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DEVELOPMENT AND PERFORMANCE EVALUATION OF FORCED CONVECTION POTATO SOLAR DRYER

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This research paper deals with the design development and testing of a forced convection solar dryer, for drying and converting to flour of high moisture content vegetables like potatoes. The angle of solar collector was made adjustable for the absorption of maximum solar radiation by the absorber plate. The air flow rate was controlled by adjustable gate valve to find the optimum flow rate for dehydration of the product. The penetration of solar radiation raised the temperature of the absorber plate of the dryer to 110°C during the operation under stagnation or no load conditions. The maximum air temperature attained in the solar air heater, under this condition was 80°C. The dryer was loaded with 12 Kg of blanched potato chips having an initial moisture content of 89.75%, and the final desired moisture content of 6.95% was achieved within five hours without losing the color of potato chips, while the moisture contents reduction was from 89.75% to 33.75% for five hours in open sun drying under shade. The drying cost for 1 Kg of potatoes flour was calculated as Rs. 245 and it was Rs. 329 in the case of an electric dryer. The life span of the solar dryer was assumed to be 20 years. The cumulative present worth of annual savings over the life of the solar dryer was calculated for blanched potato chips drying, and it turned out be Rs.163177.67/- which was much higher than the capital cost of the dryer (Rs. 25000). The payback period was calculated as 0.89 years, which was also very small considering the life of the system (20 years).
Keywords: Forced convection solar dryer, tilt angle, potato chips, potato flour, payback period of solar dryer

INTRODUCTION

Food preservation is the only method to reduce the food losses and drying is the method that is being practiced since many centuries. In case of vegetables, which are also an important food product, 50% of wet vegetables (i.e., peels) are removed as waste while cooking (Wahidi, 1996). If the vegetables peels are dried, these could also be used as feed for animals. Also, as the water is removed during drying, a lot of fuel can be saved during transportation due to less volume and weight. It has been estimated that more than 80% of the food is produced by small farmers in the developing countries (Ong, 1999). The food products are usually dried under the open sun which is a common practice. However, there are several disadvantages with the natural sun drying process. Some of the demerits include degradation due to windblown debris, rain, insect infestation, rodents, birds, over/under drying etc. (Bankole *et al*., 2005). A solar dryer minimizes almost all the problems faced during natural sun drying, thus improving the quality of the dried product. Heating modes and the manner in which the solar heat is utilized classified the solar drying systems into two major groups, namely active solar energy drying systems(most of which are often termed hybrid or forced circulation solar dryers) and passive solar energy drying systems (conventionally termed natural circulation solar drying systems). A typical active solar dryer depends solely on solar energy as the heat source but employs motorized fans and/or pumps for forced circulation of the hot drying air through the drying chamber. Drying of agricultural products with solar dryers dates back a few decades. Several efforts have been made in the past to design and develop workable solar dryers for drying of agricultural products. However, little information was available on dehydration/drying of vegetables. This study was designed with the aim to fabricate and evaluate the dryer's performance for dehydration of potato for flour production.

MATERIALS AND METHODS

In order to carry out experimental work a forced convection solar dryer was fabricated and constructed using materials available in the local market. The ensuring paragraphs discuss in detail methodology of fabrication and evaluation of a solar dehydrator for potato.

***Components of the dryer*:** The dryer designed for experimentation consisted of base frame, solar air heater, drying cabinet, drying trays and blower. All the components were fabricated from the local materials except blower which was installed according to the air capacity requirement. The detailed description of all these components is given in the following paragraphs

***Base frame*:** Keeping in view, the heavy solar air heater and drying cabinet of this dryer (capable of drying about 12-16 Kg of fresh product per day) the frame was made up of angle iron having dimensions of 0.038 x 0.038 x 0.003 m. The size of the base frame was fixed according to the length, width, height of solar air heater and drying cabinet with adjustment of tilt angle for winter as well as for summer, i.e. latitude plus 15^o and latitude minus 15^o, respectively. It was 1.52 m in length, 1.52 m in breadth and 1.68 m high**.**

Solar air heater**:** The solar air heater of the solar dryer was constructed using 0.038 x 0.038 x 0.003 m angle iron in a rectangular box having dimensions 2 x 1.5 x 0.150 m. The specifications of the solar air heater are shown in Table 1.

The bottom of the solar collector was made from 0.001 m thick corrugated aluminum sheet painted matt black. To reduce the losses from topside of the absorber plate and to increase the temperature of air, using the greenhouse effect, a 0.005 m thick plain window glass was used as transparent cover to avoid heat losses from the top. The collector air channel depth was 0.127 m and air flow channel depth between the absorber and the transparent glass cover was kept 0.1 m. The total area of the solar air heater was kept three square meters for absorption of solar radiations. The bottom end of the solar collector was temporarily closed for the dryer (to convert into multi-shelf natural convection type where no electric supply is available, with the addition of chimney at the top of drying cabinet). Top glazing was divided into three sections, keeping in view breakage chances, having a surface area of 2 x 1.5 m. Sides were covered with 0.00158 m galvanized iron sheet and also painted matt black from internal side for maximum absorption of solar radiations.

One of the novel features of the solar air heater was its variable angle of tilt. Due to the variable inclination, the solar energy input per unit aperture area was more than that of solar dryers with fixed inclination and much more than that of solar dryers with horizontal aperture. Because of this feature, this dryer works efficiently at higher latitudes during winter. Also, due to the variable inclination, it can be used effectively at places in a wider region. Collector was designed in such a way that it could be tilted to any angle for maximum reception of solar radiations. In order to prevent heat losses a 0.152 m thick ply wood sheet was used as insulation at the bottom of the absorber plate. The solar air heater was tilted to an angle about 16.28^o with respect to the horizontal, which was considered to be an optimum angle for summer season as reviewed from literature, at University of Agriculture, Faisalabad, Pakistan. On the basis of measurements, at Faisalabad (Longitude 73.07^o E, Latitude 31.43^o N and altitude 0183 m above mean sea level (Iftikhar, 1996.), where the experiment was conducted, had about 11 hours 30 minutes of daylight, with typically about 8hours per day of sunshine available for drying (Agromet Bulletin, 2009).

Drying cabinet**:** The drying cabinet of the dryer was built from 0.025 x 0.025 x 0.004 m angle iron and 0.015 m galvanized iron sheet in a rectangular shape with 0.025 m depth. The dimensions of the drying cabinet were 1.5 x 0.6 x 0.66 m. The total volume of the drying chamber was 0.591416 m^3 and was located at the top end of the solar collector keeping enough length for Plenum chamber. The drying cabinet was divided into seven divisions separated by six perforated trays. The distance between each tray was 0.076 m except upper one which was 0.125 m. Top of the cabinet was enclosed with wire net for free exit of drying air. A cover was provided using galvanized sheet of 0.015m with sufficient space of 0.125 m for exhaust air, in a hut shape to save the product from direct sunlight and rain. Access door to the drying chamber was provided at one side of the cabinet through which trays could easily be placed.

Tray area**:** Total tray area for spreading the potato chips was calculated by making chips of an average sized potato (0.01 x 0.02 x 0.05 x 0.08 m). Three millimeter chips of one Kg potato occupied a space of 0.25 square meters with minor air spaces. Consequently one square meter tray area was considered sufficient for 4 Kg potato chips. The drying trays were made from 0.025 x 0.025 x 0.0015 m angle iron and 0.001 m galvanized iron sheet with single layer of chicken wire mesh at the bottom to allow drying air to pass through

Table 1. Specifications of solar air heater

Item	Specification
Absorber material galvanized iron sheet	Plate thickness 1mm
Dimension of absorber plate	1.5 m × 2 m
Absorber area	3 m^2
Absorber coating	Dull black paint
Glazing	Normal window glass (thickness 5 mm)
Number of glazing	1
Back insulation	wood shaving sheet (thickness 0.152 m)
Collector frame material	0.038 x 0.038 x 0.003 m angle iron
Collector tilt	16.28^o (with provision to adjust)
Collector area for air flow	0.152 m^2
Absorptivity of the absorber	0.85
Reflectivity of the absorber	0.15
Effective transmittance absorbance product	0.82

the potato slices. Each tray having an area of 0.97 $m^2$was divided into four sections with iron patty for extra strength with dimensions 0.0127 × 0.0032 m to provide a rigid foundation for the drying product without any deformation.

The loading capacity of each tray was kept 3-4 Kg potato slices arranged in a single layer for quick and efficient drying. The multi-shelf design resulted in better utilization of the heated air in the different trays as the distance between consecutive bottom and top tray was 0.075 m. Thus six trays were tiered in the drying cabinet at a distance of 0.075 m having a tray area of 0.97 m^2 for drying the total product of 12-16 Kg.

Blower**:** A 0.75 KW centrifugal blower rotating at 2800 rpm was used to circulate the hot air to the drying chamber through the solar air heater. Power input to the blower was measured with an energy meter having 70.4% accuracy. Two manually operated valves were provided at the inlet side of the blower to regulate the air flow for recirculation of exhaust air. The blower was attached through corrugated PVC pipe on the lower side of the collector for forced air circulation having a maximum volume flow rate up to 7.5 m^3/ min. A perforated PVC pipe was connected with the blower's corrugated pipe in such a way that the direction of air flow was parallel to the top glazing ensuring uniform air circulation over the absorber surface.

Experimental procedure**:** The research area is located in semi-arid region according to the climatic zones of Pakistan and fall under solar zone IV with Longitude 73.07^o E, Latitude 31.43^{o}N and altitude 0183 m above mean sea level (Iftikhar, 1996). The experiment was performed in order to evaluate the solar dryer with respect to air temperature, relative humidity of ambient air, solar radiation intensity, air flow rate of drying air and stagnation temperature of solar air heater. The effects of environmental and operating parameter on the performance of the dryer were investigated using various measuring devices. Thermometer up to 110°Cwas used to measure the ambient air temperature (hanged one meter above the ground under shade) and at the top of collector (where hot air entered the drying cabinet) with a least count of 1°C and an accuracy of ±0.5°C. The velocity of air in the pipe was measured by using a hot wire anemometer placed in the path of the air circuit, which contained sensor of 0.0762 meter diameter and digital display, to show the velocity in m/s. The range of the velocities measured by this instrument was (0.1–40 m/s) with an accuracy of ±2%. A pocket weather tracker was used to measure the temperature, relative humidity, wind speed of the ambient air as well as drying air moving from the solar air heater to the drying cabinet with accuracy (±1%). Samples of the product in the dryer were weighed at one hour interval during drying using electronic digital weighing balance with ±0.001 g accuracy.

Collector efficiency**:** Heat collection efficiency was calculated with the help of equations (Duffie and Beckman, 2006).

$$\eta = \frac{Q_u}{I_T A_c}$$

$$Q_u = A_c \times F_R[(S - U_L(T_{fm} - T_a)] \quad (2)$$

$$F_R = \frac{\dot{m} C_p}{A_c U_L}\left[1 - \exp\left(\frac{A_c U_L F'}{\dot{m} C_p}\right)\right] \quad (3)$$

$$F' = \frac{h_r h_1 + U_t h_2 + h_2 h_r + h_1 h_2}{(U_t + h_r + h_1)(U_b + h_2 + h_r) - h_r^2} \quad (4)$$

<u>Top heat loss coefficient</u>

$$U_t = \left[\frac{N}{\frac{C}{T_{pm}}\left[\frac{T_{pm} - T_a}{N + f}\right]^e} + \frac{1}{h_w}\right]^{-1} + \frac{\sigma(T_{pm}^2 + T_a^2)(T_{pm} + T_a)}{\frac{1}{\varepsilon_p + 0.00591 N h_w} + \frac{2N + f - 1 + 0.133\varepsilon_p}{\varepsilon_g} - N} \quad (5)$$

<u>Bottom heat loss coefficient</u>

$$U_b = \frac{k}{L} \quad (6)$$

<u>Edge loss coefficient</u>

$$U_e = \frac{(UA)edge}{A_c} \quad (7)$$

$$U_L = U_t + U_b + U_e \quad (8)$$

<u>Determination of heat transfer coefficients: Convective heat transfer coefficient</u>.

$$h_2 = Nuk/x \quad (9)$$

$$Nu = 0.015 R_e^{0.8} \quad (10)$$

$$R_e = \frac{\rho v D_h}{\mu} = \frac{\dot{m} D_h}{A_f \mu} \quad (11)$$

$$h_r = \frac{\sigma(T_p^2 + T_c^2)(T_p + T_c)}{\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_c} - 1} \quad (12)$$

<u>Wind convection coefficient</u>

$$h_w = 5.7 + 3.8\, V_w \text{(3.13)} \quad (12)$$

Valid for wind speeds of 0 -5 m/s

To simply all the calculations a computer program was developed in Microsoft excel for quick and accurate results.

Economic analysis**:** The life cycle savings had been calculated using life cycle analysis and payback period had been calculated for end users who were reluctant to install a system with long payback periods even when there was substantial long term savings.

Table 2. Constants used in economic analysis for potato solar dryer

Sr. No.	Cost of dryer DI and economic parameters	Pak Rupees
1	Material and labor cost for the construction of dryer DI	25000/-
2	Discount rate	20%
3	Rate of inflation	5%
4	Life span of the dryer	20 years
5	Electricity cost @ Rs. 4.00/kWh	20/-
6	Cost of fresh average sized potato @ Rs. 15/Kg	180/-
7	Potato flour 1.8 Kg/batch @ Rs. 500 /Kg	900/Kg
8	Repair and maintenance cost	10% of annualized capital cost
9	Salvage value of the unit after 20 years	5000/-
10	Dryer working days	90
11	Labor @ Rs.15/Kg (washing, peeling, slicing , blanching, placing, grinding and packing)	180/batch

***Annualized cost method*:** In the first step economic analysis was carried out using annualized cost method just to compare the cost of drying with other energy sources (Sodha *et al.*, 1991). Then, the annualized cost was divided by the amount of product dried per year to obtain the cost of drying per unit weight of dried product.

RESULTS AND DISCUSSION

***Experimentation on potato solar dryer*:** Effect of 3 m^3/min air flow rate: The drying trays of the solar dryer were loaded with 12 Kg blanched potato slices having loading rate of two Kg per square meter tray area. The average temperature varied from 39.6°C to 65.2°C, while the corresponding variation in the ambient temperature was 29.1°C to 35.7°C during the time period from 900 hours to 1300 hours. However, the temperature of the dryer started decreasing after 13:00 hours due to decrease in intensity of solar radiations while during the same period, the solar radiation intensity varied between 430 and 1115 W/m^2 Fig 1. The average temperature in the dryer was 10.5 to 29.5°C higher than the corresponding ambient air temperature for the same period as mentioned above. The duration for the difference of ambient and drying air temperature above 15°C was seven hours, which was due to the lower air flow rate as compared with the other experimental flow rates, i.e. 3, 4, 5 and 6 m^3/min. The duration of existence of temperature from 10°C to 15°C above ambient is important regarding performance evaluation of solar dryers as stated by Murthy (2008).

A comparison of solar dried product was made with open drying under shade because vitamin A should be retained during drying. However, as vitamin A is light sensitive, food containing it should be dried and stored in dark places (Ruslan *et al*., 2002).

In open drying under shade, the potato chips dried from 83.41% to 16.46% moisture content in eight hours with the same intensity. Thus, the product was not sufficiently dried for grinding to make powder. Also, the moisture content was too high for long term storage. Further, the product might be unhygienic due to being exposed to flies and insects. The moisture content reduction was from 83.41% to 9.49% in eight hours in the dryer, thereby reducing the drying time as compared to open drying under shade Fig 2. Dried foods that are not completely dried are susceptible to mold as reported by Ruslan *et al*. (2002). Further, in the potato solar dryer, the product was dried under hygienic condition down to 9.49% moisture content which was grounded to flour. The dried potato flour with less than 13% moisture content had a shelf life of one year (Garg and Prakash, 2000).

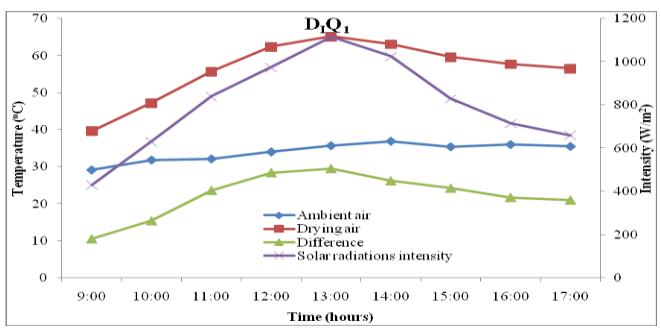

Figure 1. Solar radiation, ambient and drying air temperature difference

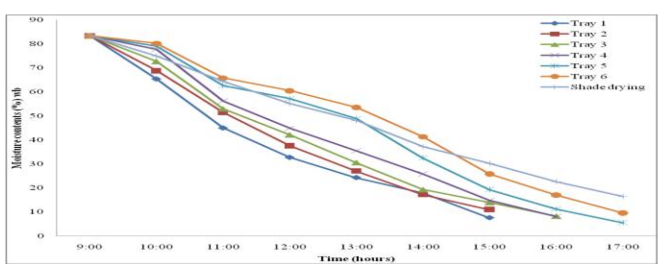

Figure 2. Drying rate in solar dryer I versus under shade drying

Thus, the product dried in potato solar dryer was suitable for grinding as well as for long term storage. The average moisture removal percentage for 1st, 2nd , 3rd, 4th, 5th and 6th drying trays was 12.64%, 12.08%, 10.74%, 10.75%, 9.74% and 9.24%, respectively, while corresponding value for open drying under shade was 8.37%. The results of drying curves obtained through experimentation were in line with the results obtained elsewhere (Sreekumar *et al*., 2008).

The drying air passing through the bottom tray (tray 1) was at higher temperature and low relative humidity whereas leaving from the last tray (tray 6) was of less temperature and high relative humidity. Moisture evaporation from the trays during drying of potato chips from 1st to the last tray was reduced due to moisture carrying capacity of the drying air which decreased with an increase in relative humidity. In first tray the moisture evaporation was high followed by a decreasing trend for the subsequent trays. It is known that as the moisture content of the product reduces, more energy is required to drive out the same amount of moisture from the product. The thermal efficiency and the useful heat gain by the solar dryer were calculated using equations 1 and 2 at the start of each hour during operation and is given in Figure 3.

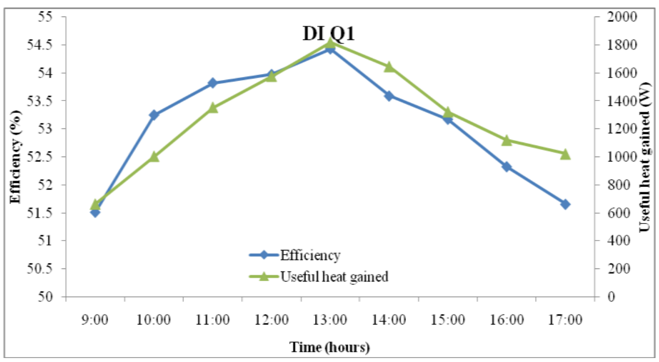

Figure 3. Efficiency and heat gain curves for dryer I with respect to time of the day

Maximum efficiency and useful heat gain of the dryer was observed at 1300 hours, i.e. 54.43% and 1820.78 watts, respectively. The reason for the higher efficiency at noon was due to higher intensity of solar radiations, temperature of ambient air as well as absorber plate resulting in high drying air temperature.

***Effect of 5 m³/min air flow rate*:** The drying trays in dryer were loaded with the same loading rate of blanched potato slices. The air flow rate was kept constant at five cubic meters per minute. The data were recorded for solar radiation incident on the aperture of the dryer, temperature and relative humidity of ambient air. The average temperature of drying air, exhaust air, relative humidity, temperature of the absorber sheet and temperature of glazing for the dryer were recorded. The parameters monitored, such as difference between the average temperature in the dryer and ambient air, with solar radiation is shown in Figure 4.

The average temperature varied from 44.9°C to 62.2°C, while the corresponding variation in the ambient temperature was 29.9°C to 35.4°C during the time period from 900 hours to 1200 hours. However, the temperature of the dryer started decreasing after 1200 hours due to the decrease in intensity of solar radiation while during the same period, the solar radiation intensity varied between 500 W/m^2 and 1050 W/m^2. The solar radiation decreased to 430 W/m^2 at 1300 hours decreasing the temperature difference between ambient and drying air to 16.2°C. However, the average temperature in the dryer was 15°C to 26.8°C higher than the corresponding ambient air temperature for the period from 900 hours to 1200 hours.

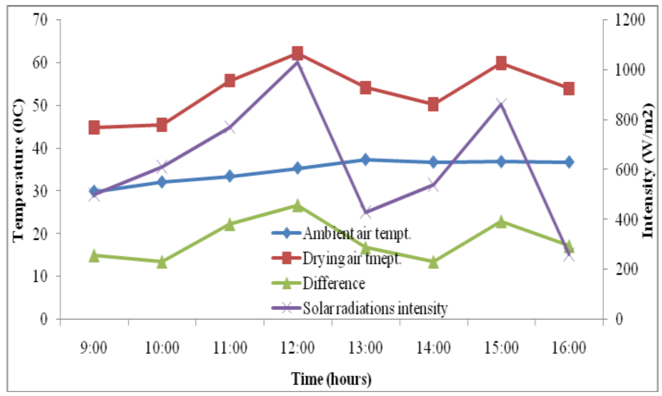

Figure 4. Solar radiations, ambient and drying air temperature difference

The average moisture content (wb) reduction of the potato slices in the dryer and in open air drying under shade as a function of drying time is shown in and Figure 5. In open drying under shade, the potato chips with same loading rate, dried from 86.65% to 27.25% moisture content in six hours. The moisture content reduced from 86.65% to 10.92% for solar dryer in the same period as mentioned above, thus the drying time as compared to open air drying under shade was reduced remarkably.

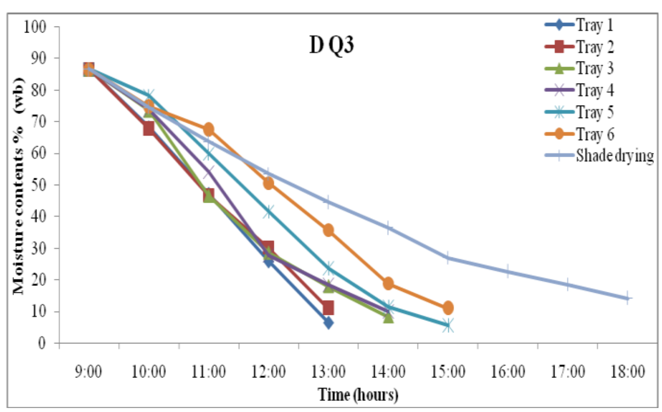

Figure 5. Drying rate in solar dryer versus under shade drying

The average moisture removal percentage for 1st, 2nd , 3rd, 4th, 5th and 6th drying trays was found 20.03%, 18.92%, 15.66%, 15.33%, 13.53% and 12.62%, respectively, while the corresponding value for open air drying under shade was 8.05%.

It was observed from the graph that with increasing flow rate, for the same solar dryer, the percentage extraction of moisture was also increased.

The thermal efficiency and useful heat gain of the solar dryer were calculated using equation 1 and 2 for each hour of operation and are given in Figure 6.

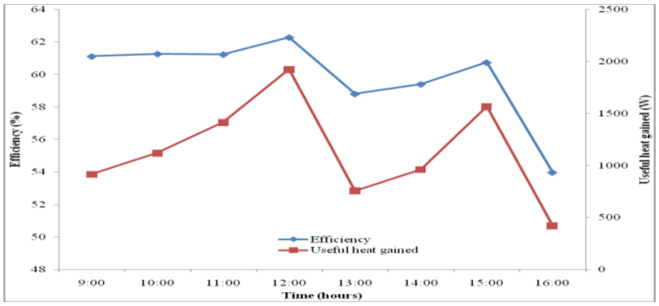

Figure 6. Dryer efficiency and useful heat gain curves with respect to time of the day

Maximum efficiency and the useful heat gain of the dryer were observed at noon i.e. 62.28% and 1924.55 watts, respectively. Higher efficiency at noon was registered due to higher temperature of ambient air as well as absorber plate resulting in high drying air temperature. There was a sudden drop in the efficiency and useful heat gain due to the drop of solar radiations intensity at 1300 hours as evident from Figure 6.

CONCLUSIONS

Based on the results of this study, the following conclusions may be drawn. The thermal efficiency of the dryers was in the range of 58 to 64 % due to low temperature operation and ultimately low heat losses. The solar dryer could dry 12 Kg potato per dryer only in five to six hours, sliced into three millimeter. The rising cost of potato in the months of November and December (Rs.45/Kg) gave a good option to poor farmer to enjoy the potato purchased @ Rs. 15/Kg during the month of March to May. By adopting this technology potato peels can be used for animal feed which were otherwise wasted and became a source of pollution in rural as well as in urban areas. The economic analysis showed that cumulative present worth of the annual saving for potato crop over the life of the dryer was much higher (Rs. 163177.67) than the capital investment for the construction of dryer DI (Rs.25000). The results indicated that the developed solar dryer could be successfully used on commercial basis for potato flour products. The best drying results were obtained at five cubic meters per minute air flow rate. The largest temperature difference between ambient and drying air occurred at the least flow rate and vice versa. The difference deceased as the flow rate increased. The maximum such temperature difference was found at three cubic meters per minute with 29.5°C for dryer under experimentation. It is worth mentioning that the results of the experiment can be used for drying highly perishable and high moisture content products such as vegetables and fruits (aimed at helping the low and middle income level population in developing countries). It can be claimed that the availability of forced convection solar dryer to farmers in developing countries like Pakistan will eliminate a major technological barrier to improve agricultural practices.

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