Solar Drying—A Sustainable Way of Food Processing

M.A. Aravindh and A. Sreekumar

Abstract In a developing country like India, having the second largest population and agriculture as the source of income to nearly 60 % of the total population, post-harvest and storage loss is a major quandary, which needs to be addressed in due diligence. Many food preservation techniques like cold storage, drying, etc., have been evolved out over the years to tackle the above losses. The major constraint is that almost all the technologies are utilizing fossil fuel resources, which are depleting very fast and wise use of these precious resources are preferred for long-term energy sustainability. Therefore, sustainable methods for food preservation are the need of the hour. Solar drying is one of the best choices in this context. Different models of solar dryers have been developed and good quantum of research is progressing in most of the countries to propagate the solar drying technology for value addition of agriculture products. The solar drying technology is a classical example to showcase how sun's free energy could be effectively utilized for the benefit of mankind. This chapter explains the different types of dryers, different aspects of solar drying, parameters involved in the drying process and the economic analysis to analyse the feasibility of the solar drying system. Case studies of a few of the successful installations are also included.

Keywords Food processing · Open sun drying · Solar drying · Economic analysis

1 Indian Agriculture and Its Economics

India has one of the oldest civilizations in the world with diverse culture, climate, food habits, etc. We mastered the art of agriculture in our infantry itself, and it has taken a speedy growth since its independence. As of now, India holds the second

M.A. Aravindh · A. Sreekumar (✉)
Centre for Green Energy Technology, Pondicherry University, Pondicherry 605014, India
e-mail: sreekmra@gmail.com

A. Sharma and S.K. Kar (eds.), *Energy Sustainability Through Green Energy*,
Green Energy and Technology, DOI 10.1007/978-81-322-2337-5_2

largest agricultural land amounting to 179.9 million hectares [Agriculture (2013), Detailed Project Report of the National Agricultural Education Project (NAEP) (2012)]. Green Revolution has elevated India to the second largest exporter and consumer of food grains in the world. With nearly 60 % of the Indian population still depends on agriculture for livelihood, it plays a major role in GDP with a share of 13.9 % in the financial year 2012–13. In April 2013 to February 2014, the export value of agricultural products from India has reached US$44.59 billion with an expected growth of 4 % in the present financial year.

1.1 Post-Harvest Losses

Even with these positive statistics worries come up when looking into the annual post-harvest loss, which is estimated to be as high as INR 2.5 lakh crores in 2013–2014 (ASSOCHAM 2014). Leading the list is West Bengal with an annual loss of INR 13,657 Crores, followed by Gujarat, Bihar and Uttar Pradesh with individual annual losses of more than INR 10,000 Crores. This is because of the shortage of food storage facilities and under utilization of advanced technologies for food processing. Currently, India has a food storage capacity of roughly 74.6 million tonnes owned by Food Corporation of India (FCI) and state agencies with an annual production of 250 million tonnes of rice and wheat alone. Hence, the storage facilities need to be enormously expanded. With the passing of Food Security Bill, the need for food storage has come to limelight. Increase in population and reduction in worldwide food production has given us less options either to produce more food or to reduce the losses by preserving or storing.

2 Preservation Methods

Agricultural crop is perishable and it will get damaged as time passes by the attack of bacteria, fungi, etc. (Simth 2011). Preserving fruits, vegetables, grains, meat, marine products, spices, etc., has been practiced for thousands of years. Some of the food preservation methods are given below.

- Fermentation

Fermentation is the method of controlled spoilage of food stuff with micro-organisms like yeast; say milk to curd or ghee, which helps in extending the usage time. This method cannot be used for all products, but there are products which are better when fermented such as rice, chocolate and coffee.

- Curing or salting

Curing or salting is the preserving method using salt which will absorb moisture from the food materials thereby making the bacteria inhospitable. Though the bacterial activity is restricted, we need to find ways to prevent moulds. Bacon, salt pork, smoked fish, olives, pickles preserved lemons, etc., are examples of salt preserved foods.

- Drying or dehydrating

Drying or dehydration is one of the oldest methods of food preservation by removing the moisture from the food materials by open drying in the sun or by passing hot air over the products. Open drying is associated with disadvantages such as contamination, insect infestation and spoilage due to rains. Other types of drying using conventional energy sources require high capital and running cost to build and operate the facilities.

- Freezing

Freezing is the method of keeping the products in cold storage. This method helps to store the products for months or even for years. Cold storage is not a feasible method particularly in developing countries as it is expensive.

- Canning

Canning is by heating and storing in containers for prolonged usage. It is expensive and also associated with risk of botulism poisoning. Botulism is a rare and potentially fatal paralytic illness caused by a toxin produced by the bacteria Clostridium botulinum.

- Irradiation

Irradiation is one of the latest technologies used for food preservation using controlled radiation to kill micro-organisms which can cause food spoilage. Thereby storage time can be extended provided the chemical make-up of the food is also unaltered.

3 Methods of Drying

In the food chain handling, drying is considered as one of the critical operations. The principle objective of drying is to supply the required thermal energy in an optimum manner yielding high-quality products. Drying is broadly classified into three types based on the temperature requirement such as low temperature, high temperature and freeze-drying. Osmovac and desiccant methods are also employed in certain situations (Garg and Prakash 1997; Suhas et al. and Nayak 2009).

3.1 Low-Temperature Drying

It is used for places where the average ambient temperature is around 10 °C. The temperature range used for this type of drying ranges from 15 to 50 °C. It uses natural or heated air with low temperature to dry the product in very longer time. Even though it is a relatively slower process and is dependent on favourable weather conditions, it has some advantages such as lesser spoilage, good quality product, less labour and capital investment.

3.2 High-Temperature Drying

High-temperature drying uses temperature starting from 50 °C, and this is the most common method in developed countries. It is used for drying high moisture content products such as fruits and vegetables. A hot air recirculation system may be employed with a dehumidification unit to increase the effectiveness of the system with less wastage of energy.

3.3 Freeze-Drying

Freeze-drying helps in removing water from fluids, say fruit juices. The operating temperature for this type of drying ranges from −10 to −40 °C. The product is first frozen and kept in low-temperature condenser or chemical desiccant. The water will get condensed or absorbed by the desiccant. It is used for drying heat-sensitive materials, but it is a slow and expensive process.

3.4 Osmovac Drying

It is a two-step process, which involves osmosis and vacuum vaporization, and is employed for drying fruit juices. Initially, the product is heated up to a temperature higher than the ambient temperature for better dehydration and then is made to undergo osmosis process. It is then carried to a chamber where vacuum drying happens.

3.5 Desiccant Drying

It is one of the best methods for dehydrating the exhaust air for recirculation, if the exhaust air is still hot. Hence, the efficiency of the system can be improved. The desiccant can be regenerated using solar heat.

4 Food Drying

Drying is one of the most prevailing methods of food preservation, where the moisture is removed preventing the growth of micro-organisms that causes food damage. This method helps in reducing the weight and volume of the product which reduces the transportation and storage load and also helps in storing the food in ambient temperature.

Drying is a process which involves a combined heat and mass transfer, where the surface moisture is removed first and the moisture from the interior is forced to move to the surface which is removed later. Hence, to enhance drying process, products are made to smaller pieces or sliced to increase the surface area. Increased surface area helps in better moisture removal. There are other parameters which also can affect the drying process such as temperature gradient, air flow rate and air humidity.

4.1 Objectives of Drying

The major objectives of the drying process are as follows:

- To reduce the food spoilage caused by larger production and limited usage. There will be huge production during some particular season but the consumption will be very less, and hence, the food will be unused leading to less income to the farmers.
- Prolonged usage of the product preventing them from spoiling due to microbial attacks.
- Drying will reduce the weight dramatically and makes transportation easy.
- High-quality dried product will have good market value and hence will bring high profit to the producers.

4.2 Classification and Selection of Dryers

Dryers are classified into five types based on the techniques in which the food is dehydrated. In open sun drying, the food is dehydrated when it is exposed directly to solar radiation. The moisture is carried away by wind as it blows above the product. Here the food products are placed in polythene sheet, mud or cement floor or on racks. In direct sun driers the food material are kept inside the drier. The air inside the drying chamber is heated up due to greenhouse effect and also product absorbs direct solar radiation. Vent holes are provided for passage of fresh air and removal of moist air from the drying cabinet. The food materials are completely protected from solar radiation in indirect dryers, which uses solar air heater to raise the air temperature. The hot air is allowed to pass through the drier, where the product is loaded. Indirect driers are essential for food which loose nutritional value on exposure to solar radiation. Hybrid dryers make use of fossil fuel or biomass fuel like rice husk to ensure a constant drying process. Fuelled dryers are driven by either conventional fuels or utility supplied electricity. (Sodha et al. 1987).

5 Solar Drying

Solar drying has been considered as one of the most promising areas for the utilization of solar energy, especially in the field of food preservation. Open sun drying is the most common method employed in tropical countries for the drying of agricultural products, food stuffs, etc. The method is simple, as it does not involve any costly equipment. The product to be dried is spread under sun, and the moisture evaporates from it over a course of time. Even though the process is simple, it suffers from disadvantages such as dust contamination, insect infestation, microbial contamination and spoilage due to rains. Product dried in this way is unhygienic and sometimes unfit for human consumption (Garg and Prakash 1997).

Solar drying can be most successfully employed as a cost-effective drying technique. It has got several attractive features. For example, energy is available free of cost and can be harnessed in the site itself. Controlled drying is also possible by this method, and it enhances the quality of dried product. Solar drying systems must be properly designed in order to meet particular drying requirements of specific crops and to give satisfactory performance with respect to energy requirements. A wide variety of solar dryers have been designed by many researchers. Drying conditions for different products will be different, and hence, the solar dryer should be designed for their particular requirement. A good design can help in producing high-quality products and hence bring good returns to the farmers.

India receives good amount of solar radiation in the range of 4–7 kWh/m^2-day around 300–330 days in a year. Thus, it is one of the most promising sources of energy. Unlike fossil fuels and nuclear energy, it is an environmentally clean source of energy. Secondly, it is free and available in adequate quantities in almost all parts of the world where people live in. Solar energy is always in an advantageous position compared with depleting fossil fuels. In a tropical country like India, most of the energy demands can be met by simple systems that can convert solar energy into appropriate forms. By proper application of technologies, excellent thermodynamic match between the solar energy resources and many end-uses can be achieved (Sreekumar 2011a, b).

5.1 Comparing Solar Drying with Other Options

When one considers solar drying, it has to be compared with other options available. In some situations open-air drying or fuelled dryers may be preferable to solar. Solar drying will only be successful if it has a clear advantage over the current practice. Table 1 lists the merits and demerits of solar drying when compared with traditional open-air drying, and then with the use of fuelled dryers (Sreekumar 2011a, b; Garg and Prakash 1997).

The comparison will assist in deciding among solar, open-air and fuelled dryers. The local site conditions will also play an important role in this decision. Some indicators that solar dryers may be useful in a specific location include

1. Conventional energy is unavailable or unreliable
2. Plenty of sunshine
3. Quality of open-air dried products needs improvement
4. Land is extremely scarce (making open sun drying unattractive)
5. Introducing solar drying technology will not have harmful socio-economic effects.

Table 1 Solar dryers compared with open-air and fuel drying

Type of drying	Merits (+) and Demerits (−) of Solar Dryers
Solar versus Open-air	+ Superior quality dried products
	+ Minimizes losses and contamination
	+ Less drying area
	+ Better preservation of nutrition and colour
	+ Less labour intensive
	+ Reduced drying duration and less chance of spoilage
	+ Bring down to safe moisture level, which allows longer storage
	+ Controlled drying
	− Comparatively more expensive
	− In some cases, food quality is not significantly improved
	− In some cases, market value of food will not be increased
Solar versus Fuelled	+ Prevents fuel dependence
	+ Operating cost is almost zero
	+ Often less expensive
	+ Reduced environmental impact
	− Requires adequate solar radiation
	− Hot & dry climates preferred

5.2 Design Consideration

As far as design of a solar drier is concerned, there is no uniform design standards applied to all the models. This is mainly because of all the drying parameters are variable from one product to another. Knowledge of heat and mass transfer combined with material properties is essential to design a solar drier as all the processes involved are highly nonlinear. Due to this, scaling of a solar drier is generally complicated. Design experience of pilot scale and field-level familiarity will be helpful for the development of a new solar dryer. An advanced design will lead to hygienic production of high-quality product with a considerable reduction in drying duration. Temperature required for a particular product to be considered an important aspects for the design of a solar dryer. During the course of time, many commercial designs are evolved out even though market penetration of solar dryer is very poor. Non-awareness about the technicalities and lack of good design to perform a suitable requirement can be considered as a barrier to large-scale deployment of solar driers. Most of the commercial models available are poorly designed without much parametric optimization. This necessitates an urgent measure of designing highly efficient, cost-effective and adaptable solar drying system. Various calculations must be performed to determine the parameters such as quantity of air required, mass of moisture removed from the produce, rise and fall of air temperature and amount of energy required, which will be useful for techno-economic feasibility analysis. The mechanical design consideration concentrates on fixing the mechanical details of the drying chamber and collector. Mechanical design studies are regarding materials for solar air heater fabrication, cabinet size, tray volume, number of trays, size of ducting and cladding, etc. The other design parameters that should be taken into account are geographical location, local climatic conditions, types of materials to be dried, available solar flux, etc. The design consideration for the drying system, i.e. the solar air heater used to supply hot air, drying chamber and ducting is discussed here separately (Sreekumar 2011a, b).

5.2.1 Design Aspects of Drying Chamber

In a commercial solar drying system for bulk product drying, the solar air heater is integrated with a drying chamber. The following are the major design parameters of a drying chamber (Garg and Prakash 1997).

(a) quantity of product to be dried per batch or day and size of the drying cabinet to hold the material
(b) capacity of the dryer (kg/batch)
(c) system for loading and unloading the material
(d) materials for dryer cabinet and tray construction
(e) arrangement to pass hot air through the material to be dried
(f) effective circulation and recirculation of hot air through the dryer
(g) a vent through which the warm moist air to remove from the drying chamber.

5.2.2 Thermodynamical Aspects

Based on the thermodynamical aspects, the quantity of air needed for drying a specified mass of the product to be evaluated. Two different methods are employed here for these calculations. They are listed below:

(i) The psychrometric chart

The capacity of air for moisture removal depends on its humidity and temperature. The study of relationship between air and its associated water is called psychrometry. On the psychrometric chart, various thermodynamic properties of moist air such as vapour pressure, relative humidity, humidity ratio, dry bulb temperature, wet bulb temperature, dew point temperature, enthalpy and specific volume can be estimated. When any two of the three temperatures are known, i.e. dry bulb, wet bulb or dew point, all other properties can be determined from the psychrometric chart.

In the psychrometric chart (Fig. 1), humidity ratio is the ordinate and dry bulb temperature is the abscissa. The upper curve of the chart is labelled wet bulb and dew point temperatures. The other curves on the psychrometric chart that are similar in shape to the wet bulb lines are lines of constant relative humidity (%). The straight lines sloping gently downward to the right are lines of constant wet bulb temperature. The interaction of a dry bulb and a wet bulb line gives the state of the air for a given moisture content and relative humidity. The amount of air needed for drying a particular quantity of product can be calculated using psychrometric chart.

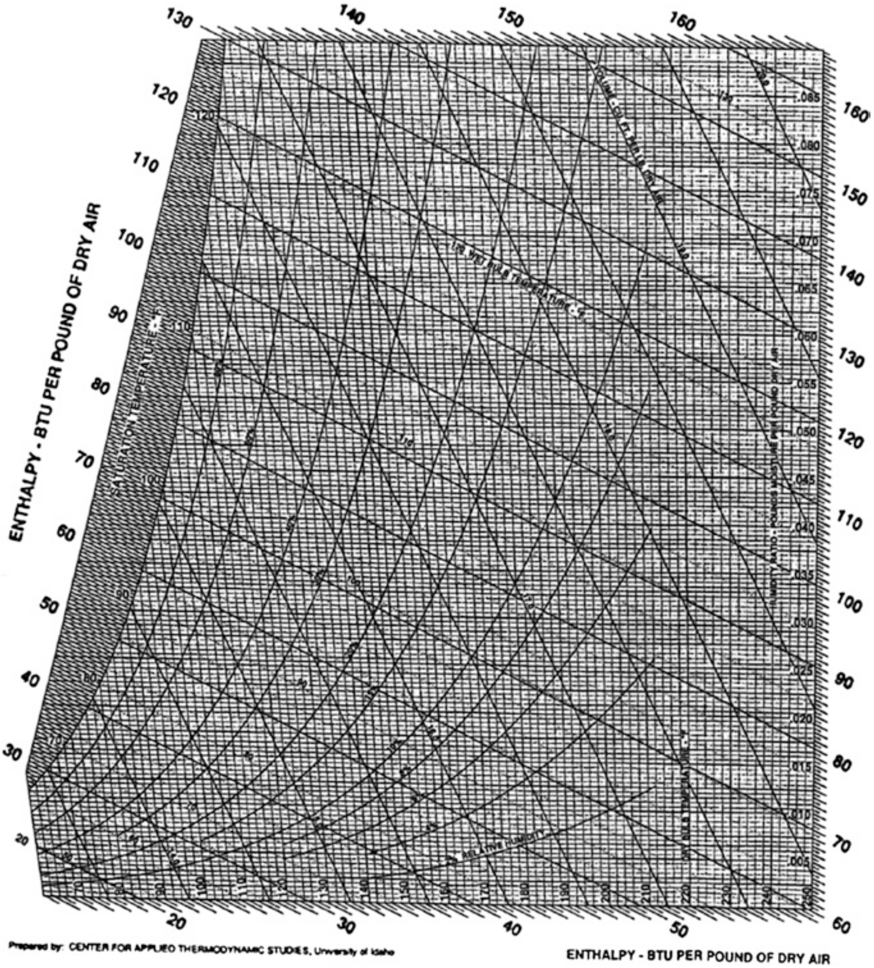


Fig. 1 Psychrometric chart (*Source* ASHRAE)

(ii) The energy balance equation for drying

The energy balance is an equation that expresses the following idea mathematically: The energy available from the air going through the food inside the dryer should be equal to the energy needed to evaporate the amount of water to be removed from the crop. The removal of water from a surface by evaporation requires an amount of heat equal to the latent heat of evaporation of water plus a current of air moving over the surface to carry away the water vapour produced. Hence, the task in solar dryer is to calculate and then achieve optimum temperature, T_f and air flow, m_a to remove the specified amount of water, m_w. So we have

$$m_w L = (T_f - T_i)\, m_a C_p$$

where m_w = mass of water evaporated; L = latent heat of evaporation; m_a = mass of air circulated; C_p = specific heat of air; T_f, T_i = final and initial temperatures.

After these, the volume of air can be determined by using the gas laws

$$\frac{V_{air}}{m_v} = \left(\frac{m_a}{m_v}\right)\left(\frac{RT}{P}\right)$$

i.e.,

$$V_{air} = \frac{m_a RT}{P}$$

where m_w, the amount of water evaporated can be read from moisture ratio scale or can be calculated from the energy balance equation.

Because the vapour pressure of bound water in hygroscopic material is less than saturation, the effect of bound water is also to be taken into account. Again, the latent heat value should be chosen to correspond to a very low vapour pressure.

The equations can be employed for evaluating various parameters as mentioned above. Here, these are made use of in calculating the quantity of air needed for drying (m_a) for various materials to be dried (Tiwari 2002).

6 Effect of Parameters on Drying

The most important parameters which determine the quality of the dried product are the mass flow rate and the temperature of the working fluid, i.e. air. Other parameters are air velocity, humidity and the required final moisture content. Effects of different parameters are discussed below (Ratti and Mujumdar 1997).

6.1 Temperature

Drying temperature is a major deciding factor, which mainly determines the quality of the dried product. High drying temperature may impair the germination capacity of seeds and also can damage the product either changing the chemical combination or smoulder the product. Lower drying temperature may lead to longer drying time which may lead microbial contamination. Recommended drying temperature with the initial and permissible moisture content for different products are shown in Table 2 (Garg and Prakash 1997). The temperature should be maintained to the permissible level so that the drying will not damage the product.

6.2 Mass Flow Rate

Mass flow rate also plays an important role in drying process. Optimum mass flow rate is designed using the temperature requirement and also the maximum air velocity which can be maintained inside the drying chamber.

Table 2 Initial and final moisture content and the maximum recommended drying temperature for different food products

Product	Moisture content (%)		Maximum drying temperature (^{o}C)
	Initial	Final (permissible)	
Paddy	22–24	11	50
Maize	35	15	60
Wheat	20	16	–
Carrots	70	5	75
Green beans	70	5	75
Onions	80	4	55
Garlic	80	4	55
Potato	75	13	75
Chilly	80	5	65
Fish	75	15	50
Apples	80	24	70
Grapes	80	15–20	70
Banana	80	15	70
Pineapple	80	15	65
Coffee	50	11	–
Cotton	50	7	75
Copra	30	5	–
Groundnut	40	9	50
Leather	50	18	35
Fabrics	50	8	75

6.3 Relative Humidity of Air

The relative humidity of air is an important factor same as that of temperature because humidity gradient between air and the product will be a major driving force in a natural convection system. Lower relative humidity of the air can increase the drying rate and will help in reducing the drying time.

6.4 Moisture Content of the Drying Product

The moisture content of the product to be dried is an important factor for determining the quality of the product and thereby the market value. Products with higher moisture content are found to have lesser drying time than those having very lesser moisture content. It is because the higher moisture content product may have better mass flow of the moisture from the interior of the product to the surface so that it is removed where the one with lower moisture content may have a thick outer skin.

7 Effect of Drying on Nutritional Value

Dried products are very good source of nutrients but the dehydration process may alter the quality of the products. This can be limited by having proper pre-treatment of the materials and also by controlling the drying process. Some of the quality parameters considered are colour, visual appeal, flavour, retention of nutrients, free from contaminant, etc. These factors will decide on the market value of the product. Pre-treatments, novel drying techniques and optimized drying methods can help in producing good quality products (Shyam 2005).

7.1 Pre-treatment and its Influence on Nutrition Loss

Blanching and dipping in solution like sulphites are the most commonly used pre-treatment methods. Steam blanching is done by direct injection of steam into the blanching chamber followed by rapid cooling. In some cases, concentrated sugar solution is used. Such pre-treatments are found to be a serious reason for nutrient loss. Reports show that there is around 80 % loss of carotene content when blanching is done. Loss of vitamins and other nutrients are also occurring due to blanching. Osmotic treatments found to have better results in retaining vitamins than other methods.

7.2 Effect of Drying on Nutrients

Drying temperature has got a significant role in vitamin loss. Temperature has to be maintained at the desired level to preserve nutrients in the product. Retention of nutrients was higher in shade drying and freeze-drying than other methods like oven or sun drying.

8 Solar Driers in the Field

Some of the successful installations of solar driers in India are given below.

8.1 SPRERI Forced Circulation Solar Dryer

Sardar Patel Renewable Energy Research Institute (SPRERI) developed a forced circulation solar dryer that uses modular air heaters of standard 2 m^2 surface area.

Fig. 2 Forced circulation solar air heater-based dryer developed by SPRERI

One such system is shown in Fig. 2. The outlet temperature from the air heater was 70 °C on clear sunny days and that inside the dryer varied from 50 to 60 °C depending on the state of drying. The system could dry two batches of 100 kg fresh onion flakes in a day. Besides onion, the system was found to be useful for drying many other farm and industrial products (Chavda and Kumar 2008).

8.2 Solar Tunnel Dryer at Udaipur

A solar tunnel dryer was developed for drying of dibasic calcium phosphate (DCP) for industrial use at M/S Phosphate India Limited, Udaipur. The loading capacity of the semi-cylindrical shaped tunnel dryer was of 1.5 tonne per batch. Two such tunnels were installed in series to accommodate 3.0 tonne of material. The maximum temperature recorded inside the solar tunnel dryer was 62 and 50 °C on a summer and winter day, respectively, which is about 15 °C higher than ambient temperature. Drying duration was 16 h for DCP up to the safe moisture content during winter seasons while total 12 h was needed during summer seasons for reducing moisture content from 37.3 to 9.4 %. The solar tunnel dryer reduced moisture content to around 10 %. The developed dryer is reported to be use in a chemical Industry near Udaipur (Singh et al. 2007).

8.3 Solar Cabinet Drier: CUSAT

A cabinet drier of area 1.27 m^2 for drying of farm products such as spices and fruits was developed by Cochin University of Science and Technology (CUSAT), India. Figure 3 shows the photograph of the dryer. It has a collector at the top and

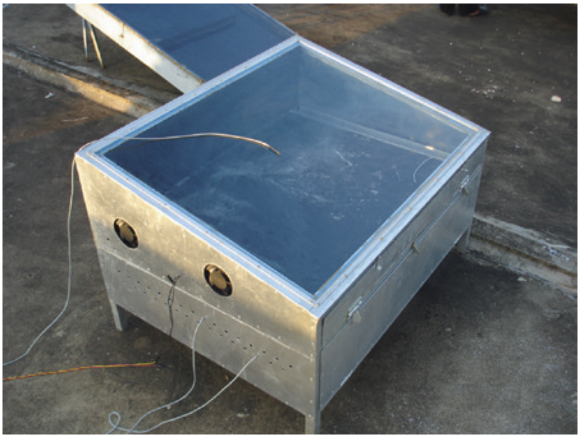


Fig. 3 Solar Cabinet Drier—CUSAT, India

a drying chamber at the bottom. This arrangement limits direct exposure of the sunlight on the product, which helps in retaining the natural colour. The loading capacity is 4 kg per batch and has two axial fans of 20 W, provided for air circulation. Bitter gourd was dried to 5 % moisture content from an initial moisture content of 95 % in 6 h (Sreekumar 2010).

8.4 Tunnel Drier for Copra Drying: Pollachi

A tunnel drier for copra drying was developed by Ayyappan and Mayilsamy in Pollachi, India (Ayyappan and Mayilsamy 2010). It was a community model greenhouse dryer with a 10 m length 4 m width. The greenhouse effect is created by having a semicircular portion on the top with a height of 3 m at the centre. UV-stabilized polyethylene film of 200 μ thickness is used as glazing material for the dryer. It has a loading capacity of 5000 coconuts per batch. Two exhaust fans of diameter 30 cm each and three air vents with butterfly valves were used for air circulation. Experimental results show that the average moisture content of the coconuts was reduced from 52 to 8 % in 57 h in full load conditions. High-quality copra was produced using the tunnel drier developed.

8.5 Drier Integrated with Solar Air Heater—CUSAT

An advanced type of solar drier having a drying cabinet and a solar air heater was developed in CUSAT, India (Sreekumar 2010). Figure 4 shows the photograph of the dryer. The collector area is 46 m^2 with a loading capacity of 200–250 kg in the drying chamber. It is used for drying fruits and vegetables with good quality. It took only 8 h to dry 200 kg of apple.

Fig. 4 Drier integrated with solar air heater—CUSAT

8.6 An Indirect Solar Dryer for Paddy Drying: Planters Energy Network

An indirect-type solar dryer for drying of paddy was installed in Theni district, Tamilnadu, India by Planters Energy Network, India, under the project for developing solar air heaters for using it in agro-based industries. The total collector area of the dryer is 212 m^2 divided into three partitions with 3000 m^3/h mass flow rate each. The loading capacity of the dryer is 12 tonnes, which is dried at a temperature of 60 °C for 6–8 h. Similar systems were also developed for drying of tea leaves, marine products, farm produce and so on (Palaniappan and Haridasan 2000).

8.7 Solar Dryer with Wire Mesh Air Heater: Pondicherry University

A solar drier integrated with a wire mesh air heater (Fig. 5) was developed in the Centre for Green Energy Technology, Pondicherry University, India (Aravindh and Sreekumar 2014a, b). As advancement in the solar air heater design, wire

Fig. 5 Solar Dryer with wire mesh air heater—Pondicherry University

mesh made of GI with wire diameter of 1 mm and pitch of 3.175 mm was used as absorber. The collector area is 6 m^2 and having a loading capacity of 30 kg in the drying chamber. It is powered with a 0.5 HP blower with a mass flow rate of 500 m^3/h. The system was developed for drying of food stuffs such as fruits, vegetables and marine products. Experiments with different products such as bitter gourd, pineapple and ivy gourd showed better results when comparing to open sun drying.

8.8 Solar Tunnel Dryer: Pondicherry University

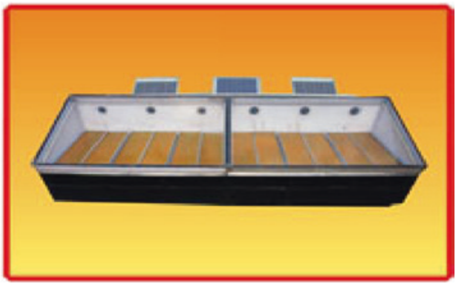
In this drier, a DC fan is used to push hot air through the drying material. Selective coated Aluminium was used as absorber plate and consists of perforated trays to load the material. The salient feature of this drier is that the fan is operated by a solar cell. Hence, this system is completely independent from the electricity grid and is suitable to far flung areas where electricity grid is not available. Another advantage is that the speed of the fan is controlled by the solar radiation availability. It will run fast peak solar hours and helps to remove the excess heat from the drier. The maximum hot air temperature recorded on a clear sunny day was 71 °C. Figure 6 shows the photograph of the solar PV operated cabinet drier. The system was used for drying of fruits, vegetables and fish.

8.9 SEED Dryer

Society for Energy, Environment and Development at Hyderabad, India developed a solar-powered air dryer for processing curry leaf, mushrooms, mango, tomato, etc. A photograph of the dryer is shown in Fig. 7. Ambient air enters from the bottom of the cabinet and gets heated by solar radiation, which penetrates through the upper glass cover. Hot air passes through the trays and carries moisture from the

Fig. 6 Solar tunnel dryer developed at Pondicherry University

Fig. 7 SEED dryer

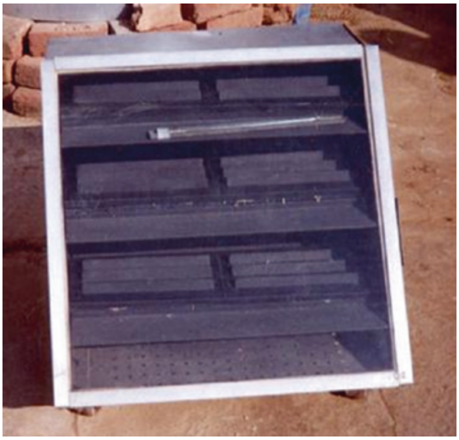


product to the space below the glass, from which it is removed with solar-powered exhaust fans. To meet the load requirement during non-solar hours, electric heating provision was also provided. Cabinet temperature recorded was in the range from 40 to 65 °C, about 15–30 °C higher than ambient temperature.

8.10 Portable Farm Dryer by Punjab Agricultural University

A low-cost natural convection solar dryer for drying different farm products was developed by Punjab Agricultural University, India. In order to facilitate loading of product, cover may be removed from the multirack dryer along with the shading devices placed over each tray. If the product is less than the total capacity of the dryer, only the top trays are used. Photograph of the dryer is shown in Fig. 8. Maximum temperature reported in the farm dryer was about 75 °C when a maximum solar radiation of 750 W/m^2 and ambient temperature of 30 °C (Singh et al. 2006).

Fig. 8 Punjab agricultural dryer



9 Economic Analysis for Solar Drying

Economic analysis for drying can be performed using three methods such as annualized cost, life cycle savings and payback period (Sreekumar 2010; Aravindh and Sreekumar 2014a, b). Annualized cost method helps in finding out the cost of drying for unit weight of the product by different drying techniques such as solar and electric heater. The drying cost of solar dryer remains almost constant over the entire life of the system, but the cost is variable in the case of electric and fossil fuel-based dryer due to the fluctuating price of electricity and petroleum products. Even though the annualized cost gives a comparative study, it is not precise due to volatile fossil fuel prices. Hence, to make a clearer understanding on the economics of the dryer, life cycle savings method is used, which determines the savings made in the future years and also to make the present worth of annual savings over the life of the system. Payback period will give the investment's return period, and hence, this determines the acceptability of the technology. For further understanding, a sample economic analysis is given below for the dryer developed by Centre for Green Energy Technology, Pondicherry University. The product used for drying is pineapple having an initial moisture content of 83 %. The parameters considered are listed in the Table 3.

9.1 Annualized Cost

Using the data from the above Table, for every 30 kg of fresh product being loaded, 7.8 kg of dried product is retrieved. With an average 250 sunny days per year with 1 batch per 2 days, it comes 125 batches per year. The cost of drying using solar drying was calculated as 30 INR per kg. While in the case of electric dryer, the cost goes up to 41.6 INR per kg.

Table 3 Parameters considered for economic analysis

1. Capital investment for solar dryer	120,000 INR
2. Capital investment for electric dryer	100,000 INR
3. Interest rate	12 %
4. Inflation rate	8 %
5. Cost of fresh pineapple	50 INR
6. Cost of dried pineapple	500 INR
7. Electricity cost	5 INR/kWh
8. Quantity of fresh pineapple loaded per batch	30 kg
9. Lifespan	15 years
10. Efficiency of the electric heater	75 %

Table 4 Life cycle savings

Year	Annual savings (INR)	Present worth of annual savings (INR)	Present worth of cumulative saving (INR)
1	270,250	245,682	245,682
2	291,870	241,215	486,897
3	315,220	236,829	723,726
4	340,437	232,523	956,249
5	367,672	228,295	1,184,544
6	397,086	224,145	1,408,689
7	428,853	220,069	1,628,758
8	463,161	216,068	1,844,826
9	500,214	212,140	2,056,966
10	540,231	208,282	2,265,248
11	583,449	204,495	2,469,744
12	630,125	200,777	2,670,521
13	680,535	197,127	2,867,648
14	734,978	193,543	3,061,191
15	793,777	190,024	3,251,215

9.2 Life Cycle Savings

With a selling cost of 500 INR for the dried product and the savings per batch of the dried product comes roughly to 1080 INR. For a saving of 1080 INR per batch, the life cycle savings is given in the Table 4. For an initial investment of 120,000 INR, the present value of the savings after 15 years of operation of the dryer was worked out nearly 3,251,215 INR.

9.3 Payback Period

The savings in the very first year is 245,682 INR for an initial investment of 120,000 INR. Hence, the investment can be recovered back in the first year itself. Calculation shows that the payback period is roughly 0.54 years which comes to around 130 drying days.

10 Conclusion

Solar drying is a promising technology for drying of food products for developing country like India, where solar energy is abundant. This can dramatically reduce the post-harvest food spoilage which is a major concern for the second largest populated country. Even though the drying conditions for every product are different, a dryer can be modelled in such a way that it can dry any product with good control parameters such as temperature and the mass flow rate. Case studies show some of many successful installations. From the case studies, it is very much evident that it is a proven technology and should be given wider publicity.

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