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Mathematical Modelling and Techno-economic Evaluation of Hybrid Photovoltaic-thermal Forced Convection Solar Drying of Indian Jujube (*Zizyphus mauritiana)*

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ABSTRACT

Two identical units of a hybrid photovoltaic-thermal (PV/T) solar dryer designed and constructed at ICAR-Central Arid Zone Research Institute, Jodhpur, were used to dry Indian jujube (*Zizyphus mauritiana*) fruit, one operated under natural and the other under forced convection modes. The fruits were dried to safe moisture content (24 %) in a period of 192 h in forced convection mode, and in 240 h in natural convection mode with drying load of 18 kg. There was a significant difference in performance of the dryer under forced and natural convection mode. The average thermal efficiency of solar energy utilization under forced convection mode was higher (16.7 %) than that of natural convection solar dryer (15.6 %). Logarithmic drying model was suitable for describing the thin layer drying behaviour of the fruit. Effective moisture diffusivity of forced convection dryer was 3.34×10^{-7} $m^2.s^{-1}$. Economic evaluation of the solar dryer indicated high value of IRR (54.5 %), and low value of payback period (2.26 years), suggesting the dryer to be cost efficient.

Indian jujube (*Zizyphus mauritiana*) is also known as *ber*, desert apple or Indian plum. It belongs to the family Rhamnaceae, and is one of the most ancient cultivated fruit trees grown in north Indian plains, particularly Rajasthan, Punjab and Haryana. The total area under Indian jujube in India is more than 80,000 ha with an annual production of 9,00,000 tonne fruits (Sharma *et al.,* 2014). It is the only fruit crop which can give good returns under rain-fed condition, and can be grown in a variety of inferior soils and climatic conditions ranging from sub-tropical to tropical. It is a perennial hardy fruit tree which gives income to resource-deficient farmers from multiple products such as fruits, fodder and fuel wood even in severe drought conditions. It is both consumed fresh and dried for its high medicinal value. For two millennia Jujube fruit, seeds, leaf, skin and root have been used for remediation of fever (Beigi, 1997). The fruit is rich in nutrients, especially vitamin A, B, protein, calcium and phosphorus (Yi *et al.*, 2012). CAZRI Gola is the main species of commercial importance with its leaves (rich in protein) which provide fodder (Pala) for livestock is used for drying.

Short shelf-life (2-4 days under ambient conditions) and post-harvest rotting are the major problems of Indian jujube fruits, and is a major concern for its marketing (Sonkariya *et al.,* 2016). There has been limited post-harvest research on Indian jujube fruit in the past two to three decades, and the information is scattered in diverse local and regional sources, especially in India (Pareek and Yahia, 2013). Drying is practiced to enhance the storage life, to minimize losses during storage and to reduce transportation costs of agricultural products (Leon *et al.,* 2002). In India, 70 % people depend on agriculture, and most farmers are subsistence farmers with limited resource to afford hi-tech facilities and equipment. Direct sun drying has been practised since ancient time, and is still being widely used in developing countries (Eswara and Rao, 2013). Although this method of drying is cheap, yet it is associated with problems of contamination as well as uneven drying.

Production of Indian jujube is increasing in China as it has good food quality and is suitable for pharmaceutical applications (Li *et al.*, 2007; Das and Dutta, 2013). Having realized the importance of the crop, emphasis is being given in China on studies involving quality analysis for processing and preservation of the fruit. Direct sun drying involves long duration, which affects the quality of the product. In order to overcome these disadvantages, drying process can be replaced with solar energy or industrial drying method as hot air drying. Mechanical drying is mainly used in industrialized countries as an alternative to sun drying, and is not applicable to small farms in India due to high investment and operating costs. India is blessed with abundant solar energy. During the winter season (November to February), most of the Indian stations receive 4.0 $kW.h.m^{-2}.day^{-1}$ to 6.3 $kW.h.m^{-2}.day^{-1}$ solar irradiance, while in summer season it ranges from 5.0$kW.h.m^{-2}.day^{-1}$ to 7.4 $kW.h.m^{-2}.day^{-1}$. The arid and semi-arid regions of the country receive higher radiation of 6.0-7.4 $kW.h.m^{-2}.day^{-1}$ mean annual daily solar radiation having 8.9 average sunshine hours a day at Jodhpur, India (Pande *et al.,* 2009).

Solar drying has been identified as a promising alternative to sun drying for drying of fruit and vegetables in developing countries because of its minimal operational cost in terms of fuel cost (Purohit *et al.*, 2006; Poonia *et al.*, 2017).It is also a convenient alternative for the rural sector and other areas with scarce or irregular electricity supply. Studies conducted on solar drying have proved that it is a good alternative to sun drying for the production of high-quality dried products (Mahapatra and Imre, 1990; Sodha and Chandra, 1994; Ekechukwu and Norton, 1999; Hossain *et al.*, 2005).

Photovoltaic/thermal(PV/T)collector is a combination of photovoltaic (PV) and thermal (T) components, and enables to produce both electricity and heat simultaneously for forced air circulation and direct thermal drying, respectively. PV/T collectors produce more energy per unit surface area than side-by-side PV modules and solar thermal collectors (Zondag,2008). Headley (1997) provided an overview of renewable energy systems/technologies (e.g. solar crop drying, PV applications, etc.) in the Caribbean (Sankat *et al.,* 2010). Huang *et al.* (2001) reported that an integrated PV/T system is economically feasible. Tonui and Tripanagnostopoulos (2007) suggested some low-cost modifications techniques to enhance heat transfer to air stream in the air channel, and used both glazed and unglazed models to improve the performance of air-cooled PV/T solar collectors. Tiwari and Sodha (2006a) developed a thermal model of an integrated photovoltaic and thermal solar (IPVTS) system, and reported that the simulations predict a daily thermal efficiency of around 58 %, which was close to the experimental value (61.3 %) obtained by Huang *et al.* (2001). Barnwal and Tiwari (2008) conducted experimental studies on grape drying by using hybrid photovoltaic-thermal (PV/T) greenhouse dryer, and found that the heat transfer coefficient for grapes varied from 0.26 $W.m^{-2}.K^{-1}$ to 0.31$W.m^{-2}.K^{-1}$ and 0.34–0.40 $W.m^{-2}.K^{-1}$ for greenhouse drying and open sun drying, respectively. Tiwari *et al.* (2016) had developed a mathematical model of photovoltaic–thermal (PVT) mixed mode greenhouse solar dryer, and found that theoretical and experimental data with correlation coefficient value (r) and root mean square percentage deviation (e) were 0.92 and 4.64, 0.99 and 0.97, 0.99 and 0.96 for solar cell, greenhouse room and crop temperature, respectively. It was also found that payback period for the system was 1.23 and 10 years on the basis of overall thermal energy and overall energy basis, respectively.

Modelling of drying process is a valuable tool for prediction of performance of solar drying systems (Sacilik *et al.,* 2006). Thin layer drying model has been found to be most suitable for characterizing the drying parameters. Several researches on mathematical modelling and experimental studies had been conducted on thin layer drying processes of various agricultural products (Doymaz, 2005; Goyal *et al.*, 2007; Corzo *et al.*, 2008; Aghbashlo *et al.*, 2009; Arslan and Özcan, 2010; Kouchakzadeh and Shafeei, 2010; Zielinska and Markowski, 2010; Doymaz and Ismail, 2011). However, there is little information in the literature on thin layer solar drying process of Indian jujube fruit.

With the above in view, a solar dryer powered by a hybrid photovoltaic-thermal (PV/T) system under forced mode was designed and developed at the ICAR-Central Arid Zone Research Institute, Jodhpur, India for drying Indian jujube. An attempt was made to evaluate the drying characteristics of Indian jujube fruit and to fit four mathematical models for describing the thin-layer solar drying process of Indian jujube. Economic analyses of the hybrid photovoltaic-thermal (PV/T) forced convection dryer was carried out in order to assess the real-time possibilities for its use.

MATERIALS AND METHODS

Design of Solar Dryer

A photovoltaic thermal (PV/T) hybrid forced convection solar dryer was designed and fabricated during the year 2016 at the ICAR-Central Arid Zone Research Institute, Jodhpur. The hybrid system was designed to enable combined production of electric energy and thermal energy from the photovoltaic panel and flat-plate collector.

The dryer consisted of a collector unit, drying chamber, DC fan, PV panel and PCM chamber for thermal storage. The PV module (glass to glass; dimension: 530 mm × 340 mm ×28 mm; 12V-20Wp) was provided at left side of the solar collector (glass 4 mm thick). The PV module produces DC electrical power to operate a 10 W DC fan for forced mode operation of the dryer. The dryer (1250 mm × 850 mm× 630 mm) was made of galvanised steel sheet (22 gauge), and consisted of four drying trays. The dimension of two drying trays made of stainless steel angle frame and stainless steel wire mesh was 0.84 m × 0.60 m, and that of another two half-trays were 0.40 m ×0.60 m. Drying material could be kept on the four perforated trays, and placed on an angle iron frame in the dryer through an openable door provided on the rear side of the dryer. A clear window glass (1219 mm × 914 mm) of 4 mm thickness was provided at the top of the box. The area of the collector for the dryer was 1.06 m^2 (Fig. 1). Six PVC plastic pipes (ID = 15.8 mm, OD =21.3 mm) were fixed on the back wall of the dryer just below the trays to introduce fresh air at the base. Actual installation of the photovoltaic thermal (PV/T) hybrid solar dryer with Indian jujube is shown in Fig. 2.

Experimental Procedure

Sample drying in solar dryer

The on-field experiments at the ICAR-Central Arid Zone Research Institute, Jodhpur, India (26°18′N and 73°04′E) were carried out using the photovoltaic thermal (PV/T) hybrid solar dryer under natural (with DC fan off) and forced convection (with DC fan on) mode during the month of January, 2017 in clear sky condition. Fresh Indian jujube fruit (18 kg) of CAZRI *gola* variety was procured for each experiment from the Horticulture Block of CAZRI, Jodhpur. Selection of fruits was based on visual assessment of uniformity in colour and geometry.

Experiments were conducted between 8:00 hour and

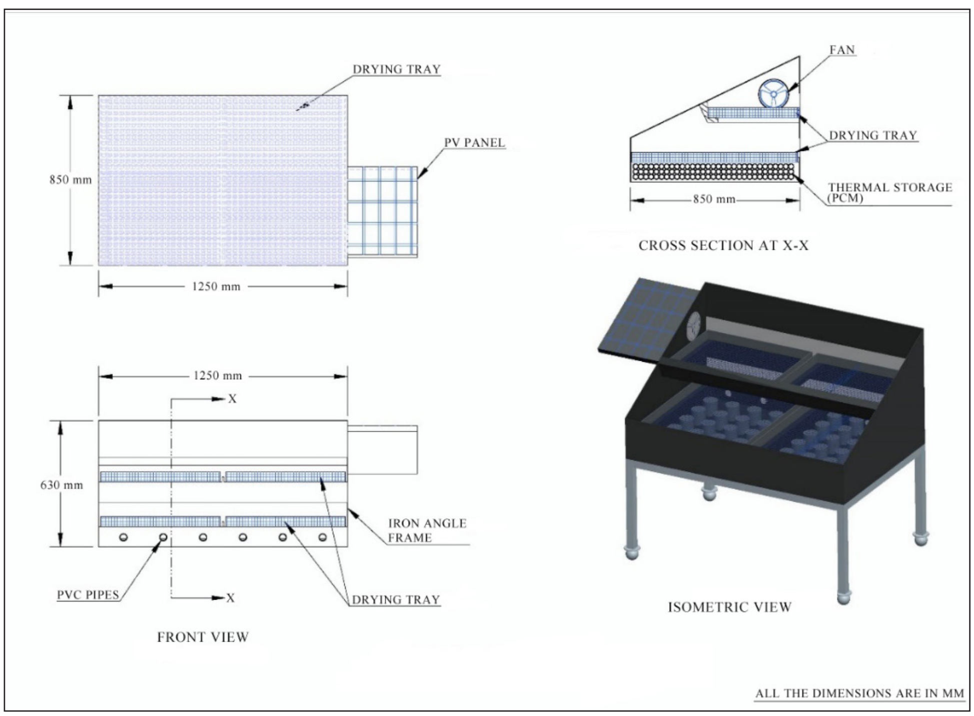

Fig. 1: Schematic diagram of photovoltaic thermal (PV/T) hybrid forced convection solar dryer

Fig. 2: Indian jujube in PVT hybrid forced convection solar dryer installed at CAZRI solar yard

18:00 hour using 18 kg of Indian jujube divided and equally distributed on the 4 trays, as shown in Fig. 2. Hourly total solar radiation intensity (G_s) on a horizontal surface was measured using a thermopile pyranometer. DTM-100 thermometer with point contact thermocouples (accuracy: 0.1˚C) was used to measure the temperatures inside the dryer. Ambient air temperature was measured using a mercury thermometer (accuracy: 0.1˚C) placed in an ambient chamber. Moisture contents of the drying product were measured at intervals of 60 min by taking 100 g of sample (measured with a digital electronic balance, Testing Instrument Pvt. Ltd., India, accuracy: ±0.001 g) from the trays.

The drying performance of Indian jujube in the PV/T hybrid solar dryer under natural convection mode (DC fan in off mode) was evaluated following the same procedure.

Measurement of Parameters

Moisture content

The moisture content of fresh and dehydrated Indian jujube was determined by hot air oven method (AOAC, 2005). About 20 g of Indian jujube was weighed into a pre-weighed moisture box and dried in an oven at 105 °C for 24 h. The sample was cooled in a desiccator and the weight of the dried sample was recorded. Determination of moisture content of samples was carried out thrice and the average value reported.

$$M_i = \left(\frac{W_i - W_f}{W_i}\right) \times 100 \qquad ...(1)$$

Where,

M_i = Initial moisture content of sample (w.b.), %,

W_i = Initial weight of sample, g, and,

W_f = Final weight of sample, g.

Drying kinetics parameters

The physiological loss in weight of Indian jujube was recorded at intervals of one hour during the drying process. Drying rate was calculated using the following equation (Doymaz, 2006):

Drying rate of Indian jujube fruit was calculated as:

$$DR = \frac{\Delta M}{\Delta t} \qquad ...(2)$$

Where,

ΔM = Loss of mass of fruit, kg water.kg^{-1} dry matter, and

Δt = Interval of time, min.

Moisture ratio

Moisture ratio (MR) and drying rate (DR) of Indian jujube fruit was calculated using the following equations:

$$MR = \frac{M - M_e}{M_0 - M_e} \qquad ...(3)$$

Where,

M = Moisture content of sample at a given time,

M_0 = Initial moisture content of sample, and

M_e = Equilibrium moisture content of sample, kg water. kg^{-1} solids.

Dryer Thermal Efficiency (η)

The efficiency of utilization of solar energy in solar dryer (ratio of heat used in evaporation of moisture from the fruit to the incident total solar radiation on horizontal plane) was worked out using the following relation (Leon *et al.*, 2002; Poonia *et al.*, 2017):

$$\eta = \frac{ML}{A\int_0^{\theta} H_T d\theta} \times 100 \qquad ...(4)$$

Where,

η = Efficiency of solar dryer, %,

A = Absorber area, m^2,

H_T = Solar radiation on horizontal plane, J.m^{-2}. h^{-1},

L = Latent heat of vaporisation, J.kg^{-1},

M = Mass of moisture evaporated from product, kg, and

θ = Period of test, h.

Statistical Analysis

In order to assess consistencies between the experimental results of moisture ratio with forced convection and natural convection solar drying, statistical analysis was undertaken. Paired-samples t-test of moisture ratio of forced and natural convection photovoltaic thermal (PV/T) solar dryer was worked out by using the following relation (Kim, 2015).

$$t_{cal} = \frac{\frac{\sum D}{N}}{\sqrt{\frac{\sum D^2 - \left(\frac{(\sum D)^2}{N}\right)}{N(N-1)}}} \quad \ldots(5)$$

Where,

SD = Sum of the differences of dryer,

SD^2 = Sum of the squared differences of dryer, and

N = Number of observations.

Drying Models

Mathematical models that describe drying mechanisms of fruit and vegetables provide the required temperature and moisture information of plum, persimmon slices and raw olive pomace (Goyal *et al.,* 2007; Doymaz, 2012; Koukouch *et al.,* 2015).

Thin-layer drying models can be categorized as theoretical, semi-theoretical and empirical models. Some semi-theoretical drying models that have been widely used are Lewis model (Lewis, 1921), Page model (Page, 1949), Henderson and Pabis (1961) model, and logarithmic model (Doymaz, 2007). These models are generally derived by simplifying general series solution of Fick's second law. These models were fitted in the experimental data in their linearized form using regression technique.

The selected models used to explain the drying data of Indian jujube are described below.

Henderson and Pabis model

The Henderson and Pabis model is the first term of a general series solution of Fick's second law. Bi-parametric exponential model is another definition of this model. The Henderson and Pabis model have produced good correlations in predicting the drying of corn (Henderson and Pabis, 1961) and pumpkins (Hashim *et al.,* 2014). This model can be written as:

$$MR = \frac{M-Me}{M0-Me} = a\,exp(-kt) \quad \ldots(6)$$

Where, a and k are the constants of the model; and t is the drying time (h).

Lewis model (Newton model)

The Lewis model is a special case of the Henderson and Pabis model, where the intercept is unity. It was used to describe drying characteristics of barley (Bruce, 1985) and strawberry (El-Beltagy *et al.,* 2007). The model is given in the following form:

$$MR = \frac{M-Me}{M0-Me} = exp(-kt) \quad \ldots(7)$$

Where, k is the constants of the model; and t is the drying time (h).

Page model

The Page model is an empirical modification of the Lewis model that corrects some shortcomings. This model has been used to describe the drying of many agricultural products, such as corn (Page, 1949), pistachio nuts (Kashaninejad *et al.*, 2007), long green pepper (Akpinar and Bicer, 2008) and green soybean (Yang and Zhu, 2015). This model is given as:

$$MR = \frac{M-M_e}{M_0-M_e} = \exp(-kt^n) \quad \ldots(8)$$

Where, k and n are the constants of the model; and t is the drying time (h).

Logarithmic model

The Logarithmic model was modified by adding an empirical constant (c) to the Henderson and Pabis model. It was successfully used to describe the drying characteristics of apricots (Toğrul and Pehlivan, 2002) and pumpkin slices (Doymaz, 2007). This model is expressed as:

$$MR = \frac{M-Me}{M0-Me} = a\,exp(-kt) + C \quad \ldots(9)$$

Where, a, k and c are the constants of the model; and t is the drying time (h).

Model selection

The drying rate constants and coefficients of the models were estimated using the non-linear least squares regression analysis by SPSS (Statistical Package for Social Scientists) 11.5.1 software package.

The coefficient of determination (R^2), chi-square value (χ^2) and root mean square values (RMSE)were the criteria used for selecting the best simulation equation of drying curve. A high degree of fitting equations should have the highest value of R^2, lower χ^2 and RMSE values(Roberts *et al.*, 2000; Madhlopa *et al.*, 2002; Tunde-Akintunde *et al.*, 2005; Gbaha *et al.*, 2007). These statistical parameters were calculated according to the following equations:

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(MR_{\exp,i} - MR_{pre,i})^2}{\sum_{i=1}^{N}(\overline{MR_{\exp,i}} - MR_{pre,i})^2} \quad ...(10)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}(MR_{\exp,i} - MR_{pre,i})^2}{N - Z} \quad ...(11)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(MR_{\exp,i} - MR_{pre,i})^2}{N}} \quad ...(12)$$

Where, $MR_{exp,i}$ and $MR_{pre,i}$ are experimental and predicted moisture ratios, respectively; N is number of observations; and z is the number of drying constants.

Estimation of Effective Moisture Diffusivity

Effective moisture diffusion coefficient (D_{eff}) reflects dehydration ability of materials under certain drying conditions, and is a significant transport property in modelling the drying process of biological materials as a function of temperature and moisture content in materials (Doymaz, 2012). The simplified mathematical Fick's second law for diffusion was used to estimate the effective diffusion coefficient of the Indian jujube fruit during drying. Analytical solution of Fick's second law is shown in the Eq.(13), considering a constant moisture diffusivity, infinite slab geometry and uniform initial moisture distribution:

$$MR = \frac{M - M_e}{M_0 - M_e} = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-\frac{n^2 \pi^2 D_{eff}\, t}{4r^2}\right) \quad ...(13)$$

Where,

D_{eff} = Effective diffusivity coefficient, $m^2.s^{-1}$,

r = Half thickness of sample, m,

n = Positive integer, and

t = Drying time, s.

For long drying times (setting n = 1), Saravacos and Raouzeos (1986) demonstrated that the Eq. (13) could be further simplified to a straight-line equation and can be expressed in a logarithmic form by taking the natural logarithm of both sides.

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}\, t}{4r^2}\right) \quad ...(14)$$

Effective moisture diffusivity was calculated using the method of slopes by plotting experimental drying data in terms of ln(MR) versus time (Domyaz, 2006). From Eq. (14), a plot of linear regression of ln(MR) versus drying time gives a straight line with a slope given as below:

$$\text{slope} = \left(\frac{\pi^2 D_{eff}}{4r^2}\right) \quad ...(15)$$

Effective moisture diffusion coefficient (D_{eff}) was then calculated according to the slope of the line obtained by the linear fitting.

Economic Analysis of Solar Dryer

Economic analysis of the dryer was carried out by computing its life cycle cost (LCC) and life cycle benefit (LCB). In addition, five economic attributes, namely, benefit-cost ratio (BCR), net present worth (NPW), annuity (A), internal rate of return (IRR) and payback period (PBP) were also determined for judging the economic viability of the dryer.

Life cycle cost (LCC)

Life cycle cost (LCC) of the inclined solar dryer is the sum of all the costs associated with a solar drying system over its lifetime in terms of money value at the present instant of time, and takes into account the time value of money (Kalogirou, 1996). Economics of PV/T hybrid solar dryer was calculated through life cycle cost (LCC) analysis. The procedure of life cycle cost estimation as adopted by Barnwal and Tiwari (2008), Singh *et al.* (2017) and Sodha *et al.* (1991) was used.

LCC (Unit) = Initial cost of unit (P_i) + P_w (O & M Costs including labour) – P_w (SV) ... (16)

$$= P_i + P_w \frac{X(1 - X^n)}{1 - X} - SV\,(1 + i)^{-n}$$

Where,

P_i = Initial investment, ₹,

P_w = Operational and maintenance expenses, including replacement costs for damaged components, ₹,

n = Life of the dryer, year,

P_w = Present worth of salvage value of the dryer at the end (SV) of life (₹),

e = Annual escalation in cost, fraction, and

i = Interest or discount rate, fraction.

Life cycle benefits (LCB)

The annual benefit was obtained by using total drying cycle of product. Thus, the total annual benefit from dried product was estimated as adopted by Barnwal and Tiwari (2008), Singh *et al.* (2017) and Sodha *et al.* (1991).

$$LCB = R\frac{X(1-X^n)}{(1-X)} \quad ...(17)$$

Where R is the annual benefit (₹) and $X = \frac{1+e}{1+i}$

Benefit cost ratio (BCR)

This ratio was obtained when the present worth of the benefit stream was divided by the present worth of the cost stream. The mathematical benefit-cost ratio (Barnwal and Tiwari, 2008; Singh *et al.*, 2017) can be expressed as:

$$\text{Benefit cost ratio (BCR)} = \frac{\text{Life cycle benefits of hybrid solar dryer}}{\text{Life cycle cost hybrid solar dryer}}$$

$$BCR = \frac{R\frac{X(1-X^n)}{(1-X)}}{P_i + P_w - P_w(SV)} = \frac{LCB}{LCC} \quad ...(18)$$

Net present worth (NPW)

The NPW was determined as the difference between present worth of savings and cost of investment. It is the sum of all discounted net benefits throughout the project, and expressed as:

$$NPW = LCB - LCC \quad ...(19)$$

Annuity (A)

The annuity (A) of the dryer indicates the average net annual returns. The procedure of annuity estimation adopted by Barnwal and Tiwari (2008), Singh *et al.* (2017) and Sodha *et al.* (1991) was used as:

$$\text{Annuity} = \frac{NPW}{\sum_{t=1\ to 10}\left(\frac{1+e}{1+i}\right)^n} \quad ...(20)$$

Payback period

The payback period shows the length of time between cumulative net cash outflow recovered in the form of yearly net cash inflows. The pay-back period was determined as (Barnwal and Tiwari, 2008; Singh *et al.*, 2017):

$$(-)\ LCC + LCB = 0 \quad ...(21)$$

Internal rate of return (IRR)

The internal rate of return is threshold rate at which the NPW is zero. The IRR can was determined using the following relationship (Barnwal and Tiwari, 2008; Singh *et al.*, 2017):

$$I_{RR} = \text{lower discount rate} + \frac{\text{Difference of discount rate x NPW at lower discount rate}}{\text{(NPW at lower discount rate – NPW at higher discount rate)}} \quad ...(22)$$

RESULTS AND DISCUSSION

Drying Characteristics

The daily mean values of drying chamber temperature, ambient temperature and solar insolation during the 10-day natural convection drying varied from 40 °C to 70 °C, 15 °C to 28 °C, and 480 W.m^{-2} to 875 W.m^{-2}, respectively;with their corresponding average values being 66 °C, 25 °C, and 750 W.m^{-2}, respectively. The daily mean values of drying chamber temperature, ambient temperature and solar insolation during the 8-day forced convection drying varied from 38°C to 67°C, 13 °C to 26°C, and 469 W.m^{-2} to 850 W.m^{-2}, respectively. The variations in solar insolation, ambient temperature and temperature inside upper and lower trays with fruits loaded during natural and forced convection drying are shown in Fig. 3 and Fig. 4, respectively.

The effect of drying temperature on drying time was considerably pronounced, and is in agreement with the results for several food materials as plums (Goyal *et al,* 2007), pumpkin slices (Doymaz, 2007), pistachio nuts (Kashaninejad *et al.*, 2007) and castor oil seeds (Perea-Flores *et al.*, 2012). Generally, the decrease in drying time resulted from the higher driving forces for heat transfer (due to larger temperature difference) and for mass transfer (due to larger difference in relative humidity).

The variations in moisture content (w.b.) of the fruit on each day of drying is shown in Fig. 5. It can be seen that the moisture content reduced from 80 % to 24 % within 8 days under forced convection solar drying, and 10 days under natural convection drying. The moisture content

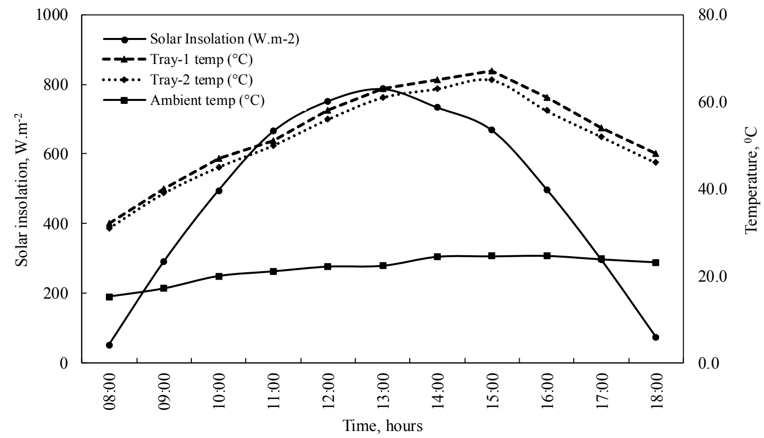

Fig. 3: Temperature and solar insolation variations during load test (Indian jujube) under natural convection drying

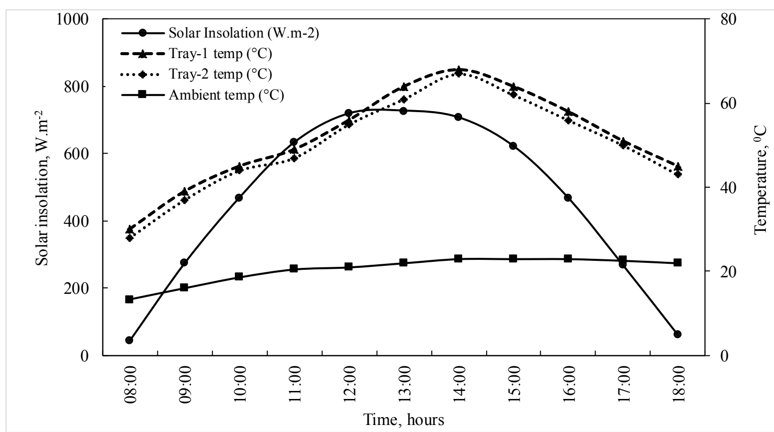

Fig. 4: Temperature and solar insolation variations during load test (Indian jujube) under forced convection drying

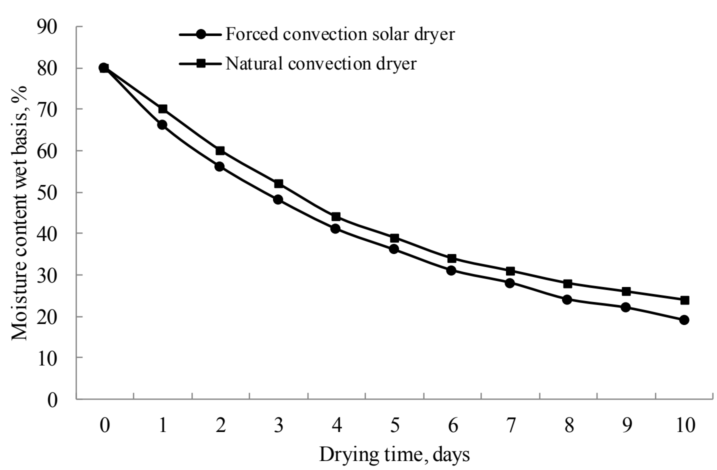

Fig. 5: Variations of moisture content of Indian jujube during natural and forced convection solar drying

of fruit reduced to 19 % on the 10th day under forced convection drying. The moisture content, however, reduced to 24 % after 8 days of drying, and could be safely stored for further use. The final moisture content of dried jujube under different conditions ranged from 28 % to 25 % on wet basis. This was in agreement with the result of study on Chinese Jujubes (Yi *et al.,* 2012). In contrast, it took 20 days to dehydrate the same quantity of Indian jujube fruits under open sun drying (Poonia *et al.,* 2017).

The drying rate in the solar dryer increased sharply when the moisture content fell below 66 per cent. The shape of the drying curve indicated a rapid moisture removal from the product at the initial stage, which later decreased with increase in drying time. Thus, the moisture ratio decreased continually with drying time. This continuous decrease in moisture ratio indicated that diffusion had governed the internal mass transfer. This was in agreement with earlier results on figs (Piga *et al.,* 2004), lettuce and cauliflower leaves (Lopez *et al.,* 2000) and Indian jujube (Das and Dutta, 2013), tomatoes (Doymaz, 2007) and amasya red apples (Domyaz, 2010).

Overall Thermal Efficiency under Natural and Forced Convection Drying

The overall efficiency of solar drying is affected by several factors as drying time, climatic conditions (solar insolation and temperature), drying characteristics of materials, and structure of the drying devices. The collector efficiency indicates the utilized heat against the heat input in the form of solar insolation.

Since each experiment was started at 8 AM and the setup had not yet stabilized, drying efficiency was low at 8 AM, Fig. 6. Increase in efficiency of bottom flow during the evening might be attributed to the heat storage by the insulation. When insolation drops, the stored heat is retrieved, thereby maintaining higher air temperature leading to higher thermal efficiency. The efficiency of the natural and forced convection system was least at the peak insolation hour at 12 PM (Fig. 6). This was due to the plate temperature rising rapidly in the noon with higher insolation, but the heat removal capacity of the air at a fixed velocity was not adequate for this additional load. The captive heat in the collector chamber stayed, and was lost to the surroundings in the form of various losses leading to lower efficiencies of the system. If the air velocity in the collector chamber was increased in order to improve the efficiency, the air outlet temperature from the collector would decrease. Hence, a balance had to be maintained between collector efficiency and air outlet temperature.

The average efficiency of solar energy utilization under natural convection solar dryer was 15.6 %, and under forced convection solar drying was 16.7 per cent. Figure 7 shows that higher efficiency was observed at initial stage of drying, while at later stage the dryer thermal efficiency decreased due to decrease in moisture content. Initially the unbound moisture was being removed depending only on the surface area. With increase in drying time, the difference between the curves (natural and forced convection) reduces as the rate of moisture removal reduced depending on the surface area as also on start of the falling rate phase of drying. The average thermal efficiency continuously dropped as the rate of moisture removal slowed during falling rate period, even though the input energy remained the same. At the end of the day, the efficiency of natural convection solar drying was 7.0 %, and that

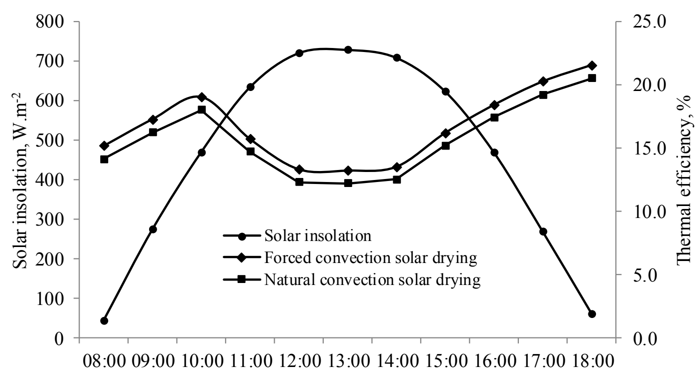

Fig. 6: Average thermal efficiency of collector as compared to solar insolation under natural and forced convection solar drying

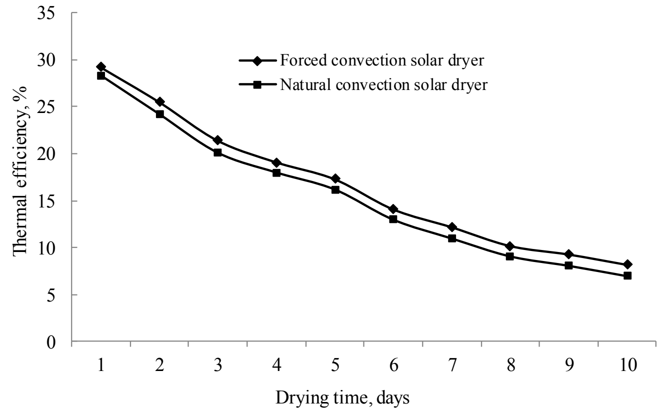

Fig. 7: Cumulative dryer efficiency for drying trays under natural and forced convection solar drying

of forced convection solar dryingwas 8.2 per cent. The result was in agreement with previous investigations reporting that the average thermal efficiency was 16.5% underforced convective, flat-plate solar heat collector dryer for drying cauliflower (Kadam and Samuel, 2006) and 12.1 % for low-cost solar dryer for *ber* (*Zizyphus mauritiana*) fruit (Poonia *et al.,* 2017). The overall thermal efficiency was 18.6 % for convective drying of sponge-cotton (Aissa *et al.,* 2014).

Comparison of Forced and Natural Convection Drying

A paired-samples t-test was conducted to compare the moisture ratios of forced and natural convection photovoltaic thermal (PV/T) solar dryer. Since table value of t-test at degree of freedom (df) = 10 and probability level (p) = 1 % and 5 % were 4.587 and 2.228, respectively, and t-calculated value of 7.596 was higher than t-table, a significant difference between the means (Table 1) was observed. These results suggested that forced convection photovoltaic thermal (PV/T) solar dryer was more effective as compared to natural convection photovoltaic thermal (PV/T) solar dryer.

A comparative study of natural and forced convection PVT hybrid solar dryer indicated that the thermal efficiency of forced convection mode (16.7 %) was better than that of natural convection mode (15.6 %).The time required for drying in forced convection mode was (8 days) less than natural convection mode (10 days).

Table 1. Statistical analysis of moisture ration of natural and forced convection photovoltaic thermal (PV/T) solar dryer

Sl. No.	Time, day	Moisture ratio, %		D	D^2
		Forced convection PV/T hybrid solar dryer	Natural convection PV/T hybrid solar dryer		
1.	0	80	80	0	0
2.	1	66	70	4	16
3.	2	56	60	4	16
4.	3	48	52	4	16
5.	4	41	44	3	9
6.	5	36	39	3	9
7.	6	31	34	3	9
8.	7	28	31	3	9
9.	8	24	26	2	4
10.	9	21	23	2	4
11.	10	19	21	2	4

Therefore, forced convection mode was considered for drying modelling and cost economic analysis.

Fitting of Drying Models

The moisture ratios (MR) were fitted to four drying models (Henderson and Pabis model - Eq. (6); Lewis model -Eq. (7); Page model -Eq. (8); and Logarithmic model -Eq. (9)) in order to estimate the moisture ratios as a function of drying time. The R^2, χ^2 and RMSE values were used to evaluate the models. The results of the statistical analysis for the four models are presented in Table 2.

The model that best predicted the drying process would have higher values of R^2, and lower values of χ^2 and RMSE. The ranges of R^2, χ^2 and RMSE values were between 0.9881–0.9982, 0.000047–0.00014, 0.007338–0.012605,respectively. The R^2 values were greater than the acceptable R^2 value of 0.97(Perea-Flores *et al.,* 2012). The logarithmic model exhibited highest R^2 values, and χ^2 and RMSE values were relatively lower than those for the other tested models (Table 2). Logarithmic model was thus considered to be best suited to satisfactorily describe drying characteristics of Indian jujube fruits.

The experimental and predicted moisture ratio by logarithmic model is shown in Fig. 8. The predicted values of the model were in good agreement with the experimental results. This confirmed that the logarithmic model could be used to explain thin-layer solar drying behavior of Indian jujube. The logarithmic model has also been found to be suitable to explain the drying behaviour and moisture ratio evolution of apricot (Faal *et al.*, 2015); black grapes (Domyaz, 2006); chilli pepper (Tunde-Akintunde, 2011); onion slices (Sharma *et al.*, 2005) and water chestnut (Singh *et al.*, 2008).

Effective Moisture Diffusivity (D_{eff})

Fick's second law can be used to describe the drying process of Indian jujube fruits due to the fact that the drying occurred mainly in the falling-rate period, and liquid diffusion controlled the process as mentioned earlier. The application is widely accepted by many researchers (Doymaz and İsmail, 2011; Perea-Flores *et al.*, 2012; Bezerra *et al.*, 2015).

The effective moisture diffusivity was computed by using thegraph of ln (MR) against time, Fig. 9. Moisture diffusivity of Indian jujube fruits was 3.34×10^{-7}m^2.s^{-1}at

Table 2. Statistical performance of thin-layer drying models

Sl. No.	Model	R^2	χ^2	RMSE
1.	Henderson and Pabis	0.9900	0.00014	0.0125
2.	Lewis model	0.9881	0.00041	0.0126
3.	Page	0.9913	0.00001	0.0121
4.	Logarithmic	0.9982	0.00004	0.0073

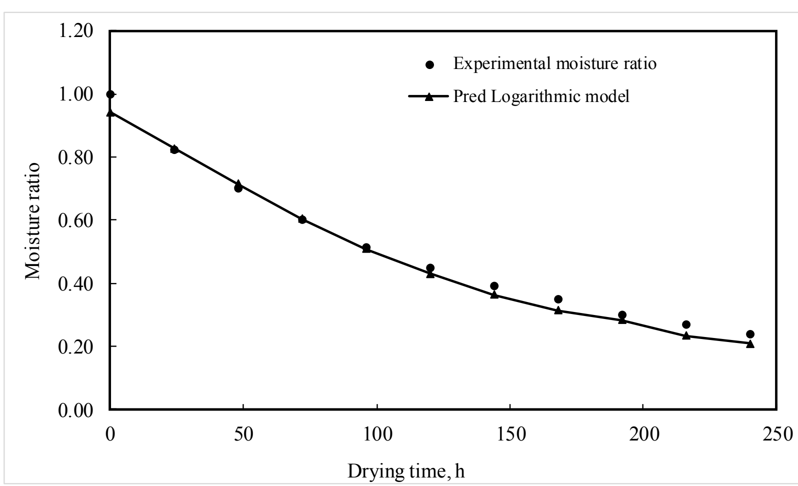

Fig. 8: Experimental and predicted moisture ratio by logarithmic model for Indian jujube fruit

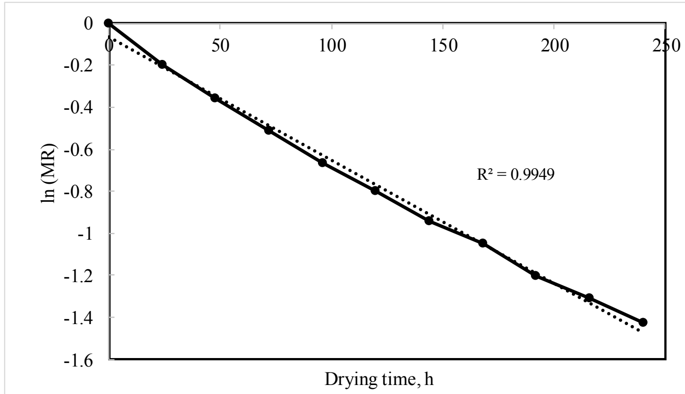

Fig. 9: ln (MR) versus drying time (logarithmic model) for drying of Indian jujube

30-65 °C during the experiment for a loading rate of 18 kg. This was similar to the results for thin-layer drying of sweet sorghum stalks (from 7.20×10^{-9} to 1.91×10^{-8} $m^2.s^{-1}$) at 30–70 °C (Shen *et al.*, 2011), $4.08\times10^{-8} m^2.s^{-1}$ to $2.35\times10^{-7} m^2.s^{-1}$ for convective drying of pumpkin at 30–70 °C (Hashim *et al.*, 2014). The result was in agreement with the previous investigations that the values of effective diffusivities lie within the general range of $10^{-11} m^2.s^{-1}$ to $10^{-7} m^2.s^{-1}$ for all agricultural and food products (Wang *et al.*, 2007). The difference in D_{eff} for different biological materials might be due to different drying temperatures employed, physical or chemical pre-treatment, moisture content and sample variety, composition and geometry of drying materials.

Economic Viability of Dryer

Economic analysis of the dryer was carried out by computing its life cycle cost (LCC), life cycle benefit (LCB), benefit-cost ratio (BCR), net present worth (NPW), annuity (A), internal rate of return (IRR) and pay back period (PBP) of the dryer were determined for judging the economic viability of the dryer. The initial investment (P_i) of the dryer unit was ₹ 14,000. The annual cost of operation and maintenance (O&M) including labour was considered as ₹ 4,000. The salvage value was taken as 10% of initial investment. The values of five economic attributes, namely, benefit-cost ratio (BCR), net present worth (NPW), annuity (A), internal rate of return (IRR) and pay back period (PBP) are presented in Table 3.

The annual benefit was obtained by using the dryer for 10 drying cycles each for Indian jujube and Indian cherry (*Cordia myxa* L.). The quantity of Indian jujube dried was 180 kg costing about ₹ 3,600. The weight of dried Indian jujube fruit was 60 kg, which accrued ₹ 9,000 at a rate of ₹ 150 per kg, giving profit of ₹ 5,400. Similarly, drying of 180 kg of Indian cherry ensured profit of ₹ 30 per kg resulting in gain of ₹ 5,400. Thus, the total annual benefit from dried product was ₹ 10,800. Considering interest rate of 10% and life of the dryer as 10 years, LCC and LCB of the dryer was ₹ 43,153 and ₹ 80,171.

Table 3. Values of economic attributes

Sl. No.	Economic attribute	Value
1.	BCR	1.86
2.	NPW	37018
3.	A	4988.95
4.	IRR, %	54.50
5.	PBP, year	

The net present worth of investment NPW) made on dryer was ₹ 37,018. Based on the NPW, it was concluded that fabrication of the dryer is economical as compared to solar biomass hybrid dryer (Dhanushkodi *et al.,* 2015) and hybrid photovoltaic/thermal greenhouse dryer (Barnwal and Tiwari, 2008).

The benefit-cost ratio ofthe dryer was 1.86. Sachidanada*et al.* (2014) found the benefit-cost ratio of a biomass fired drier for copra drying (requiring 22 h to reduce initial moisture content from 57.4 % (w.b.) to 6.8 % (w.b.)) was 1.4 and 1.19 for two driers tested.

The annuity of the dryer was found to be ₹ 14,272. The payback period was estimated as 2.26 years, and lower than the expected life of 10 years for the dryer. The payback period of a solar tunnel drier is 4 years for basic mode drier, and 3 - 4 years for optimum mode driers (Hossain et al., 2005). Barnwal and Tiwari (2008) reported payback period of 1.25 years for a hybrid PV/T greenhouse dryer (costing ₹ 7,400) for drying grapes under forced mode of operation.

The internal rate of return (IRR) was 54.5% in the present case, which is high for a project to be economically viable.

CONCLUSIONS

Drying rate of Indian jujube under forced convection was higher than that of Indian jujube under natural convection. Thermal efficiency of the dryer under forced convection mode (16.7 %) was better than that under natural convection mode (15.6 %), and the time required for drying in forced convection mode (8 days) was less than natural convection mode of dryer (10 days). Logarithmic thin-layer dying model fittest most among four thin-layer drying models to explain the drying behaviour of the fruit under forced convection mode. Moisture diffusivity of the forced convection solar dryer was 3.34×10^{-7} $m^2.s^{-1}$. The cost-efficient hybrid forced convection PV/T solar dryer considerably reduced the drying time, energy consumption as compared to natural convection dryer. The use of the hybrid solar dryer at remote locations/ rural areas can help in reducing post-harvest losses as well as carbon emission.

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