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Performance evaluation and economic analysis of inclined solar dryer for *Capsicum annuum* L. (Red chilli) drying

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ABSTRACT

This study presents an assessment of the performance and economic viability of solar dryers for drying perishable agricultural products. The dryer was constructed using locally sourced materials such as galvanized iron sheet, M.S. angle, glass, and S.S. wire mesh. The ability to tilt the dryer allows for optimal solar radiation absorption throughout the year in Jodhpur, India. It is well-established that a tilted surface captures more solar radiation compared to a horizontal plane, hence the utilization of a solar dryer in this research. A drying experiment was carried out in January 2023 using the dryer to dehydrate red chilli (Capsicum annuum L.). The maximum stagnation temperature inside the drying chamber was recorded at 65°C, which decreased to 55°C when loaded with 10 kg of chilli, while the outside ambient temperature was 26°C on a clear sky day (from 08:00 h to 18:00 h) in January 2023. Over the course of seven days, the moisture content of the chilli decreased from 80% (wet basis) to approximately 9%. The open sun drying method took 14 days for reducing the moisture content of red chillies to the same level. The dryer's thermal efficiency was calculated to be 16.25%. The economic analysis of the solar dryer indicated a high internal rate of return (IRR) of 82.5% and a short payback period of 1.50 years, highlighting its cost-effectiveness. The cost-benefit ratio was found to be 1.98, demonstrating the potential of solar dryers as a substitute for traditional drying methods. Economic parameters such as net present value (₹40220) and system annuity (₹5430) confirmed the economic feasibility of the system. Inclined solar dryers in remote or rural areas have the potential to significantly reduce post-harvest losses and carbon emissions. The adoption of solar dryers would greatly benefit farmers in the arid region of Rajasthan.

Keywords: Inclined solar dryer, red chilli, moisture content, thermal efficiency, drying time, cost benefit ratio

INTRODUCTION

Chilli, also known as *Capsicum annum* L, is a significant spice that is cultivated in India. It is grown across an area of 7.44 lakh hectares, resulting in an annual production of 18.66 lakh MT. This spice holds a crucial position in the commercial spice industry and is widely utilized as a universal spice. In the Indian diet, chilli plays a vital role. It is not only used as a spice worldwide but also in the production of beverages and medicines. Chilli is a rich source of vitamins, particularly vitamin A and C. The majority of the chillies produced in India are consumed domestically, with only 5 to 7 percent being exported. The shelf life of freshly harvested chillies is approximately 2-3 days, with a 12-15% cumulative loss (Fudholi *et al.,* 2014). To prevent the growth of microflora and maintain quality, it is necessary to reduce the moisture content and provide aeration to the chillies post-harvest. Therefore, it is essential to dry the chillies quickly without compromising their color and pungency. Traditionally, fresh chillies are preserved by sun-drying the fruits immediately after harvest without any special treatment. During traditional drying, the fruits are laid out in the sun on a hard dry surface such as concrete or the flat roof of a house, in thin layers. The chillies are regularly turned to ensure uniform drying and prevent discoloration or mold growth. Sun drying of chillies typically takes 14-21 days, depending on weather conditions.

To address these drawbacks, one can opt for solar drying or industrial drying methods like hot air instead of the traditional drying process. Mechanical drying, commonly used in developed nations as a substitute for sun drying, is not feasible for small farms in India due to the high costs involved in both investment and operation. The arid region is blessed with renewable energy sources like solar energy, wind power, and biogas. The average value of solar energy in arid region of India varies from 5.8 to 6.3 kWh m-

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^{2}day^{-1} (Poonia *et al.,* 2022a). Solar drying has emerged as a promising substitute for sun drying in developing nations such as India, primarily due to its minimal operational cost in terms of fuel expenditure (Purohit *et al.,* 2006; Poonia *et al.,* 2017). The utilization of solar energy for drying purposes offers several advantages, including being a cost-effective, renewable, and abundant source of energy. Moreover, it is environmentally friendly and economically viable, making it a favorable choice for rural farmers (Sharma *et al.,* 2009). Additionally, solar drying proves to be a more convenient option for rural areas and regions with limited or irregular access to electricity. Extensive research on solar drying has demonstrated its efficacy as a superior alternative to open sun drying, resulting in the production of high-quality dried products (Mahapatra and Imre, 1990; Sodha and Chandra, 1994; Ekechukwu and Norton, 1999 and Hossain *et al.,* 2005).

The drying characteristics of red chilli were studied by Wade *et al.* (2014) and compared with different drying methods such as open sun drying, indirect solar cabinet dryer, solar tray dryer, and hot air oven. The results showed that the highest drying rate was observed in the solar tray dryer (57–0.03), followed by the hot air oven (47–0.08), indirect solar cabinet dryer (33.8–0.24), and open sun drying (31–0.01) under similar conditions. Sadhna *et al.* (2006) reported that the initial moisture content of fresh red chillies ranged from 300 to 400% (db), which is too high for processing and storage. Therefore, it is essential to reduce the moisture content of chilli to 8–9% (db). Hossain and Bala (2007) found that the moisture content of red chilli decreased from 2.85 kg to 0.05 kg (db) in 20 hours using a solar tunnel dryer, while it took nearly 32 hours to achieve a moisture content of 0.09 kg using conventional sun drying. Fudholi *et al.* (2013) conducted drying experiments on chilli using open-sky method and solar drying with convection. They found that it took 33 hours to reduce the moisture content from 80% (wb) to 10% (wb) in solar drying, while it took 65 hours in open-sky drying. Enclosed solar drying not only reduces the drying time by 49%, but also minimizes the risk of contamination when chillies are exposed to the ambient environment. Chatchawal *et al.* (2017) reported that it took 52 hours to dry red chilli from 74% to 13.5% (wb) in a low temperature solar drying system. Kaewkiew *et al.* (2012) dried 500 kilograms of red chilli with an initial moisture content of 74% (wb) in 3 days, while natural sun drying required 5 days. Janjai *et al.* (2011) used a solar greenhouse dryer to dry 300 kg of red chili, reducing its moisture content from approximately 75% to 15% in 3 days, with an estimated payback period of 2.5 years. Kumar *et al.* (2020) carried out experiments on drying 250 kg of red chilli using a large-scale natural convection solar greenhouse dryer. Their findings revealed that the solar dryer decreased the moisture content of red chilli from 79% (w.b.) to approximately 10% (w.b.) within 55 hours, in contrast to the 124 hours required for open-sun drying, resulting in a 56% reduction in drying time. The thermal efficiency of the dryer was determined to be 16.25% for chilli drying, with a specific energy consumption of 6.06 kWh/kg.

With this in view, an inclined solar dryer was designed and developed at ICAR-Central Arid Zone Research Institute, Jodhpur to dry perishable agricultural produces. The ability to tilt the dryer allows for maximum solar exposure throughout the year in Jodhpur, India, and an optimally inclined surface receives 22.8% more solar radiation compared to a horizontal surface. Consequently, the optimally tilted solar dryer was utilized for this research. The study aimed to assess the drying characteristics of chilli to outline the thin-layer drying process for solar drying of chilli.

MATERIALS AND METHODS

Design of solar dryer

An inclined solar dryer was designed and fabricated at the workshop of ICAR-Central Arid Zone Research Institute, Jodhpur, India. The solar dryer (1280 mm ×980 mm) based on the natural convection operation principle mainly consists of a rectangular box made of galvanized steel sheet (22 gauge) with two drying trays. A glass roof (area of collector 1.25 m^2) made of clear window glass (4mm thick) is provided at the top of the box and a layer of dried pearl millet stems insulation is provided at the base (Fig. 1). The dimension of two drying trays made of stainless steel angle frame and stainless steel wire mesh was (950 mm ×600 mm). The drying material can be kept on two trays and can be placed on an angle iron frame in the dryer through an openable door provided on the rear side of the dryer. Six plastic pipes are fixed in the front wall of the dryer just below the trays to introduce fresh air at the base. Two tapered slits are made on the sidewalls of the dryer for escaping the hot moist air from the drying chamber. An overhang over these slits protects the material from rain and wire mesh in these slits safe guards against flies and squirrels. An adjustable iron angle stand is provided to keep the dryer at optimum tilt by latitude and season of operation. The actual installation of the optimally tilted solar dryer is shown in Fig. 2.

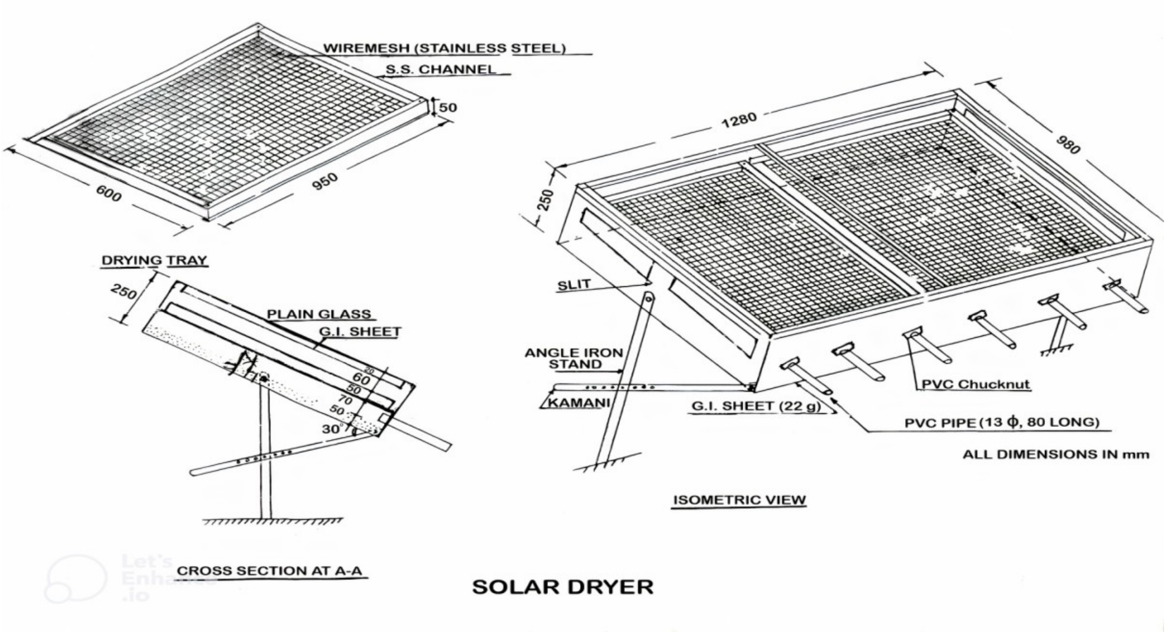

Fig. 1: Schematic diagram of inclined solar dryer

Fig. 2: Drying of red chilli in the inclined solar dryer

Experimental procedure

The experiments was conducted at ICAR-CAZRI, Jodhpur, India (26°18'N and 73°04'E) in January 2023 under clear sky conditions. To carry out the drying experiment, 10 kg of fresh chilli vegetables were obtained and divided equally on trays placed on the left and right sides of a solar dryer and open sun drying setup. The experiments took place between 8:00 am and 6:00 pm. A thermopile pyranometer was used to measure the hourly total solar radiation intensity (Gs) on a horizontal surface. Inside the dryer, temperatures were measured using a DTM-100 thermometer equipped with point contact thermocouples, accurate to 0.1°C. The ambient air temperature was measured using a mercury thermometer placed in an ambient chamber, accurate to 0.1°C. The moisture content of the samples was determined following the method described by Poonia *et al.* (2022a). Every 60 minutes, a 100 g sample was taken from the trays using a digital electronic balance (Testing Instrument Pvt. Ltd., India) with an accuracy of ±0.001 g to measure the moisture content of the drying product. The initial and final moisture contents of the samples were determined using the drying oven method at 105°C. The difference in mass before and after drying in the oven provided the moisture content.

The initial moisture content of chilli vegetables on a wet basis was calculated using the relation:

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

Where M_i is the initial moisture content of chilli on wet basis expressed in %, W_i is the initial weight of chilli in g and W_f is the final weight of chilli in g. The recorded moisture contents for each sample were then used to plot the drying curves. The drying rate of chilli vegetables were calculated using following equation.

$$DR = \frac{\Delta M}{\Delta t} \text{------------------ (2)}$$

Where, ΔM = loss of the mass of the chilli (kg water/kg dry matter); Δt = interval of time (m)

Thermal efficiency (η)

The efficiency of the system's drying process is determined by the ratio of energy needed to evaporate moisture to the heat provided to the dryer. In the case of a solar collector, the heat supplied to the dryer is derived from the solar radiation received by the collector. The system drying efficiency serves as a metric to evaluate the overall performance of a drying system. The subsequent equation can be utilized to calculate this efficiency (Poonia *et al.,* 2018a and 2022a):

 -------------- (3)

Where A = Absorber area (m^2); H_T = Solar radiation on horizontal plane (J m^{-2} hr^{-1}); L = Latent heat of vaporisation (J kg^{-1}); M = Mass of moisture evaporated from the product (kg); θ = Period of test (hr) and η = Efficiency of the solar dryer.

Economic analysis of PV hybrid solar dryer

Economic analysis of the dryer was carried out by computing five economic attributes, namely, net present value (NPV), pay-back period (PBP), benefit-cost ratio (BCR), annuity (A) and internal rate of return (IRR) determined for judging the economic viability of the dryer.

Net Present Value (NPV): The objective of calculating the net present value is to compare the value of future benefits with the cost of the initial investment and take into account the suitable interest rate. The net present value of solar devices was worked out using following equation (Singh *et al.,* 2020):

$$NPV = \frac{(E-M)}{a}\left[1-\left(\frac{1}{1+a}\right)^n\right] - C \text{------------} (4)$$

- Initial cost (C) = Rs 9000 /-, a = (0.10) and n = 10 years
- Gross benefits from sale of products (E) = Rs 10800/-
- Maintenance cost of dryer (M) = Rs 4000 /-

where, C is initial cost, a is the rate of interest, n is the number of years

The Benefit-Cost Ratio (BCR): Benefit-cost ratio was expressed as the ratio of sum total of initial cost and net present value to the initial cost as given below,

$$BCR = \frac{C + NPV}{C}$$

$$BCR = 1 + \frac{NPV}{C} \text{----------} (5)$$

2.8.3 Annuity (A): The annuity (A) of the project indicates the average net annual returns. This term can be given as,

$$A = \frac{NPV}{\sum_{t=1\ to\ n} \left(\frac{1}{1+a}\right)^n} \text{---------} (6)$$

Pay Back Period (PBP): Payback period was worked out as the length of time required to recover initial investment through net average annual cash inflows generated by investment. PBP was calculated by equation:

$$PBP = \frac{\log\frac{(E-M)}{a} - \left(\log\frac{(E-M)}{a} - C\right)}{\log(1+a)} -------------(7)$$

Internal rate of return (IRR): At 10% interest rate the NPW is Rs 40220/- respectively and 60% rate of interest the NPW is Rs 3516.44. However, the NPW is negative at 90% interest rate (i.e. NPW = Rs –804.93/-). The IRR can determine using the following relationship and taking low discount rate as 60% and higher discount rate as 90%.

$$IRR = lower\,discount\,rate + \frac{Difference\,of\,discount\,rate\,x\,NPV\,at\,lower\,discount\,rate}{(NPV\,at\,lower\,discount\,rate - NPV\,at\,higher\,discount\,rate)} -----(8)$$

RESULTS AND DISCUSSION

The drying trial for dehydrating chillies in this dryer was conducted in the winter season and performance was compared with open-courtyard sun drying. Equal quantities (10 kg) of chillies were deployed inside as well as outside the dryer. The exposure surface areas were the same in both cases. Hourly recordings of the air temperature inside the dryer, particularly at the center of the drying trays, and the surrounding air temperature were taken from 08:00 hr to 18:00 hr during the drying process. Furthermore, the solar radiation on the glass surfaces of the dryers was monitored hourly. Random samples were chosen to determine the initial and final moisture content of the products, cut into small pieces if necessary, weighed using a precise scale with an accuracy of 10^{-5}gm, and then oven-dried. The drying trays were weighed every 2 to 3 hours throughout the experiment until the product reached a consistent weight, indicating it had reached its equilibrium moisture content. The moisture content of the materials was calculated based on the weight difference. The highest temperature observed inside the drying chamber was 65°C, but when ten kg of chilli was loaded, the maximum temperature dropped to 55°C, while the outside temperature was 23°C. The variations in solar insolation, ambient temperature, and internal dryer temperature during the drying trials with chilli are depicted in Fig. 3.

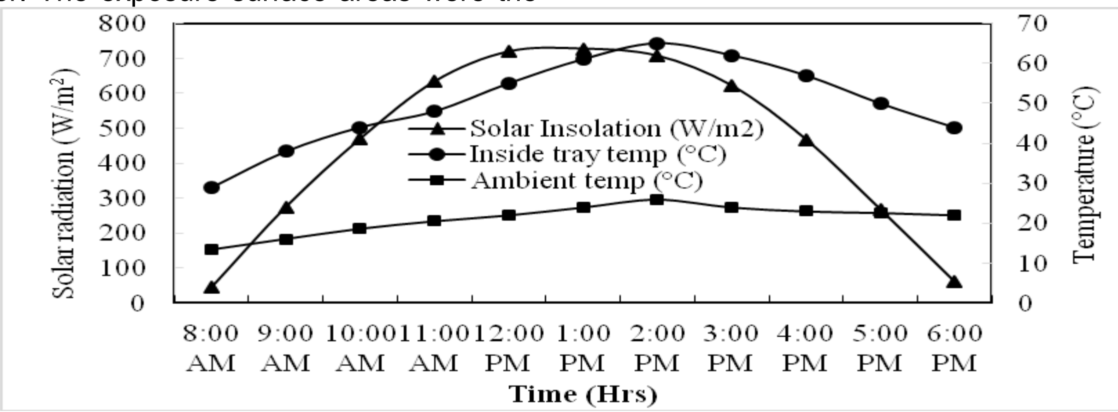

Fig.3. Temperature and solar insolation variation with time for load test (chilli)

The variation of measured moisture content (wet basis) of the chillies on each day of drying trials was shown in Fig. 4. It can be seen that the moisture content was reduced from about 80% to 9% within 7 days by the solar drying method and on 6th day it come 25%, however after 7 days (9% moisture content) it could be safely stored for further use. In contrast, it took 13 days to dehydrate the same quantity of chillies by open sun drying. From the steep slope of the drying curve (Fig. 4) it can further be seen that the drying rate in the solar dryer increases sharply when the moisture content falls below 65%. On the other hand, the drying curve is flat in the case of the open courtyard method. The shape of the drying curve indicates 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 indicates that diffusion has governed the internal mass transfer. This is in agreement with the results of study on ber (Poonia *et al.,* 2018a and Das and Dutta, 2013) and in date palm fruits (Poonia *et al.,* 2022b).

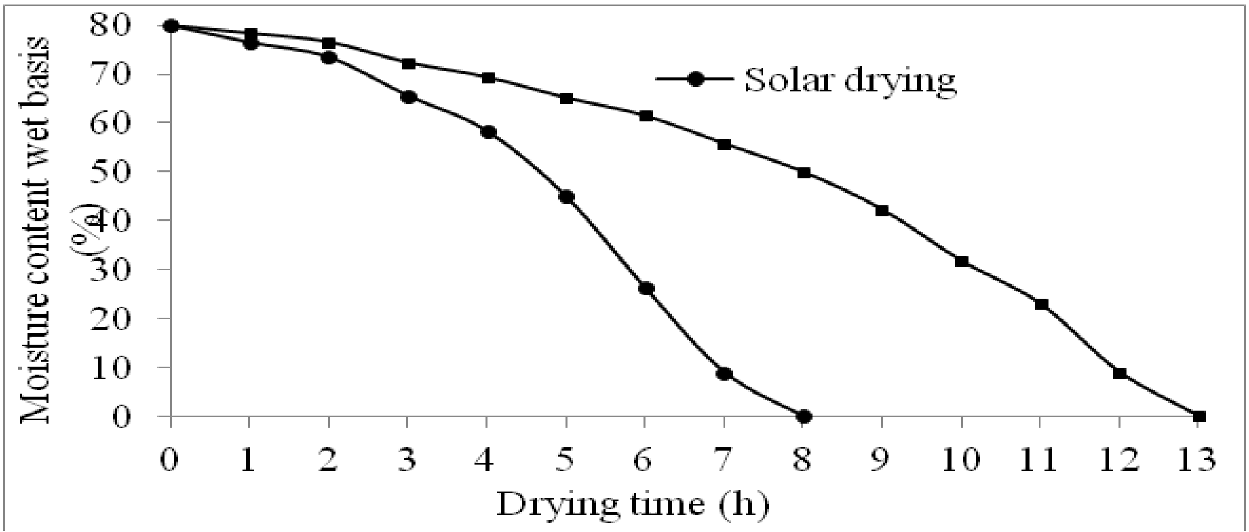

Fig. 4: Variation of moisture content of chilli during solar and open sun drying against drying time

The overall efficiency of the drying is affected by several factors such as drying time, climatic conditions (solar insolation and temperature), the drying characteristics of the dried materials, and structure of the drying devices, etc. The average efficiency of solar energy utilization in the solar dryer was calculated by equ (3), and it was found that about 16.25% solar energy was utilized in this solar dryer. During the drying process, it was observed that higher efficiency was observed at the initial stage of drying. Later, this dryer efficiency was decreased due to decreased moisture content. Moreover, the efficiency at a higher drying load of 10 kg might be due to the highest drying time.

Analysis of economic viability

The total cash inflow and outflow for the fabrication of the solar dryer were used to calculate the net present value (NPV) of the project. The initial cost of the dryer is Rs 9,000 with a discount rate of 10% and a device life span of 10 years. The gross benefit from selling the product is Rs 10,800. By using Equ (4), the NPV of the investment in the solar dryer is determined to be Rs 40,220. Based on the NPV, it can be concluded that the fabrication of the dryer is more economical compared to the solar biomass hybrid dryer (Dhanushkodi *et al.,* 2015) and PVT hybrid solar dryer (Poonia *et al.,* 2018 a, b). The benefit-cost ratio for the dryer is calculated by dividing the present worth of the benefit stream by the present worth of the cost stream using Equ (5), resulting in a ratio of 1.98. Equ (6) is used to determine the annuity of the dryer, which indicates that the average net annual returns from the dryer amount to Rs 5430. The payback period for the dryer is 1.50 years, which is lower than its expected lifespan of 10 years. In comparison, the payback period for the PVT hybrid solar dryer is 2.26 years with an initial investment of Rs. 14,000 (Poonia *et al.,* 2018a). The internal rate of return (IRR) can be determined using Equ (8). At an interest rate of 10%, the NPW is Rs 41,830. At a 60% interest rate, the NPW is Rs 3516.44. However, at a 90% interest rate, the NPW is negative (i.e., NPW = Rs -804.93). The IRR in the present case is 82.5%, which is significantly higher than the cost of capital, indicating that the project is economically viable. The values of five economic attributes, namely, benefit-cost ratio (BCR), net present worth (NPW), annuity (A), internal rate of return (IRR) and payback period (PBP) was presented in Table 1.

Table 1 . Values of economic attributes

Attributes economics	Values
BCR	1.98
NPW	40220 Rs
A	5430 Rs
IRR (per cent)	82.5 %
PBP (years)	1.50 years

CONCLUSIONS

An optimally tilted solar dryer can be utilized for the dehydration of fruits and vegetables. The initial moisture content of chilli was decreased from 80% (wet basis) to approximately 9% within a span of seven days. The solar dryer reduces drying time by 50% compared to open-sun drying. The average thermal efficiency of the dryer for chilli drying was determined to be 16.25%. Farmers can dehydrate vegetables when they are abundant and inexpensive. Dehydrated vegetables can be sold during the off-season when vegetable prices are high, enabling farmers to generate additional income. The economic assessment of the inclined solar dryer unit demonstrated that its high internal rate of return (IRR) of 82.5% and low payback period of 1.50 years make it highly cost-efficient. The utilization of an inclined solar dryer significantly decreases drying time, energy consumption, and enhances the quality of dried products. Implementing inclined dryers in remote locations or rural areas can greatly reduce post-harvest losses and carbon emissions, providing substantial benefits to farmers in developing nations.

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