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A Review on Solar Drying Techniques and Solar Greenhouse Dryer

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Abstract: *Solar energy is a renewable energy and drying of products in sun is the oldest way. It has been used for the preservation of agricultural products since a long time. There are three types of drying- open sun drying, direct drying and indirect drying. Open sun drying is drying of product openly in sun but it has some demerits to overcome these, various drying techniques have been proposed in recent years. Direct drying and indirect drying can be done using greenhouse dryer which can further be classified as greenhouse dryer with natural convection (passive mode) or with forced convection (active mode). The products which are drying in greenhouse dryer have a better quality than open sun drying. It has also advantages that crop are protected from dust, rain, insects, animals etc. Solar greenhouse dryers are available in different size and design and are used for drying various crops and agriculture product. Drying is also possible by an artificial mechanical drying process using fossil fuels. But this method has negative impact on the environment and also it is costly whereas the greenhouse drying has no harmful impact on the environment and is dependent on weather condition. In present paper a literature review on solar drying has been done. It has been found that for higher production rate photovoltaic integrated greenhouse dryer are best suited. Product quality and production rate are higher for greenhouse dryer as compare to open sun drying.*

I. Introduction

Rapidly increasing population in world has created food problems for the entire population. This rapid increase in the population has a direct impact on food balance of any country. Because there is a shortage of storage facilities and poor processing techniques the quality and quantity of food grains are continuously deteriorating. So it become mandatory to reduce food losses during production time for maintain the right balance between food supply and population growth. However, in rural areas it is difficult to maximizing the food production capabilities of small farmers. To solve this problem of preserving the food products solar drying has become one of the main processing techniques in sunny areas.

There is an abundant solar radiation on the earth. In recent years, it has become more popular to use the solar energy. Various processes such as drying, heating, cooking, and distilling can be done by using solar energy. Solar energy in terms of energy application can be categorized into electrical and thermal applications. In many developing countries it is feasible, economical and also ideal for farmers to use of solar thermal systems for conserve grains, fruits and vegetables in the agricultural sector [1].

Because of environmental concerns, expected depletion of conventional fossil fuels and fluctuation in the price of fossil fuel, the potential of using solar energy in the agricultural sector has increased. In tropical and subtropical countries one of the most attractive and promising applications of solar energy systems is solar assisted drying system. Drying of agricultural crops in the sun is traditional process. For the agricultural produce drying is one of the most important post handling processes. It can improve quality of harvested products, extend shelf life to maintain relatively constant price of products, improve the bargaining position of the farmer and reduces post harvest losses. During drying process, most of the water is taken out from the product, it also lowers transportation cost. Large open space area is required for direct sun drying. It is also dependent on the availability of sunshine, affected by foreign materials such as dusts, litters and is exposed to birds, insect and rodents. Hence, most agricultural produce must be dried first before them to be stored. Otherwise insects which multiply in moist conditions such as fungi, make them unusable [2].

In solar crop drying, moisture from the product is transported to surrounding by the process of evaporation. Solar thermal crop drying is a complex process in which simultaneous heat and mass is to be transferred [3].

One of the oldest method known to man for preservation of food is drying of fruits and vegetables and it has great effect on the quality of dried products. The major objectives of drying the agricultural product are reduction in moisture content to a level, which allows safe storage over an extended period. The growth and reproduction of microorganisms which cause decay is prevented by removing the moisture. Due to moisture removal there is a substantial reduction in weight and volume. It minimizing packing, storage and transportation cost and under the ambient temperatures it also enables storability of the product. In drying process changes such as structural and final quality of the product is affected due to physic-chemical modifications. Currently among post-harvest technology of agricultural products, the hot air drying is most widely used method. A more uniform, hygienic and attractively coloured dried product can be produced rapidly by using this method [4].

II. Type of Solar Drying

In the presence of solar energy there are three modes of drying: (i) open sun, (ii) direct and (iii) indirect.

Based on the method of solar-energy collection and its conversion to useful thermal energy the working principle of these modes depends [5].

a) Open Sun Drying:-

By using solar energy the working principle of open sun drying is simple. The solar energy of shorter wavelength falls on the uneven crop surface. Depending upon the colour of crops some part of this energy is absorbed by the surface and the remaining is reflected back. The radiation which is absorbed by the crop is converted into thermal energy and the temperature of crop start to increase. Due to this the long wavelength radiation from the surface of crop is lost to ambient air through moist air. Also there is convective heat loss too in addition to long wavelength radiation loss because the wind blowing through moist air over the crop surface. In the form of evaporative losses evaporation of moisture takes place and the crop is dried. Further in the interior of the product a part of thermal energy absorbed is conducted. Due to this there is a rise in temperature inside the crop and also water vapours are formed and then start to diffuse towards the crop surface and finally thermal energy in the crop is lost. The moisture removal is rapid in the initial stages as the excess moisture is on the product surface. Depending upon the type of product and rate at which the moisture in the product moves to the surface by a diffusion process, the drying period depends [6].

There are some disadvantages and considerable losses of open sun drying, such as rodents, birds, insects and micro-organisms can fall or destroy the crop. Also there is a risk of unexpected rain or storm. Some of the characteristics for open sun drying are over drying, insufficient drying and contamination by foreign material like dust dirt, insects, and micro-organism as well as discolouring of crop by UV radiation. In general, international quality standards are not fulfilled by the final product when they are openly sun dried. This leads to unacceptance of crop in the international market [5]. It is loss by birds and beast and also exposed to various contaminations such as dirt, pest infestation. In addition, crops like maize there is the possibility of aflatoxin contamination [7].

The large amounts of products which are processed by large firms in open drying are not suitable. Higher cost of labour, larger area requirement and decreased quality of products are some disadvantages of this process and before the products can be ready for storage it is a labour-intensive process [8]. Open sun drying totally depends on conditions of environmental, such as solar radiation, wind and other ambient conditions [9]

Jain and Tiwari [10] studied the thermal behaviour of open sun drying of green chillies, green pea, white gram, onions, potatoes and cauliflower. They developed a mathematical model to predict the crop temperature, rate of moisture removal and air temperature for a steady state condition and found that the rate of moisture transfer for the cauliflower and potato slice is significantly high as compare to other crop. Open sun drying process is a very slow process and it can also lead to considerably huge losses. The products dried under the open sun drying usually do not reach international standard quality was also added.

b) Direct Solar Drying:-

In direct type of solar dryer, solar radiation is incident on the crops such as grapes placed for drying after passing through a transparent cover usually glass or plastic. The transparent cover reduces direct convective losses to the surroundings and increases temperature inside the dryer [11].

Sharma et al. [5] used a cabinet dryer. Solar radiation is incidence on the glass cover and a part of its reflected back to atmosphere and remaining part is transmitted inside cabin dryer. Further, a part of transmitted radiation inside cabin dryer is reflected back from crop surface and the remaining part is absorbed by the crop surface. The absorption of solar radiation causes the temperature of crop increase and long wavelength radiation starts to emit by crop which is not allowed to escape to atmosphere because of presence of glass cover. Thus inside the chamber temperature of the crop becomes higher as compare to open sun drying. One more purpose served by the glass cover is the reduction in direct convective losses to the atmosphere which further leads to rise in temperature of crop. However, inside the chamber convective and evaporative losses occur from the heated crop. The air entering into the chamber from below takes moisture away and escapes through top where another opening is provide.

Sharma et al. [12] used a small hot box made up of wood material and having length about three times of its width for drying of grapes. For absorbing solar radiation transmitted through the glass cover the sides and bottom of the cabinet were painted black internally. Ventilation holes for air were provided at the bottom and upper sides of the dryer. On aluminium tray the grapes were spread which was having wire mesh at the bottom and then exposed to solar radiation. The evaporation of moisture was observed with rise in temperature of grapes. This warm moist air created a partial vacuum inside the dryer when passed through upper ventilation holes by natural convection. From the holes provided at the bottom, the ambient air entered into the cabinet, passes through the wire mesh on which grapes were spread. Grapes were at a higher temperature due to absorption of solar radiation passing through the glass cover and air escapes through the upper ventilation holes with moisture vapours. Qualities of dried grapes were improved by reducing contamination such as dust, insect infestation and animal or human interference. This dryer when tested took about 3-4 days for drying 10 kg of grapes.

c) Indirect Solar Drying:-

The easiest method of solar drying is direct solar drying; however, but it has also some disadvantages such as:

a) The quality of the products is reduces when direct exposure to solar radiation and the vitamins and nutrients from them is also reduces.
b) Rate of drying is very slow.
c) There is no control over rate of drying.
d) Products are directly exposed to poor solar conditions and uneven climatic changes.

These disadvantages are overcome by using indirect type solar dryers. For product drying indirect solar drying is the new and more effective technique. The products are not directly exposed to solar radiations in this type of drying but the air is heated by using solar radiation. This heated air is then passed through the product which is to be dried. Thus by convection and diffusion moisture may be lost from the product [13].

Goyal and Tiwari [14] designed a reverse observer dryer. In that system, heat of sun is firstly collected by the solar collectors, heat is then passed to air and after that air passes heat on to the dryer cabinet from where the drying takes place.

Another principle of indirect solar drying uses a solar air heater which is a separate unit. This unit collect the solar-energy for heating the air entering into this unit. The separate drying chamber where the crop is kept is connected by air heater. The air which is heated is allowed to flow through wet crop. Here, by convective heat transfer between the hot air and the wet crop the heat is provided from moisture evaporation. The drying is basically by the difference in concentration of moisture between the air in the vicinity of crop surface and the drying air. In indirect type of solar drying systems a better control over drying is achieved and the good quality of product is obtained [5].

III. Types Of Solar Greenhouse Dryer

Kumar et al. [15] have presented the detailed classification of greenhouse dryer. Based on structure the greenhouse dryer is mainly classified into two types (i) dome shape and (ii) roof even type. The main objective of dome shape greenhouse dryer is to utilize the maximum global solar radiation. Proper mixing of air inside the dryer occurs in roof even type greenhouse dryer has advantages.

Prakash and Kumar[16] classified greenhouse dryer based on the mode of heat transfer (i) greenhouse dryer under passive mode and (ii) greenhouse dryer under active mode. Each dryer can be operated in both mode either passive (natural convection) or active mode (forced convection).The greenhouse dryer under passive mode works on the principle of thermosyphic effect. In this dryer, air gets out through the chimney or by the ventilator provided at the roof. In greenhouse dryer under active mode the humid air is ventilated by the help of an exhaust fan provided at the ventilator.

a) Greenhouse Dryer Under Natural Convection (Passive Mode):-

Basunia and Abe [8] used a mixed-mode type natural convection solar dryer for drying rough rice. They used a page’s equation to describe drying rate of the dryer. Based on the ratio of differences between the initial and final moisture content of rise and the (Equilibrium Moisture Content) EMC, the page model depends. The page model fitted with the moisture content with a standard error of 0.387%. N and K were the drying parameters in Page's equation and it was a linear function of temperature and relative humidity. The experimental results showed that for drying rough rice in mixed-mode type natural convection solar dryer was useful.

Jain and Tiwari [17] proposed a greenhouse dryer under natural convection mode. They dried cabbage and peas in greenhouse dryer under natural convection and at the same time the same amount of these crops was also dried in open sun. For both modes of drying convective mass transfer coefficient (h_c) was calculated. The study showed that as compare to open sun drying, the convective mass transfer coefficient (h_c) of drying inside the greenhouse dryer under passive mode from where the crop is dried is lower.

Tiwari et al. [18] evaluated the convective mass transfer coefficient during drying of jaggery in the roof type even span greenhouse. They used different masses of jaggery. Convective mass transfer coefficient was evaluated by regression analysis using the experimental data moisture evaporated, temperatures of jaggery, greenhouse room air and relative humidity. It was found that for a given size of greenhouse dryer the convective mass transfer coefficient is a strong function of temperature, mass of jaggery and relative humidity. Initially the value of convective mass transfer coefficient was found to be higher and after some time it started to decreases. Similar results were also observed for evaporative mass transfer coefficient.

Farhat et al.[19]proposed a polyethylene greenhouse dryer under natural convection(passive mode) for drying of pepper. Previously a model was validated in laboratory conditions which gave satisfactory predictions of solar drying process in naturally ventilated greenhouse. To confirm improvements in final quality of the product, the quality study was done which showed an improvement of the product aspect and better hygienic conditions. They also found that there was more than 83% of weight reduction at the end of the drying process.

Kumar and Tiwari [20] studied and evaluated convective mass transfer coefficient for the roof type even span greenhouse dryer for the different shape and size of jaggery. They conducted an experiment for three different dimensions of jaggery $0.03\times0.03\times0.01 m^3$, $0.03\times0.03\times0.02\ m^3$, and $0.03\times0.03\times0.03\ m^3$ and two different sets of experiment with jaggery quantity of 0.75 kg and 2.0 kg for each dimension of Jaggery pieces. The jaggery with dimensions of $0.03\times0.03\times0.02\ m^3$ had more convective mass transfer coefficient in natural convection mode than that in force convection mode of the dryer.

Kumar and Tiwari [21] proposed a thermal modelling for greenhouse dryer having even span roof for jaggery drying. This model is used to predict the greenhouse inside air temperature, jaggery temperature and mass of jaggery during drying (moisture evaporated). They conducted an experiment separately for 0.75 kg and 2.0 kg of jaggery pieces which is having dimensions of $0.03\times0.03\times0.01\ m^3$.This model was validated with experimental value and it is found to be in good agreement for the complete drying of jaggery under natural convection conditions.

Tiwari et al. [22] proposed a roof-type even span greenhouse dryer under passive mode and presented energy and exergy analyses for fish drying. The analysis was used to predict the greenhouse room temperature, fish surface temperature and moisture evaporated during drying. The experimental values and predicted value both are found to be in good agreement. Its coefficient of correlation varied from 0.94–0.99.

Prakash and Kumar [23] have proposed an ANFIS (Adaptive Neuro Fuzzy Inference System) model for the greenhouse dryer under passive mode and used it to predict the greenhouse inside air temperature, jaggery temperature and mass of jaggery during drying (moisture evaporated). They used it to forecast thermal performance of dryer on the basis of ambient temperature and solar intensity. They conducted experiments separately for 0.75 kg and 2.0 kg of jaggery pieces which is having dimensions of $0.03\times0.03\times0.01\ m^3$. They experimentally and analytically validate the model. Study showed that in ANFIS model gives the better results as compare to thermal model.

Prakash and Kumar [24] proposed a artificial neural network (ANN) model for the roof type greenhouse dryer under natural convection mode. During drying process they predict the mass of jaggery inside the greenhouse dryer hourly. The artificial neural network (ANN) model was used to predict the dried jaggery mass on hourly basis. Jaggery was dried in the dryer until the constant variation occurs in the mass of jaggery. The input parameters for artificial neural network (ANN) modelling were solar radiation, ambient temperature and relative humidity. They found that the results of the artificial neural network (ANN) model were in good agreement with experimental drying data of jaggery mass.

Gbaha et al. [25] proposed a direct type natural convection solar dryer. The dryer was simple in design and manufactured by local materials like wood, blades of glass, metals. The cassava, bananas and mango slices were dried in the dryer. To evaluate thermal performance of dryer the influence of parameters such as solar incident radiation, drying air mass flow and effectiveness which governing heat and mass transfers were analyzed. The moisture content was reduced to 80% in 19 hours for cassava and 22 hours for sweet banana to reach the safety threshold value of 13%. The dryer was easy to use and also had moderate cost. For the selected food materials, they found that thermal performance of the dryer was higher as compared to open sun drying in terms of heat and mass transfers.

Forson et al. [26] designed and used a mixed-mode natural convection solar crop dryer for drying cassava and other crops. A batch of cassava of 160 kg with initial moisture content of 67% was used as load and to reach desired moisture content of 17%, 100 kg of water was required to be removed. For test location Kumasi, the drying time was assumed to be 30–36 hours with average solar irradiance of 400 W/m^2 and ambient conditions of 25 °C and 77.8% relative humidity. To achieve the drying efficiency of 12.5% a minimum solar collection area of 42.4 m^2 was required according to the design. When they tested under full designed load with solar irradiance of 340.4 W/m^2 and ambient conditions of 28.2 °C and 72.1% relative humidity, the drying time was of 35.5 hours and drying efficiency of 12.3% was evaluated. They found that the proposed design procedure is sufficiently reliable.

Berinyuy et al. [27] designed and constructed a solar tunnel dryer with double pass and heat storage using local materials. Authors evaluated it for drying high moisture leafy vegetables and other agricultural products. There is a significant reduction in drying time and an improvement of the product quality when cabbage, amaranth, bitter leaf and pepper were taken as a load. The results showed that drying was continuous during low sunshine periods because of heat storage. Depending on the crop drying time was reduced by 30% to 50%. The quality of the dried product was acceptable in taste and colour. The initial cost was relatively high and running cost was low and the payback period was found to be less than two years. They found that heat storage also permit continuous drying environmental conditions such as rainfall and high relative humidity which was not possible in open-air sun drying.

b) Greenhouse Dryer under Forced Convection (Active Mode):-

Jain and Tiwari [17] performed a study of convective mass transfer coefficient and rate of moisture removal from cabbage and peas for three modes of drying open sun drying, greenhouse dryer under natural convection and force convection as a function of climatic parameters in New Delhi, India. For all three modes of drying the convective mass transfer coefficient is calculated. It was found that in the initial stage of drying the value of convective mass transfer coefficient inside the greenhouse dryer is double in the force convection mode as compare to in natural convection mode. It was also found that in the beginning of the drying time (5-6 hours) the rate of moisture evaporation is maximum. The mass transfer rate became essentially constant after 20 hours of drying time.

Tiwari et al. [18] evaluated the convective mass transfer coefficients of different masses of jaggery which is drying in the roof type even span greenhouse dryer in both natural and forced convection modes. The jaggery was dried till it attained almost constant mass. The data of temperatures of jaggery, mass evaporated, greenhouse room air temperature and relative humidity were measured experimentally and by regression analysis this data was used to evaluated the convective mass transfer coefficient. It was found that under forced convection complete drying of jaggery was faster as compare to natural convection mode. Also, in forced convection the convective mass transfer coefficient is higher as compared to natural convection mode. It was also found that for a given size of greenhouse dryer the convective mass transfer coefficient is a strong function of temperatures, mass of jaggery and relative humidity.

Kumar and Tiwari [20] have studied and evaluated the effect of variation in the shape and size of jaggery pieces under natural and forced convection of greenhouse dryers on convective mass transfer coefficient. From the study it was observed that in forced mode the convective mass transfer coefficient for the jaggery having dimensions $0.03 \times 0.03 \times 0.03\ m^3$ was more.

Tiwari et al. [22] presented energy and exergy analysis for greenhouse dryer under active and passive mode. The results showed that due to the continuous removal of inside humid air greenhouse drying in the active mode was faster than passive mode.

Condori M. et al. [28] built and tested a new low cost tunnel greenhouse drier design for a forced convection in the North of Argentina. The red sweet pepper and garlic were used for experiment. By using the measured experimental data, dryer thermal efficiency was calculated. A linear relation between the solar radiation and the drier temperature was obtained. A prototype drier was tested and it gave a good drying rate, final moisture content and dried product aspect. As expected from the solar radiation exposition there were no appreciable deteriorations in final colour of the dried product and colour obtained of both the products was also acceptable. Good thermal performance was obtained during sunny days.

Condori and Saravia[29]presented an analytical study which describes the performance of a tunnel greenhouse drier. A linear relationship between the incident solar radiation and the output temperature of greenhouse dryer is obtained by considering the greenhouse as a solar collector. By using characteristic function of the drier and as a function of the drying potentials the drier performance was evaluated. Almost constant production is obtained each day which is shown by results. When the generalized drying curve concept is applied to both the first tunnel cart and the single chamber drier case, result obtained is of similar kind. As compared with the single chamber drier case an improvement of 160% in the production is obtained in simulation tests with red sweet pepper. If the double chamber drier is considered an improvement around 40% is observed.

Hossain and Bala [30] proposed a mixed mode type solar tunnel drier with forced convection for drying green chillies and hot red for the tropical weather conditions of Bangladesh. Two exhaust fans were used for the dryer and it is operated by a photovoltaic module. The drying time was considerable reduced by using solar tunnel drier. The average temperature rise in the dryer was almost constant and 21.62^{o}C above the ambient temperature. The quality of dried products is better in terms of colour and pungency when compare to products which is dried under the sun.

Nayak and Tiwari [31] have proposed energy and exergy analysis for green house dryer integrated with photovoltaic/thermal. The experiment is conducted in the clear sky conditions and it was validated with the experimental result.

Barnwal and Tiwari [32] designed and constructed hybrid photovoltaic-thermal (PV/T) greenhouse dryer of 100 kg. Dryer was used to dry the Thompson seedless grapes and forced mode convection was produced using DC fan. For comparison, grapes were also dried in open as well as shade. The greenhouse dryer performance is compared with natural drying and shade drying. The result showed that the convective mass transfer coefficient for greenhouse dryer was lower in comparison to open sun drying and the product dried inside the greenhouse dryer had a far superior quality and colour as compare to that in natural drying.

Janjai et al.[33] have presented an experimental study and simulated performance of a photovoltaic (PV)-ventilated greenhouse dryer under active mode for drying peeled longan and banana. The dryer have a parabolic roof structure covered with polycarbonate plates on a concrete floor. Three exhaust fan powered by 50 Watt photovoltaic (PV) module were used to ventilated the inside humid air. In the greenhouse dryer the peeled longan get dried only in 3 days whereas it took 5 to 6 days in open sun drying under similar conditions. For banana the drying time is only 4 days in the greenhouse drying whereas in open sun drying it took 5 to 6 days under similar conditions. The quality of greenhouse dried products in terms of colour and taste was of high-quality than naturally dried product.

Janjai et al. [34] has been developed and tested a large scale parabolic shape active greenhouse dryer having capacity of 1000 kg in Champasak, Lao Peoples Democratic Republic. The dryer was covered with polycarbonate sheet and base of the dryer was a black concrete floor. To ventilate the dryer nine DC fans were used which were powered by three 50 Watt solar cell modules. The banana, chilli and coffee were dried in this test. It was found that the drying time of banana with the initial moisture content of 68% was 5 days while it took 7 days in natural sun drying in same weather conditions. The drying time of chilli with the initial moisture content of 75% was 3 days while in natural sun drying it took 5 days. Also the drying time of coffee with initial moisture content of 52% was 2 days and in natural sun drying it required 4 days. It was found that the there is a considerable reductions in drying time in comparison with the natural sun drying and the products which are dried in the solar greenhouse dryer had a good colour with high quality.

Kumar and Tiwari [35] studied and evaluated the convective mass transfer coefficient for different masses (300g, 600g and 900g) of onion flakes in natural and forced greenhouse drying. In the off sun shine hours and as compare to open sun drying, the experimental study shows that drying rate for the greenhouse dryer was higher. As the mass of the onion is increased, the convective mass transfer coefficient is also increased.

IV. Conclusion

In this paper the design, performance, advantages and disadvantages of various types of solar dryer are studied. As per present study, the greenhouse dryer with forced convection is found to be best for high moisture content. But for low moisture content natural convection dryer is best suited. For commercial use photovoltaic integrated solar greenhouse dryer are most suitable as the production rate increases with the increase in flow rate of air. These systems do not need electricity from grid. So they can be used in remote area also.

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