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ORIGINAL ARTICLE

Drying Kinetics, Quality and Economic Analysis of a Domestic Solar Dryer for Agricultural Products

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Abstract
In this study, design, development and testing of an indirect solar dryer for rural domestic use is reported. Qualitative and quantitative methods have been deployed to derive the appropriate design for the solar dryer, based on the local expectation and drying requirements. Local materials and resources have been used to construct the dryer, making it portable, affordable, and accessible, thus, promoting a do-it-yourself ('DIY') model. Bitter gourd (*Momordica charantia*), okra (*Abelmoschus esculentus*), raw mango (*Mangifera indica*) and hirda (*Terminalia chebula*) have been tested for the performance evaluation, as these items are typically openly sun dried for using them in later seasons or as sellable products. Results show that moisture content of the food products is brought down to acceptable limits, while retaining the color using this solar dryer. The functioning of the fabricated solar dryer has been demonstrated to the local people of the selected villages to encourage them to use the dryer and to receive their feedback.

Keywords Solar dryer · Rural application · Low cost · Appropriate technology · Developing countries

Abbreviations

wb	Wet basis
ref	Reference sample
T_a	Ambient temperature
T_d	Temperature of drying chamber
T_o	Collector outlet temperature
Ti	Collector inlet temperature
RH	Relative humidity of the atmosphere
M_d	Moisture content (wet basis)
MR	Moisture ratio
W_d	Weight of the dried product
W	Weight of the product
M_0	Initial moisture content
M_t	Moisture content at time t
ΔE	Total color change
L^*	Lightness
a^*	Red/green coordinate
b^*	Yellow/blue coordinate
CI	Confidence interval
A_c	Collector area
$\dot{m}$	Air mass flow rate
Ex	Exergy
C	Specific heat of air
Ex_{dci}	Exergy inflow of the drying chamber
Ex_{dco}	Exergy outflow of the drying chamber
Ex_{loss}	Exergy loss
IP	Improvement potential
G	Solar radiation
T_{dci}	Temperature of drying chamber at inlet
T_{dco}	Temperature of drying chamber at outlet
L	Latent heat of vaporization of water at exit air temperature
R^2	Coefficient of determination

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Introduction

India is one of the largest producers of fruits and vegetables (National Horticulture Board 2014); however, it is also one of the top countries with high post-harvest losses (Singh et al. 2014). Nearly 30% of the total fruit and vegetable production is wasted due to lack of adequate storage facilities, absence of proper handling, transportation, pre- and post-harvest treatment, and processing (Assocham 2013). People impacted by post-harvest loss are small-land-holding farmers, middlemen, and consumers.

Drying of the fresh produce locally is one of the ways to decrease the post-harvest losses and thereby improve the food security (Aggarwal 2012; Gbaha et al. 2007). It can generate livelihood options and dried food can also act as a source of nutrition during lean season, especially in rural areas. Drying of a food commodity is generally the process of removing excess water (moisture) to reach the standard specification of moisture content. Traditionally, small-scale open sun drying is practiced in villages. Open sun drying, as defined by Brenndorfer et al. (1987), is the spreading of food commodities on a flat surface exposed to the sun. The food commodities to be dried are heated directly by the sun rays and their moisture is removed by natural circulation of air. It is the cheapest method of drying as this process does not require any external source of energy except sunlight (Hii et al. 2012). Even though sun drying is the earliest and most common method of drying, it has several limitations associated with it. It is labor intensive and time consuming. It requires large space and is prone to contamination (Soponronnarit 1995). Despite these limitations, open sun drying is widely prevalent in rural India due to technical, financial, social and environmental, and instrumental barriers of renewable technologies.

A number of problems regarding open sun drying and solar drying have been identified by studies such as Timilsina et al. (2012) and Painuly (2001). Purohit et al. (2006) in their study state that solar dryers face stiff competition (as suggested by past experience) in Indian villages because of the large prevalence of open sun drying, and thus, a careful design of solar dryer is crucial for its adoption by the villages. Many designed renewable technologies are reported to be unsuitable for use in rural remote locations. These technologies are mainly designed for increased efficiency and are typically too complicated, economically less viable, and thus not sustainable in the longer run. Wilkins (2002) and UNGASS (1999) reported that insufficient attention is given to adaptation of the sophisticated and/or advanced technology according to the changing location. For designing an appropriate solar dryer according to location, understanding the prevalent drying activities of a place, and the limitations of present drying activities are very important.

Absence of accessibility of skilled manpower for different tasks such as designing, fabrication, installation, operation, and maintenance has been mentioned as one of the barriers for the acceptance of renewable technologies (Kapoor et al. 2014; Reddy and Painuly 2004; Rao and Kishore 2010; Luthra et al. 2015). There is a problem of absence of local manufacturers.

Financial and economic viability is another important economic barrier affecting its adoption (Tiwari 2016; Azad 2008; Chandrasekar and Kandpal 2004; Pohekar et al. 2005; Doukas et al. 2008; Rao and Kishore 2010). There is high initial capital cost, operational and maintenance cost, transportation cost, etc. Poor purchasing power of potential users has been a significant hurdle to the acceptance of renewable technologies (Pohekar et al. 2005; Adhikari et al. 2008). Social, environmental, and health costs should also be considered instead of only monetary costs.

According to Urpelainen and Yoon (2015), an important reason of failure of solar devices in India is the lack of peoples' participation in the projects. Social acceptance is very important and decisive for the dissemination of these technologies. The local culture, religion and superstitions of the community need to be understood when projects are planned to avoid problems later on in the development stage of the technology. In addition, the social fabric of the community, the hierarchy and decision-making process need to be given due consideration when planning. Local capacity building through the transfer of knowledge and investments in research, development and demonstration of the new technology should be given due importance. Institutional barrier is also very important and efforts should be made to overcome them (Schneider et al. 2008; Painuly 2001).

The objective of the present work is, thus, to design a suitable solar dryer after assessing the drying needs of the rural people, their current drying practices and constraints. To that end, two tribal villages of the state of Maharashtra in India were selected. Tribal villages were chosen as they were the worst sufferers of being subjected to household poverty and food insecurity. The current drying practices, the limitations of existing drying process and feasibility of introducing a new solar dryer in the villages were surveyed. Based on this feedback collected, a solar dryer is designed according to the needs of the people. Features of an appropriate and sustainable solar dryer were identified. The economic aspects of adopting solar dryers in villages were also investigated in this study.

Data and Methods

Field surveys were conducted during the months of September–December, 2016. Village survey, household survey, participatory rural appraisal (PRA) activities, seasonality and focused group discussions (FGDs) (Cavestro 2003) were conducted to collect qualitative and quantitative data. Mixed-mode research methodology (Creswel 2014) is undertaken to get a broader perspective as the practice of each household is different, and the problems and experience of each vary. A solar dryer according to the requirements of people was constructed and experiments were conducted from January to May, 2017. The operation of the solar dryer in the village was demonstrated during May–June, 2017.

Assessment of Needs and Constraints in the Study Area

Two tribal villages, Asane and Gorad, were surveyed for their existing drying practices. Gorad is a village located in Vada tahsil of Palghar district in the state of Maharashtra having 97.18% schedule tribe (ST) population. Asane is a village located in Ambegaon tahsil of Pune district in the state of Maharashtra with 91.57% schedule tribe (ST) and 4.21% schedule caste (SC) of the total population. The practice of open sun drying of fruits and vegetables for self-consumption and hirda for commercial use is prevalent in Gorad and Asane, respectively. Dried vegetables such as pumpkin, bitter gourd, okra (*bhindi*), and brinjal are dried when they are available and consumed in lean season. However, they cannot be stored for long and they catch mold. In case of hirda, color and dust contamination are the two parameters which determine the price of dried hirda in the local market. The darker the black color of dried hirda is, the better is the price fetched. Drying raw mango is not prevalent in Gorad because of susceptibility to high contamination and mold formation. The main difficulty of open sun drying is the cumbersome way of monitoring the food commodities. In addition, taste and color of the food items are also compromised during the drying process. Moreover, due to contamination and mold formation, many food commodities cannot be dried satisfactorily and, therefore, are spoiled.

The desirable features of the dryer are identified after interacting with the villagers and local NGO officials working in the area, and are listed below:

1. The solar dryer should preferably be fabricated with local resources and should be of 'DIY' model.
2. It should easily be fabricated by the local carpenter in the village.
3. The solar dryer should be of dismantling type, so that people can keep it safe from monsoon and also transport to other places.
4. The solar dryer should also not depend even partially on electricity as the power supply is very unreliable in the selected villages.
5. It should be of domestic capacity so that it can be easily maintained and used in every households.

Classification of Solar Dryers

Based on the heating, solar dryers are mainly classified into two broad categories (Ekechukwu and Norton 1999; Fudholi et al. 2010; Saxena et al. 2015):

1. Passive solar dryers or natural-circulation solar dryers.
2. Active solar dryers, or forced circulation solar dryers.

According to mode of solar heat utilization, active and passive solar dryers can be further divided into direct solar dryers, indirect solar dryers, and mixed-mode solar dryers. For use in remote areas, passive solar dryers are more attractive than active dryers despite their lower efficiency (Ekechukwu and Norton 1999). Another additional category is the hybrid solar dryer, which has additional source of energy for drying, and is more efficient (Bena and Fuller 2002; Fudholi et al. 2010; Husham Abdulmalek et al. 2018; Saxena et al. 2013; Saxena et al. 2015) with auxiliary source of heat such as biomass burner, which might be a feasible option for rural use in the selected villages.

Direct passive solar dryers are also called as integral-type natural-circulation solar dryers. The food commodities are covered by transparent sheet or glass and placed in an enclosure. However, there are many disadvantages including product damage due to local overheating, non-uniform color of the dried material and slow overall drying rates due to poor vapor removal (Ekechukwu and Norton 1999).

In indirect passive solar dryers, also called distributed-type natural-circulation solar dryers, solar radiation is not directly incident on the material to be dried. Air is heated in a solar collector which then enters the drying chamber to dry the product. Distributed passive solar dryers have higher operating temperatures than direct dryers and sun drying, and produce higher quality products (Ekechukwu and Norton 1999). In addition, there are dryers that operate on mixed-mode combining the features of the direct and the indirect type natural-circulation solar dryers.

Low-Cost Domestic Solar Dryers

Singh et al. (2004) developed a small-sized, natural-circulation, multi-shelf domestic solar dryer for drying various products at home. Mwithiga and Kigo (2006) built a small solar dryer having a mild steel absorber plate and a polyvinyl chloride transparent cover with limited sun tracking capability. Das and Kumar (1989) designed a low cost vertical collector chimney for drying paddy in rural locations. An active solar cabinet dryer was developed by Society for Energy, Environment and Development (SEED) in 1996 to decrease the drying time of Gum karaya from 10–15 days to 2–3 days (Eswara and Ramakrishnarao 2012). Esper et al. (1989) developed a low-cost solar air heater for the drying of agricultural products in tropical countries. Ahmad (2001) constructed a simple solar dryer from easily available, cheap plastic wrapping film with air bubbles. A temperature difference of around 10 °C was measured in the dryer. Saleh and Badran (2009) developed and tested a household solar dryer with transparent outside surfaces. In this dryer, maximum possible solar energy was collected leading to a longer drying period, comparing the approach to a dryer having a tracking system. Hallak et al. (1996) developed a direct solar dryer in the shape of a staircase. Tiris et al. (1996) developed a dryer with a solar air heater and a drying chamber. They tested the dryer for sultana grapes, green beans, sweet peppers, and chili peppers and compared results against traditional sun-drying. There are many low-cost solar dryers for domestic applications reported in the literature. Table 1 summarizes most of them.

As seen from Table 1, a number of low-cost domestic solar dryers have been reported in the literature, but there is lack of literature in which a dryer has been fabricated based on the requirements of people in remote rural location, with locally available materials, as a DIY model, and also where the makers have tried to make it sustainable by demonstrating it in the villages, conducting trials, and initiating focused group discussion.

Construction of Solar Dryer

The solar dryer shown in Fig. 1a is designed as per the requirements. The schematic diagram of the solar dryer is shown in Fig. 1b. The solar dryer designed is portable, durable and can be dismantled. The dryer consists of a flat collector plate, solar air heater, drying chamber, plastic cover, insulation, and chimney. The fabricated solar dryer is 75 cm wide, 165 cm long, 120 cm high and occupies a floor area of 1.2 m^2.

The collector plate is an aluminum sheet of 144 × 75 cm. It is painted matt black on the exposed face so as to increase its absorptivity of optical radiation. To have the option of dismantling the dryer, the collector sheet was not fixed and instead F channel was used to slide the collector sheet in place. This provision is also useful when collector sheet has to be changed. The collector is inclined at an angle of 20° so as to maximize the irradiation received during the months of March–May in south and central India. A tapering exit from the collector outlet into the drying chamber was made as it leads to low frictional losses. The collector and drying chamber are seamlessly integrated into a single unit to avoid any possible leakages. A clear flexible plastic sheet covers the collector plate to create a greenhouse effect. Glass is avoided to reduce weight as well as breakage. The air gap between the collector plate and plastic sheet is kept at 2 cm.

To make the dryer slick, durable, and low cost, semi-marine ply of 6 mm thickness is used as the cladding material and the sole insulating material. To make the dryer light weight, aluminum angles are used as the main structural elements. Multiple angles have been used as a support to the aluminum absorber sheet to reduce the sagging of both the aluminum sheet and the glazing.

The collector plate and plastic sheet bend up and continue as the front side of the chimney which is made of the same width as that of the collector plate and drying chamber. The dimensions of the chimney are 75 × 50 × 20 cm. The height of the chimney is 50 cm, which can be easily modified. The drying chamber, located at the junction of collector and chimney, has the provision of holding up to four trays. The trays are made up of a wooden frame and stainless steel mesh of size 2 × 2 mm. The drying chamber can be accessed by a door at the back. The door and the back of the chimney are made of acrylic material, so that the food items' condition, quality and color can be easily monitored if needed. The door has horizontal revolving axis, instead of vertical revolving axis, and magnetic stoppers to avoid any air leakage in case of malfunctioning of door or magnetic stoppers.

Experimental Methods

Drying experiments were conducted in the terrace of old solar laboratory of IIT Bombay in Mumbai (latitude 19°04′22″N, longitude 72°52′57″E) for 5 months from January 2017 to May 2017. The solar collector was kept facing south.

The instantaneous value of global solar radiation intensity was measured by a pyranometer (Model-DWR 8101, Make-DynaLab) having accuracy ± 1 W/m^2. Relative humidity and ambient temperature were monitored using Testo 174H data loggers having accuracy of ± 3% RH (range 0–100% RH) and ± 0.5 °C (range − 20 to 70 °C), respectively. Twelve calibrated *T* type thermocouples (0–300 K range) having accuracy of ± 1 °C were attached at different points of the dryer to measure the temperature. The drying products were weighed in an electronic balance (± 0.001 kg) after every hour. Air velocity was measured with hot wire anemometer (range 0.2–20 m/s) having accuracy of ± 0.03 m/s. Controlled experiments under the same conditions were also conducted on the same material by open sun drying.

Ambient temperature and temperature at different points of the solar dryer were recorded in all the experiments

Table 1 Summary of the literature on low-cost indirect solar dryers

References	Description	Efficiency	Temperature of chamber	Produce
Madhlopa et al. (2002)	An indirect passive solar dryer with composite absorber systems	Thermal efficiency of the flat plate collector, with glass cover glazing and wire mesh absorber was approximately 17 and 21%, respectively	Temperature of the drying air from the collector outlet raised from about 31.7 to 40.1 °C around noon	In the dryer, mango slices are dried from initial moisture content of about 85% (wb) to final of 13% (wb) while retaining 74% of ascorbic acid
Maiti et al. (2011)	An indirect, natural-convection batch-type solar dryer having 1.8 m^2 area of the collector fitted with north–south reflectors	Maximum efficiency of collector with the help of reflectors was recorded to be 58.5% at no load condition	During the 5-h drying period, from 10 a.m. to 3 p.m., the dryer temperature is 10–15 °C higher than the ambient temperature	In the dryer, 3.46 kg of 'papad' (a variety of Indian wafer) can be dried to 12% wb in 5 h
Bolaji (2005)	Indirect natural-convection solar dryer consisting of an air heater, an opaque crop bin, a chimney, a glass cover and black absorber plate	Maximum efficiency recorded was 21%	Maximum temperature recorded inside the collector was 64 °C in average and 57 °C for the drying chamber, while the maximum ambient temperature observed was 33.5 °C	It was used to dry maize during the month of August 2003
Scanlin (1997)	Indirect passive solar dryer prototypes with locally available tools and materials. Sun Lite HP plastic was used as glazing material	–	The dryers can produce temperature of 54–82 °C	–
Svenneling (2012)	Indirect passive domestic solar dryer having heat storage. The solar collector has an area of 1.05 m^2 and the air duct has a gap of 0.2 m. Plexiglass is used as a glazing material. A 1.2-m-long chimney with a diameter of 0.1 m was made from metal sheet and is connected to the drying chamber	The moisture content was reduced from 90% (wb) to about 10% in 16 h.	When using the solar dryer at the test location, the temperature in the collector and the drying chamber reached approximately 60 and 50 °C, respectively	In one batch 14 slices (roughly between 140–420 g) of pineapples are loaded, and gets dried in 16 h
Alonge and Adeboye (2012)	Indirect mode domestic passive solar dryer	Pepper can be dried from an initial moisture content of 78.9% (wb) to 24% (wb) in 51 h	The maximum temperature in the indirect solar dryer recorded was 48 °C while the ambient temperature was 39 °C	180 g of pepper can be dried in 51 h. The drying rate of the produce in the indirect passive solar dryer was 2.55 g/h while it was 2.17 g/h in open sun drying
Boulemtafes-Boukadoum and Benzaoui (2011)	Indirect passive dryer. It has a simple flat plate collector with glass as glazing material. The device operated at not more than 0.2 m/s	The thermal efficiency is reported to be between 10 and 30%, and the exergy to be between 2 and 48%		Mint drying samples took 2 days (14 days) to dry

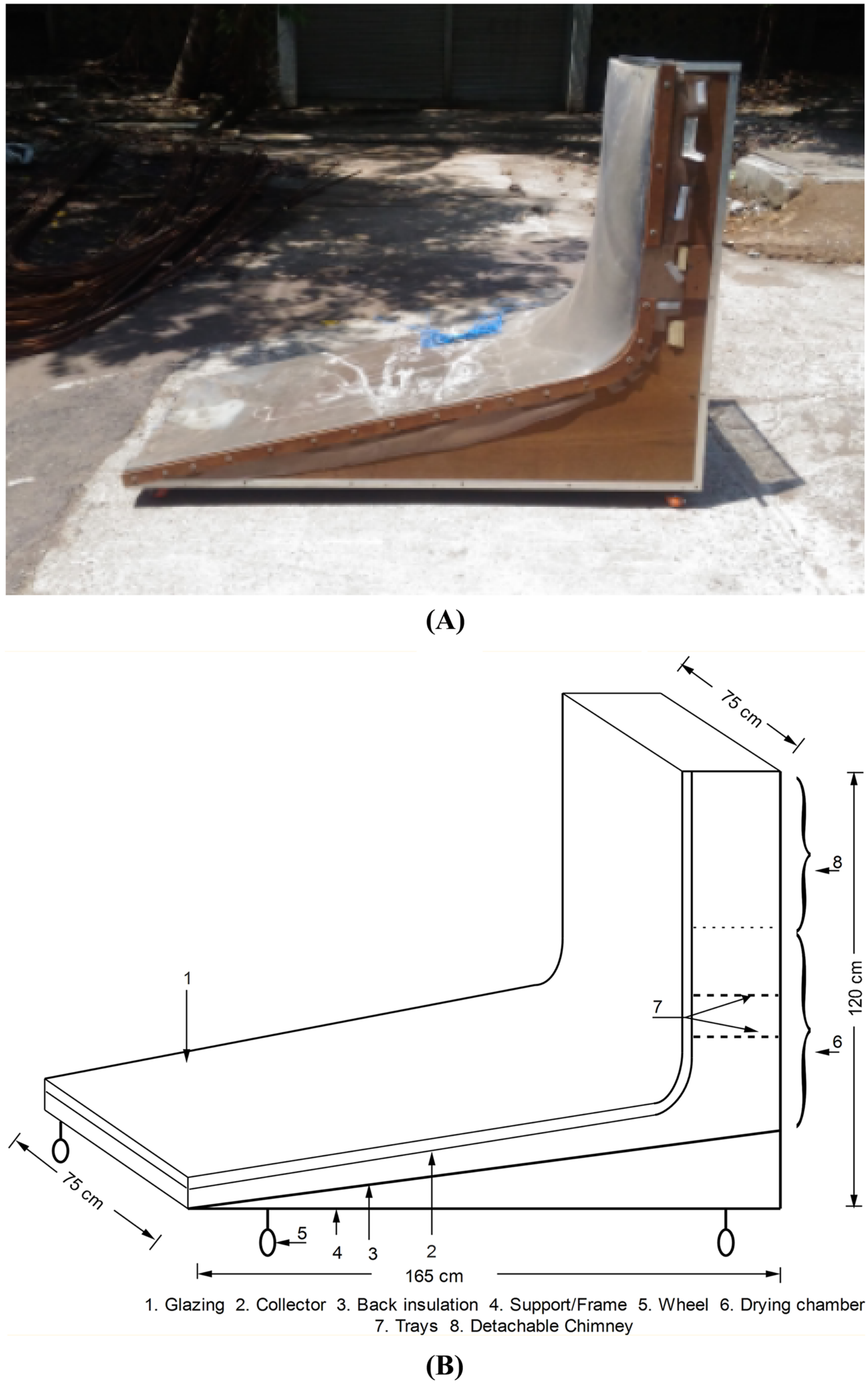

Fig. 1 Image (**a**) and schematic (**b**) of the designed solar dryer

conducted. Drying experiments were conducted on bitter gourd, okra, hirda, and raw mango. Selection of hirda and mango was based on the availability of fruits in the villages, whereas bitter gourd and okra were picked up because of the practice of drying them for self-consumption. The vegetables to be dried were bought daily from the same source to maintain the quality and consistency of the raw material. They were carefully checked to discard the spoilt ones. Bitter gourd and raw mango were then sliced into 3–5 mm thickness across the main axis, while okra was slit along the axis. Then they were weighed and placed in the solar dryer. Hirda was dried as whole, as done in villages. Simultaneous open sun drying was also conducted. All the parameters were measured hourly from 9 a.m. to 5 p.m.

The moisture content (wet basis), moisture ratio (MR) and drying rate during drying experiments were determined using the following equations (Dejchanchaiwong et al. 2016):

$$M = (W - W_d)/W_d, \tag{1}$$

$$\mathrm{MR} = M_t/M_0, \tag{2}$$

where W and W_d are, respectively, the weight of the product and weight of the dried product. M_0 and M_t are the initial moisture content and moisture content at time t, respectively. MR is the moisture ratio.

The lightness (L^*), red/green coordinate (a^*), and yellow/blue coordinate (b^*) of the dried vegetables were measured in a colorimeter (MiniScan XE Plus model colorimeter, Hunter Associate Laboratories Inc., Virginia, USA). Fresh vegetables were considered as reference and color deviation (ΔE) (Janjai 2012) was determined using the below equation. Lower the ΔE, more appealing is the dried product.

$$\Delta E = \sqrt{\left(\left\{(L^* - L^*_{\mathrm{ref}})^2 + (a^* - a^*_{\mathrm{ref}})^2 + (b^* - b^*_{\mathrm{ref}})^2\right\}\right)}. \tag{3}$$

The methods considered for evaluation of economic performance are annualized cost method (Sodha et al. 1991), life cycle savings, and payback period methods. This approach is similar to the one adopted by Elkhadraoui et al. (2015).

Uncertainty analysis of the experiments was performed using the following equation (Fudholi et al. 2013; Moffat 1988; Yahya et al. 2016, 2017):

$$W_R = \left[\left(\frac{\partial R}{\partial x_1} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \ldots + \left(\frac{\partial R}{\partial x_n} w_n)^2\right)\right]^{1/2}. \tag{4}$$

Performance Analysis of the Solar Dryer

Energy and exergy analyses were carried out to ascertain the thermal performance of the fabricated solar dryer according to the work carried out by Fudholi et al. (2014a, b, 2015, 2016).

Energy Analysis

The thermal efficiency of a solar collector is the ratio of useful heat gained to the solar radiation incident on the plane of the collector. It was estimated according to the following equation (Duffie and Beckman 1980; Sukhatme 1998; Fudholi et al. 2014a, b, 2015, 2016):

$$\eta_c = \frac{\dot{m}C(T_o - T_i)}{GA_c}. \tag{5}$$

System drying efficiency is the ratio of the energy required to evaporate moisture to the heat supplied to the solar dryer. Since the solar dryer constructed was a natural-convection type, the system efficiency was calculated as (Fudholi et al. 2014a, b, 2015, 2016)

$$\eta_d = \frac{WL}{GA_c}. \tag{6}$$

Exergy Analysis

The exergy values were calculated using Eq. (7) (Fudholi et al. 2014a, b, 2015, 2016). It is the general form of the exergy equation when applied to a steady flow system.

$$Ex = \dot{m}C\left[\left(T - T_a\right) - T_a ln\frac{T}{Ta}\right]. \tag{7}$$

For the exergy inflow of the drying chamber

$$\mathrm{Ex}_{dci} = \dot{m}C\left[\left(T_{\mathrm{dci}} - T_a\right) - T_a ln\frac{T_{\mathrm{dci}}}{Ta}\right]. \tag{8}$$

For the exergy outflow of the drying chamber

$$\mathrm{Ex}_{\mathrm{dco}} = \dot{m}C\left[\left(T_{\mathrm{dco}} - T_a\right) - T_a ln\frac{T_{\mathrm{dco}}}{Ta}\right]. \tag{9}$$

However, during the solar drying process, exergy loss is determined by

$$\mathrm{Ex}_{\mathrm{loss}} = \mathrm{Ex}_{\mathrm{dci}} - \mathrm{Ex}_{\mathrm{dco}}. \tag{10}$$

The exergy efficiency is defined by Fudholi et al. (2014a) as the ratio of exergy used in drying the product to exergy of the drying air supplied to the system. However, it is explained as the ratio of exergy outflow to energy inflow

Table 2 Uncertainty of parameters during drying experiments

Parameter	Unit	Uncertainty comment
Measured		
Ambient temperature	°C	± 1.13
Temperature of drying chamber	°C	± 1.62
Collector outlet temperature	°C	± 1.62
Relative humidity of the atmosphere	%	± 3
Weight of the dried product	g	± 9
Air velocity	m/s	± 0.03
Global radiation	W/m^2	± 3.87
Diffused radiation	W/m^2	± 3.87
Lightness	–	± 0.94
Red/green coordinate	–	± 0.28
Yellow/blue coordinate	–	± 0.41

for drying chamber. A similar approach has been followed here to determine the energy efficiency:

$$\eta_{Ex} = \frac{Ex_{dco}}{Ex_{dci}} = 1 - \frac{Ex_{loss}}{Ex_{dci}}. \quad (11)$$

The improvement potential (IP) of a solar dryer is calculated by the following equation (Fudholi et al. 2014a, b). Lower the energy loss, higher is the IP.

$$IP = (1 - \eta_{Ex})Ex_{loss}. \quad (12)$$

Results and Discussion

Table 2 shows the evaluation of uncertainty of the measured parameters during drying experiments using Eq. (4).

Results of Drying Experiments

Solar radiation and ambient relative humidity were measured in the experiments conducted. Figure 2a shows the temperature attained while drying in 1 day. The temperature of the ambient air varies from 31 to 40 °C, while the temperature of the drying chamber ranged from 31 to 55 °C. The ambient relative humidity varies from 30 to 65%. Maximum temperature attained in the drying chamber is recorded to be 55 °C for an ambient temperature of 38 °C. Figure 2b shows the global radiation and diffused radiation measured.

Drying of Bitter Gourd, Okra and Raw Mango

Figure 3 shows the reduction in moisture content with time for three different produce for varying loads in the solar dryer and Fig. 4 shows the same for open sun drying for the same vegetables. Initial moisture content of bitter gourd was found to be 89% (wb). Moisture content (wb) of 1.2, 3.5,

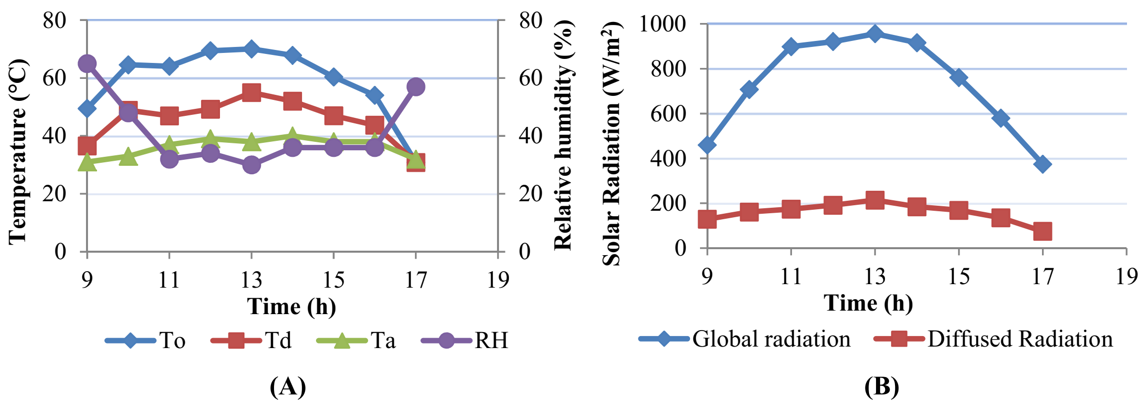

Fig. 2 Temperature (**a**), relative humidity and solar radiation (**b**) variation along the day

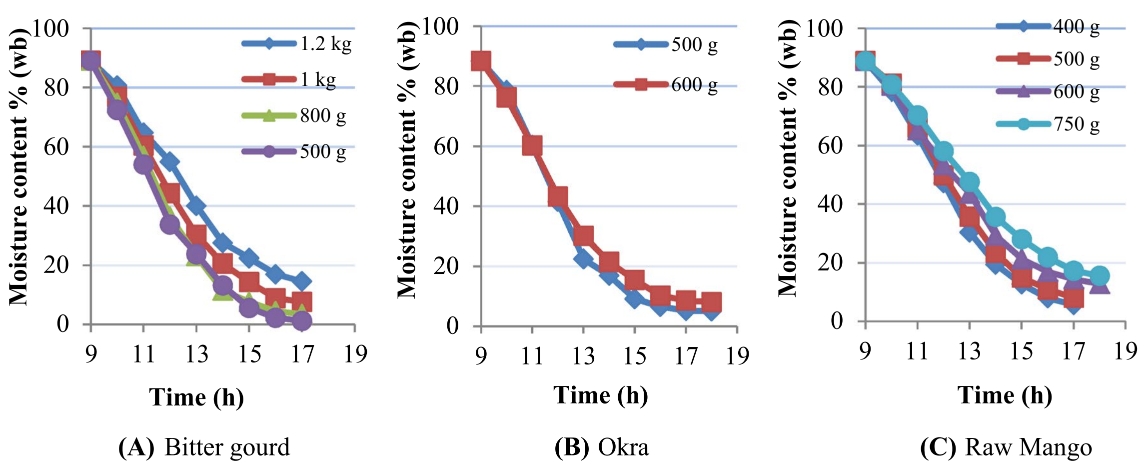

Fig. 3 Variation of moisture content of solar-dried products with drying time for varying loads. **a** Bitter gourd, **b** okra, and **c** raw mango

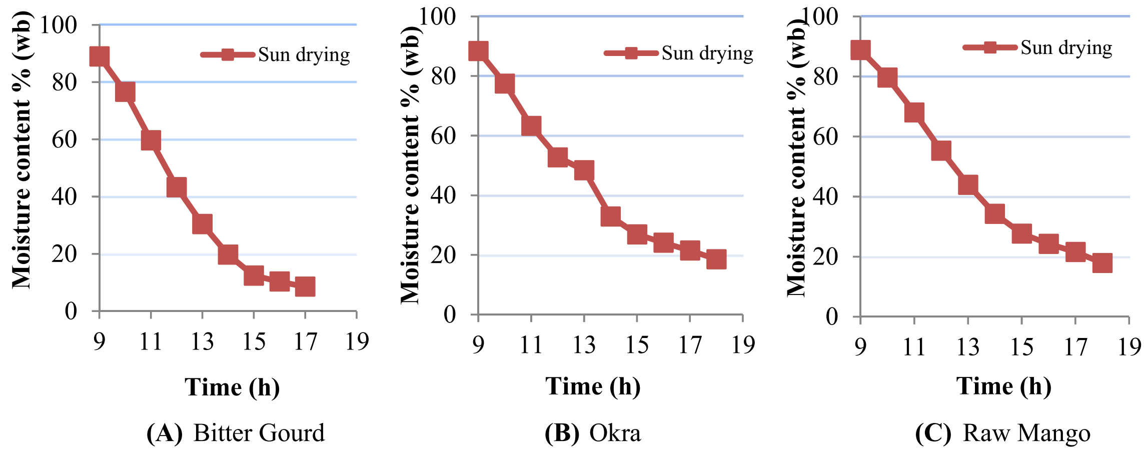

Fig. 4 Variation of moisture content of open sun-dried products with drying time for varying loads. **a** Bitter gourd, **b** okra, and **c** raw mango

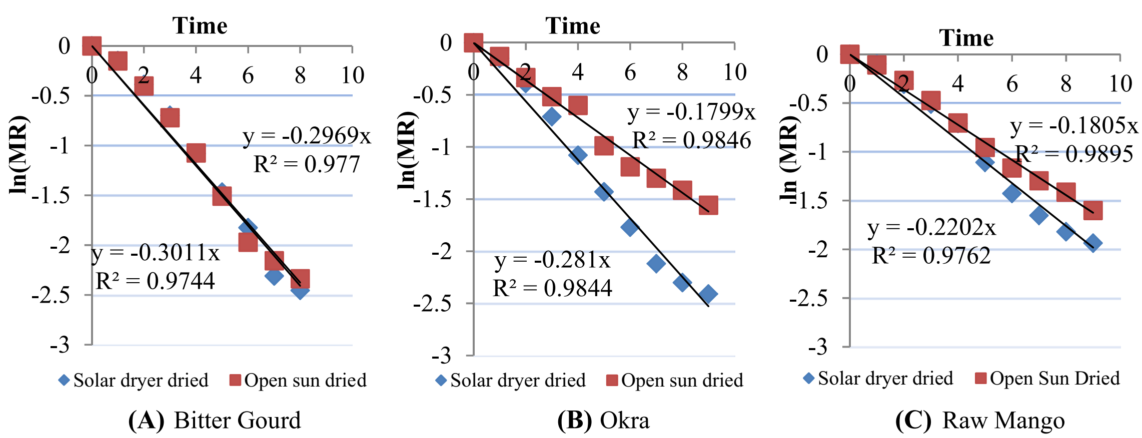

Fig. 5 Determination of drying rate for solar dryer-dried and open sun-dried products. **a** Bitter gourd, **b** okra, and **c** raw mango

7.6, and 14.6% were observed for 500 g, 800 g, 1 kg and 1.2 kg of solar-dried bitter gourd at 5 pm while, in open sun it reached 8.5%. 600 g of sliced okra reached 8.6% moisture content (wb) at 5 p.m. from initial moisture content of 88.4% and 8.1% at 6 p.m. 500 g okra reached 5% moisture content at 6 p.m. The final moisture content of open sun-dried okra at 6 p.m. was found to be 18.6% (wb). Final moisture content of 400 and 500 g at 5 p.m. reached 5.7 and 8% (wb), respectively, from initial moisture content of 88.8% (wb). The final moisture content of 600 and 750 g raw mango was found to be 12.8 and 15.6%, respectively, at 6 p.m. The uncertainty of moisture content of the solar-dried and sun-dried products is found to be ± 0.015 g of water/g wet material from Eq. (4). The uncertainty of moisture ratio is ± 0.021.

Drying rate was determined for both solar dryer-dried and open sun-dried products, as shown in Fig. 5. For determining the drying rate of the solar dryer, max loading capacity of the dryer was taken, i.e., 1 kg for bitter gourd, 600 g for okra, and 600 g for raw mango. According to the first-order kinetics, drying rate in the solar dryer was found to be 0.30/h with R^2 of 0.97 (CI 95%) for bitter gourd, 0.28/h with R^2 of 0.98 for okra and 0.22/h with R^2 of 0.98 for raw mango. For open sun drying it was 0.30/h with R^2 of 0.98 (CI 95%) for

Table 3 Color testing parameters of fresh, open sun-dried and solar-dried bitter gourd and okra

Commodity	Condition	Parameters		
		*L**	*a**	*b**
Bitter Gourd	Fresh	49.43	− 8.59	31.3
	Sun dried	51.11	2.34	16.58
	Solar dried	45.28	− 3.15	24.41
Okra	Fresh	49.58	− 5.86	24.17
	Sun dried	33.3	− 1.31	14.37
	Solar dried	37.02	− 3.48	18.06

bitter gourd, 0.18/h with R^2 of 0.98 for okra and 0.18/h with R^2 of 0.99 for raw mango.

Bitter gourd and okra were tested in the color calorimeter along with visual examination to examine how the dried products resemble the raw compared to open sun. Color testing parameters (L^*, a^* and b^*) were determined for fresh, open sun-dried, and solar-dried samples of bitter gourd and okra, and are given in Table 3. ΔE for open sun-dried and solar-dried bitter gourd was determined to be 18.41 and 9.71, respectively, using Eq. (4). ΔE for open sun-dried okra was 19.54 and solar-dried okra was 14.17. From visual inspection too, solar-dried products resembled fresh products more than open sun-dried ones. Dried raw mango was visually examined as they are needed to make *amchoor* (an Indian spice), which is in powdered state. It was observed that the dried mango pieces attained the same consistent light color which is needed to fetch good price whereas open sun-dried mango pieces were inconsistent in color. The uncertainty of total color change is calculated to be ± 1.50 from Eq. (4).

Drying of Hirda

Fruit of the plant Myrobalan—*Terminalia chebula*—is called hirda in local language (Maharashtra, India). Hirda is open sun dried in tribal villages of Maharashtra. It is mentioned in a separate sub-section as it is dried as a whole unlike the others where they are sliced. For experimentation, Hirda was laid out in the sun and in the trays of solar dryer to dry. 1 kg of fresh hirda was loaded into the dryer. Figure 6a shows the comparison of time taken in solar dryer and in open sun drying. Initial moisture content of hirda was found to be 68.6%. Hirda in the solar dryer took 5 days to reach less than 10% moisture content (wb) and 8 days by open sun drying. On day 5 at 5 p.m., moisture content of hirda in the solar dryer reached 9.2% (wb), while in open sun drying it reached 22.1% (wb).

Drying rate for hirda in solar dryer and open sun was found out according to the first-order kinetics as shown in Fig. 6b. Drying rate in the solar dryer was found to be 0.36/day with R^2 of 0.96 and for open sun drying it was 0.24/day with R^2 of 0.99.

Color and dust contamination are the two parameters which decide the selling price of hirda in the market. Darker the color of hirda, higher is the price in market. In the village, people step on it so that it dries faster and attains the black color, thus contaminating it in the process. With the use of solar dryer, dust-free hirda was produced without compromising on the color. By visual inspection, color of solar-dried hirda was found to be better than sun-dried hirda, as it acquired a blackish color while open sun-dried hirda acquired a brownish color.

Performance of the Solar Dryer

The domestic solar dryer took 8 h to dry 1 kg of bitter gourd from the initial moisture content of 89 to 7.6% (wb), as mentioned earlier. The drying activity was carried out thrice on three consecutive days.

The average solar radiation was 648 W/m^2 at a mass flow rate of 0.012 kg/s. The average collector efficiency is 21%, and the maximum collector efficiency is 38%. The thermal efficiency rates during the 8 h of drying are shown in Fig. 7 for 3 days (Day 1 or D1, Day 2 or D2, and Day 3 or D3) which illustrates the increase in the thermal efficiency of the collector at a low solar radiation. Figure 7 also shows the energy gained from the collector. The average system drying efficiency was also calculated to be 10.73% from Eq. (6), which is acceptable for indirect passive solar dryers.

The exergy efficiency of the solar drying process calculated according to Eq. (7) was 17–44%, with an average

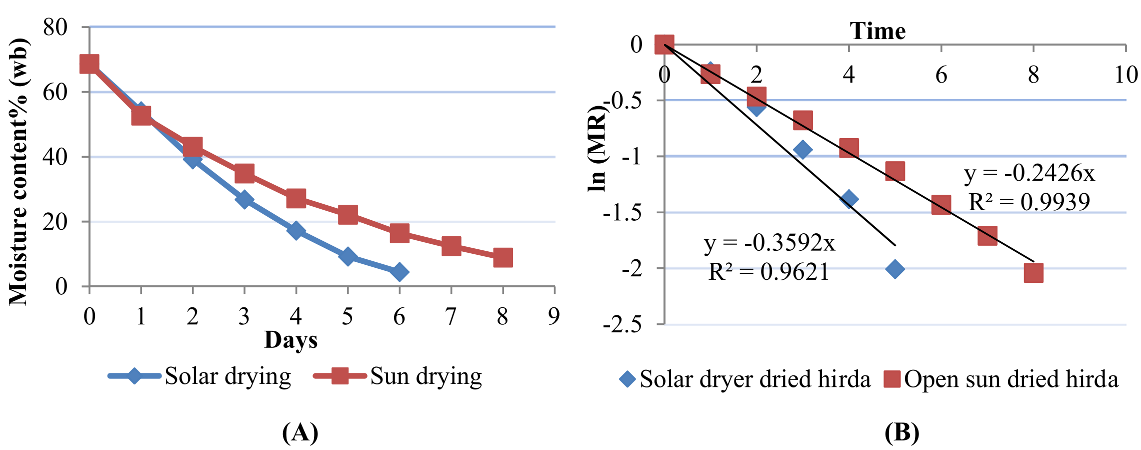

Fig. 6 Variation of moisture content of solar-dried and sun-dried hirda with **a** drying time and **b** determination of drying rate in

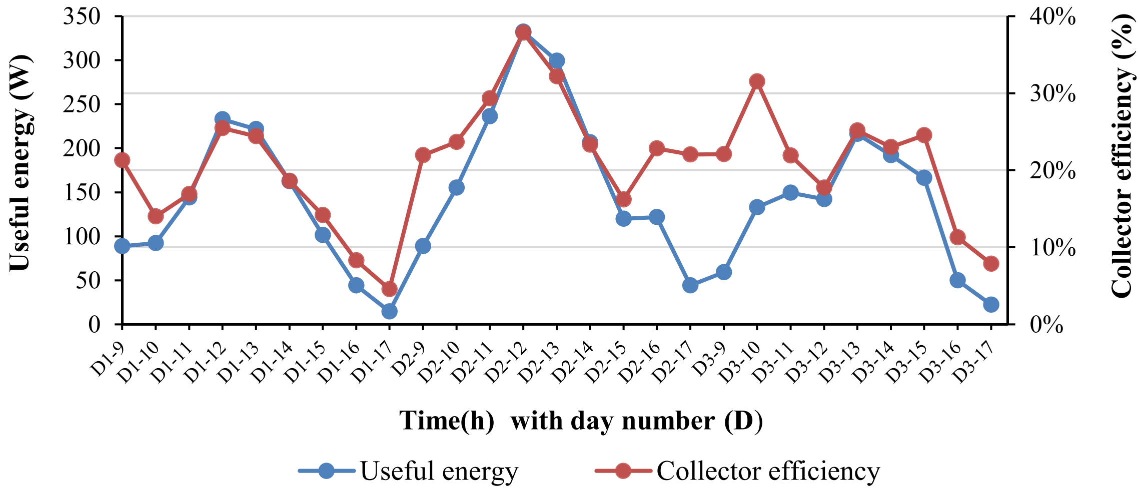

Fig. 7 Energy gained from the collector and thermal efficiency with drying time

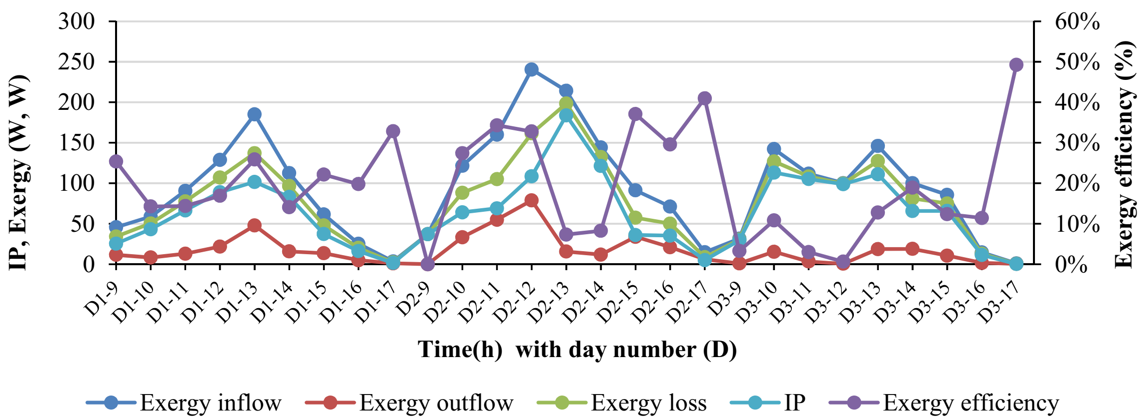

Fig. 8 Variation of hourly exergies (inflow, outflow, and loss), exergy efficiency and improvement potential

of 31%. The improved potential (IP) ranged from 0.25 to 184 W, with an average of 64 W. Figure 8 shows the hourly variation of exergy inflow, exergy outflow, exergy loss, exergy efficiency and IP of the solar drying process from 9 a.m. to 5 p.m.

Economic Analysis of Dryer

Based on the climatic condition of the state of Maharashtra (India), at least 250 solar days in a year are considered. For economic analysis, the inflation rate was taken as 4% and interest rate as 7%. The cost of fabricating the dryer is Rs. 6000. Branded as well as non-branded dried products are available in the market. Non-branded products are usually of poor quality and low shelf life. Solar-dried products are hygienically dried, as there is no dust accumulation and air contamination their quality can be considered better than non-branded ones (Singh et al. 2004; Sreekumar et al. 2008). The calculations of this section are based on the assumption that there is a constant demand of dried products and the solar-dried products fetched the same price as the branded products in the market.

The annualized cost of solar dryer was calculated to be Rs. 939.84 and the total amount of bitter gourd that can be dried in the dryer in a year was 52.5 kg. Cost of drying per kg of dried bitter gourd in the dryer came out to be Rs. 17.9. Cost of drying 1 kg of bitter gourd was determined to be Rs. 132.19. Saving per kg of dried bitter gourd when sold at Rs. 350/kg was Rs. 217.81 and saving per day was determined to be Rs. 45.74.

The cumulative present worth of annual saving for drying bitter gourd over the life of dryer was determined to be Rs. 94,346. Table 4 in "Appendix" shows the calculated value of annual savings, present worth of annual savings and present worth of cumulative savings. The payback period for drying bitter gourd was calculated to be 0.56 year, i.e., 140 solar days. The payback period of 0.56 year is very small compared to the life of the dryer (10 years) and it can be utilized profitably. The results reported in this section, however, vary depending on product, place, and time.

Discussion

The designed solar dryer produced much better results than open sun drying which is practiced in the villages while drying bitter gourd, raw mango, hirda, and okra. Bitter gourd and okra dried in the solar dryer are more appealing compared to the open sun drying by visual inspection and ΔE value. Hirda, on drying in the solar dryer, attained a darker color (without compromising on the dust contamination) compared to open sun drying which fetched a better price in the market. Uniform color was obtained while drying raw mango in solar dryer as needed in markets. There were reports of difficulty in drying raw mango in Asane for commercial purposes because of mold formation and dust accumulation. In open sun drying, raw mango cannot be dried in a day, and because of reabsorption of moisture, there is mold formation, as informed by the people in Asane. Same problem with okra was also reported by people of Gorad. The problem of mold formation was solved using the solar dryer, and okra and mango can be dried satisfactorily in a day. The loading capacity of the dryer has also been determined.

Demonstration

The solar dryer fabricated was taken to Asane village for demonstration and dissemination, after design and performance evaluation of the solar dryer. Field trials were conducted in Asane for demonstration of working of the dryer and its handling. A fabrication manual was designed where each and every step of construction was described to encourage the people to construct dryers locally. The designed manual was distributed to encourage people to make their own solar dryers. An informal training on how to use the dryer was imparted to the villagers. A focused group discussion was also conducted for better understanding of the response of the villagers, especially women, to such solar dryers.

Conclusion

- A low-cost natural-convection solar dryer is designed and constructed for rural domestic use according to requirements of people. The indirect dryer can be dismantled, portable and durable. The solar dryer designed can be fabricated in village using local resources without external support or help.
- At the peak point, temperature in the drying chamber is around 15 °C higher than the ambient temperature.
- Solar dryer is very efficient as food commodities in the solar dryer dry much faster than open sun drying. Mold formation and contamination issue are also solved with the use of dryer.
- Performance analysis is carried out to determine the efficiency of the designed solar dryer.
- Color analysis of the dried food products is performed in a colorimeter to determine the color retention in comparison to open sun drying. There is better retention of color in the solar dryer.
- Economic analysis of the solar dryer is carried out by annualized cost method, life cycle savings, and payback period methods. The designed dryer has a payback period of 0.56 years.
- Operation of the designed solar dryer was demonstrated in villages and a positive feedback was gathered from the people.

This project can be a way forward for rural development by generation of livelihood option and food security for the villages.

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Appendix

See Table 4.

Table 4 Economics of solar dryer for bitter gourd

Years	Annualized cost of dryer (Rs)	Annual savings (Rs)	Present worth of annual savings (Rs)	Present worth of cumulative savings (Rs)
1	939.84	11,435	10,687	10,687
2	939.84	11,892	10,387	21,074
3	939.84	12,368	10,096	31,170
4	939.84	12,863	9813	40,983
5	939.84	13,377	9538	50,521
6	939.84	13,912	9270	59,521
7	939.84	14,469	9011	68,802
8	939.84	15,048	8758	77,560
9	939.84	15,650	8512	86,072
10	939.84	16,276	8274	94,346

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