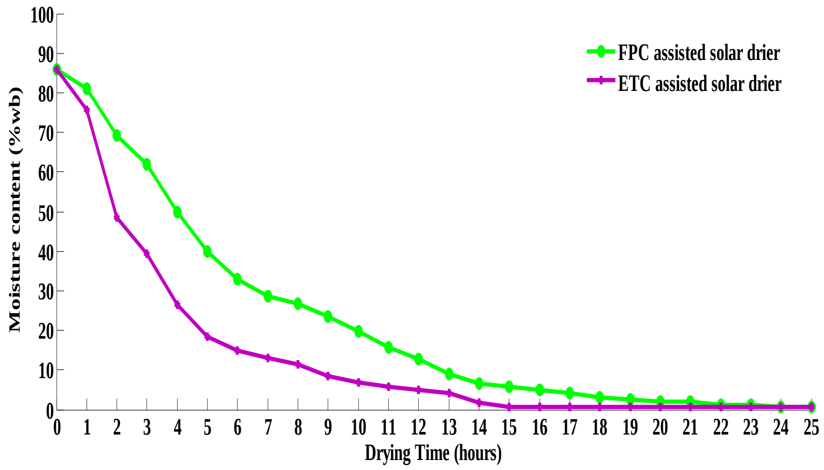

Fig. 4 Comparison of variation of moisture content (wb) of cluster beans with respect to drying time in ETC assisted solar drier and FPC assisted solar drier

For drying mango slices, ETC assisted solar drier takes 5 hours to reach safe moisture content of 8.5% (wb) from initial moisture content 78% (wb) whereas FPC assisted solar drier takes 12 hours to reach the same moisture content.

Cluster beans dried in ETC assisted solar drier and FPC assisted solar drier takes 9 hours and 13 hours respectively to reduce the initial moisture content from 85.8% (wb) to a final safe moisture content of 8.9% (wb).

Table 2. Results of different thin-layer mathematical models applied for solar drying of Mango slices in ETC assisted solar drier and FPC assisted solar drier.

Model	Drying constants	R^2	Reduced χ^2	RMSE
Solar drying of Mango slices in ETC assisted solar drier				
Newton	k = 0.176	0.997	0.00026	0.01555
Page	k = 0.132, n = 1.148	0.998	0.00022	0.01365
Modified Page	k = 0.172, n = 1.148	0.998	0.00022	0.01365
Henderson and Pabis	k = 0.185, a = 1.052	0.997	0.00027	0.01521
Logarithmic	k = 0.174, a = 1.063, c = -0.021	0.997	0.00029	0.01518
Two term exponential	k = - 0.006, a = -2.426	0.271	0.07236	0.24904
Wang and Singh	a = -0.119, b = 0.004	0.920	0.00795	0.08256
Midilli et al*	**k = 0.138, n = 1.138, a = 1.014, b = 0.000194**	**0.998**	**0.00022**	**0.01303**
Solar drying of Mango slices in FPC assisted solar drier				
Newton	k = 0.176	0.993	0.00067	0.02540
Page	k = 0.132, n = 1.148	0.998	0.00023	0.01457
Modified Page	k = 0.172, n = 1.148	0.998	0.00023	0.01457
Henderson and Pabis	k = 0.185, a = 1.052	0.995	0.00045	0.02029
Logarithmic	k = 0.174, a = 1.063, c = -0.021	0.996	0.00038	0.01822
Two term exponential	k = - 0.006, a = -2.426	0.592	0.03879	0.18821
Wang and Singh	a = -0.119, b = 0.004	0.975	0.00237	0.04651
Midilli et al*	**k = 0.138, n = 1.138, a = 1.014, b = 0.000194**	**0.998**	**0.00023**	**0.01403**
**Best fitting model*				

The efficiency of the ETC assisted solar drier and FPC assisted solar drier is found to be 51.45% and 30.68% respectively to dry mango slices & 41.90% and 32.26% respectively to dry cluster beans.

The experimental moisture ratio of mango and cluster beans is determined using equation (3). Eight thin layer mathematical models are applied for solar drying of mango slices and cluster beans in the solar driers assisted with ETC and FPC separately. The moisture ratio for mango and cluster beans are predicted for each model using nonlinear regression analysis with IBM SPSS 20 statistical package. The drying constants and coefficients of the drying models are also found out using IBM SPSS 20 statistical package. Model having highest correlation coefficient (R^2), lowest reduced chi-square (χ^2) and lowest root mean square (RMSE) is considered to be the most relevant model.

Table 2 shows the results obtained for different thin-layer mathematical models applied on solar drying of mango slices in ETC assisted solar drier and FPC assisted solar drier. Results show that except Two-term exponential model and Wang & Singh model, the value of R^2 for all other models applied on solar drying of mango slices range from 0.993 to 0.998 showing best fit of drying curves. Model developed by Midilli et al is found to be the most relevant model which has highest R^2 value of 0.998 for both the solar driers (ETC and FPC assisted). Midilli et al model is found to have lowest reduced chi-square value of 0.00022 and 0.00023 for ETC assisted solar drier and FPC assisted solar drier respectively. Also the model is found to have the lowest RMSE value of 0.01303 and 0.01403 for ETC assisted solar drier and FPC assisted solar drier respectively. Results obtained for Page model and Modified Page model are also in good agreement with the model as suggested by Midilli et al in the case of drying of mango slices.

Table 3. Results of different thin-layer mathematical models applied for solar drying of Cluster beans in ETC assisted solar drier and FPC assisted solar drier.

Model	**Drying constants**	**R^2**	**Reduced χ^2**	**RMSE**
Solar drying of Cluster beans in ETC assisted solar drier				
Newton	k = 0.268	0.986	0.00130	0.03493
Page	k = 0.240, n = 1.075	0.987	0.00127	0.03337
Modified Page	k = 0.265, n = 1.075	0.987	0.00127	0.03337
Henderson and Pabis	k = 0.279, a = 1.040	0.988	0.00122	0.03272
Logarithmic	k = 0.292, a = 1.032, c = 0.015	0.988	0.00126	0.03199
Two term exponential	k = - 0.009, a = -2.418	0.516	0.04861	0.20624
Wang and Singh	a = -0.179, b = 0.008	0.947	0.00531	0.06821
Midilli et al*	**k = 0.239, n = 1.136, a = 1.025, b = 0.0002**	**0.990**	**0.00114**	**0.02923**
Solar drying of Cluster beans in FPC assisted solar drier				
Newton	k = 0.152	0.986	0.00128	0.03516
Page	k = 0.097, n = 1.217	0.996	0.00036	0.01826
Modified Page	k = 0.147, n = 1.217	0.996	0.00036	0.01826
Henderson and Pabis	k = 0.163, a = 1.077	0.992	0.00080	0.02721
Logarithmic	k = 0.147, a = 1.096, c = -0.036	0.994	0.00059	0.02287
Two term exponential	k = - 0.005, a = -2.431	0.635	0.03592	0.18209
Wang and Singh	a = -0.104, b = 0.003	0.983	0.00164	0.03897
Midilli et al*	**k = 0.107, n = 1.180, a = 1.021, b = 0.000074**	**0.997**	**0.00036**	**0.01760**
**Best fitting model*				

Similarly, Table 3 shows the results obtained for different thin-layer mathematical models applied on solar drying of cluster beans in ETC assisted solar drier and FPC assisted solar drier. From the results, it is clear that the value of R^2 ranges from 0.983 to 0.997 showing good fit of drying curves for all models except Two-term exponential model and Wang & Singh model. Model developed by Midilli et al shows best results for drying of cluster beans in both the solar driers. ETC assisted and FPC assisted solar driers has highest R^2 value of 0.990 and 0.997 respectively, lowest reduced chi-square value of 0.00114 and 0.00036 respectively and lowest RMSE value of 0.02923 and 0.01760 respectively.

Fig. 5 to Fig. 8 indicate that the moisture ratio obtained by performing experiment in the solar driers assisted with ETC and FPC for both mango slices and cluster beans is in good agreement with the predicted moisture ratio for Midilli et al model obtained using statistical package IBM SPSS 20 package.

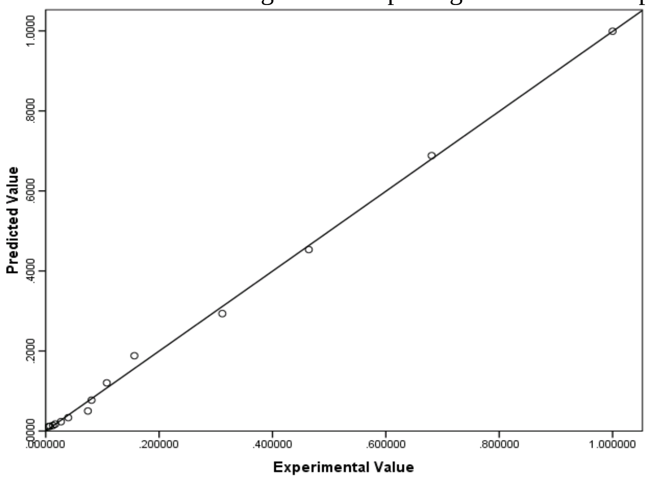

Fig. 5 Comparison between experimental and predicted moisture ratio for mango slice in ETC assisted solar drier using Midilli et al model

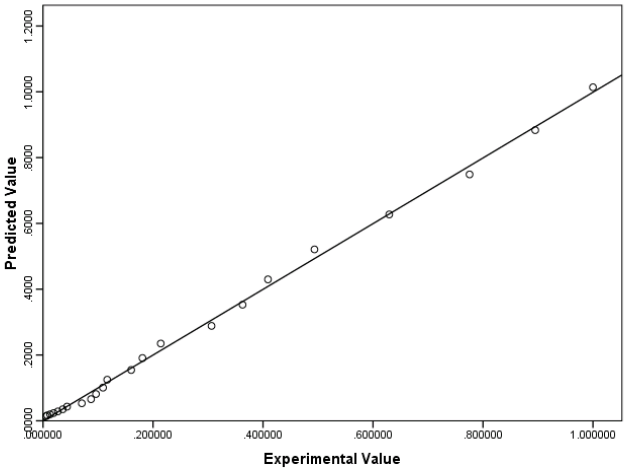

Fig. 6 Comparison between experimental and predicted moisture ratio for mango slice in FPC assisted solar drier using Midilli et al model

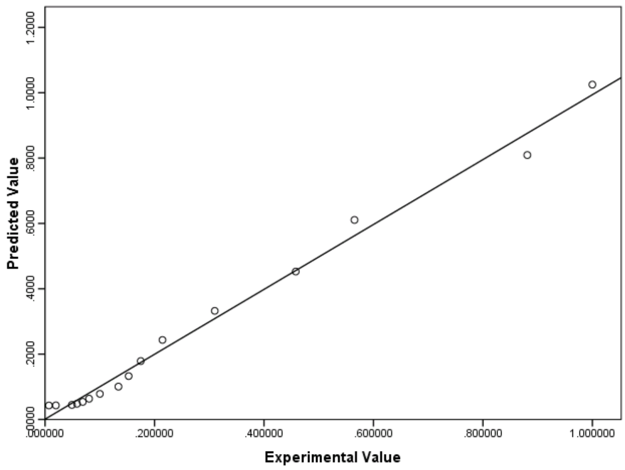

Fig. 7 Comparison between experimental and predicted moisture ratio for cluster beans in ETC assisted solar drier using Midilli et al model

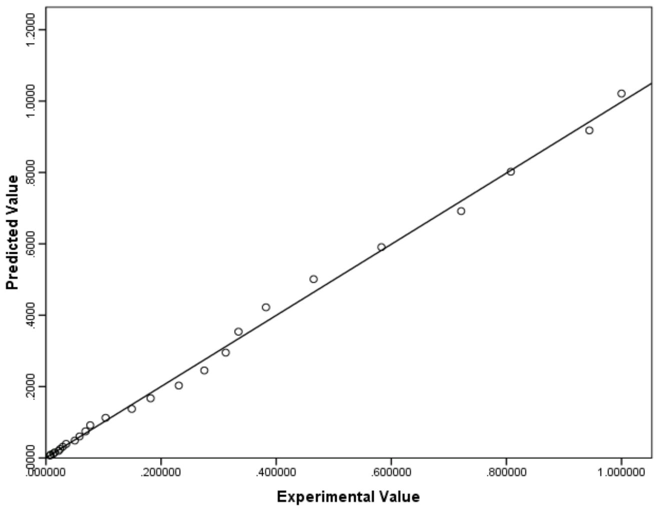

Fig. 8 Comparison between experimental and predicted moisture ratio for cluster beans in FPC assisted solar drier using Midilli et al model

4. CONCLUSION

A novel solar drier has been designed and developed using evacuated tube collector (ETC). The performance of the designed drier is compared with the existing Flat Plate Collector (FPC) assisted solar drier. Drying of mango slices and cluster beans are carried out in both the solar driers under the climatic conditions of Thanjavur, India. The efficiency of the designed solar drier is much better than the efficiency of FPC assisted solar drier. Also, the drying time required by the sample to reach safe moisture content is reduced considerably in ETC assisted solar drier than the FPC assisted solar drier. The performance of ETC assisted solar drier is found to be good even in poor weather condition (cloudy) whereas the performance of FPC assisted solar drier is very poor in poor weather condition. The designed solar drier assisted with ETC can be used to dry large quantities of various agricultural products. The drying kinetics of mango slices and cluster beans are investigated for both the solar driers using IBM SPSS 20 statistical package. The results indicate that Midilli et al model having highest R^2 value, lowest reduced chi-square value and lowest RMSE value is the most relevant model compared to all other models to illustrate the drying characteristics of mango slices and cluster beans.

The proposed solar drier with ETC for drying agricultural products is found to be more satisfactory than the solar drier assisted with FPC.

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