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Review on Indian Solar Drying Status

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Abstract The tremendous rise in demand for energy has led to a scarcity of conventional sources of energy like fossil fuels, thereby pushing us in search of alternative sources of energy. Sun is the ultimate source of energy, and there is a need to harness it to sustain the growth of mankind. The purpose of this review is to examine different ways to harness solar energy and use it to dry various agricultural produce. A brief review of various types of solar dryers being used in India is presented in this article. With the advancement in science and technology, several inexpensive, efficient, and innovative solar drying devices for drying different agricultural products have been discussed. Solar dryers can reduce significant amounts of moisture and thus preserve the products for longer time periods. This reduces product wastage and enhances the productivity of farmers.

Keywords Solar drying system · Open sun drying · Indirect solar dryer · Hybrid solar dryer · Crop drying · Moisture content · India

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Introduction

India has about 10 % losses of the postharvest products, which is about 15 million tons of food grains per year [1]. This is quite a significant amount of loss in this developing country, where there is a strong struggle to achieve food security. Although the production rate has been increasing due to technological advancement, the percentage of postharvest loss remains unchanged. Drying is an effective methodology to minimize the postharvest losses. For generations, open sun drying has been used to dry agricultural produces, and even now, about 70 % of the grain drying happens by open sun dryers [1, 2]. In this method, the product is kept under open sky and dried directly under the sun, as shown in Fig. 1. The self-explanatory working principle of open sun drying (OSD) with various losses is shown in Fig. 2.

However, this drying methodology has several disadvantages, such as product that may get degraded due to debris in the wind, rain, problems of over drying/under drying, contaminations due to humans and animals, labor intensive, inferior quality, large surface area, etc. [3••]. In addition to this, the drying rate and efficiency are reduced because of over or under drying, inconsistent sunshine, frequent rainfalls especially during monsoon season, etc. After social and industrial revolutions, various artificial mechanical dryers came into existence. These processes of drying require huge energy and capital investment; hence, artificial drying process becomes highly expensive and pollutes the environment.

In this era of energy crisis, there is a need for an alternative source of energy to meet energy requirements, as well as support eco-friendly atmosphere. The atmosphere is severely affected by the various pollutions

Fig. 1 Open sun drying of the rough rice [3••]

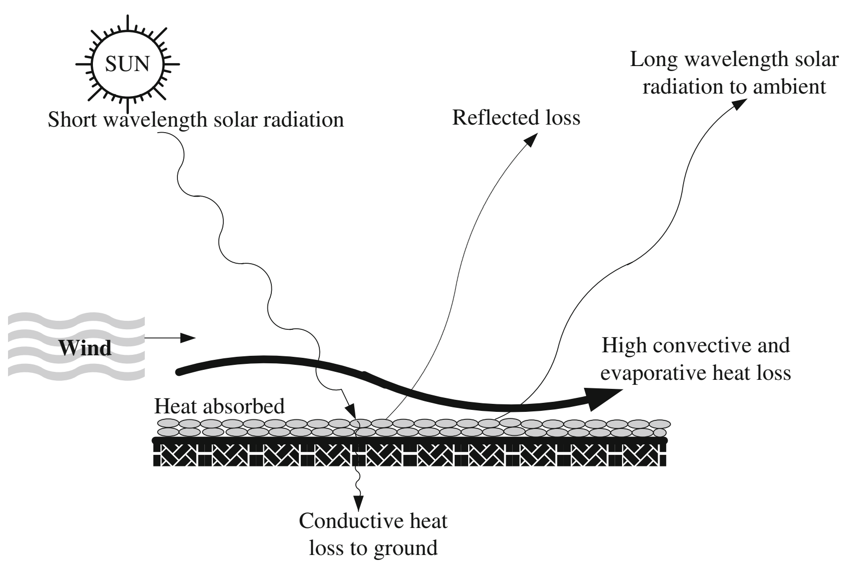
from burning fossil fuels. As the sun is the primary source of all energy sources, harnessing solar energy is the best and the most suitable alternative of all [4, 5•]. Solar energy is mainly the heat and light emitted by the sun. About half of the solar radiation is in the visible short-wave range of the electromagnetic spectrum. These radiations can be captured and utilized into useful forms of energy like heat, light, and electricity.

For developing nations like India, solar food processing is the newest, efficient, and advanced technology introduced for addressing different food problems in postharvest stage. By this concept, the energy investment in the food preservation can be diminished and pollution can also be minimized. It has wide range of applications in the agricultural-based small-scale industrial sector under the Indian scenario. This saves energy, reduces drying time, occupies smaller surface area, and enhances life and quality of products, and most importantly is being eco-friendly [6]. Many types of fruits, vegetables, peanuts, and beverages are in the list of agricultural products that have been dried by solar dryers, because their drying temperatures are less than 70 °C, which comes in the low-temperature thermal drying process. In addition, flowers, herbs, and medicinal plants have also been dried effectively in solar dryers [7].

Solar dryers are being used extensively and efficiently in India:

- To dry the agricultural produce
- To dehydrate fruits and vegetables in food processing industries
- To preserve the dairy products
- To seasoning of timber and wood
- To dry the textile materials in textile industry

Fig. 2 Working principles of open sun drying [4]



Merits and Demerits of the Solar Drying Systems

The following are the major advantages of the solar drying [4]:

1. The products dried in solar dryers are found to be superior in their nutrient contents, as compared to the products dried in open sun drying. This is mainly due to avoidance of overdrying and/or underdrying of the products.
2. The losses occurring in the solar dryers are almost insignificant.
3. The products are protected from adverse weather conditions and destruction of different pathogens and can be left in the dryers during night.
4. Since no fuel is required in this system, the use of solar dryers not only saves precious conventional fuel but also reduces the environmental pollution.
5. Solar drying is eco-friendly and more energy-efficient.
6. Solar dryers have a high life span, as compared to mechanical dryers.

Although solar drying is quite beneficial in developing countries such as India, the process has certain demerits, including the following:

1. The desired quality of the dried products may not be obtained in some cases.
2. Plenty of solar radiation is required for optimum drying process.
3. The drying time is often longer than in the case of mechanical dryers.
4. The process is costlier in the short run.

Working Principles of Solar Dryers

The main purpose of any solar dryer is to provide heat to the product under controlled conditions. In general, most of the agricultural produces require temperatures less than 70 °C for effective drying. A consolidated list of crops with maximum allowable temperature along with initial and final moisture contents is being presented in Table 1 [3••, 4].

Under such conditions, solar dryers can easily substitute the mechanical dryers, as well as the open sun dryers, because they provide drying temperatures of up to 65 °C. Solar dryers not only provide relatively high drying temperatures but also provide less relative humidity. This creates an ideal atmosphere for drying by increasing the vapor pressure of the inside moisture of the crop and decreasing the relative humidity of the drying air [4, 5•]. Hence, the capacity of the dry air to carry out moisture increases significantly; thereby, drying of the product takes place in less time.

Solar dryers can be operated under either forced convection mode or natural convection mode of heat transfer. The solar dryer operated under forced convection mode is also called an active mode solar dryer, while the solar dryer operated under natural convection mode is called passive mode solar dryer.

Types of Solar Dryers Used in India

These are various types of solar dryers used in India [4], namely

1. Direct solar dryers
2. Indirect solar dryers
3. Mixed mode solar dryers
4. Innovative solar dryers

Direct Solar Dryers

In the direct solar dryer, solar radiation is directly absorbed by the product to be dried (Fig. 3). In India, there are two prominent types of direct solar dryers being used. One is cabinet dryer and the other one is the greenhouse dryer. The working principles of direct solar crop drying are shown in Fig. 3.

These dryers are cost-effective and easy to fabricate using locally available materials. Both dryers can either be operated under natural convection (passive) mode or forced convection (active) mode of heat transfer. Such dryers are best suited for the low-level thermal drying because the inside temperature of the dryer reaches about 45–70 °C and the inside relative humidity is found to be very low (<50 %), as compared to the ambient relative humidity. Hence, most of the crops can be dried up to a safe level of moisture content in such dryers. Prakash and Kumar dried tomato flakes in modified greenhouse dryers under active mode and under open sun drying in Bhopal, India [8••]. Their proposed greenhouse dryer is an upgraded version of the traditional greenhouse dryer. In this system, two major losses were reduced by suitable provisions. In order to minimize the solar radiation losses from the north wall, opaque mirror was applied. Thermal energy losses through the ground were reduced by covering the floor with a double layer of the black PVC sheet, with holes in the upper layer. Such modifications saved 35.71 % of the drying time, as compared to that for the open sun drying. The embodied energy and energy payback time of the developed dryer were 628.7 kWh and 1.14 years, respectively. The net CO_2 mitigation was calculated as 38.06 t in the lifetime of the dryer. The earned carbon credit varies from 12,561 to 50,245 INR in its life cycle for different agricultural produces. The dried tomato flakes were found to be more nutrient as compared to the open sun-dried product.

Table 1 Details of moisture content and maximum allowable temperature of various agricultural produces

S. no.	Crop	Initial moisture content (w.b. %)	Final moisture content (w.b. %)	Maximum allowable temperature (°C)
1	Paddy raw	22–24	11	50
2	Paddy parboiled	30–35	13	50
3	Maize	35	15	60
4	Wheat	20	16	45
5	Corn	24	14	50
6	Rice	20–22	11	50
7	Pulses	20–25	9–10	40–60
8	Oil seed	80	7–9	40–60
9	Green peas	80	5	65
10	Cauliflower	70	6	65
11	Carrot	70	5	75
12	Green beans	80	5	75
13	Onion	80	4	55
14	Garlic	80	4	55
15	Cabbage	75	4	55
16	Sweet potato	75	7	75
17	Potatoes	75–82	7	75
18	Chilies	80	5	65
19	Apricot	85	18	65
20	Apples	80	24	70
21	Grapes	80	15–20	70
22	Bananas	80	15	70
23	Guavas	80	7	65
24	Okra	80	20	65
25	Pineapple	80	10	60
26	Tomatoes	96	10	60
27	Brinjal	95	6	60

From [3••, 4]

Kamble et al. have designed and developed a solar cabinet dryer with a thermal storage concept [9]. Gravel bed was applied to store the thermal energy. The dryer was tested to dry green chili. The dryer took 56 h to dry the green chili of

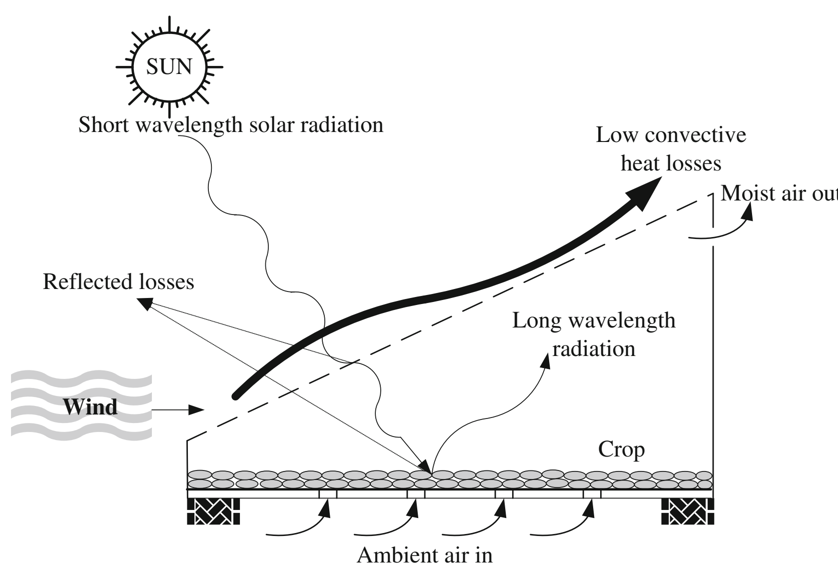


Fig. 3 Working principles of direct solar dryers [4]

15 kg from initial moisture content (MC) of 88 % wet basis to a final MC of 7 % wet basis. However, it took 104 h in the open sun-drying condition. The experiments were conducted in the Central Institute of Agricultural Engineering, Bhopal, India.

Indirect Solar Dryer

In the indirect solar dryer, the drying product is kept separately in a box which is called drying chamber. The working principles and concepts of indirect solar dryer are shown in Fig. 4.

Ambient air is supplied to a solar air heater by the thermosiphon effect/centrifugal fan and is heated up in the solar air heater when it comes in contact with absorber. The hot air is supplied through a pipe/duct to the drying chamber from the solar air collector. The indirect solar dryer can be operated into two modes, indirect solar dryer under active (forced convection) mode and indirect solar dryer under passive (natural convection) mode. The indirect solar dryer under passive mode was found to be suitable for the low moisture content crops, while the active mode dryer was found to be suitable for high moisture content crops.

In general, indirect solar dryers under active mode are more prominent than passive mode dryers. Shrivastava and Kumar have done an experimental investigation of indirect solar dryer under active mode for fenugreek drying in Bhopal, India [10••]. Experiments were conducted simultaneously in the indirect solar dryer, as well as in open sun drying. The indirect solar dryer reduced the drying time and produced more nutrient fenugreek, as compared to the open sun drying. The thermal efficiency of this indirect solar drying system was 31.42 %, which is quite satisfactory.

Singh et al. have designed and developed an indirect solar dryer under active mode, for use in hot and dry climatic situations [11]. The experiments were conducted in Jaipur, India, to dry green chili. The whole system has two major parts: One is solar energy conversion device (solar air heater) and the other is solar energy utilization device (drying chamber). The total volume of the drying chamber was 0.125 m^3 and the surface area of air heater was 1.0527 m^2. The unique feature of their proposed system was that the four baffles (40 cm × 3 cm × 7 cm) were fitted in between the absorber plate and the black coated surface to enhance the heat transfer. The collector was inclined to 45° with respect to the horizontal and facing toward the south-north direction to receive maximum solar radiation. The MC on wet basis was reduced to 13 % from 90 % initial MC in 10 h. There was a maximum of 20 °C difference between ambient and greenhouse dryer temperatures, and the overall solar energy conversion efficiency was reported as 50.2 %. Hence, this can be considered an energy-efficient indirect solar dryer under active mode.

Mixed Mode Solar Dryers

Direct and indirect drying concepts are applied in mixed mode solar dryers. Crops are directly exposed to solar radiation as well as getting hot from solar air heating collector, which helps in reducing the drying time. The process involves acquiring thermal energy by air in a collector, and then, the hot air is passed into the drying chamber. The drying chamber is composed of transparent cover for allowing solar radiation. The mixed mode solar dryer can be operated in either active or passive mode. Tripathy has done experimentation and modeling of the mixed mode solar dryer under passive mode [12]. Experiments were conducted to dry potato cylinders and slices from an initial moisture content on wet basis of 82 % in the designed system. A final moisture content of 12 % was achieved in 210 and 330 min for potato cylinders and slices, respectively. This is because potato cylinders have less volume per unit surface area as compared to potato slices. By applying thin layers drying modeling, the modified page model showed superior performance than other models in describing the drying curve.

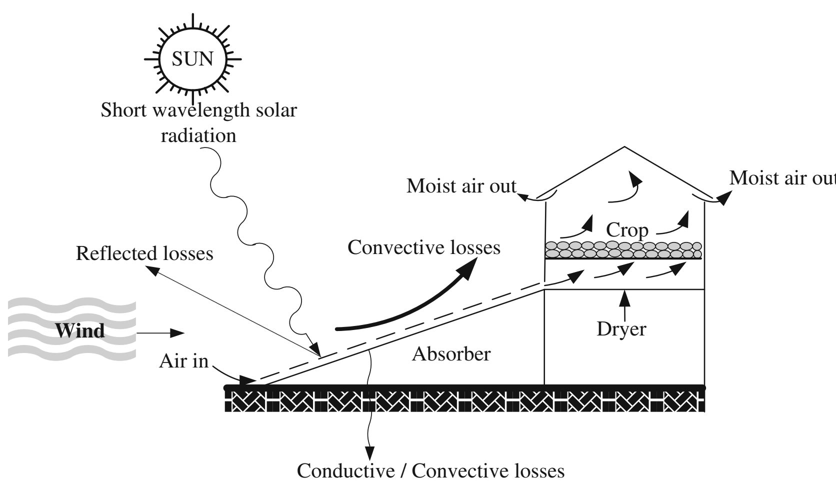


Fig. 4 Working principles of indirect solar dryers [4]

Fig. 5 Photograph of low-cost solar dryer [16]

Basumatary et al. designed and developed a low-cost cabinet solar dryer with mixed mode concept, operating under passive mode [13]. The shape of the drying chamber is in the triangular prism form. The whole system was developed from locally available materials, with the cost of the dryer being only 1250 INR. Drying of green chili was tested in the proposed system. The dryer showed superior drying performance as compared to the open sun drying.

Innovative Solar Dryers

Researchers have developed various innovative solar dryers in order to enhance the performance and efficiency of the classical solar dryers. Saravanan et al. attempted to develop a hybrid dryer consisting of a solar flat plate collector, a biomass heater, and a drying chamber [14]. Experiments were conducted for cashew nut drying under both active and passive modes. The temperature inside the dryer varied from 50 to 70 °C, which is quite suitable for drying various crops. Moisture content was reduced to 3 % from an initial value of 9 % in 7 h, under the active mode, and with conversion efficiency of 5 %, whereas under the passive mode dryer, it took 9 h for reducing same level of MC with 3.17 % conversion efficiency. It shows that there was not a significant difference in performance of both dryers. The fuel-wood consumption during the drying process was 0.5 and 0.75 kg/h in the active and passive modes, respectively, which is quite high. Hence, these systems need further attention in their design as they do not seem energy-efficient.

Sundari et al. have developed an innovative dryer with evacuated tube collector, and with and without heat storage material (gravel) [15]. The drying system was tested for drying of chili in the meteorological conditions of Thanjavur, Tamil Naidu, India. The initial MC on wet basis of the chili was 87.36 % and the final moisture content was 3.4 %. The experiments were performed in three different modes of drying, namely open sun drying, proposed dryer with thermal storage, and proposed dryer without thermal storage. The dryer with thermal storage took 10 h to reach the desired final moisture content; however, the dryer without thermal storage took 12 h of drying time. The drying time for the open sun dryer was 32 h. In conclusion, it appears that the application of evacuated tube collectors clearly enhances the performance of solar dryers.

Recent Developments of Solar Dryers in India

Tidke and Somani [16] developed a low-cost solar dryer and tested it in Mumbai (India) as shown in Fig. 5. This dryer is a simple box with clear PVC plastic sheet at the top. A 95 % of the moisture evaporation taking place in this dryer was due to the greenhouse effect. The process preserves the color and texture of the product. The proposed system can be used to dry the majority of the fruits and vegetable at the domestic level.

Fig. 6 The schematic diagram of the experimental setup

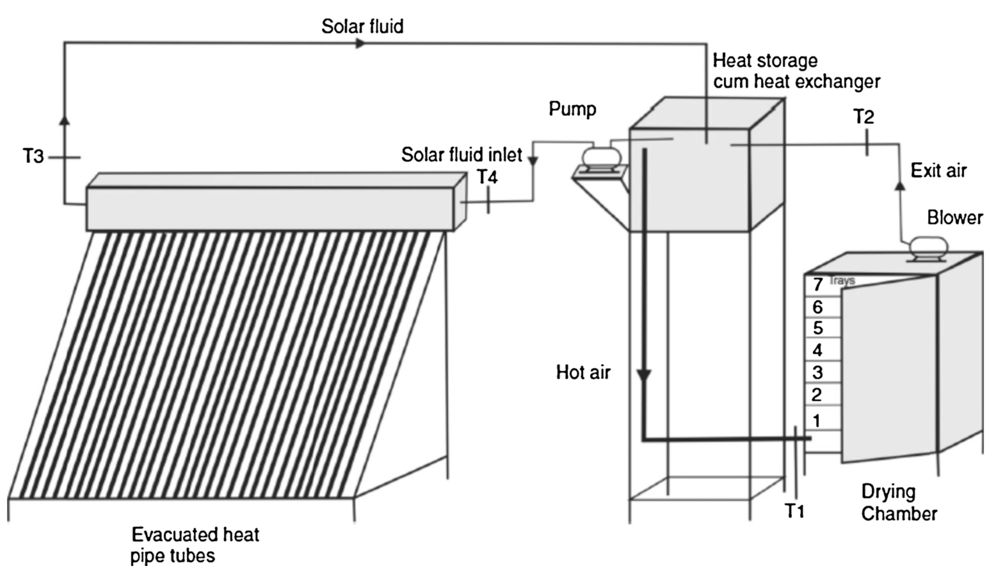


Fig. 7 Photograph of the thermal storage based solar dryer [19]

Shringi et al. [17] have done the innovative thermodynamic analysis for examining the drying performance of solar dryers. The schematic diagram of the experimental setup is shown in Fig. 6. The proposed system was used to dry the garlic cloves. The study is being conducted both forced convection mode as well as natural convection mode of heat transfer mode. The energy and exergy efficiency in natural convection mode of heat transfer mode varies from 43.06 to 83.73, 5.01 to 55.30, 3.98 to 14.95, and 67.06 to 88.24 %, in forced mode of heat transfer, respectively.

Tripathy et al. [18] have designed, developed, and tested the performance analysis of the self-tracking solar dryer with the indirect passive mode. This system was used for drying of the potato cylinder. Various thermal parameters were evaluated such as convective heat transfer coefficient (h_c), specific energy consumption (SEC), and specific heating rate (SHR). The variation of h_c is 11.73 to 16.23 W/m^2/°C, and the average value of SES is 3491 kJ/kg. The SHR reduces with dimensionless moisture content.

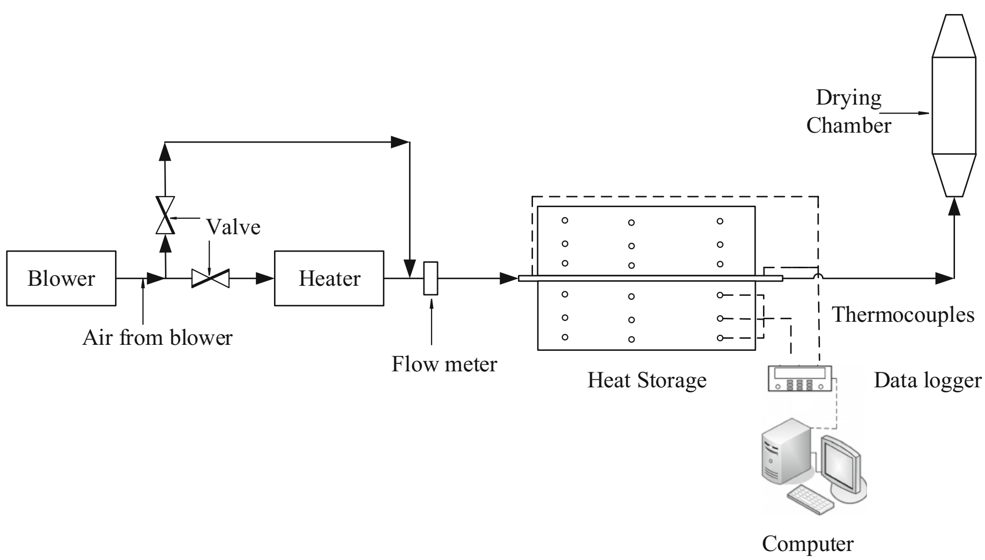
Jain and Tewari [19] have designed and developed thermal energy storage based solar dryer for herbs drying. The system consists of flat plate solar collector, packed bed phase change energy storage, and drying chamber as shown in Fig. 7. It is operated on natural convection mode of heat transfer. It is designed to dry 12 kg of leafy herbs. The 50-kg phase change material is used in this system. It stores energy during the sunshine hour and releases energy in the off sunshine hour. It can release up to next 5–6 h in off sunshine hour and increase 6 °C in the drying chamber as compared to the ambient temperature. The experimentation was conducted in the month of June in the Jodhpur, Rajasthan, India. The capital on the return is 0.65 year and the simple payback period is 1.57 year.

Agarwal and Sarviya [20] have developed a shell and tube latent heat storage for solar dryer using paraffin wax as heat storage material as shown in Fig. 8. The system was tested in the Bhopal, India, climatic zone. Due to thermal storage, the temperature of the drying chamber is raised 5–17 °C in the off sunshine hour for the next 10 h.

Conclusion

Different types of solar dryers have been reviewed in this paper. Greenhouse solar dryers and solar dryers with thermal energy storage have been employed successfully in various food process industries. Most of the solar drying systems are easy-to-construct, user-friendly dryers and are suitable for small-scale factories, as well as for rural farming. This low-

Fig. 8 A schematic diagram of the complete experimental setup [20]



cost food drying technologies can be readily used in rural areas to reduce spoilage and improve product quality. Optimally designed active solar dryers are found to be more effective and more controllable than the natural-circulation types. In most of the active solar dryers, the fan is driven by electrical energy from solar photovoltaic panels. This makes active dryer totally independent from grid/fossil fuel, which is most suitable for rural and remote areas. This review may be useful in motivating people to adopt eco-friendly solar drying.

Compliance with Ethical Standards

Conflict of Interest Om Prakash, Anil Kumar, and Yahya I. Sharaf-Eldeen declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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