# PERFORMANCE EVALUATION OF INDIRECT TYPE FORCED CONVECTION SOLAR MANGO DRYER
## A Sustainable Way of Food Preservation

by

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*India like other developing countries adopts many food preservation technologies using fossil fuels. But the fossil fuel resource depletes over the years and is non-renewable. Therefore, solar drying technology is preferred as a sustainable method for food preservation. The present study is aimed at a sustainable livelihood initiative for drying fruits and vegetables through solar technology intervention using an indirect forced convection type solar dryer. Such a dryer of 15 kg capacity has been designed and fabricated for drying mangoes. Performance indicators such as instantaneous collector efficiency, drying efficiency, drying rate, COP, heat utilization factor, and moisture content on a dry basis are evaluated as 59%, 32.25%, 0.15178 kg/hr, 0.77, 0.229, and 2.55, respectively by considering maximum outlet collector temperature, drying chamber temperature and atmospheric temperature. Economic indicators such as pay-back period and cost-benefit ratio are also evaluated as 1.439 and 2.0008, respectively. The dryer can be used by rural people of Odisha for earning their livelihood.*

Key words: *solar dryer, forced convection, food preservation, fruits and vegetables, pay-back period*

## Introduction

India demands an increase in clean energy generation which is considered an alternative solution for attaining a better quality of life. The objective of food preservation is to prevent food spoilage and deterioration of food products. There are several methods used for food preservation such as canning, freezing, pickling, blanching*, etc.* Food preservation also reduces food wastage and also ensuring the availability of fruits and vegetables during off-seasons. Drying is one of the oldest processes of food preservation which removes moisture from the food products and prevents it from damage. Solar drying technology is a sustainable method of food preservation. It is based on clean energy technology which aims to dry food products hygienically and quick process in comparison the traditional method of drying.

Many different solar dryers are available depending upon the type of hot air circulation inside the drying chamber. Based on the hot air circulation and exposure to solar irradiation, a solar dryer may be classified as direct type, indirect type, mixed-mode type, and hybrid type. In direct type, the food product is directly open to sunlight and the drying chamber is

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made up of good heat-conducting material. In the indirect type, the dryer is integrated with a solar collector and a drying chamber. The heat generated from the collector will be circulated through the drying chamber instead of direct exposure of solar radiation a food product. In the mixed-mode type, the dryer is a combination of both direct exposure of solar intensity to the drying chamber as well as warm air circulation from a solar collector. The hybrid type is the recently developed dryer that can be used day and night. The forced convection solar dryer is more efficient as compared to the natural-convection mode due to the constant flow of hot air inside the drying chamber as it is integrated with the blower. It increases the heat transfer rate and also increases the drying rate.

Rabha *et al.* [1] have developed a forced convection tunnel solar dryer in which ghost chili pepper and sliced ginger are successfully dried within different temperature ranges. They have calculated the parameters like overall thermal efficiency, specific energy consumption, and exergy efficiency. Mugi and Chandramohan [2] have done economic analysis as well as energy and exergy analysis of forced convection solar dryers. The pay-back period (1.46 years) is less for forced convection dryers due to less drying period as compared to natural-convection dryers (2.15 years). The average drying efficiencies are 10.4% and 8.9%, respectively under forced and natural-convection solar dryers. The specific energy consumption and specific moisture extraction rate of forced convection are 1.532 kWh/kg and 0.6526 kg/kWh, respectively while for natural-convection are 1.784 kWh/kg and 0.5603 kg/kWh, respectively. The collector efficiency under forced and natural-convection is 63.3 and 53.84%, respectively. Castillo-Tellez *et al.* [3] have done an experimental study on an indirect type forced convection solar dryer for drying red chili (*Capcicum anuum L.*). It is observed that the drying time is reduced in case of a higher velocity range as compared to the lower velocity range. Gilago and Chandramohan [4] have carried out a performance study of a natural and forced convection indirect type solar dryer for drying ivy gourd. The average actual heat supplied for natural and forced convection is 776.6 W and 997.76 W, respectively. Similarly, the collector efficiencies for the same are 62.56% and 77.2% while drying efficiencies as 6.62% and 7.8%, respectively. Forced convection gives the best performance as compared to natural-convection dryers. Simo-Tagne *et al.* [5] have performed a numerical simulation study on combined natural and forced convection for drying cocoa beans. The drying kinetic, drying rate, thermal efficiency, and pay-back period have been evaluated. Bunchan *et al.* [6] have performed a simulation study to increase the heat transfer rate of an absorbing plate of indirect forced convection solar dryer by placing wire mesh stainless porous material on it. Nusselt number and friction factor are increased because of swirling movement. Mugi and Chandramohan [7] have studied the performance of forced and natural-convection indirect type solar dryer for drying guava slices. The average drying efficiencies of forced and natural-convection solar dryers are 6.84% and 5.42%, respectively. The value of effective diffusion coefficient, mass transfer coefficient, and heat transfer coefficient are also increased by 34.12%, 55.55%, and 55.59%, respectively in forced convection as compared to natural-convection type solar dryer. Bhavsar and Patel [8] had done a performance study of cabinet type solar dryer under forced and natural-convection air circulation for drying 4 kg of ginger. It is found that the forced convection type is more efficient compared to the natural-convection type. Hidalgo *et al.* [9] have evaluated a direct type solar dryer under natural and forced convection mode for drying green onion. The PV panel is used to run eight coolers for the circulation of air inside it. The average efficiency and specific energy consumption have been evaluated. The average drying efficiency under forced and natural-convection solar dryers is 34.2% and 38.3%, respectively. The specific energy consumption for forced and natural-convection solar dryer is 18.3 kWh/kg and 16.4 kWh/kg, respectively. Mugi and Chandramohan [10] had done energy and exergy analysis of indirect type solar dryer under natural and forced convection mode. The mass-flow rate of air is increased in forced convection type by integrating trapezoidal duct at the inlet of collector and fan is operated by the solar PV panel. The average exergy efficiency, drying efficiency, and collector efficiency are also evaluated. The average solar air collector and drying efficiencies are 74.98% and 24.95%, respectively under forced convection while under natural-convection it is 61.49% and 20.13%, respectively. The value of average exergy efficiency for solar air collector and drying chamber in forced convection is 2.03 and 59.32%, respectively while for natural-convection it is 2.44% and 55.45%, respectively.

A passive indirect type solar dryer has been analyzed consisting mainly of a solar collector, dehydrating chamber, and chimney used for dehydrating apples. The COP is obtained as 87%, mass reduction of 89% with a 32.78 MJ of energy delivered to the system by Tedesco *et al.* [11]. Extensive experiments have been conducted by Haytem *et al.* [12] for drying apple peels obtained from organic waste of food processing industries under different drying temperature ranges and two different flow rate conditions (150 $m^3$ per hour and 300 $m^3$ per hour). It is found that the drying efficiency increases with the rise in temperature and mass-flow rate. Koua *et al.* [13] have studied an indirect type solar dryer for drying cocoa beans. The parameters like moisture content desorption isotherms and thermo-physical properties such as thermal conductivity, thermal diffusivity, and shrinkage are calculated. Doder *et al.* [14] have done modelling of convective intermittent drying of in-shell walnuts and its influence on deep bed drying simulation. Deep bed drying simulation showed that a fixed bed of walnuts should not be bigger than 15-20 cm. Suresh *et al.* [15] have done a performance study on drying mint leaves using a forced convection solar dryer. Performance parameters such as collector and drying efficiencies have been calculated as 30.33% and 1.63% for the first day at a mass-flow rate of 0.75 m/s and 29.41% and 1.89% for the second day at a mass-flow rate of 1.25 m/s, respectively. It is found that as the mass-flow rate increases system efficiency decreases. Wang *et al.* [16] have done both theoretical and experimental studies of drying characteristics and drying kinetics of mango slices in an indirect forced convection solar dryer by using an auxiliary heating device. It has been observed that temperature varies at four different locations of the drying chamber and thermal efficiency ranges from 30.9-33.8% at a drying temperature of 52 °C.

The present study discusses the solar drying of mangoes through indirect forced convection. Though enough research has been pursued on solar drying of mangoes, but more study is needed on the performance indicators, evaluation of economic parameters, enhancement of system efficiency, and reduction of heat loss. The current work investigates to develop an energy-efficient solar dryer through the use of proper insulation, corrugated absorbing plate, and double cover transparent glass plates. Finally, validation and comparative assessment have been performed with the recent literature.

The present study is to evaluate the performance indicators such as instantaneous collector efficiency, drying efficiency, the drying rate of different types of dryers, coefficient of performance, heat utilization factor, and moisture content on a dry basis for drying 15 kg of mangoes in an indirect type solar dryer through forced convection. Economic parameters such as cost-benefit ratio and pay-back period have been determined. The present design enhances the drying rate by the constant mass-flow rate of hot air using a DC blower.

## Experimental analysis

### *Experimental set-up*

An experimental set-up of the solar dryer is needed consisting of major components solar collector, and a drying chamber is shown in fig. 1.

In this present study, solar drying of mangoes inside the drying chamber has been discussed. A complete experimental procedure is illustrated for evaluating the thermal performance characteristics of the solar dryer. The main components of the experimental set-up of indirect type forced convection solar dryer are a flat plate collector, drying chamber, solar panel, and DC blower. The collector of the surface area of 1 m$^2$ consists of a transparent glass plate, absorbing plate, and glass wool as an insulator. Two numbers of transparent glass plates with a gap of 1.5 inches and 5 mm thickness are provided in the collector to transmit maximum solar radiation the absorbing plate. A 1.5 mm corrugated type black coated Aluminum sheet is preferred as an absorbing plate to absorb the maximum solar radiation received from the transparent plate and to increase the heat transfer rate. Glass wool of 75 mm is provided at the bottom of the collector and the side of the drying chamber for reducing heat loss. The collector is tilted at 20° facing towards the South as per the latitude of Bhubaneswar location (20.2961°N, 85.8245 °E) to achieve maximum sun radiation incident on it. Both the solar panel and collector are installed in the same direction as shown in the fig. 1. The drying chamber in the form of a rectangular box with dimensions 1 m × 0.5 m × 0.5 m is made up of stainless steel. Both inner and outer surfaces are black coated to absorb maximum solar radiation. Three stainless steel wire mesh type trays are provided with 110 mm uniform spacing to place food products and for proper circulation of hot air over them. A 10 W solar panel is electrically connected to run the 6 V DC blower of 60 mm diameter provided at the outlet of the drying chamber for removing moist air. Top, bottom, and side losses have been reduced by placing glass wool as an insulator and proper sealing of both the solar drying chamber and collector. By using two numbers of transparent cover plates such as glass plates, transmitivity of incoming solar radiation increases, and losses due to re-radiation reduces.

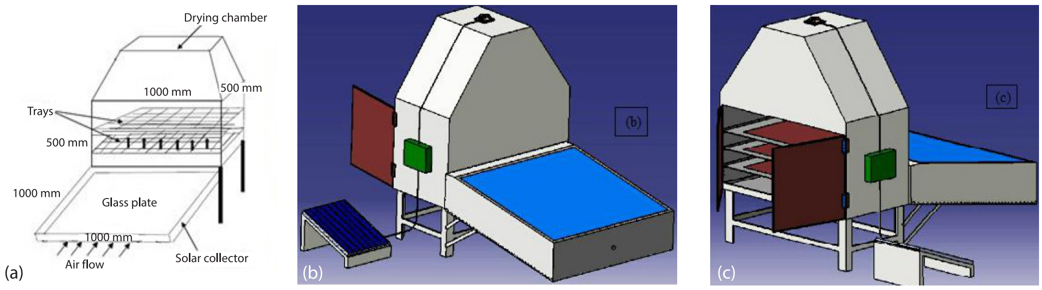


**Figure 1. Experimental set-up; (a) schematic diagram, (b) CATIA model of front side, and (c) back side**

### *Experimental procedure and performance testing*

Before starting the experiment, the solar dryer is placed in a shadow-free location for more exposure to the sun's rays. A proper assessment of site location is very important to capture maximum solar radiation. As the dryer is a portable type, it can be placed at any location as per the availability of maximum incident solar radiation. The experiments have been conducted in the sunny hours from 9 a. m. to 4 p. m. in April. The collector is tilted and fixed at 20° as per the latitude of location so that the maximum solar radiation incidents on the glass surface of the collector. In this experiment, 5 kg of green mangoes is taken for testing in the solar dryer for the preparation of the pickle. But some preprocessing of mangoes is needed before putting them in the drying chamber. The mangoes are initially washed, dried, and sliced as per the requirement of pickle size. Then the mangoes are properly mixed with salt and turmeric powder for preservation purposes. Before placing the sliced mangoes inside the drying chamber, the chamber is preheated for half an hour. Then the sliced mangoes are evenly placed inside the three trays in equal quantities. The trays are made of wire-mesh type for proper circulation of hot air. The temperature and humidity at every point of the solar collector as well as the drying chamber are measured every one-hour time interval. The experiment has been completed in three days considering 7 hours of drying time. The initial and final mass of the product is measured after completion of the experiment for each day and finally, dried mangoes are collected for making pickles. An additional tray filled with sliced mangoes is placed outside the dryer for the open sun drying process to make a comparative assessment of the obtained results. Different measuring instruments have been shown in fig. 2. The details of measured parameters, models of instruments, accuracy, and ranges are given in tab. 1.


**Figure 2. Measuring instruments; (a) infrared radiation pyrometer, (b) hygrometer, (c) light meter, and (d) anemometer**

**Table 1. Details of measuring instruments**

| Measuring instruments | Measured parameters | Model of measuring instruments | Accuracy | Ranges |
|---|---|---|---|---|
| Infrared thermometer | Temperature | MT-5 | ±2°C/±2% | –40 ~ 550 °C |
| Temperature/ humidity meter | Humidity | KUSAM-MECO, KM919 | Humidity: ±2.5% for 30-80%, ±3.0% for 20-29.9% and 80.1-89.9, ±5% for 1-19.9 and 90.1-99.9 | Temperature: –20.0 ~ +60.0 °C Humidity: 1.0 ~ 99.9% RH |
| Light meter | Solar radiation | KUSAM-MECO-LUX 99 | ±5% | 2000-50000 Lux |
| Anemometer | Velocity | KUSAM-MECO, KM-909 | ±3% FS | Temperature: 20.0 ~ +60.0 °C Wind velocity: 0.0-30.0 m/sec |

### *Uncertainty analysis in measurements*

Uncertainty is generally associated with the dispersion of values with experimental measurement. It defines the margin of doubt existing in any measured values and how significant the doubt is. In the experimental results, it is significant to measure the uncertainties errors by:

$$U_R = \left[ (U_{R1})^2 + (U_{R2})^2 + (U_{R3})^2 + (U_{R4})^2 + .......(U_{Rn})^2 \right]^{1/2} \tag{1}$$

where $U_R$ is uncertainty result and $U_{R1}$, $U_{R2}$, $U_{R3}$, $U_{R4}$ are uncertainty of measured parameters such as temperature, humidity, solar radiation and velocity, respectively. The uncertainty result is calculated as 5.45% using eq. (1) and confidence level is calculated as 94.53%. The values of uncertainties of each measured parameter such as temperature, humidity, solar radiation and velocity are ±2%, ±2.5%, ±5%, and ±3%, respectively.

### *Evaluation of performance indicators of solar dryer*

The inside temperatures, relative humidity, solar radiation, and speed of hot air are measured at every one-hour interval by a non-contact type infrared radiation pyrometer, hygrometer, light meter, and anemometer, respectively. The mass-flow of hot air is calculated from its speed in the drying chamber. The performance of a solar dryer is dependable on the aforementioned parameters. The amount of energy required for drying is equal to the sum of energy required for raising food product temperature to dry air temperature in form of sensible heat, latent heat of vaporization for removing moisture from food products, and the amount of heat lost from the drying chamber. Performance indicators such as drying efficiency, drying rate, heat utilization factor, coefficient of performance, moisture content on a dry basis, moisture ratio, specific energy consumption, pay-back period, and cost-benefit ratio have been analyzed as presented below.

A complete theoretical and mathematical modelling consideration for the design of solar-based forced convection type is given. The drying requirements like the initial mass of food products, $m_{if}$, initial and final moisture content, $MC_{dbi}$, $MC_{dbf}$, collector outlet temperature, $T_o$, drying chamber temperature, $T_d$, and ambient temperature, $T_a$, is used to determine the removal of moisture content on a wet basis, $m_{wr}$, instantaneous collector efficiency, $\eta_c$, drying efficiency, $\eta_t$, drying rate (DR), heat utilization factor (HUF), COP, and moisture removal on dry basis, $M$, using eqs. (2)-(5) [7] and eqs. (6)-(10) [17], respectively as presented below.

The removal of moisture content on a wet basis is given:

$$m_{wr} = m_{if}\left(\frac{MC_{dbi} - MC_{dbf}}{1 - MC_{dbf}}\right) \tag{2}$$

The instantaneous collector efficiency is given:

$$\eta_c = \dot{m}_a C_p \left(\frac{T_o - T_i}{A_c \times I}\right) \tag{3}$$

where $\dot{m}_a$ [kgs$^{-1}$] is the mass-flow rate of dry air, $C_p$ [kJkg$^{-1}$K$^{-1}$] – the specific heat, $T_i$ [°C] – the inlet temperature of the collector, $I$ [Wm$^{-2}$] – the instantaneous flux on the tilted surface, and $A_C$ [m$^2$] – the area of solar collector.

Performance indicators such as drying efficiency, drying rate, heat utilization factor, COP, moisture content on a dry basis, moisture ratio, specific energy consumption, and payback period have been discussed below.

The $\eta_t$ is a measure of the overall effectiveness of the drying system. It generally depends on the moisture to be evaporated, latent heat of evaporation, the surface area of the collector, and instantaneous flux incident on a tilted surface. It is defined as the ratio of energy required to evaporate moisture from the food products by supplementing hot air:

$$\eta_{\text{thermal}} = \frac{m_{wr} \times L}{A_C \times I} \tag{4}$$

where $L$ is the latent heat of evaporation.

The DR of food products is defined as the ratio of the difference in two successive moisture contents and the time difference, d$t$:

$$DR = \frac{MC_{db(t+\mathrm{d}t)} - MC_{db(t)}}{\mathrm{d}t} \tag{5}$$

where $MC_{db(t + \mathrm{d}t)}$ is moisture content of food products at time, $t + \mathrm{d}t$, and $MC_{db(t)}$ moisture content of food products at time period $t$.

The HUF is defined as the ratio between temperatures reduces due to the drying period to temperature increase during the heating period. It is calculated from the collector temperature, $T_c$, drying chamber temperature, $T_d$, and ambient temperature, $T_a$, using:

$$HUF = \frac{T_c - T_d}{T_c - T_a} \tag{6}$$

where $T_c$ [°C] is the collector outlet temperature.

The COP is defined as the ratio between the temperature difference between the dryer and ambient air temperature to a temperature difference between the collector and ambient air temperature. It is calculated:

$$COP = \frac{T_d - T_a}{T_c - T_a} \tag{7}$$

Moisture content ratio on a dry basis, $m_{dr}$, is calculated from the initial and final moisture contents:

$$m_{dr} = \frac{MC_{dbi} - MC_{dbf}}{MC_{dbf}} \tag{8}$$

Performance indicators such as pay-back period and cost-benefit ratio have been discussed below using eqs. (9) and (10) [18]. The pay-back period (PBP) is an important economic parameter of a solar drying system. It is defined as the time needed to recover the initial investment for the project from the savings obtained during that period. It is calculated as explained:

$$\mathrm{PBP} = \frac{C_{\mathrm{total}}}{M_{\mathrm{dryproduct}} P_{\mathrm{dryproduct}} - M_{\mathrm{freshproduct}} P_{\mathrm{freshproduct}} - M_{\mathrm{dryproduct}} X} \tag{9}$$

where $C_{\mathrm{total}}$ = total capital cost for the dryer = total material cost + total labor cost for manufacturing. The $X$ = drying cost = annual cost/amount of dried product per year, $M_{\mathrm{dry\ product}}$ = annual production of dry product, $M_{\mathrm{fresh\ product}}$ = mass of fresh products, $P_{\mathrm{dry\ product}}$ = price of dry product, and $P_{\mathrm{fresh\ product}}$ = price of fresh product.

The cost-benefit ratio is defined as the ratio of total benefit received per year to the total capital cost of a developed system and is given:

$$\text{Cost} - \text{benefit ratio} = \frac{\text{Total benefit received per year}}{\text{Total capital cost of the developed system}} \tag{10}$$

## Results and discussion

### *Temperature profile of the solar collector*

The temperatures at various locations of the collector such as inlet, glass plate, absorbing plate, and outlet of the solar collector have been measured every one-hour time interval from 9.00 a. m. to 4.00 p. m. Also, the instantaneous ambient temperature is recorded. These test readings have been taken for three days considering 7 hours per day. It is observed that as the temperature of the air inside the collector increases, the humidity of air reduces, and the moisture carrying capacity of air increases. Due to the presence of a DC blower provided at the outlet of the collector, the hot air is forced into the drying chamber. This hot air absorbs the moisture from the food product to be dried. The moist air is exhausted into the atmosphere from the drying chamber by a DC blower placed at the top of the dryer. On the first day of the test, it is observed that maximum temperatures of the ambient, absorbing plate and outlet of the collector are recorded as 39 °C, 99.2 °C, and 71 °C, respectively. On the second and third days, a similar test has been conducted and the corresponding highest temperatures are measured as 40.5 °C, 87 °C, 62.4°C, and 40.5 °C, 87 °C, and 67.1 °C, respectively as shown in the fig. 3. The unsaturated hot air coming from the outlet of the collector is passed inside the drying chamber and absorbs moisture contained in food products.

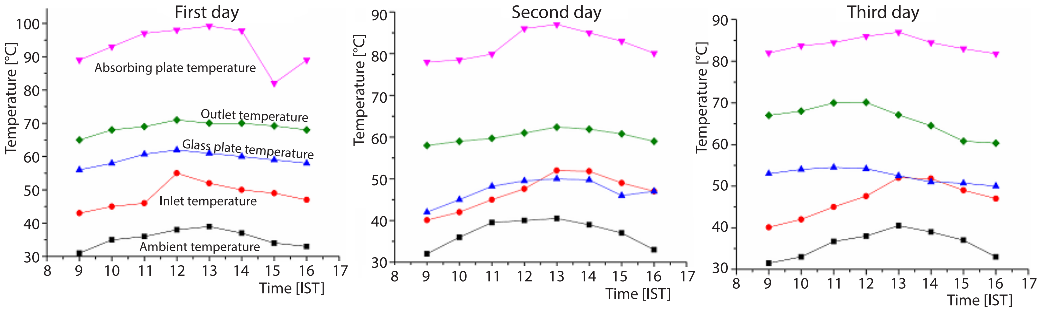


**Figure 3. The temperature profile of collector on 1st, 2nd, and 3rd day *vs.* time**

### *Temperature variation of the solar drying chamber*

To measure the inside tray temperature, the dryer is kept in a shadow-free location exposed to maximum solar radiation. For the experiment, the considered parameters for three days are presented in fig. 4. The experiment is started at 9 a. m. and every one-hour interval, the inside temperatures of four trays are measured by a non-contact type pyrometer. It has been found that there is a small variation in temperature from Tray 1 to Tray 3 inside the drying chamber occurs for placing wire mesh type trays. On the 1st day, the highest temperature for the 1st, 2nd, and 3rd trays are measured as 60.3 °C, 59.7 °C, and 58 °C, respectively. The hot air is circulated through the wire mesh type tray and it is observed that maximum evaporation of moisture from food products take place in 1st tray. On the second day, the highest temperatures are 61 °C, 60 °C, and 59.8 °C for 1st, 2nd, and 3rd trays while the ambient temperature is 40.5 °C. The temperature inside the tray gradually decreases from 1 p. m. to 4 p. m. Similarly, on the third-day temperatures are recorded as 64 °C, 63 °C, and 60 °C for 1st, 2nd and 3rd trays at 1 p. m. At the exhaust of the dryer moist air with a temperature of 59°C is dissipated into the atmosphere

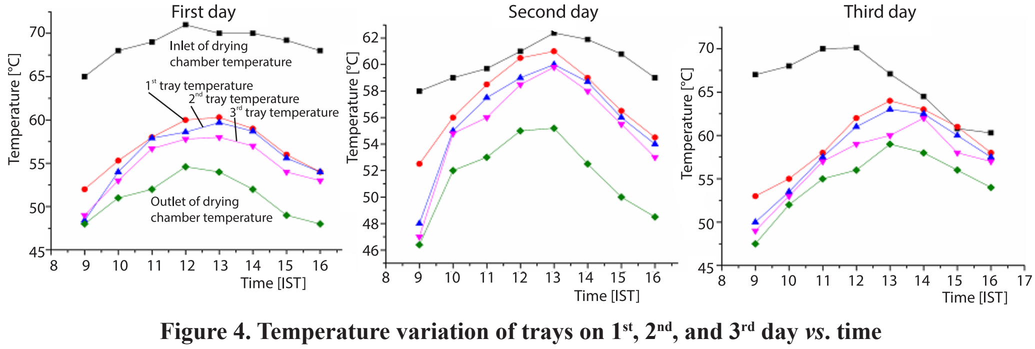


**Figure 4. Temperature variation of trays on 1st, 2nd, and 3rd day *vs.* time**

using a DC blower. It has been observed that the temperature in Tray 1 is more as compared to the temperature at the outlet of the drying chamber. In Tray 1, dry, hot and low humidity air circulates due to which the liquid moisture of mango evaporates in the vapour form to the top of the drying chamber. This vaporized moisture mixes with the hot air at the top of the drying chamber resulting in a fall in temperature. Due to this, there is a variation in temperature between the 1st tray and at the outlet of the drying chamber. Moreover, as Tray 1 is placed at bottom of the drying chamber and the outlet of the collector, the vaporized moisture from Tray 1 will move upward reducing the temperature in Tray 2 and Tray 3 placed above. The temperature variations of different trays have been shown in fig. 4.

### *Relative humidity profile of drying chamber*

The comparison between RH of ambient and hot air inside the drying chamber, and exhaust moist air recorded for three days is represented in fig. 5. The RH is measured using a hygrometer at a regular interval of time. At 1 p. m.. on the 1st day, the RH of heated and unsaturated air is recorded as 38% while for atmospheric air is 51%. As the temperature inside the drying chamber increases, RH gradually decreases, and hence the removal of moisture from food products increases. At exhaust of drying chamber, RH of moist air is recorded as 39%. It is thus observed that the RH of circulated hot air inside the drying chamber is less as compared to ambient air and exhaust moist air at the outlet of the drying chamber.

At 1 p. m. on the 2nd day, the RH for the 1st, 2nd, and 3rd tray and outlet of the drying chamber is measured as 38.7%, 38.9%, 38.5%, and 38.4%, respectively while ambient air is 50%.

Similarly, at the same time on the 3rd day, RH is measured for the 1st, 2nd, and 3rd tray and outlet of the drying chamber are 36%, 35.9%, 35.8%, and 36%, respectively while ambient air is 50.9%. It is observed that the humidity of air at the exhaust of the drying chamber increases as compared to hot air circulated inside the different trays.

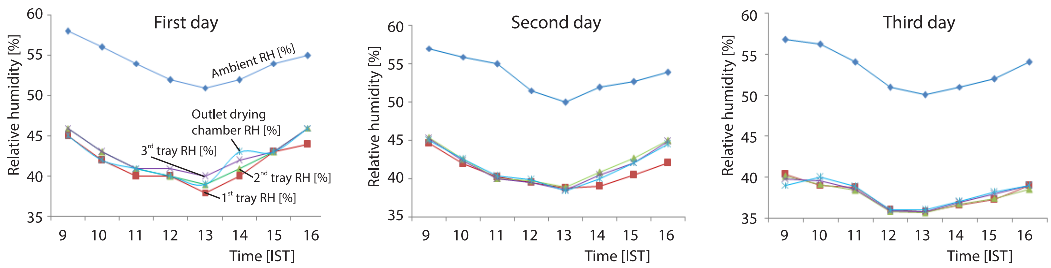


**Figure 5. Different relative humidity profiles of the drying chamber and ambient air *vs.* time on the 1st, 2nd, and 3rd day**

### *Velocity variation of the dryer*

Different temperature range for different products is considered. But there should be enough and a constant mass-flow rate of hot and dry air is required for removing moisture within a specific time. The velocity of air at the inlet of the collector and outlet of the drying chamber is measured. A DC blower with a diameter of 60 mm is connected for removing moist air from the drying chamber and the velocity of air is recorded by anemometer. The maximum velocity of moist air at the outlet of the drying chamber is measured as 2.37 m/s while at inlet collector air velocity is 0.9 m/s. By taking the density of air at 40 °C as 1.127 kg/m$^3$, and the velocity of air at the inlet of the collector as 0.9 m/s, the mass-flow rate of air is calculated as 0.0028 kg/s while considering velocity at the outlet of the drying chamber as 2.37 m/s, the mass-flow rate is calculated as 0.0075 kg/s and a very small variation of the mass-flow rate of air is observed from 9 a. m. to 4 p. m. On the second day, the maximum velocity at the outlet of the drying chamber is 2.35 m/s and at the inlet of the collector is 0.9 m/s. The maximum mass-flow rate of air at the inlet collector is calculated as 0.0028 kg/s while at the outlet of the drying chamber is 0.00748 $m^3/s$ by considering the density of air at 40 °C as 1.127 $kg/m^3$. On the third day, the maximum velocity at the outlet of the drying chamber is 0.89 m/s and the mass-flow rate at the inlet of the collector and outlet of the drying chamber are 0.0028 kg/s and 0.00748 kg/s, respectively. Figure 6 represents velocity variation for the outlet of the drying chamber and inlet of the collector.

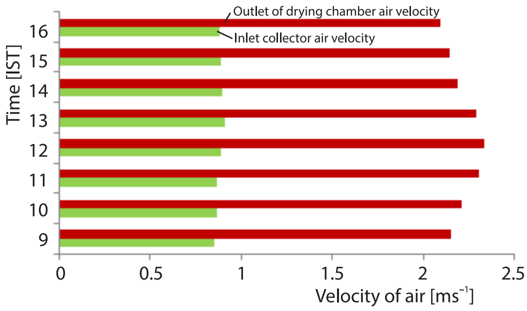


**Figure 6. Velocity variation of solar dryer**

### *Measurement of solar irradiance of collector*

The solar radiation incident on a glass plate is recorded at regular intervals of time by using a light meter and presented in tab. 2. Maximum solar radiation measured during April for the 1st, 2nd, and 3rd day is 670 $W/m^2$, 657 $W/m^2$, and 643 $W/m^2$, respectively at 1 p. m. It is observed that the amount of incident solar radiation on the glass plate of the collector increases from 9 a. m. to 1 p. m. and reduces from 1 p. m. to 4 p. m.

**Table 2. Measurement of solar radiation of glass plate of the collector in $W/m^2$**

| Time in IST | 1st day | 2nd day | 3rd day |
|---|---|---|---|
| 9 | 451 | 432 | 434 |
| 10 | 478 | 467 | 454 |
| 11 | 551 | 502 | 548 |
| 12 | 635 | 609 | 602 |
| 13 | 670 | 657 | 643 |
| 14 | 640 | 650 | 621 |
| 15 | 601 | 579 | 537 |
| 16 | 509 | 501 | 436 |

### *Comparison study of drying rates of different types of solar drying*

The sample initial, final mass, drying time, and percentage of mass reduction are compared for open Sun drying and solar drying. The drying time required in a solar dryer is 24 hours while in open solar drying is 56 hours. The average percentage of mass reduction in three trays has been evaluated and compared with open Sun drying. It is found that the percentage of mass reduction in forced convection, open, and natural-convection solar drying are 50%, 22%, and 41%, respectively. The initial and final mass of mangoes on the 1st, 2nd, and 3rd days have been evaluated for both forced convection and open solar drying system as shown in fig. 7.

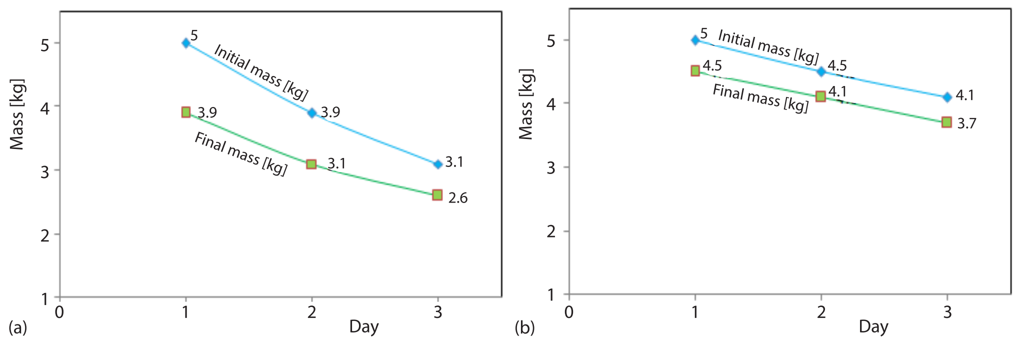


**Figure 7. Initial and final mass of mangoes for 1st, 2nd, and 3rd day during the drying process; (a) forced convection solar drying and (b) open sun drying**

The average drying rate on the 1st, 2nd, and 3rd days is shown in fig. 8. Drying rate is more in forced convection as compared to natural-convection and open solar drying process by considering 7 hours of drying time in each day. Figure 9 represents the result before and after drying of mangoes inside the drying chamber. It has been observed that the quality and nutritional content of dried mangoes in a solar dryer is more than that of the products dried under an open solar drying process. The quality such as taste, aroma, and color is better in the case of forced convection solar drying systems in comparison open sun drying and natural-convection solar drying processes. This is due to the highest loss of vitamins from the dried products because of the highest exposure to ultraviolet radiation during open solar drying. Secondly, mangoes dried under open and natural-convection solar drying are slowly dehydrated and contain higher moisture due to a longer period of drying which causes losses of vitamins. The dried mangoes in a forced convection solar dryer are preserved for a longer period.

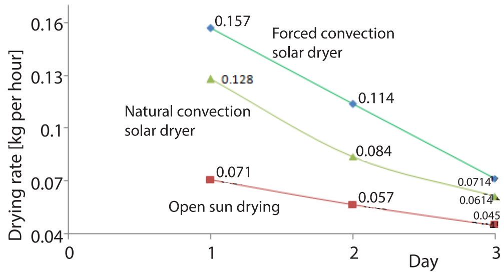


**Figure 8. Average drying rates of open Sun drying, forced, and natural-convection solar dryer**


**Figure 9. Drying of mangoes inside the drying chamber; (a) before drying and (b) after drying**

### *Performance indicators*

- Instantaneous collector efficiency, $\eta_c$, has been calculated as 59% by taking maximum mass-flow rate air as 0.0048 kg/s, maximum temperature difference at the inlet and outlet of the collector as 34 °C, average instantaneous flux in the tilted surface as 434 W/m$^2$ as described in section *Evaluation of performance indicators of solar dryer*.
- The drying efficiency, $\eta_{thermal}$, has been obtained as 32.25% by taking the moisture evaporated, $m_{WT}$, as 9.5625 kg from 15 kg of fresh food products, latent heat of evaporation, $L$ as 2260 kJ/kg, collector area $A_c$ as 1 m$^2$, instantaneous flux on the tilted Surface I as 670 W/m$^2$ as given in section *Evaluation of performance indicators of solar dryer*.
- The DR is evaluated as 0.15178 kg per hour by taking the moisture to be evaporated as 3.1875 kg from 5 kg of fresh food products and time is taken, $t$ as 21 hours as given in section *Evaluation of performance indicators of solar dryer*.
- The HUF is calculated as 0.229 from the collector temperature, $T_C$, as 710 °C, drying chamber temperature, $T_d$, as 640 °C, and ambient temperature, $T_a$, as 40 °C as given in section *Evaluation of performance indicators of solar dryer*.
- The COP is calculated as 0.77 using as given in section *Evaluation of performance indicators of solar dryer*.
- The moisture content on a dry basis, $M$, is calculated as 2.55 from the initial moisture content as 0.71 and final moisture content as 0.2 as explained in section *Evaluation of performance indicators of solar dryer*.

### *Economic evaluation of solar dryer*

The economic viability of any system is very important for the success and commercialization of any new technology. Different economic indicators are used for the economic evaluation of forced convection solar dryers. The costs and economic parameters are represented in tab. 3. The total capital cost of the solar dryer during installation and construction is 30736 INR. The annual cost of the solar dryer is 32236 INR and it is the sum of total capital cost. Maintenance cost (assuming 1% of the capital cost) and labour cost. The drying cost, $X$, is 75 INR. which is obtained from eq. (8) presented in section *Experimental analysis*. The amount of fresh products to be dried is taken as 1000 kg. The annual production of dry products is 430 kg.

**Table 3. Cost data and economic evaluation of solar dryer**

| Items | Cost per year [INR] | Cost per year [USD] |
|---|---|---|
| Total capital cost = material cost + labour cost | 30736 | 384.79 |
| Annual cost = maintenance cost (assuming 1% of capital cost) + labour cost | 32236 | 403.55 |
| Drying cost, $X$ | 75 | 0.94 |
| Annual price of fresh product, $P_{fresh\ prouct}$ | 55000 | 688.55 |
| Annual price of dry product, $P_{dryproduct}$ | 64500 | 807.47 |

The pay-back period is calculated as 1.439 years as discussed in section *Experimental analysis*. Similarly, the cost-benefit ratio is evaluated as 2.0008.

### *Validation and comparison of experimental data*

To validate the results obtained from the aforementioned experiment, parameters such as average drying chamber temperature, average collector efficiency and average drying efficiency have been compared with the results obtained from the previous literatures as shown in tab. 4. It has been observed that the present solar dryer has higher performance values comparing to previous literatures considering same testing condition.

**Table 4. validation of experimental data for previous and present study**

| Reference | Type of dryer | Testing condition | Average drying chamber temperature [°C] | Average collector efficiency [%] | Average drying efficiency [%] |
|---|---|---|---|---|---|
| Present study | Indirect type forced convection solar dryer | Sample: Mango; mass: 5 kg, time 7 hours | 57 | 59 | 32.25 |
| [19] | Forced convection solar dryer | Sample: Mushroom slices, time: 9 hours | 43.8 | 67.85 | 67.66 |
| [16] | Indirect type forced convection solar dryer | Sample: Mango; mass: 24 kg; time: 24 hours | 52 | 49.06 | 30.9 |
| [7] | Indirect type forced convection solar dryer | Sample: Guava slices; mass: 800 g, time: 14 hours | 47.5 | 65.37 | 6.84 |
| [4] | Indirect type forced convection solar dryer | Sample: Ivy gourd; mass: 800 , time: 13 hours | 32-62 | 77.2 | 7.8 |

## Conclusion

The present initiative is aimed to develop a forced convection solar dryer for hygienically drying mangoes. This is an environmentally friendly and quick process of drying for higher value addition food products. There is a constant mass-flow rate of air and more uniformity of hot air circulation is achieved by using a DC blower powered by a solar panel. Various performance indicators such as instantaneous collector efficiency, drying efficiency, drying rate, COP, HUF, and moisture content on a dry basis are obtained by considering solar radiation incident on collector, temperature, RH of drying chamber as well as collector. Instantaneous collector efficiency, drying efficiency, drying rate, HUF, COP, and moisture content on a dry basis are evaluated as 59%, 32.25%, 0.15178 kg per hour, 0.229, 0.77, and 2.55, respectively. A comparison assessment has been made for both forced, natural-convection, and open solar drying system. By taking the same period of drying time, it is found that the average drying rate in forced, natural-convection, and open solar drying is 0.157 kg, 0.128 kg, and 0.071 kg per hourr, respectively. The maximum temperature at the outlet of the collector and drying chamber is recorded as 71 °C and 64 °C, respectively which is sufficient enough to dry the food product. It is experimentally found that the temperature inside the forced convection solar dryer increases by 20-30 °C more than the ambient air temperature. The percentage of mass reduction is more in forced convection solar dryer compared to the traditional open Sun drying process. Economic indicators such as pay-back period and cost-benefit ratio are evaluated as 1.439 years, and 2.0008, respectively by considering various economic parameters. Validation and comparison of experimental data are also conducted. More research can be pursued for reducing heat loss and also using a thermal storage device.

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