Journal of Food Processing & Technology
ISSN: 2157-7110

Tiwari, J Food Process Technol 2016, 7:9
DOI: 10.4172/2157-7110.1000623

Perspective | Open Access

A Review on Solar Drying of Agricultural Produce

Anupam Tiwari*

Department of Food Science and Technology, NIFTEM, Kundli, India

Introduction

The conventional drying system to preserve fruits, vegetables, grains, fish, meat, wood and other agricultural products is sun drying which is a free and renewable source of energy. But, for large-scale production, there are various known limitations of sun drying as damage to the crops by animals, birds and rodents, degradation in quality due to direct exposure to solar radiation, dew or rain, contamination by dirt, dust or debris. Also this system is labour- and time intensive, as crops have to be covered at night and during bad weather, and have to be protected from attack by domestic animals. There is also a chance of insect infestation and growth of microorganism due to non-uniform drying. The advancement of sun drying is solar drying systems in which products are dried in a closed system in which inside temperature is higher [1]. Major advantage includes protection against flies, pests, rain or dust. Several significant attempts have been made in recent years to harness solar energy for drying mainly to preserve agricultural products and get the benefit from the energy provided by the sun. Sun drying of crops is the most widespread method of food preservation in most part of India and world because of solar irradiance being very high for the most of the year. As this technique needs no energy during day time, it is more beneficial to the small scale farmers who can't afford the electricity or other fuel for drying. If it is necessary to dry product in night or in bad weather, an additional bio-fuelled heater can be used for heat supply.

The high temperature dryers used in commercial countries are found to be economically viable in developing countries only on large agro sectors and generally it is not affordable by small and medium entrepreneurs because of high cost and process variability [2-5]. Therefore, the introduction of low cost and locally manufactured solar dryers provides a promising alternative to reduce the grand post-harvest losses. The opportunity to produce high quality marketable products appears to be a chance to improve the economic situation of the farmers. Taking into account the low income of the rural population in developing countries, the relatively high initial investment for solar dryers still remains a barrier to a wide application [6]. However, if it is manufactured by locally available material such as wood, glass etc., it will be economically affordable by the farmers.

Solar Energy

The sun is the primal energy producer of our solar system. Because of continuous nuclear fusion taking place in its core, a tremendous amount of energy is generated; a small fraction of the energy produced in the sun hits the earth and makes life possible on our planet. Solar radiation causes all natural cycles and activities such as rain, wind, ocean currents, photosynthesis and several other phenomena which are crucial for life. The entire world energy need has been based from the very beginning on solar energy [7-9]. All fossil fuels (coal, gas, oil) are converted form of solar energy. The solar surface temperature of the sun is 6000°C which corresponds to 70,000 to 80,000 kW/m^2 radiation intensity. Earth receives only a very small portion of this energy. In spite of this, the incoming solar radiation energy in a year is some 2 × 10^{17} kWh; this is more than 10,000 times the yearly energy demand of the whole world [10,11]. The solar radiation intensity outside the atmosphere is nearly 1,360 W/m^2 (solar constant). When the solar radiation penetrates through the atmosphere some of the radiation is lost so that on a clear sky sunny day in summer, 800 to 1000 W/m^2 (global radiation) can be obtained on the ground.

Global Radiation

The duration of the sunshine as well as its intensity dependents on the time of the year, weather conditions and naturally also on the geographical position. The amount of annual global radiation on a horizontal surface may thus reach in the Sun Belt regions over 2,200 kWh/m^2. The global radiation composes of direct and diffuse radiation. The direct solar radiation is the component which falls from the direction of the sun [12-16]. The diffuse radiation component is created when the direct solar rays are scattered from the different molecules and particles in the atmosphere into all directions, i.e. the radiation becomes dispersed. The amount of diffuse radiation is dependent on the climatic and geographic conditions. The global radiation and the proportion of diffuse radiation is greatly affected by clouds, the condition of the atmosphere (e.g. haze and dust layers) and the path length of the beams through the atmosphere. The global radiation is shown in Figure 1.

Drying

Drying is commonly described as the operation of thermally removing water content to yield a solid product. Moisture held in loose chemical combination, present in the product matrix or even trapped in the microstructure of the solid, which exerts a vapour pressure less than that of pure liquid is called bound moisture. Moisture in excess of bound moisture is called unbound moisture.

When a solid is subjected to thermal drying, two processes occur simultaneously:

A. Transfer of energy (mostly as heat) from the surrounding environment to evaporate the moisture from the surface.

B. Transfer of internal moisture to the surface of the solid and its subsequent evaporation due to application of energy.

The drying rate can be governed by the rate at which the two processes proceed. Energy transfer as heat from the surrounding environment to the wet solid can occur as an outcome of convection, conduction, or radiation and in some cases as a result of a combination of these effects [14,17-21]. Various dryers differ in type and design, depending on the principal method of heat transfer applied. In most

***Corresponding author:** Anupam Tiwari, Department of Food Science and Technology, NIFTEM, Kundli, India, Tel: 8222925689, Fax: 8222925689; E-mail: anupamtiwari5@gmail.com

Received August 16, 2016; **Accepted** September 16, 2016; **Published** September 21, 2016

Citation: Tiwari A (2016) A Review on Solar Drying of Agricultural Produce. J Food Process Technol 7: 623. doi: 10.4172/2157-7110.1000623

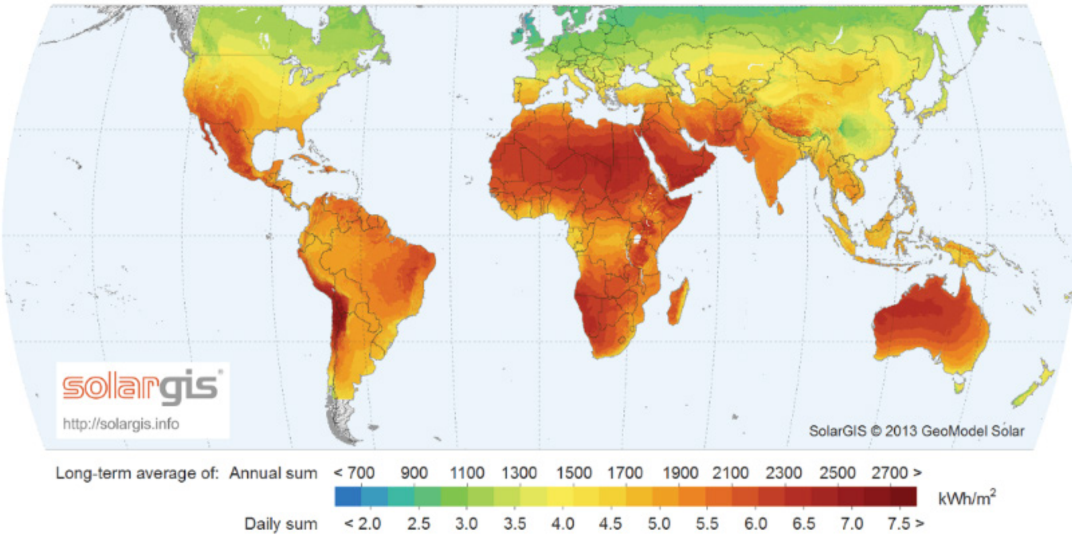

Figure 1: World map of global horizontal irradiation.

cases, heat is transferred to the surface of the wet solid and then to the interior. However, in dielectric heating, radio frequency (RF) or microwave drying, energy is supplied to generate heat within the solid and flows to the exterior surfaces.

Process A, the removal of moisture as vapour from the material surface, depends on the external conditions such as temperature, air humidity and flow, area of exposed surface, and pressure [22]. Process B, the movement of moisture within the solid, is a function of the physical nature of the solid, diffusion rate, and its moisture content.

Apart from weather conditions the drying behaviour of agricultural crops during drying depends on the:

- Product
- Size and shape
- Initial moisture content
- Final moisture content
- Bulk density
- Thickness of the layer
- Turning intervals
- Temperature of grain
- Temperature, humidity of air in contact with the grain
- Mechanical or chemical pre-treatment
- Velocity of air in contact with the grain

In a drying operation, any one of these processes may be the limiting factor regulating the rate of drying, although they both continue simultaneously throughout the drying cycle.

Early work on solar drying in India

Solar drying was modification of traditional sun drying technique which is tried for all agricultural commodities [23]. Initially, solar dryer was used for non-agricultural commodities and later, its use was extended to dry agricultural products. Some literature review of works conducted in solar drying is presented in Table 1.

Solar Dryer

The objective of a solar dryer is to provide ample amount of heat i.e. more than ambient heat under given humidity. It increases the vapour pressure of the moisture confined within the product and decreases the relative humidity of the drying air so that the moisture carrying capacity of the air can be increased. Air is drawn through the dryer by natural convection or sometimes by a fan. It is heated as it passes through the collector and then partially cooled as it catches moisture from the material [24-27]. The material is heated both by the air and sometimes directly by the sun. Warm air can hold more moisture than cold air to maintain relative humidity, so the amount of moisture removed depends on the temperature to which it is heated in the collector as well as the absolute humidity of the air when it entered the collector. The moisture absorption capacity of air is affected by its initial humidity and by the temperature to which it is subsequently heated.

Classification of solar dryer

Commonly, dryers can be classified according to their operating temperature, as two main groups: high temperature dryers and low temperature dryers. However, dryers are also classified broadly according to their heating sources into fossil fuel dryers (more commonly known as conventional dryers) and solar-energy dryers [28]. Although, all practically-realised designs of high temperature dryers are fossil fuel powered, while the low temperature dryers are either fossil fuel or solar-energy based systems.

To classify the various types of solar dryers, it is necessary to change the complex constructions and various modes of operations to the basic principles. Solar dryers can be classified based on the following measures:

- Mode of air movement: Hot air circulation mechanism
- Air flow direction: Ventilation
- Solar insulation exposure: Area available for heating air

Solar dryers can also be classified primarily according to their heating modes and the manner in which the solar heat is utilised. In broad terms, they can be classified into two major groups, namely:

Year	Place	Product	Dryer type
1954	National Physical Laboratory (NPL), New Delhi	Coal	Solar heated air
1955	National Physical Laboratory (NPL), New Delhi	Jaggery from sugar cane juice and palm juice	Plane glass mirror concentrators
1968	Khadi and Village Industries Commission (KVIC), Ahmedabad	Jaggery from palm nira	Plane glass mirror concentrators
1972	Forest Research Institute (FRI), Dehradun	Timber	Solar Kiln
1972	Central Arid Zone Research Institute (CAZRI), Jodhpur	Fruits and vegetables	Solar cabinet dryer
1978	Annam alai University	Paddy	Solar paddy dryer
1980	National Industrial Development Corporation (NIDC)	Grain	Solar grain dryer

Table 1: Early work done in solar drying system in India.

A. Active solar-energy drying system (most of which are often termed hybrid solar dryer).

B. Passive solar-energy drying system (conventionally termed natural-circulation solar drying system).

The performance of solar dryers is significantly dependent on the weather conditions. Both the heat required for removing the moisture as well as the electricity necessary for driving the fans are generated in the most cases by solar energy only [29]. In addition to the pre-treatment of the product, the weather conditions have the biggest influence on the capacity of product that can be dried within a certain time period. The drying time is short under sunny conditions and accordingly extended during adverse weather conditions. The difference in drying capacity between dry and rainy season has to be taken into consideration for the calculation of the yearly capacity of the dryer.

The utilisation of solar energy as the only energy source is recommended for small-scale dryers where the risk of spoilage of big quantities of crops due to bad weather is low [30-32]. If large-scale solar dryers are used for commercial purposes it is strongly recommended to equip the dryer with a back-up heater to bridge periods with bad weather. A huge advantage of solar dryers is the fact that different types of fruits and vegetables can be dried. The quality of products dried in this way is excellent, due to the fact that the food is not in direct sunlight (cabinet or in-house dryer), and due to a shorter drying process-up to a one third of the time in comparison to traditional sun drying.

The drying operation must not be considered as merely the removal of moisture since there are many quality factors that can be adversely affected by incorrect selection of drying conditions and equipment. Some desirable properties of dried products are:

• Low and uniform moisture content

• Minimal proportion of broken and damaged grains

• Low susceptibility to subsequent breakage

• High viability

• Low mould counts

• High nutritive value

• Consumer acceptability of appearance and organoleptic properties.

Even where there is a demand for technical changes, farmers may find it difficult to adopt recommended technologies, because of economic problems, labour constraints, or lack of materials. To promote solar drying in India because of its potential, government is providing financial and technical assistance to the emerging entrepreneurs in this field.

Advantages of solar dryer

• The higher temperature, movement of the air and lower humidity increases the rate of drying.

• Food is enclosed in the dryer and therefore protected from dust, insects, birds and animals.

• The higher temperature deters insects and the faster drying rate reduces the risk of spoilage by microorganisms.

• The higher drying rate also gives a higher throughput of food and a smaller drying area (approximately one third).

• The dryers are waterproof, therefore, the food does not need to be moved during raining.

• Dryer can be constructed from locally available materials and are relatively low cost.

Limiting issues with solar dryer

• Can be only used during day time when adequate amount of solar energy is present.

• Lack of skilled personnel for operation and maintenance.

• Less efficiency as compared with modern type of dryers.

• A backup heating system is necessary for products require continuous drying.

Design Consideration

Air collectors

The solar air collector is designed to heat air when irradiated by the sun. The basic components are: cover, absorber, air passage and insulation. Solar radiation transmitted through the cover heats the absorber, which in turn heats the air in the air passage.

A general typology for air collector can be defined according to their sub elements in the following way:

Absorbers:

▪ Non-permeable

▪ Underflow

▪ Underflow with fins in air flow

▪ Over flow

▪ Overflow and underflow

▪ Permeable

▪ Glazed matrix (Metal of cloth)

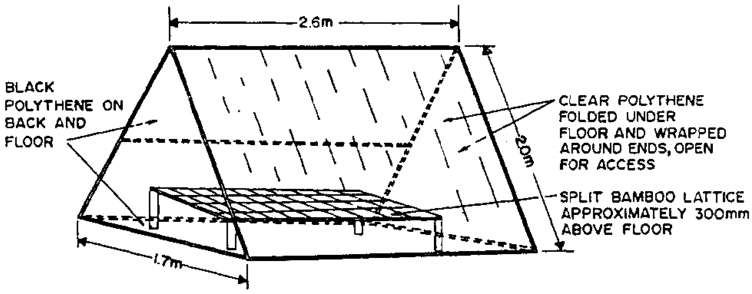

Figure 2: Tent dryer.

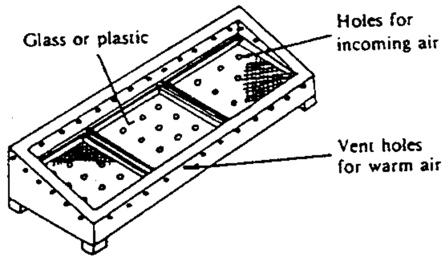

Figure 3: Box dryer.

- Perforated metal, unglazed
- Window collector
- Hybrid (Air/Water)
- Hybrid(Air/Photovoltaic)

Absorber coating:

- Selective
- Non-selective

Glazing:

- Single
- Double
- Unglazed

Orientation of the solar absorber

The orientation of the solar panel is dependent on the location of the operation. Generally, it is considered as it should be place at an angle of the latitude passing through that place. If the place is in northern hemisphere, it should be facing south and if it is in southern hemisphere, it should be facing north. For the places in the equator, it should be facing in vertical direction.

Ventilation

The air flow rate is important to the overall system performance. Higher air flow rate consumes more power and lower air flow rate causes poor thermal performance. In general-

- The higher the mass flow rates, the higher the efficiency of the collector.
- The electrical energy of the fan increases with the mass flow rate of air.
- The effect of leakages increases with the air flow rate.

Different types of solar dryer are mentioned below:

Tent dryer: Tent solar dryers are cheap and simple to build and consist of a frame of wood poles covered with plastic sheet. Black plastic should be used on the wall facing away from the sun. The product to be dried is placed on a support above the ground [12]. It takes same amount of time for drying of products as in open air drying. The main purpose of the dryers is to provide protection from dust, dirt, rain, wind or predators and they are usually used for fruit, fish, coffee or other products for which wastage is otherwise high. Tent dryers can also be taken down and stored when not in use. They have the disadvantage of being easily damaged by strong winds [15] (Figure 2).

Box dryer: The box-type solar dryer has been widely used for small scale food drying. It consists of a wooden box with an attached transparent lid. The inside surface is painted black and the product is supported on a mesh tray above the dryer floor. Air flows into the chamber through holes in the front and exits from vent holes at the top of the back wall [15] (Figure 3).

Solar cabinet dryer: The cabinet is a large wooden or metal box and the product is located in trays or shelves inside a drying cabinet. If the chamber is transparent, the dryer is named as integral-type or direct solar dryer. If the chamber is opaque, the dryer is named as distributed-type or indirect solar dryer. Mixed-mode dryers combine the features of the integral (direct) type and the distributed (indirect) type solar dryers. The combined action of solar radiation incident directly on the product to be dried and hot air provides the necessary heat required for the drying process [33,34]. In most cases, the air is warmed during its flow through a low pressure drop solar collector and passes through air ducts into the drying chamber and over drying trays containing the crops. The moist air is then discharged through air vents or a chimney at the top of the chamber [35-38]. It should be insulated properly to minimise heat losses and made durable (within economically justifiable limits). Construction from metal sheets or water resistant cladding, e.g. paint or resin, is recommended.

Heated air flows through the stack of trays until the entire product is dry. As the hot air enters through the bottom tray, this tray will dry first. The last tray to dry is the one at the top of the chamber.

The advantages of this system are:

- Simple in construction.
- Low labour costs.
- Simply load and then unload.
- The product need not be exposed to the direct rays of the sun which reduces the loss of colour and vitamins.
- Heat storage systems can be applied.

The disadvantages of this system are:

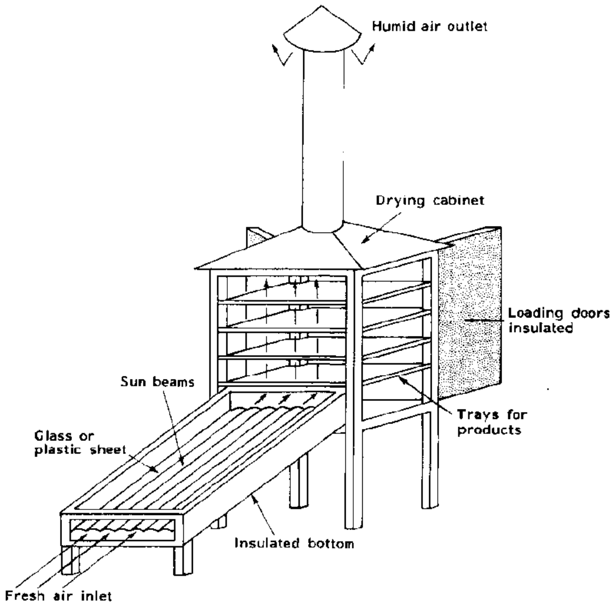

Figure 4: Solar cabinet dryer.

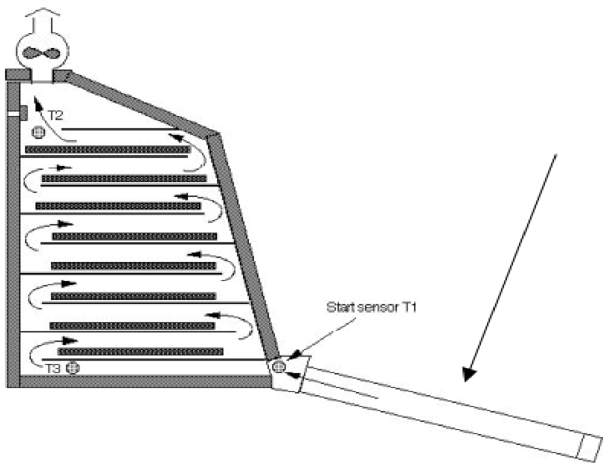

Figure 5: Active solar cabinet dryer [39].

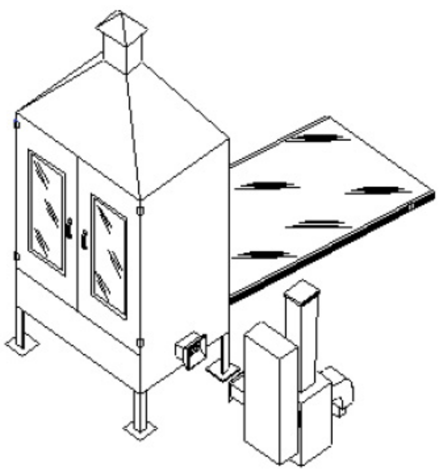

Figure 6: Cabinet dryers with back-up heating [37].

- A tendency to over-dry the lower trays.
- Low efficiency, in terms of fuel consumption, in the later stages of drying when most of the trays got dried [15] (Figure 4).

Active solar cabinet dryer: Active solar dryers are also termed as forced convection or hybrid solar dryers. Optimum air flow can be provided in the dryer across the drying process to control temperature and moisture in wide ranges independent of the weather conditions. Moreover, the bulk depth is less restricted and the air flow rate can be controlled. Hence, the capacity and the reliability of the dryers are enhanced considerably compared to natural convection dryers. It is generally agreed that well designed forced-convection distributed solar dryers are more effective and more controllable than the natural-circulation types [39,40]. The use of forced convection can reduce drying time by three times and decrease the required collector area by 50%. Consequently, dryer using fans may achieve the same throughput as a natural convection dryer with a collector six times as large. Fans may be powered with utility electricity if it is available, or with a solar photovoltaic panel. Almost all types of natural convection dryers can be operated by forced convection as well [41] (Figure 5).

Cabinet dryers with back-up heating: Generally, solar dryer utilizes solar energy to heat the air which limits their efficiency only for sunny days. One major disadvantage of solar dryers is that they are normally not used with any form of back-up heating [8]. For commercial producers, this factor limits their ability to process a crop when the weather is poor or during night. It also extends the drying time because drying can only occur during the daytime when there is adequate solar radiation. This not only confines the production but also results in an inferior product. For commercial producers, the ability to process continuously with reliability is important to meet up the market demand.

Biomass, particularly wood, is the most common source of energy in rural areas of developing countries, provided that over use of it should not create the unsustainable pressure on the local resources. Wood can be a natural source of energy, if usage is balanced by new plantation [42,43]. Currently, it is often burned inefficiently and so there is need for simple, affordable combustion devices, which can be used to complement appropriate solar technologies such as the cabinet dryer (Figure 6).

Greenhouse dryer: The thought of a greenhouse dryer is to combine the function of the solar collector with a greenhouse system. The roof and wall of this solar dryer can be made of transparent materials such as glass, fibre glass, UV stabilized plastic or polycarbonate sheets. The transparent materials are fixed on a steel frame support or pillars with bolts and nuts and sealing to prevent humid air or rain water leaking into the chamber other than those introduced from the inlet opening. To increase solar radiation absorption, black surfaces should be provided within the structure. Inlet and exhaust fans are placed at proper position within the structure to guarantee even distribution of the drying air. If designed properly, greenhouse dryers can allow a greater degree of control over the drying process than the cabinet dryers and they will be more appropriate for large scale drying.

Ekechukwu [14] has developed a natural convection greenhouse dryer consisted of two parallel rows of drying platforms (along the long side) of galvanised iron wire mesh surface laid over wooden beams. A fixed inclined glass roof over the platform allowed solar radiation over the product. The dryer, aligned lengthwise in the north-south axis, had black coated internal walls for improved absorption of solar radiation. A ridge cap made of folded zinc sheet over the roof provides an air exit vent. Shutters at the outer sides of the platforms regulated the air inlet. A simplified design of the typical greenhouse-type natural-circulation solar dryer consists of a transparent semi-cylindrical drying chamber with an attached cylindrical chimney, rising vertically out of one end, while the other end is equipped with a door for air inlet and access to the drying chamber. The chimney (designed to allow for a varying height) has a maximum possible height of 3.0 m above the chamber and a diameter of 1.64 m. The drying chamber was a modified and augmented version of a commercially-available poly tunnel type greenhouse.

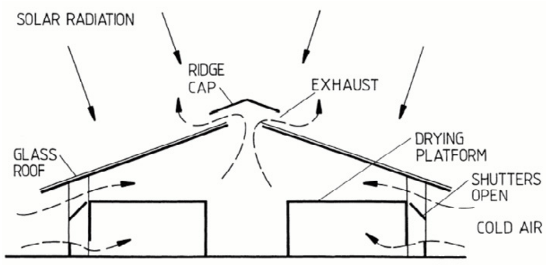

Figure 7: Greenhouse dryer [8].

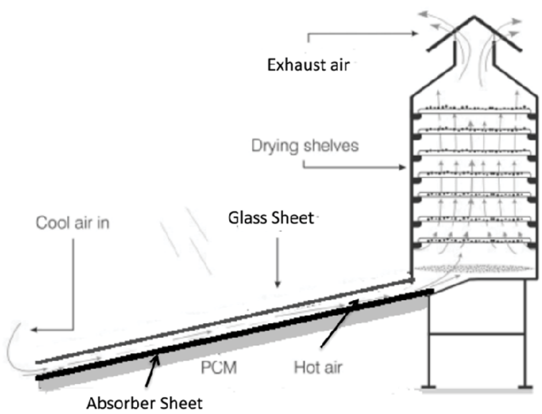

Figure 8: Solar drying system using PCM.

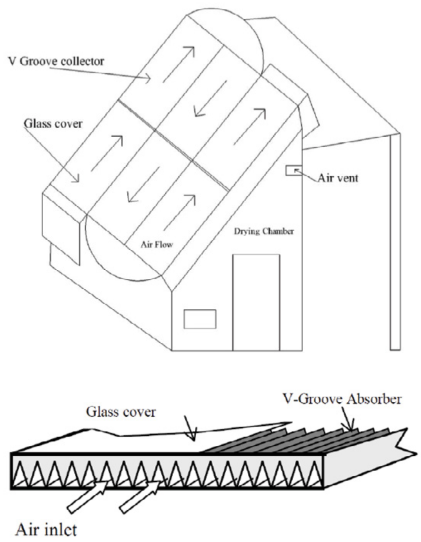

Figure 9: Solar drying system using the V-groove solar collector [9].

The dryer operates by the action of solar-energy striking directly on the product within the dryer. The product and a vertically-hung, black absorbing curtain within the chimney absorb the solar radiation and are heated which, in turn, heats surrounding air. As this heated air rises and flows up the chimney to the outside of the dryer, fresh replenishing air is drawn in from the other end of the dryer. Apart from the obvious advantages of passive solar-energy dryers over the active types (for applications in rural farm locations in developing countries), the advantages of the natural circulation solar-energy ventilated greenhouse dryer over other passive solar-energy dryer designs include its low cost and its simplicity in both on-the-site construction and operation. Its major drawback is its susceptibility to damage under high wind speeds (Figure 7).

Different Advancements in Solar Drying

Solar drying system using phase changing material

A phase-change material (PCM) is a substance with the properties like a high heat of fusion (Latent Heat), melting and solidifying at a certain temperature and capable of storing and releasing large amounts of heat energy during phase change. It is also known as "Latent Heat Storage (LHS) units".

Broadly, Heat energy are of two types:

a. Sensible Heat (changes Temperature).

b. Latent Heat (No change in Temperature).

PCMs changes its phase at a constant temperature, by storing a large amount of latent heat and again changes back its phase by releasing the stored heat, which is used for heating or drying purpose. Solid-Liquid PCMs are used generally used as handling of material in this stage is easier. The thermal energy transfer occurs when a material changes from solid to liquid, or liquid to solid. Initially, these solid–liquid PCMs perform like conventional storage materials; their temperature rises as they absorb heat [26]. PCMs absorb and release heat at a nearly constant temperature. They store 5-14 times more heat per unit volume than sensible storage materials such as water [16]. Pluss® Polymers Pvt Ltd is a materials research and manufacturing company involved in the field of Speciality Polymeric Additives and Phase Change Materials (PCMs) for thermal energy storage. A schematic diagram of PCM assisted solar dryer is given below (Figure 8).

Solar drying system using the V-groove solar collector

Fudholi et al. [9] has reported that for an average solar radiation of 700 W/m^2, if V-groove type solar collector with the collector area is about 15 m^2, an average output temperature of 50°C can be achieved with an air flow rate of 15.1 m^3/min. Experimental studies on the performance of a solar assisted drying system on herbal tea, chilies, and noodles have been conducted. Hot air was discharged into the drying chamber from outlet duct, which is strategically located for optimum performance. A 10 kW auxiliary heat source has been used for continuous operation and more effective temperature control. Herbal tea or green tea contains many organic compounds and the processing requirements differ depending on specifications on the types of tea to be produced. Discoloration of herbal tea will occur if the drying process is delayed (Figure 9).

Fresh tea leaves have an initial moisture content of 87% (wb). Drying is required to lower the final moisture content of 54% (wb). This will allow the green colour of the tea to be maintained. The auxiliary heater is on if the drying chamber temperature is below 50°C. The flow rate is fixed at 15.1 m^3/min. The initial weight of the fresh tealeaves is 10.03 kg and the final weight is 2.86 kg.

Double pass solar collector with fins

In double pass solar collector with fins system, ambient air is initially passed over the black absorbing surface then through fins which are used to increase the heat transfer area. In this way the temperature of the air can be increased significantly to dry the product. Sopian et al. [40] has developed this drying system with capacity of up to 300 kg. The main components are solar collector array, auxiliary heater, blower, and drying chamber. The size of the chamber is 4.8 m in length, 1 m width and 0.6 m in height. The four collectors are set in series (Figures 10a and 10b). The collector area is 11.52 m^2, the mass flow rate is between 0.05-012 kg/s and the average drying temperature is 50°C to 65°C.

The system is used to dry seaweed (*Eucheuma Cottonii*) and is a source of income, particularly in Semporna, Sabah. The seaweed industry has been carried out by communities, associations as well as individuals. Seaweed is widely used in production of food and medical products and industry manufacture at present. Problems faced by the people of seaweed farmers are raining days, requirement of large space for open drying and long drying time. Under open sun drying conditions usually it take 10-14 days for it to be 10% of original weight. The initial and final moisture content of seaweed are 90% (wb) and 10% (wb) respectively. The drying time is about of 14 hours at average solar radiation of about 544 W/m^2 and air flow rate 0.06 kg/s. The collector, drying system and pick-up efficiencies were found to be 37%, 27% and 92% respectively for 40 kg of material.

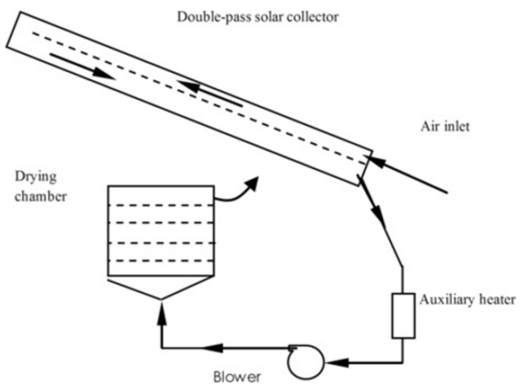

Figure 10a: Double pass solar collector with fins [40].

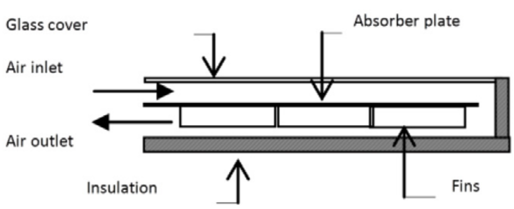

Figure 10b: Double pass solar collector with fins [40].

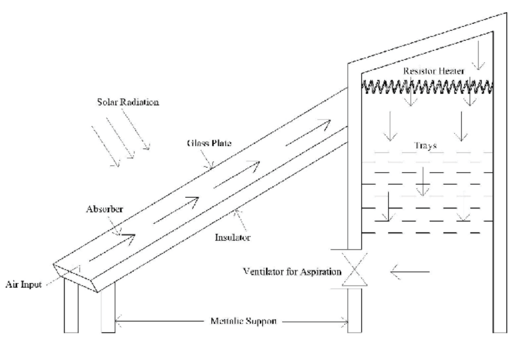

Figure 11: Solar drying system with indirect heating [5].

Indirect active hybrid solar–electrical dryer system

In hybrid type of solar dryer, an additional source of heating air is provided along with solar collector so that the overall temperature of the drying air can be increased. This system is also applicable where continuous drying is required and solar radiation is not available. Boughali et al. [5] had studied the indirect active hybrid solar–Electrical dryer in the eastern Algerian Septentrional Sahara. The indirect active hybrid solar–electrical dryer was fabricated and installed at LENREZA laboratory (Laboratory of New and Renewable Energy in Arid Zones), university of Ouargla, Algeria. It consisted mainly of a flat plate solar collector, drying chamber, electrical fan, resistance heater (3.75 kW: accuracy ± 2%) and a temperature controller. The solar air collector has an area of 2.45 m^2, and was inclined at an angle of 31° (latitude of Ouargla city) with the horizontal facing south all the time and used a black painted metal of 0.002 m thickness to absorb most of the falling solar radiation. The cover losses were minimized by placing a glass cover of 0.005 m thickness over the top of the black absorbing metal sheet, and a layer of polystyrene was sandwiched between two parallel metal sheets and back insulator to provide insulation. The air was passed under the glass sheet, between the glass and the absorber. The solar collector was connected directly to the drying chamber without any air ducts to reduce pressure drop.

The drying cabinet constructed with a galvanized iron box with insulated polystyrene walls of dimensions 1.65 m × 0.60 m × 1.00 m containing six product trays each tray has an area of 0.4 m^2 with possibilities to extend up to eight product trays. The drying trays were made of a wooden frame on all four sides and a wire mesh on the bottom to contain the samples and/or to change the position of the trays. The door of the dryer was properly sealed to forbid air leakage. In solar drying process, the auxiliary heater was used to adjust the drying air temperature. The preliminary heating of air was done by solar radiation which was again heated by electrical resistance, if its temperature was less than drying temperature required; which is controlled thermostatically and then ventilated by an exhaust fan through the product to the environment. The exhaust fan of 20 cm diameter was manually controlled by a valve, allowing the choice of the desired air mass flow. The fan was fixed below product trays at the bottom of the dryer to check an even distribution of air and to remove the humidity of the product to the surrounding (Figure 11).

Solar drying system with chemical heat pump

In chemical heat pump assisted solar dryer the heat is generated by introducing exothermic chemical reactions. This heat is used to heat up the ambient air. The chemical reactions undergoing in this type of system are generally reversible type where solar energy is used to regenerate the chemicals for further use. Ibrahim et al. [21] have designed the solar-assisted chemical heat system consists of four mean components solar collector (evacuated tubes type), storage tank, chemical heat pump unit and dryer chamber. In this study, a cylindrical tank was selected as a storage tank. The chemical heat pump unit contained of reactor, evaporator and condenser. In the chemical heat pump a solid gas reactor coupled with a condenser or an evaporator. The reactor contains a salt which reacted with the gas, the reactions used in this study was:

$$CaCl_2.2NH_3 + 6NH_3 \rightarrow CaCl_2.8NH_3 + 6\Delta Hr$$

Fadhel et al. [31] have made the drying chamber comprised of multiple trays to hold the drying material and expose it to the air flow. The general working of chemical heat pump take place in two stages: adsorption and desorption. The adsorption stage is the cold production stage, and this is followed by the regeneration stage, where decomposition takes place. During the production phase, the liquid-gas transformation of ammonia produced cold at low temperature in the evaporator. At the same time, chemical reaction between the gaseous ammonia and solid would release heat of reaction at higher temperature. The incoming air was heated by condensing refrigerant (ammonia) and enters the dryer inlet at the drying condition and performs drying. After the drying process, part of the moist air stream leaving the drying chamber is diverted through the evaporator, where it was cooled, and dehumidification takes place as heat was given up to the refrigerant (ammonia). The air was then passing through the condenser where it was reheated by the condensing refrigerant and then to the drying chamber. Lemon grass was used as the drying material (Figure 12).

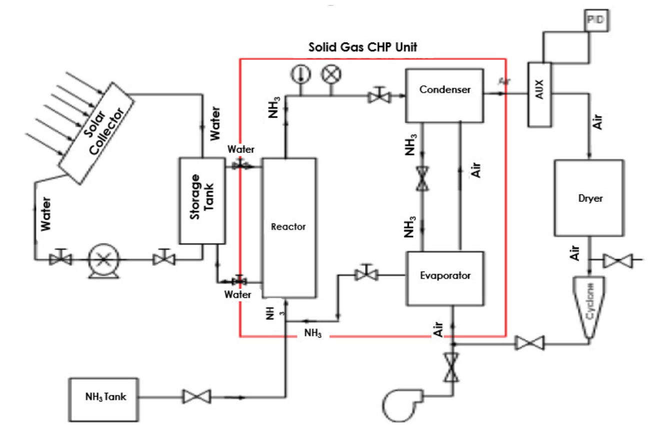

Figure 12: Solar drying system with chemical heat pump [20].

Solar dryer with dehumidification system

The temperature of air in drying process affects the quality, evaporation capacity as well as drying period. In addition, shorted time period is required for higher temperature drying. At higher temperature, pure water vapour pressure becomes higher; therefore, the difference between water vapour partial pressure and pure water vapour pressure becomes higher. This pressure difference is the driving force of water evaporation to the air. This driving force is directly proportional to the evaporation rate of water to air. However, drying at high temperature is not suitable for the materials which are sensitive to heat because it can cause cracks, browning which further reduce the taste of final product as well as the evaporation of the active ingredients such as in medicinal herbs (Figure 13).

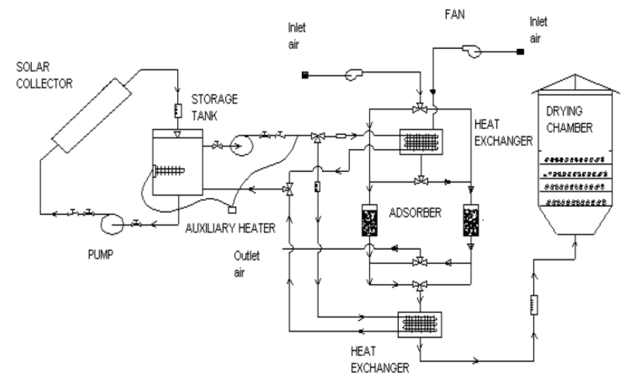

Figure 13: Solar drying system with dehumidification system [31].

Yahya et al. [28] have developed a solar dehumidification system for medicinal herbs has been developed. The system consisted of a solar collector, an energy storage tank and auxiliary heater, water to air heat exchanger, a water circulating pump, drying chamber, and adsorbent. It was made up of essentially three processes, namely regeneration, dehumidification, and batch drying. During regeneration process, the air outside the dryer is heated with the heat exchanger and is supplied to the adsorbent. The adsorbent is heated with this hot air and water content rate is reduced, removing the water content. The water content is evaporated by the hot air and leaves the dryer. During dehumidification (adsorption) process, the air inside the dryer passes through the heat exchanger by use of the blower. However, since no hot water is circulated in the heat exchanger, the air reaches the adsorbent. The air is dehumidified with the adsorbent and is supplied the drying load as the dry air. The relative humidity and temperature of the drying chamber were 40% and 35°C respectively.

Summery about different advanced solar dryers

Details of process parameters of certain dryers are shown in Table 2.

Solar drying of different agricultural products using various solar dryers and other dryers

In Table 3, various solar dried agricultural commodities are listed with the observed changes in quality during drying.

Dryer	Sample	Remark
Double Pass solar dryer V-groove DPSD(V)	Herbal tea	Solar collector area: 15 m^2, Drying temperature: 50°C Air flow rate: 15.1 m^3/min Moisture reduction: from 87% to 54 % (wb)
Double Pass solar dryer with fins DPSD(F)	Seaweed	Solar collector area:11.52 m^2, Drying temperature: 55°C Air flow rate: 2.6-6.3 m^3/min Moisture reduction: from 90% to 9 % (wb)
Indirect active hybrid solar – Electrical dryer system (IAHSDE)	Sliced tomato	Solar collector area: 2.45 m^2 , Drying temperature: 65°C, Air flow rate: 1.8, 2.82 and 3.7 m^3/min
Solar assisted chemical heat pump drying system (SACHPDS)	Lemongrass	Drying Temperature: 55ºC, Air flow rate: 1- 3m/s Moisture reduction: from 85% to 13% (wb), CoP: 2
Solar-Assisted Dehumidification System (SADS)	Medicinal Herbs	Rh: 40%, Temperature: 35°C, Air velocity: 3.25 m/s Efficiency: 70%, CoP: 0.3

Table 2: Summary of advanced solar dryer with process parameters.

Fruits and vegetables	Type of solar dryer	Major findings	References
Wild coriander	Direct cabinet solar dryer and indirect cabinet solar dryer	- The highest retention of natural colour and absence of browning were observed from samples using indirect solar dryer. - Essential oil from samples dried in the indirect solar dryer was closer in its composition to those obtained from oven or the fresh one.	Banout et al. [4]
Olives leaf	Indirect forced convection solar dryer	- The values of L* parameter of the solar dried olive leaves increase compared to the fresh one. - The luminance of the leaves was improved by solar drying but the greenness of the leaves reduced. - The olive leaves dried at 40°C (1.62 m^3/min) exhibited the lowest DPPH radical scavenging activities.	Bahloul et al. [7]
Coffee	Solar dryer with black transpired air solar collector	- Coffee beans dried faster in the solar dryer with acceptable quality and no serious defects. - No OTA (Ochratoxin) forming fungi was found in solar dried sample.	Chapman et al. [9]
Grapes and figs	Indirect and direct solar dryers	- Vitamin C content of solar dried fruits was low due oxidation, especially when the samples were either scalded or sulfurized. - The colour of solar dried grapes showed high acceptance as compared to the natural dried sample (medium acceptance). - The texture and colour of figs dried using mixed solar dryers showed better acceptance than the sun dried samples.	Gallali et al. [10]
Vanilla	Solar greenhouse dryer	- Export quality standard (Grade A) with vaniline content of 2.36% was obtained. - Average drying time for vanilla pods was between 49 to 53.5 hr with drying temperature ranging from 33°C to 65°C and RH of about 34% during day time.	Abdullah et al., [11]
Pistachio nuts	Direct solar dryer	- Both solar and sun dried samples showed splendid taste as compared to hot air dried sample. - No aflatoxin was found in both sun and solar dried pistachio nuts.	Ghazanfari et al. [13]
Sweet potato	Green house solar dryer	- Solar dried sample showed negligible losses in total carotenoids as compared to sun and hot air dried samples. - Sun dried sample showed the lowest retention value.	Bechoff et al. [17]
Henna, rosemary, Marjoram and Moghat	Unglazed transpired solar dryer	- Oil obtained from medicinal plants dried in the solar dryer were higher in quantity as compared to the traditional drying methods. - Higher test scores for sensation were obtained for the solar dried plants (marjoram, moghat and rosemary) in terms of colour, odour, and taste.	Hassanain [18]
Cocoa beans	Direct solar dryer	- Overall quality evaluation (flavour, acidity, fermentation index, appearance and odour) indicated that loading of 20 kg cocoa beans is optimum. - At this load, drying time was shorter and this reduces the risk of putrefactive development in the beans due to unfavourable weather condition.	Hii et al. [19]
Lemon slices	Solar dryer associated with the PV Module	- Dried lemon samples with bright colour were observed under complementary solar drying using gradual temperature increment (36°C-52°C). - Lesser browning was observed in solar dried samples with comparison of hot air dried sample at 60°C.	Chen et al. [22]
Indian gooseberry	Forced Convective solar dryer	- Flaking treated sample retained maximum ascorbic acid (76.6%) because of reduced exposure of the sample in the drying air. - Flaking and pricking treatments showed minimum loss of taste and flavour.	Verma and Gupta [24]
Chilli	Solar assisted biomass drying	- Overall drying efficiency of the system was estimated at 10.08% as compared to solar cabinet drying at 7.4% and sun drying at 4.3%, respectively.	Leon and Kumar [25]
Thyme	Solar dryer using wire basket	- The essential oils extracted from the oven dried and solar dried samples were 0.5% and 0.6% (per 100 g dry wt), respectively. - The oleoresin and ash content were 27% for both drying methods and 1.6%, 2.03% and 2.25% for the fresh, oven dried and solar dried samples, respectively.	Balladin and Headley [26]
Corn	Solar assisted heat pump in store dryer	- To reduce the moisture content of the corn from 16.6% to 14.5% (w.b), elapsed drying time was 240 hr. - Power consumption per grain ton to reduce the moisture content by 1 % was 1.24 kWh and the value was much lower than the official standard (2.0 kWh).	Li et al. [27]
Pegaga leaf	Solar assisted dehumidification dryer	- The colour of solar dried pegaga leaf did not become darker due to the lower air temperature and Rh used (T< 56°C, RH< 36%). - Pegaga leaf dried at 65°C using hot air became darker.	Yahya et al. [30]
Papaya latex	Solar air dryer	- A protease activity of 2655 units/g was obtained at pH 5.5 and 285 units/g only at pH 9.0.	Macalood et al. [32]
Rice	Mixed mode passive solar dryer	- Higher degree of whiteness was found in solar dried rice than sun dried rice. - Similar flavour was found in both sun dried and solar dried sample.	Mehdiza et al., [33]
Green Leaves	Indirect solar dryer	- Solar dried sample showed higher losses of β-carotene and ascorbic acid as compared to hot air cabinet drying upon storage because of prolonged drying time. - Chlorophyll loss was also higher in solar dried sample. - Faster drying conditions showed better retention of the quality parameters of leafy green vegetables.	Negi and Roy [34]
Carrots	Solar cabinet dryer	- Longer drying time leads to higher loss of β-carotene - Exposure to light resulted to oxidation. - Low rehydration ratio was observed due to greater shrinkage in solar dried samples.	Prakash et al. [35]
Turmeric	Solar biomass dryer	- Dried turmeric rhizomes resulted from solar drying by two different treatments viz. water boiling and slicing were found similar in terms of physical appearance. - Open sun dried sample was found having lesser volatile oil.	Prasad et al. [36]
Cocoa beans	Indirect and direct type solar dryers	- The dried beans from the direct solar dryer were more brittle and higher in acidity than the open air and indirect solar dryers. - Dried beans from the indirect solar dryer showed the highest overall quality.	Bonaparte et al. [38]
Plums	Greenhouse Dryer	- Both solar and open sun drying of plums pre-treated by combination of 1% potassium hydroxide and 60°C dipping temperature or by combination of 1% sodium hydroxide and 60°C dipping temperature ensued in relatively higher values of redness and yellowness as compared to hot air drying. - The combined effect of solar radiation and these pre-treatment combinations reduced the darkish colour of plums during solar drying and open sun drying.	Tarhan [43]

Table 3: Quality of solar dried products from selected studies.

Crop	Region	% of Total Production	Types of dryers
Chilli	Andhra Pradesh (51%), Madhya Pradesh (11%), Karnataka (9%), Rajasthan (5%), Orissa (4%), Maharashtra (4%), West Bengal (4%)	25	1. AIT*solar tunnel dryer (AC) 2. AIT solar tunnel dryer (DC/PV) 3. Low cost solar agricultural dryer 4. New solar dryer 5. Hybrid solar dryer
Mushroom	Punjab (50%), Haryana and Himanchal Pradesh (40%), Uttar Pradesh, Rajasthan, Jammu and Kashmir	1.5	1. Solar tunnel dryer, 2. Solar hybrid dryer, 3. Natural convection solar dryer
Groundnut	Gujarat (29.63%), Tamilnadu (20.78%) Andhra Pradesh (15.23%), Karnataka (7.82 %)	18	1. Integrated solar dryer, 2. AIT solar batch dryer, 3. Mixed mode natural convection solar dryer
Pepper	Kerala (85%), Karnataka (10%), Tamil Nadu (3%)	25	1. Mixed mode solar dryer, 2. Integrated solar grain dryer, 3. Natural convection solar cabinet dryer, 4. Natural convection solar chimney dryer
Yam	Not available	1.1	1. Direct passive solar dryer, 2. Mixed mode solar dryer

Table 4: Different popular solar dryers used for different crops.

S. No.	Model	Loading capacity approx. (Weight)	Solar window	Drying area in all trays	Solar photovoltaic panel 12 VDC	Electrical backup 220 VAC
1	SDM-8	8 kg	0.37 sq. m.	0.56 sq. m.	3.5 W	1 kW
2	SDM-50	50 kg	2.23 sq. m.	3.6 sq. m.	20 W	4 kW
3	SDM-100	100 kg	4.46 sq. m.	7.2 sq. m.	50 W	8 kW
4	SDM-200	200 kg	9.00 sq. m.	14.4 sq. m.	100 W	10 kW

Table 5: Different solar dryers with their specifications.

A comparative study of commonly used solar dryer in India for different agricultural commodities was also conducted by Tiwari et al. [36].

Different Organisations Working with Solar Dryers

Society for energy, environment and development (SEED)

SEED is a NGO started in 1987, mainly to promote rural entrepreneurs. Currently, it is engaged in drying of fruits and vegetables using solar cabinet dryer. It has also started manufacturing solar dryer for its customers. SEED has installed around 180 solar dryers, both demonstration and commercial models, in 18 states of India, starting from Kashmir to Trivandrum and Gujarat to West Bengal. Five solar dryers were exported to Saudi Arabia, Australia, Malaysia, and Mauritius. Five production cum training centres have also been established in different regions of the country to conduct skill development in the food processing industry. About 1,000 women and SHGs, NGOs, and youth were trained in solar processing of various food products in solar dryers. NABARD Award for Rural Innovations 2012 for Solar Food Processing and Dryers was awarded to the SEED. Some specifications of solar dryers are listed in the Tables 4 and 5.

Planters energy network (PEN)

PEN was started as registered society in 1989 at Madurai Kamaraj University, India to promote renewable energy in the field of solar drying of various agricultural produce. PEN has introduced many solar dryers of capacities varying from 250 Kg to 1000 Kg per batch. It has also installed. These units were tested in South India as well as in Ladakh. A factory near Kodaikanal processes organically grown dehydrated cut fruits, which are very popular in Europe using solar heat. Shyam Coperative in Ladakh operates a 400 kg capacity solar drying unit gets higher price for its finished products due to higher quality and appearance. Nearly 8 large units for drying fruits and vegetables are in usage in Ladakh region including one in Kargil. A 55 m^2 area solar collector generated sufficient hot air to dehydrate in 8 hours around 120 kg of mango concentrate. This unit has a backup heating with bio-mass fuel. This project will handle a minimum of 30 tons of fruit concentrate per annum and create employment of 1500 man-days per year. These kinds of unit could be replicated throughout the country mainly on the mango and other fruits growing areas.

Kraftwork solar private limited

Kraftwork is the pioneer of solar water heating technology in Kerala with over 18 years of experience in manufacturing and commissioning Solar energy systems. Kraftwork has over 7000 solar thermal installations all over Kerala and Tamilnadu. Kraftwork has been in the cutting edge of research and developing solar driers for the market. They have developed several models of solar dryers both in house and in association with several universities that cater to a wide range of industries and products such as Nagarjuna Herbal Concentrates and P.D.D.P Milk Dairy.

RenXSol EcoTech private limited

The hot air is fed into a chamber as fluidized bed or controlled atmospheric rooms where the produce is kept. Based on the design requirements, various end use applications can be designed for drying produce such as:

- Agricultural products as vegetables, fruits, used in fruit concentrates, chocolates, by army etc.
- Spice products as cardamom, chilly, turmeric, etc., which are also promoted for export grade by Spices Board of India
- Tea leaves, coffee seeds in plantations
- Industrial products such as carbide powder, sand, chemicals, detergents etc.
- Tobacco leaves for making of cigarettes, coir drying and other products

S. No.	Name and Address	Phone/Fax/ e-mail etc.
1	**M/S Planters Energy Network (PEN)** No. 5, Powerhouse Street N.R.T. Nagar, Theni-625531, Tamilnadu	Phone: 04546-255272/ 255271 Telefax: 04546-255271 E-mail: pen01@sify.com mdu_pen@sancharnet.in
2	**M/S NRG Technologies** 989/6, GIDC Estate, Makarpura, Vadodara-390010	Phone and Fax: 0265-2642094 E-mail: nrgtechnologists@yahoo.com
3	**M/S Kotak Urja Pvt.Ltd.** No. 378, 10th Cross, 4th Phase Peenya Industrial Estate, Bangalore -560 058.	Tel. (080) 23560456-7; Fax: 23562233 E-mail: kotakurja@vsnl.com
4	**Sardar Patel Renewable Energy Research Institute** Post Box No. 2, Vallabh Vidyanagar-388120, Gujarat	Ph.: 02692-231332/ 35011, Fax: 02692-37982 E-mail: director@spreri.org
5	**M/S ATR Solar** #1, RMR Complex, 2nd Floor, SS Colony, North Gate, (opp. Devaki Scans) Madurai-625010	Tel: 0452-3025400 Mobile: 9344453444, 9843265400. E-mail: atrsolar@gmail.com Web: www.atrsolar.com
6	**M/S Steelhacks Industries** 525-526, G.I.D.C., Vithal Udyognagar 388121, Dist. Anand. Gujarat. (INDIA)	Tel: 91-2692236156,235518 Fax: 912692236534 E-mail: info@unisolar.com unisol26@gmail.com Web: www.unisolar.com
7	**"Akshya Vikas" Convention** 29/2862, Near Gandhi Square Poonithura P.O., Cochin – 682 038	Ph.: 0484-2707228, 2707339 Mob: 91-9847113501 E-mail: info@kraftworksolar.com kraftworksolar@hotmail.com Web: www.kraftworksolar.com
8	**RenXSol EcoTech Private Limited** #256, 1st Floor, 6th Main, 7th Cross, MICO Lyt., BTM II Stg., Bangaluru-560076	Ph.: 080-40954343 E-mail: marketing@renxol.com Web: www.renxsol.com

Table 6: Different solar dryer suppliers.

Types of solar dryer	Initial investment (Rs.)	Operating and maintenance cost per year (Rs.)	Life (Year)
Solar cabinet dryer	5000	200	5
Green house crop dryer	2000	-	5
Reverse absorber cabinet dryer	8000	200	5
Conventional active solar dryer	15000	200	5
Hybrid PVT integrated	43000	1000	35
Greenhouse dryer	39000	200	30

Table 7: Different solar dryers with their cost.

- Flowers, grapes, etc. specialized application.

Known manufacturers/suppliers/institutions involved in installation of flat plate collector based solar driers/air heating systems in India

According to the information available in the Ministry of New and Renewable Energy, India, there are no standards on solar dryers/air heating systems and the manufacturers/ suppliers/ institutions cited in Table 6 below have been installing the systems based on the technical know-how and experience available with them.

Economical Aspect of Solar Dryers

Solar dryers are generally capital intensive and therefore the financial feasibility is the key to compete with any of the other commercial dryers. The financial analysis generally includes the cost of dryer (fixed cost), cost of drying (operating cost) and payback. They can be viable only if the annual cost of extra investment on the solar dryer could be balanced against fuel savings, or if the equipment cost could be reduced. The user or dryer designer optimizes cost, energy efficiency, quality, and price of the final product. Payback is the measure of time (number of days/months/years) it takes to recoup the total investment made on a dryer, in the form of operational cash inflow. Continued use of the dryer rather than seasonal use will decrease the drying cost and payback. Economic analysis on a solar dryer should also incorporate the cost benefits due to improved quality, higher yields, less floor area and quicker drying. The cost of a solar dryer of 50 kg capacity ranges from about Rs. 30,000 to Rs. 50,000. Larger industrial - scale systems may cost between Rs. 4 lakhs to 10 lakhs. (FICCI report). The cost of different types of solar dryer is listed below in Table 7.

Government Initiatives to Promote Solar Dryers in India

Jawaharlal Nehru National Solar Mission (JNSSM) was launched on the 11th January, 2010 by the Prime Minister to encourage ecologically sustainable growth while dealing with India's energy security challenges. The objective of the JNNSM is to establish India as a global leader in solar energy, by creating the policy conditions for its promotion. The immediate aim of the Mission is to focus on establishing a favourable environment for solar technology penetration in the country both at a centralized and decentralized level. The first phase (up to 2013) will focus on capturing of the low hanging options in solar thermal; on promoting off-grid systems to serve populations without access to commercial energy and modest capacity addition in grid-based systems. In the second phase, after taking into account the experience of the initial years, capacity will be aggressively worked up to create conditions for up scaled and competitive solar energy penetration in the country. Under this scheme 30% subsidy can be provided for the installation of solar energy driven equipment. However, some states, such as Tamilnadu, also provide subsidy up to 50% for setting up solar dryers.

References

1. Rajkumar P (2007) Drying kinetics of tomato slices in vacuum assisted solar and open sun drying methods. Dry Technol 25: 1349-1357.
2. Ibrahim M, Sopian K, Daud WRW, Alghoul MA (2009) An experimental analysis of solar-assisted chemical heat pump dryer. Int J Low- Carbon Technol 4: 78-83.
3. Jayaraman P, Gupta D (1995) Handbook of industrial drying. Marcel Decker Inc, New York.
4. Banout J, Havlik J, Kulik M, Kloucek P, Lojka B (2010) Effect of solar drying on the composition of essential oil of sacha culantro (*Eryngium foetidum* L) grown in the peruvian amazon. J Food Process Eng 33: 83-103.
5. Boughali S, Benmoussa H, Bouchekima B, Mennouche D, Bouguettaia H, et al. (2009) Crop drying by indirect active hybrid solar - electrical dryer in the eastern Algerian septentrional Sahara. Solar Energ 83: 2223-2232.
6. Chapman K, Twishsri W, Marsh A, Naka P, Ngangoranatigarn P, et al. (2006) Robusta coffee drying alternatives in south thailand-includes a new solar dryer.
7. Bahloul N, Boudhrioua N, Kouhila M, Kechaou B (2009) Effect of convective solar drying on colour, total phenols and radical scavenging activity of olive leaves (*Olea europaea* L). Int J Food Sci Technol 44: 2561-2567.
8. Ekechukwu OV (1999) Review of solar-energy drying systems I: an overview of drying principles and theory. Energy Convers Manag 40: 593-613.
9. Fudholi A, Sopian K, Othman MY, Ruslan MH, AlGhoul MA, et al. (2008) Heat transfer correlation for the V-Groove Solar Collector. Santander, Cantabria, Spain.
10. Gallali YM, Abujnah YS, Bannani FK (2000) Preservation of fruits and vegetables using solar drier. Renew Energ 19: 203-212.
11. Abdullah K (1997) Drying of vanilla pods using a greenhouse effect solar dryer. Dry Technol 15: 685-698.
12. Arinze EA, Sokhansanj S, Schoenau GJ, Trauttmansdorff FG (1996) Experimental evaluation, simulation and optimisation of a commercial heated-air batch hay drier. J Agri Eng Res 63: 301-314.
13. Ghazanfari A, Tabil L, Sokhansaj S (2003) Evaluating a solar dryer for in-shell drying of split pistachio nuts. Drying Technol 21: 1357-1368.
14. Hale DV, Hoover MJ, O'Neill MJ (1971) Phase change materials hand book. Alabaa Marshal Space Flight center.
15. FAO (1995) Agricultural services bulletin No.119. Food and Agriculture Organization of the United Nations, Rome.
16. Barnwal P, Tiwari GN (2008) Grape drying by using hybrid photovoltaic-thermal (pv/t) greenhouse dryer: an experimental study. Solar Energ 82: 1131-1144.
17. Bechoff A, Dufour D, Dhuique-Mayer C, Marouzé C, Reynes M, et al. (2009) Effect of hot air, solar and sun drying treatments on provitamin a retention in orange- fleshed sweet potato. J Food Eng 92: 164-171.
18. Hassanain AA (2010) Unglazed transpired solar dryers for medicinal plants. Dry Technol 28: 240-248.
19. Hii CL, Abdul Rahman R, Jinap S, Che Man YB (2006) Quality of cocoa beans dried using a direct solar dryer at different loadings. J Sci Food Agri 86: 1237-1243.
20. Ibrahim M, Sopian K, Daud WRW, Alghoul MA, Yahya M, et al. (2009) Solar chemical heat pump drying system for tropical region. WSEAS 5: 404-413.
21. Chen HH, Hernandez CE, Huang TC (2005) A study of the drying effect on lemon slices using a closed-type solar dryer. Solar Energ 78: 97-103.
22. Sopian K, Supranto MY, Othman WRW, Yatim D (2007) Double-pass solar collectors with porous media suitable for higher temperature solar assisted drying systems. J Energ Eng 133: 1-18.
23. Hii CL, Ong SP (2012) Quality characteristics of solar dried products, in solar drying. Fundamentals, Applications and Innovations, Singapore.
24. Verma RC, Gupta A (2004) Effect of pre-treatments on quality of solar-dried amla. J Food Eng 65: 397-402.
25. Leon MA, Kumar S (2008) Design and performance evaluation of a solar-assisted biomass drying system with thermal storage. Dry Technol 26: 936-947.
26. Balladin DA, Headley O (1999) Evaluation of solar dried thyme (*Thymus vulgaris linné*) herbs. Renew Energ 17: 523-531.
27. Li Y, Li HF, Dai YY, Gao SF, Wei L, et al. (2011) Experimental investigation on a solar assisted heat pump in-store drying system. Appl Therma Eng 31: 1718-1724.
28. Yahya M, Sopian K, Theeran MY, Othman MY, Alghoul MA, et al. (2008) Experimental and Theoretical Thermal Performance of Double Pass Solar Air Heater with Porous Media, Proceedings of the 7th WSEAS, International Conference on system science and simulation in Engineering (ICOSSSE '08), Venice, Italy, November 21-23: pp 335 - 340.
29. Macalood JS, Vicente HJ, Boniao RD, Gorospe JG, Roa EC, et al. (2013) Chemical analysis of *Carica papaya* L . Crude Latex. Americ J Plant Sci 4: 1941-1948.
30. Yahya M, Othman MY, Sopian K, Daud WRW, Yatim B, et al. (2004) Quality of pegaga leaf dried in a solar assisted dehumidification drying system.
31. Yahya M, Sopian K, Daud WRW, Othman MY, Yatim B, et al. (2008) Performance of a solar assisted dehumidification system for *Centella asiatica* L.
32. Fadhel MI, Sopian K, Daud WRW, Alghoul MA (2010) Performance analysis of solar-assisted chemical heat-pump dryer. Solar Energ 84: 1920-1928
33. Mehdizadeh Z, Zomorodian A (2009) A study of the effect of solar drying system on rice quality. J Agricultur Sci Technol 11: 527-534.
34. Negi PS, Roy SK (2001) Effect of drying conditions on quality of green leaves during long term storage. Food Res Int 34: 283-287.
35. Prakash S, Jha SK, Datta N (2004) Performance evaluation of blanched carrots dried by three different driers. J Food Eng 62: 305-313.
36. Prasad J, Vijay VK, Tiwari GN, Sorayan VPS (2006) Study on performance evaluation of hybrid drier for turmeric (*Curcuma longa* l.) drying at village scale. J Food Eng 75: 497-502.
37. Bena B, Fuller RJ (2002) Natural convection solar dryer with biomass back-up heater. Solar Energ.
38. Bonaparte A, Alikhani Z, Madramootoo CA, Raghavan V (1998) Some quality characteristics of solar dried cocoa beans in St. Lucia. J Sci Food Agri 76: 553-558.
39. Weiss W, Buchinger J (2012) Solar drying. AEE INTEC Publication, A-8200 Gleisdorf, Feldgasse 19, Austria.
40. Sopian K, Alghoul MA, Alfegi EM, Sulaiman MY, Musa EA, et al. (2009) Evaluation of thermal efficiency of doublepass solar collector with porous-nonporous media. Renew Energ 34: 640-645.
41. Sreekumar A (2010) Techno-economic analysis of a roof-integrated solar air heating system for drying fruit and vegetables. Energ Conver Manag 51: 2230-2238.
42. Crapiste GH, Rotstein E (1997) Design and performance evaluation of dryers. Handbook of Food Engineering practice, CRC Press, New York.
43. Tarhan S (2007) Selection of chemical and thermal pre-treatment combination for plum drying at low and moderate drying air temperatures. J Food Eng 79: 255-260.

Citation: Tiwari A (2016) A Review on Solar Drying of Agricultural Produce. J Food Process Technol 7: 623. doi: 10.4172/2157-7110.1000623