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"A Review: Development and trends in solar drying technologies"

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Abstract — ***Drying is one of the best methods to preserve agricultural products for long time but it requires lot of energy. As availability of electricity per capita in developing and under developed countries is very less, thus the electricity uses for heating purpose cannot be economically and environmentally justified option. So, entrapment of thermal energy from solar radiation may be the best option for drying. Solar energy can be utilized for drying in different ways namely open sun drying and closed drying (direct and indirect). Open sun drying have various disadvantages like contamination of dust particles, bacteria in crop, after drying etc. To overcome these problems greenhouse drying or closed drying has been developed. This review is an attempt to explore different types of drying systems was developed across the world.***

Keywords-Active solar dryer; Passive solar dryer; Direct solar dryer; Indirect solar dryer; open sun drying.

"I. INTRODUCTION"

In the majority of developing countries, agriculture represents the biggest part of the economy. About 60-80% of the working population is employed in agriculture. Despite these large numbers, food production still does not meet the needs of the population. The lack of appropriate preservation and storage systems caused considerable losses, thus reducing the food supply significantly. The problem of this shortage can be solved by two methods:

I.) Increasing food supply, and
II.) Controlling population growth.

But, both of the solutions require a considerable amount of capital and time to fulfill the objective [1]. Esper and Muhlbauer have given a third and most viable solution to the world's food problem and this is to reduce the food loss [2]. Also, the failure in food production caused by crop-failures as well as significant seasonal fluctuations in availability can be cancelled out by food conservation, e.g., by drying.

The traditional method of solar drying in the Asia-Pacific region is by open air drying where the product to be dried is exposed directly to the sun. Having visited a number of countries, Ong studied the numerous designs available for solar drying in Asia-Pacific region, namely, Natural convection cabinet type solar dryer, forced convection indirect solar dryer and the Greenhouse type solar dryer, were discussed in detail [3].

Open sun drying of crops is the most common and widespread method of food preservation in a lot of countries due to solar irradiance being very high for the most of the year. There are some drawbacks relating to this traditional method of drying, i.e., spreading the crop in thin layers on mats, trays or paved grounds and exposing the product directly to the sun and wind. These include poorer quality of food caused by contamination by dust, insects, rain and micro-organisms. Also, this system is labour- and time intensive, as crops have to be covered at night and during bad weather, and the crops continuously have to be protected from attack by domestic animals. Esper and Muhlbauer found many advantages of closed solar drying over open sun drying like improvement in product quality on the basis of colour, texture and taste, no contamination by dust, insects, rain, microorganism, and decrement in drying time up to 20% - 50%, reduction of the drying and storage losses, considerable increase in life of the products [2].

A.-J. Perea Moreno et al. analyzed the drying behavior under the solar greenhouse dryer with conditions of several piles of wood chips which was compared to the same shaped piles under open sun method. The result shows that solar greenhouse dryer can achieve 25 ^{0}C higher temperature and 20% less relative humidity compared to open sun method [4]. A mixed mode type solar tunnel drier was used by Hossain and Bala to dry red and green chillies. Drying time in three systems were compared and found least time 20h in solar tunnel drier to reduce moisture content from 2.85 to 0.05 Kg Kg^{-1} (d.b.) compared to 0.09 and 0.4 Kg Kg-1 (d.b.) in improved and conventional drying systems in 32h [5].

The major barrier in adoption of solar driers is their cost as their pay-back period time is very high. Atul sharma et al. reviewed some low cost easy to fabricate and easy to operate solar dryers that can be manufacture from locally available material, suitably employed at small scale factories or at rural areas [6]. Janjai and Tung developed a roof-integrated solar dryer and evaluated its economic performance. They concluded that the investment in this dryer is economically promising as the Investment rate return (IRR) and pay-back period (PBP) are noted 70.3% and 3.9 years, respectively [7].

Another difficulty in adopting solar driers is unavailability of drying during off sun-shine hours. To overcome this, new technologies are developed using desiccant units and PCM based thermal storage units to making solar dryers functional even during off sun-shine hours. S. Esakkimuthu et al. developed a Phase Change Material (PCM) based thermal heat storage unit for heating air used in a dryer. An organic salt, HS-58 based phase change material used to store the excess energy during peak sun-shine hours which was recovered off after the sun-shine hours [8]. An indirect forced convection desiccant integrated solar dryer designed and fabricated by Shanmugam and Natarajan to investigate its performance under the hot and humid conditions of Chennai, India in sun-shine and off sun-shine hours [9].

"II. TYPES OF SOLAR DRYERS"

All drying systems can be classified according to their heating sources into conventional dryers (fossil fuel operated), and solar energy dryers. Further, solar dryers classify based on methods used for transferring heat to the product. Following Ekechukwu, solar dryers can be classified primarily according to their heating modes and the manner in which the solar heat is utilized. Basically, they can be classified into two parts: Active solar dryers and Passive solar dryers.

Three distinct sub classes of either the active or passive solar drying systems can be classified based on the design arrangement of system and the mode of utilization of the solar heat, namely, Direct gain (integral-type), Indirect gain (distributed-type), Mixed mode type solar dryers.

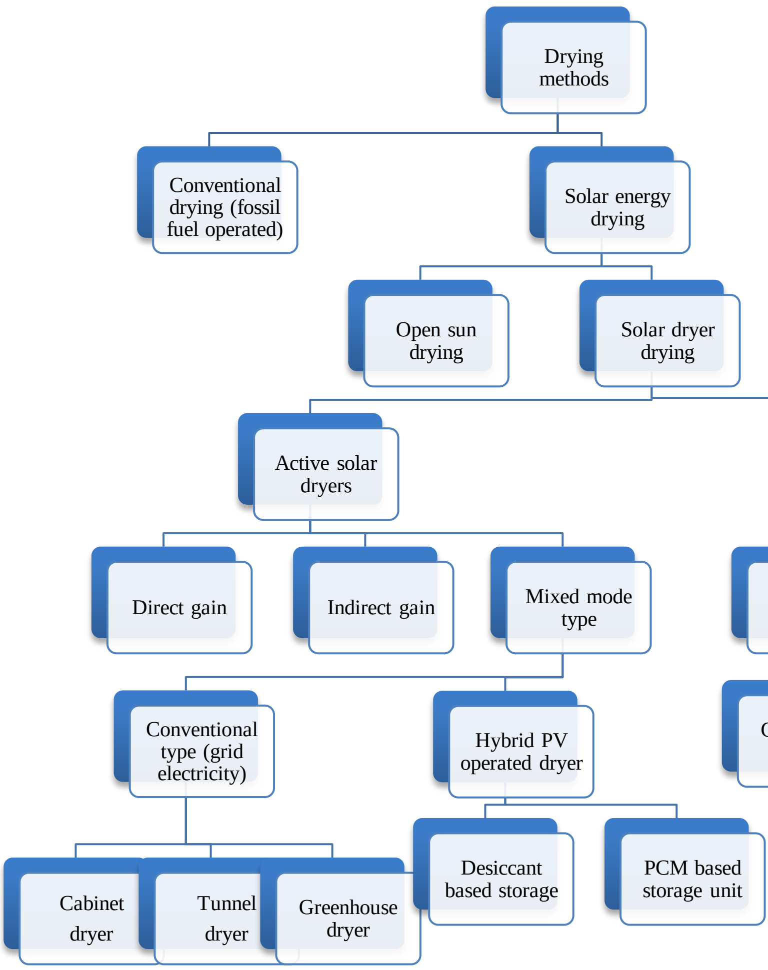

Figure 1. Types of Drying Methods

2.1. Open Sun Drying

In the case of open sun drying a part of the solar radiation incidents on the uneven crop surface and reflected back. The remaining part of solar energy is absorbed by the crop surface. Absorption of radiation depends upon the color of crops. Heat gained by the crop results in convection loss and mass transfer from the surface of the crop to ambient air through moist air. The speed of blowing air over the crop surface decides the rate of convective heat loss. The crop dries due to evaporation of moisture in the form of evaporative losses. Further, some part of absorbed thermal energy penetrate into the interior of the crop with the help of conduction. Convective and conductive losses result in mass decreases in the form of moisture evaporated from the crop surface. Solar drying depends upon the rate at which the moisture within the product moves to the outer surface by a diffusion process depending upon the type of the product [10,11].

2.2. Passive Solar Dryer

The working principle of passive solar dryer is based on thermosyphon effect. In this effect, solar-heated air is circulated through the crop either by buoyancy forces or as a result of wind pressure or in combination of both. The humid air or circulated air ventilated through opening is provided at the roof of greenhouse or through chimney.

2.3. Active Solar Dryer

In the case of active solar dryer, circulation of hot air is done by the help of external means, such as fans or blowers. Active solar energy dryer requires electricity to run the fan which can be harnessed from photovoltaic module or grid. The brief details of the work done on Active solar dryers by different researchers are listed with reference in Table 1.

The Active and Passive solar energy dryers may further be divided into three types categorized on the basis of the way sun light impinges upon the surface of the space under drying process as follows [12,13]:

1. Direct solar dryer
2. Indirect solar dryer and
3. Mixed mode solar dryer

2.3.1. Direct Solar Dryer: Direct solar dryers have the material to be dried placed in an enclosure, with a transparent cover on it. Heat is generated by absorption of solar radiation on the product itself as well as on the internal surfaces of the drying chamber.

2.3.2. Indirect Solar Dryer: The solar radiation is not directly incident on the product to be dried in indirect solar dryers. It has main advantage that the crop is not directly exposed to solar radiation which help to avoid cracking problem in crop. In the indirect solar dryer, a separate unit is used to collect thermal energy which is known as solar air heater. Further a separate drying chamber is used for drying the crop. The ambient air heated in solar air heater which is allowed to circulate through crop placed in drying chamber.

2.3.3. Mixed-mode Solar Dryer: This type of dryer has combined feature of direct and indirect mode of solar dryer. Mixed mode drying issued when faster drying rate is required. In this system, solar energy has been taken from flat plate air collector as well as drying chamber.

Table 1. Active Solar Dryers and their contribution

1.	Bala B K et al. [14]	Experiments have been performed on solar tunnel drier having drying product as pineapple. The drying air temperature varies from 34.1 to 64 ^{0}C. The moisture content of pineapple reached to 14.13% (w.b.) from 87.32% (w.b.) in 3 days of drying while it reached to 21.52% (w.b.) in traditional drying for similar period.
2.	Roonak Daghigh and Abdellah Shafieian [15]	Roonak and Abdellah designed, constructed and tested a heat-pipe evacuated tube solar dryer with a heat recovery system where, water was used as working fluid and air was used as intermediate fluid. The raw water was heated by the solar loop and stored in a storage tank, depending upon the system requirement hot water sent to heat exchanger where, its heat delivered to the blown air. The maximum air temperature of the dryer was 44.3 ^{0}C. Also, they obtained expression for Effectiveness of dryer.
3.	S. Nabnean et al. [16]	Presented a performance evaluation on solar dryer for drying osmotically dehydrated cherry tomatoes. The dryer consists of drying cabinet, heat exchanger, water type solar collector and water type heat storage unit. During the experiment, values of the solar radiation, drying air temperature and drying air relative humidity ranges from 38-915 W/m^2, 30-65 ^{0}C, 16-80%, respectively. Collector efficiency in a typical day was within range of 21-69%. The moisture content of the tomatoes reduced to 15% (w.b.) from an initial value of 62% (w.b.) within 4

		days where, as the sun-dried samples were reduced to 40% (w.b.) within same period. The pay-back period of the dryer estimated to be 1.37 years.
4.	Hegde et al. [17]	An indirect, active type solar dryer was designed to dry agricultural products. The experiments were conducted to dry banana slices and to study its drying characteristics like rate of drying and quality in terms of taste, colour and shape. The dryer has two different air flow configurations: Top flow & Bottom flow and two different mounting arrangements: Conventional trays & wooden skewers. The results showed that the bottom flow provided 2.5^{0}C higher chamber temperature and 3.1% moisture content difference when compared to top flow. Also, drying rate increase when wooden skewers were used instead of conventional trays.

"III. DRYING IN OFF-SUN SHINE HOURS"

S. Esakkimuthu et al. developed a Phase Change Material (PCM) based thermal heat storage unit for heating air used in a dryer. An organic salt, HS-58 based phase change material used to store the excess energy during peak sun-shine hours which was recovered off after the sun-shine hours. The experiments results showed that at high mass flow rates, the collector efficiency is also higher due to the reduction in heat losses. They also observed that by selection of the phase change material with suitable phase change temperature, avoids overheating of air during the peak sunshine hours, thereby, avoiding the spoilage of food products due to excessive heating. They concluded that by supplying air at lower mass flow rate during the discharging process, maximum capacity of the storage system can be utilized and uniform supply of heat for a longer duration of time during off sunshine hours can be achieved [8].

M. Mohanraj and P. Chandrasekar developed and tested an indirect, forced convection type solar dryer integrated with sensible heat storage unit for drying chilly. An air flow rate of 0.025 Kg/s kept, which reduces moisture content of chili to 9.1% (w.b.) from 72.8% (w.b.) in 24h. The overall dryer efficiency and specific moisture extraction rate was 21% and 0.87 Kg/kWh, respectively. The maximum and minimum drying air temperatures at the drier inlet were noted to be 68 ^{o}C and 43 ^{o}C during peak and off sunshine hours, respectively [18].

3.1. Desiccant based drying systems for night operation

An indirect forced convection and desiccant integrated solar dryer is designed and fabricated by Shanmugam and Natarajan to investigate its performance under the hot and humid conditions of Chennai, India. The system consists of flat-plate solar air collector, drying chamber and a desiccant unit. Drying experiments have been performed for green peas at different flow rats. The system pickup efficiency, specific moisture extraction rate, dimensionless mass loss, mass shrinkage ratio and drying rate were discussed [9].

Further, Shanmugam and Natarajan modified the desiccant integrated solar dryer with four main parts namely a flat-plate solar air collector, a drying chamber, desiccant bed and a centrifugal blower. The system was operated in two modes, sunshine hours and off sunshine hours, and drying experiments were conducted with and without the integration of desiccant unit. The effect of a reflective mirror on the drying potential of the desiccant unit was also investigated and the results showed that the inclusion of reflective mirror on the desiccant bed causes faster regeneration of the desiccant material [19].

Wisut Chramsa-ard et al. developed a desiccant bed solar dryer that has dehumidification system used for decreasing drying air humidity by install Silica Gel Beds (SGB) on Top, West and East side for continuously drying process. The Top SGB has highest adsorption rate next is the West SGB and the last is the East SGB. The experiments were carried out by continuously operated and divided into two parts, with-humidification system and without-dehumidification system. The parameter that affects to adsorption rate of silica gel are air temperature which, inverse proportional to the adsorption rate and humidity ratio of humid air which, directly proportional to the adsorption rate [20].

"IV. SUMMARY"

This paper presents a review of different types of solar energy dryers. The solar dryers are found to have several merits as compared to direct drying of the crops using solar radiation. Such as, force mode drying is better than natural, the quality and colour of the crop can be retained by using indirect drying, the low-density crop drying is faster in comparison to high density crop drying, the cost of solar drying (per kg) is less in comparison to an electric drying, thin bed drying is better and uniform moisture removal rate compared to deep bed drying.

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