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DEVELOPMENT AND PERFORMANCE EVALUATION OF A LOCALLY FABRICATED PORTABLE SOLAR TUNNEL DRYER FOR DRYING OF FRUITS, VEGETABLES AND MEDICINAL PLANTS

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The research was conducted to fabricate and develop a portable solar tunnel dryer (STD) for the drying of fruits, vegetables and medicinal plants. The system was designed as a portable system for decentralized applications at various sites to satisfy the drying requirements of small farmers and co-operatives. The cross sectional area of the solar tunnel dryer was trapezoidal in shape having 0.254 m^2 face area, with length and width of three meters and one meter respectively. It comprises a collector section (1.35 m) long and a drying section (1.65 m long) and two PV powered DC fans to provide the required air flow rate over the perishable agricultural products to be dried. Transparent polythene cover was used to close the dryer on top side to maintain the steady state air flow within the dryer. It has been observed that the drying air temperature was easily raised by some 8-14°C above the ambient temperature at air velocity ranges 0-1 m s^{-1}. The efficiency of the solar tunnel dryer was found to be 40-45%. Psychrometric analysis was also carried out within the dryer and the process curves were drawn. The process curves were found similar to a conventional dryer showing that this dryer can be successfully utilized for the drying of agricultural products using solar energy.
Keywords: solar collector, drying unit, face area, psychrometric analysis

INTRODUCTION

Drying process plays a crucial role in post harvest technology for preservation of agricultural products. Due to the increasing cost of electricity and fossil fuels, application of solar energy for drying of various agricultural products has become the need of the time. It is not only economical but also ceases the gas emissions. By solar drying, huge amount of national revenue can be saved by avoiding the spoilage of agricultural products due to non-availability of conventional processing facilities. In the drying process, food material is preserved by evaporating a significant amount of water to prevent it from decay and spoilage (In different agricultural products, moisture contents can be up to 85% (w.b). Solar drying is a clean and hygienic way to process the products according to international standards without any expenditure on energy costs. Although solar energy occupies larger area comparatively yet it also improves product quality like conventional high tech. dryers and saves time and money for drying. In the present scenario, solar energy is successfully being utilized for complete drying of agricultural products, as well as it can be used as a supplement to artificial drying systems (Muhlbauer, 1986).

Now it is possible to design solar dryers by keeping in view the needs of the farming community and end-users. Industrial and commercial applications can easily be met by using forced circulation solar drying (FCSD) systems because these technologies provide good control of temperature and air distribution system within the dryer unit. These systems also facilitate to couple with the existing drying systems. Roof space available in small-scale industries would normally permit installation of systems of one to two tons per day capacity. This is not only an efficient method of drying but also produces better quality products (Naween, 2009).

Keeping all facts in view, the study objectives were to design and fabricate, evaluate the performance of STD and to develop psychometric curves for drying of various agricultural products.

MATERIALS AND METHODS

The solar tunnel dryer was designed as a portable solar system for drying of various agricultural products at various sites being developed and fabricated in the Agricultural Engineering Workshop, University of Agriculture, Faisalabad. .

Development of portable solar tunnel dryer (STD)**:** The portable STD consists of two parts, solar collector and solar drying unit. The length of solar collector unit and drying unit are 1.35 m and 1.65 m respectively. Solar collector has a base black plate which acts as a black body to absorb solar radiant energy and transforms incoming sunlight into heat. In the process, the heated air becomes relatively dry and is blown over the required product to be dried, where it takes up moisture. Incoming sunlight on this half of the device additionally help to evaporate humidity from the foods. Due to the small fans (2.5 Watt each) powered by a photovoltaic module (PV), reasonably stable temperatures are achieved within the system. These fans provide air stream to prevent the overheating of the drying product during high range of solar radiations. Since the PV-module provides maximum power in this case, the fans also run at maximum speed. When the solar radiations become weak, the module provides less power and the fan runs relatively slowly, whereby the air remained within the dryer for a longer time span. The schematic diagram of the portable solar tunnel dryer is shown in Figure 1.

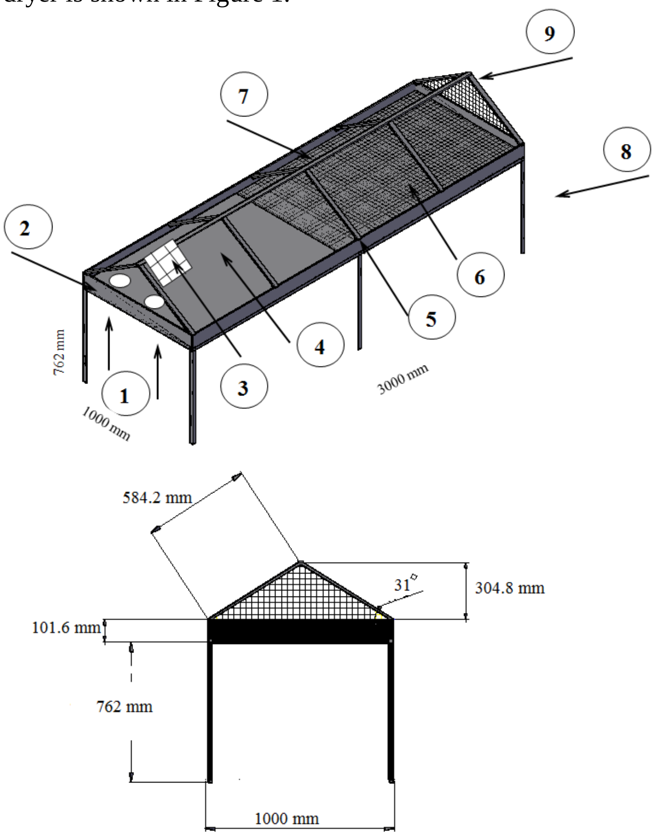

Figure 1. Schematic diagram of portable solar tunnel dryer

(1. DC Fans, 2. Thermal insulation, 3. Solar module, 4. Solar collector, 5. Side metal frame, 6. Drying section, 7. Roof structure and PE-cover, 8. Base structure for supporting the dryer, 9. Outlet of the drying tunnel)

***Design Parameters*:** Duffie and Beckman (1991) suggested that the slope of the tunnel should be maintained by subtracting and adding 10° in the latitude of the site for summer and winter respectively. Since the site (University of Agriculture Faisalabad) has latitude equal to 31.2°, so the same slope angle of the tunnel was selected, acceptable in both seasons.

Length and width of the dryer were decided keeping in view the easy portability at the desired locations. The height was selected to facilitate easy handling during loading and unloading of the products.

The function of collector section is to heat the air before entering into drying section. So a locally available and cheap black painted galvanized iron (GI) sheet (1372 mm × 1000 mm × 0.356 mm) was used for the collector and behaved like a perfect black body. A transparent polythene cover (transmissivity = 0.89-0.84) was used to transmit all the solar radiations through the cover. Moreover, the cover is used to minimize the conduction and convection heat losses to the atmosphere. Adsten et al. (2002) suggested that optimum area of the collector should be 40-45% of the dryer area to best utilize the available heat. Size of collector area was selected in such a way that all the heat energy carried by the air must be fully used for the drying of agricultural products placed in the tunnel dryer.

A low cost locally available thermocol was used to insulate the collector and drying unit. The insulation was held with bolts and silicon binding. The entire collector and dryer body were adequately insulated with 50 mm thickness thermocol insulation to minimize the losses of heat. The optimum air velocity (more than 1 m s^{-1}) was used as suggested for STD (Hohenheim design). The volumetric flow rate (Q) is equal to the air velocity times the cross section of the dryer (Clement, 2004).

The size of the PV panel was selected in accordance with the fan volumetric flow rate and velocity of air at the exit of STD. Solar module (5 W) having dimension 250 mm×200 mm was used for assisting the air from DC fans attached with collector unit. The purpose of PV operated DC fans is to increase and decrease the fan speed during high and low solar radiations respectively to maintain the optimum temperature within the dryer.

The orientation of the dryer was maintained in East-West direction in order to achieve maximum solar radiations during the whole day. The tunnel slope was also designed to achieve maximum radiations perpendicular to the surface of the dryer in order to enhance the thermal efficiency of the solar dryer.

***Performance evaluation of solar tunnel dryer*:** The overall drying efficiency is defined as the ratio of energy output of the dryer to the total energy input. Thus, overall efficiency of the system is given in Eq. (1) (Schirmer *et al.*, 1996)

$$\eta = \frac{Q_d}{Q_s} \qquad (1)$$

Where, Q_d is the heat energy available per unit time for drying in STD in kW, Q_s is the solar energy available per unit time at the collector section of STD in kW. Q_s is calculated by using Eq. (2)

$$Q_s = \frac{A_c I_t}{1000} \qquad (2)$$

Where, A_c is the total collector area in m², I_t is the total solar radiations in W m^{-2}.
Collector efficiency is defined as the ratio of energy output from the collector area to solar energy input to the collector area. Solar energy input to the collector is computed using Eq. (3)

$$Q_d = m\, C_p\, \Delta T \qquad (3)$$

Where C_p is the specific heat of air in kJ kg^{-1} K^{-1}, ΔT is the change in temperature between collector exit and the ambient temperature in K, m is the mass flow rate of air in kg s^{-1}

Heat gained through the dryer**:** The heat gained through the dryer was calculated without keeping any sample in the dryer (no load condition). For the performance evaluation, an anemometer was placed at the end of the collector section to measure the air velocity within STD. Due to unequal air distribution in any channel, a single point of measurement is not enough but grid was employed to record data at various points. Thermometers were used to record the dry bulb and wet bulb temperatures at ambient condition, collector exit and dryer exit sections.

Solar drying of different agricultural products**:** For experimental procedure and calculation, two points were selected to locate the psychometric processes within STD. Dry bulb and wet bulb temperatures were recorded at different time intervals during the drying process of the product. At the beginning of each experimental run, the initial moisture content of product was measured by oven drying method at a temperature of 105°C for 24 hours (ASAE, 1997).

Moisture removal rate**:** Moisture removal rate is calculated by using Eq. (4)

$$DR = m_a (H_2 - H_1) \qquad (4)$$

Where H_1 and H_2 are the humidity ratios at the dryer section inlet and outlet respectively (kg of water/kg of dry air), m_a is the mass flow rate of air in kg S^{-1}. The mass flow rate of air is calculated by using the Eq. (5)

$$m_a = \rho \times V \qquad (5)$$

Where, ρ is the density of air in kg m^{-3}, V is the volumetric flow rate of the fan in m^3 S^{-1}

Heating Capacity of STD**:** Capacity of STD for a mass flow rate of ma of dry air is given in Eq. (6)

$$Q = m_a (h_2 - h_1) \qquad (6)$$

Where Q is the capacity of STD (kW), h_1 and h_2 are the enthalpies of air entering and leaving dryer section in kJ kg^{1}

Psychometric analysis of product within the dryer**:** Psychrometric charts graphically represent the thermodynamic properties of air. For the psychometric analysis of the product inside the dryer, the dry bulb temperature and wet bulb temperature were measured from three different points of STD. These two measured values were used to locate a point on psychrometric chart. From this point, relative humidity, absolute humidity, specific volume, enthalpy and other physical and thermal parameters were determined.
The intensity of solar radiation was recorded by the Pyranometer (SP Lite: response time < 1 s; Error = ± 5%).

RESULTS AND DISCUSSION

Five experimental runs were conducted to evaluate the performance of STD at no load condition. Experimental data on solar radiation, ambient air temperature, air velocity and temperatures inside the dryer were recorded and drawn on graphs as well on psychrometric charts. All these psychrometric values were calculated at different stages with the help of Engineering Software (PsychroCalc-1.1.0 and PsycPro-1.1.16).
By using Eq. (3), the energy available from STD was found to be 0.43 kW and the energy available at the solar tunnel dryer was calculated 0.95 kW with the help of pyranometer and by using Eq. (2). So the overall efficiency of the STD was found 45.26% by using Eq. (1). This result was in accordance to the findings of Basunia *et al*. (2011) and Bala *et al*. (2005). This high overall efficiency for the solar tunnel dryer was due to the fact that the solar tunnel dryer is a forced convection solar dryer and the drying unit receives energy from both collector and incident radiation.

Psychrometric representation of STD with no load experimental run**:** The main purpose of dryer is to increase dry bulb temperature which expands and decreases relative humidity of air for absorbing maximum moisture from the product.
In conventional dryer, the heaters are used to increase the dry bulb temperature of air which consumes high energy cost. But in STD a black base plate acts as air heater which absorbs heat from direct sun exposure. The process line in Figure 2 represents the dryer performance at ambient condition (A) and collector outlet (B). This also shows the addition of sensible heat trend line by rise in dry bulb temperature. The straight performance line has shown no change in absolute humidity but the relative humidity has decreased as dry bulb temperature increased. So the STD performed like a conventional dryer showing that solar renewable energy can be successfully utilized to replace the fossil fuels for the dehydration of agricultural products.
Five experimental runs were conducted for solar drying of fruits (Apple), vegetable (Fenugreek/Methi) and medicinal plants (Mentha-Lonifolia/Mint). Experimental data on solar radiation, ambient air temperature and relative humidity, air velocity inside the dryer and temperatures at three different positions, ambient condition (A), collector section exit (B), drying section exit (C) of the dryer along the length were recorded. During experiments of these products drying, dry bulb and wet bulb temperatures from three points of STD were recorded.

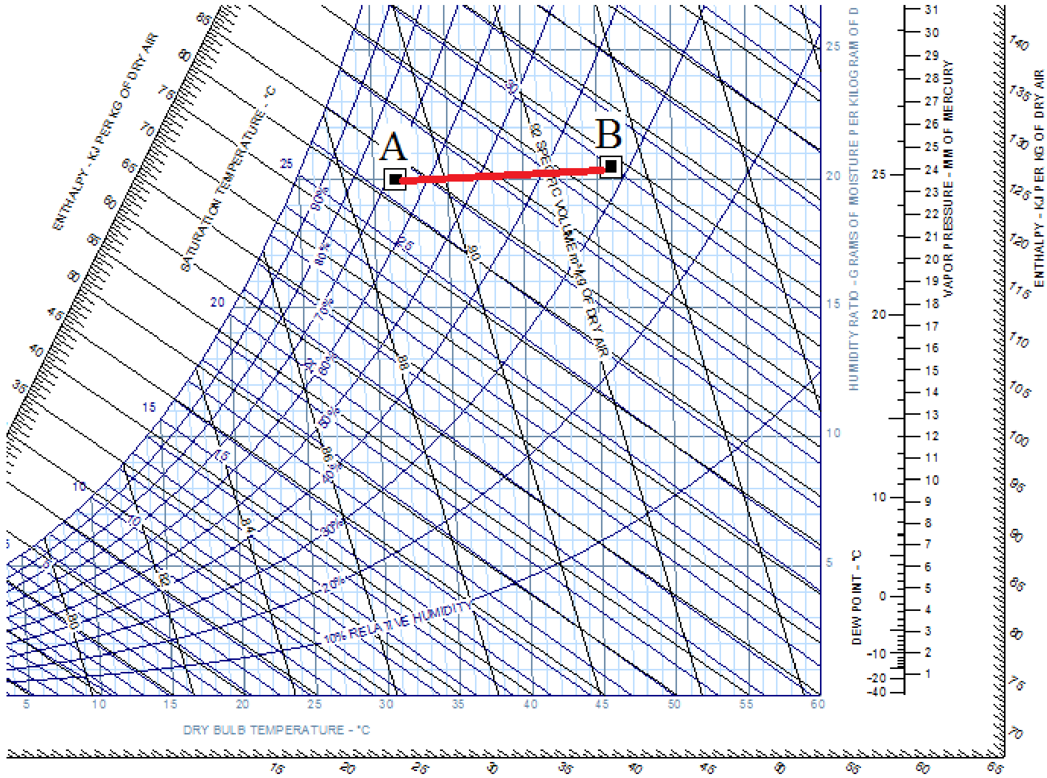

Figure 2. Psychrometric chart representation during no load test of STD

***Psychrometric representation of STD for experimental drying of Mentha-Lonifolia/Mint*:** The detailed representation and performance curves of STD at different time intervals (from 10:00 AM to 2:00 PM) for experimental drying of Mentha-Lonifolia are shown in Figure 3.

This graph shows the process line from point B to C. It has been observed as the drying process commenced, the dry bulb temperature decreased as the dry air evaporated the moisture contents from the agricultural product. It is also evident that the relative humidity of the air increased towards the end of the process. This is due to the fact that the dry air absorbed water contents from the products to achieve the equilibrium condition with the moisture contents of the products following the adiabatic principles of evaporation (Law of conservation of energy). The graph also show that air conditions were not saturated at the exit. It means that a significant amount of heat energy wasted during the drying process. The results showed that the experiments were conducted at low charge. It is concluded that the solar tunnel dryer should be run by increasing the product weight so that the point C of the process curve should touch the R.H curve at saturation point to utilize the potential of heated air. Under practical conditions, it is impossible to fully utilize the potential of the heated air as the sorption of the product is also taken in consideration. It is also evident that the system was not fully insulated on upper side that is why the heat exit from drying section to environment during cloudy hours thus raised the temperature of drying section during sunny hours.

***Variation of drying rate (DR) throughout the dryer*:** Drying rate describes the amount of water removed per unit time. Figure 4 presents the values of drying rate as a function of drying time.

The drying rate changes in different manner as it compared with conventional batch type dryer. In conventional dryers, the bottom part of the batch is dried first as it is subjected to hot air first and then the drying front is changing from bottom to top and air condition remain saturated until whole product is dried. In case of STD, the whole layer of the drying material remained in contact with heated air coming from collector section and evaporated the moisture from the entire batch simultaneously. Consequently, the moisture content did not remain constant with respect to time. The moisture removal rate decreased towards the end of the process. So the decreasing trend in Fig.4 is in accordance with the theoretical aspect of STD.

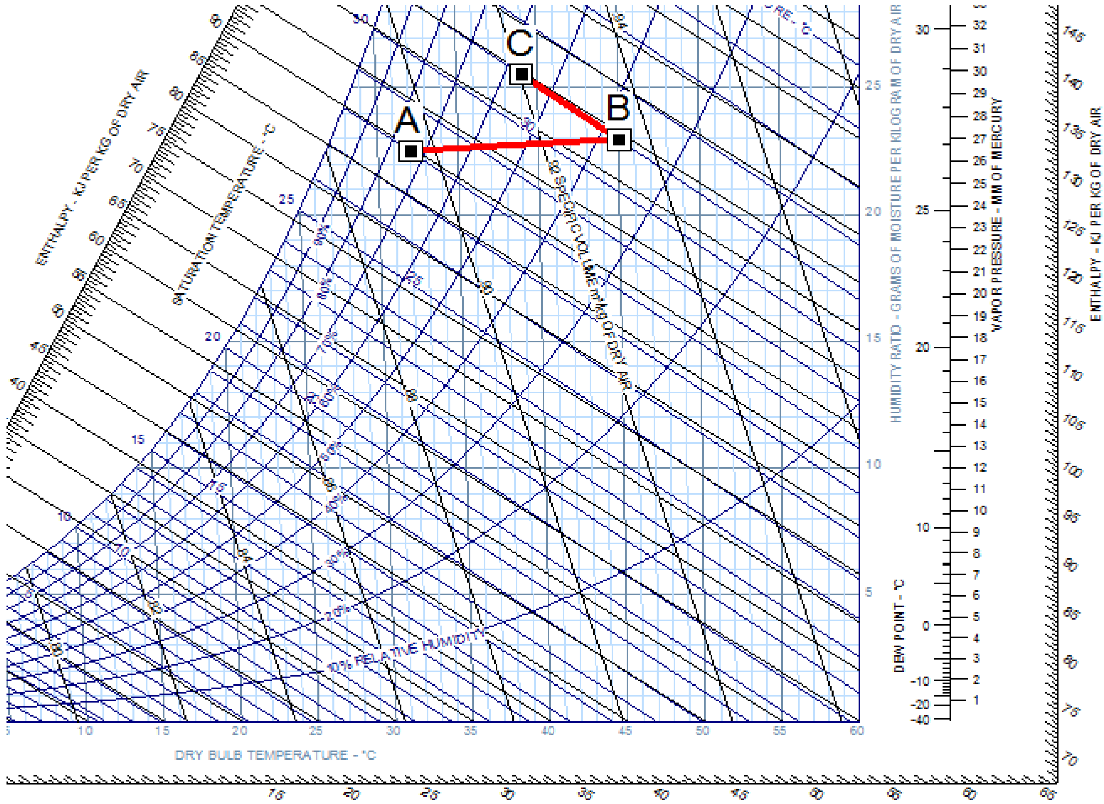

Figure 3. Psychrometric chart representation during load test of STD

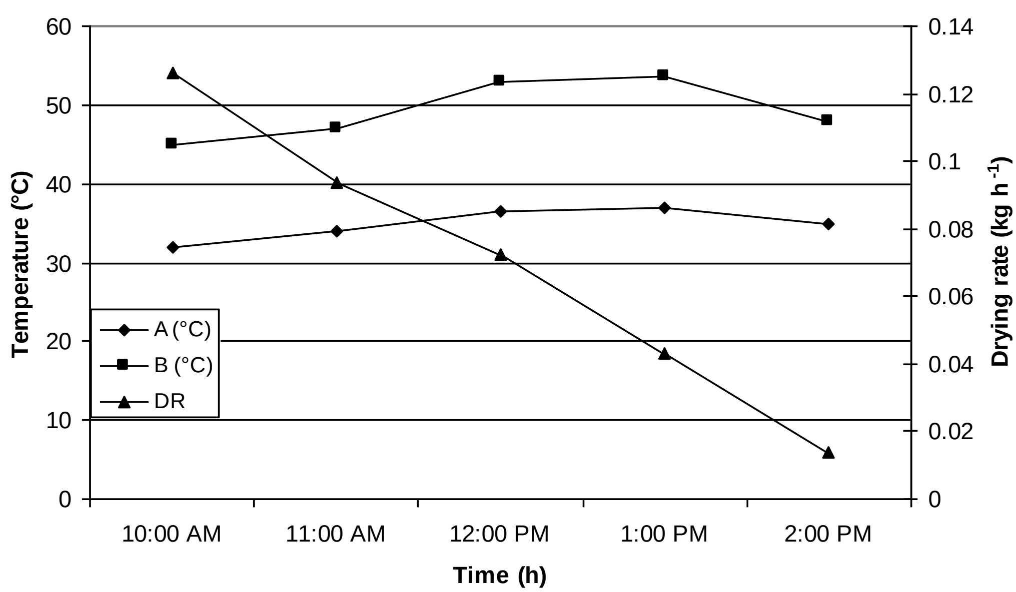

Figure 4. Variations of drying rate with the time of the day for a typical experimental run

***Statistical analysis*:** Fig.5 shows the heat added to system (STD) and the heat used for drying. Line bar shows the heat available on collector section and brick bar shows the heat consumed in product drying and two vertical two pole lines on top of the bars show the standard error.

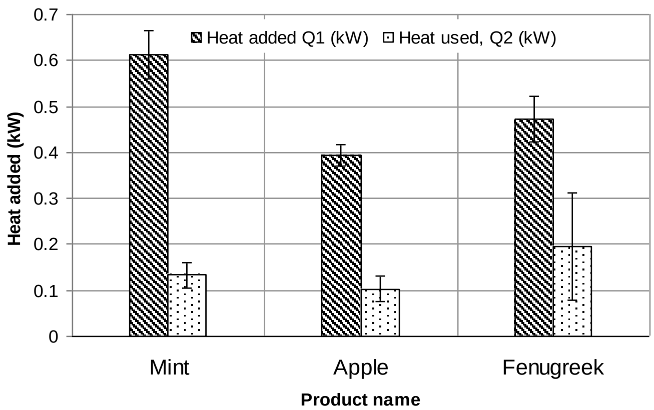

Figure 5. Statistical representations of sample experiments

Portable STD was designed and developed for vegetables, fruits and medicinal plants. So the value of heat exhausted from drying section was changing according to the product type and quantity. In Mentha-Lonifolia/Mint drying, the small weight covers all the drying area of the STD compared with other products (Apple and Fenugreek). It is also clear from Fig. 5 that this dryer was under loaded for all the experiments run, using different products in the form of apples, vegetable or medicinal plants, as there was significant difference between the heat used and heat available. The study also concludes that optimum batch size per product should be fixed to facilitate the farming community in order to best utilize this technology for the value addition of different agricultural products.

***Conclusions*:** This dryer is simple in construction and it can be constructed using locally available materials by the local craft man. The solar tunnel dryer was operated by a photovoltaic module independent of electric grid. The photovoltaic has the advantage that the temperature of drying air is automatically controlled by the solar radiation. The photovoltaic driven solar tunnel dryer must be optimized for efficient operation. Psychrometric chart can be successfully utilized for STD by plotting a process curve. The process curve can be used to evaluate the dyer performance during the dehydration process. The STD dried products are protected from dirt, insects and climatic conditions due to its perfect sealing. The air leaving the dryer was found to have still greater potential for drying more products. However, this should also be considered for other products, as this dryer is designed for multi-products use. The solar based renewable technology is free from operating cost and can play a vital role in promoting the field of post-harvest technology using solar energy.

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