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A REVIEW OF SOLAR DRYERS FOR DRYING AGRICULTURAL PRODUCTS

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ABSTRACT

Food problem in most of the developing countries is largely due to the inability to preserve food surpluses rather than to lower production because agricultural products such as fruits and vegetables are seasonal and have high moisture content at the time of harvesting. Agricultural products if left as such will biologically degrade due to the growth of microorganisms. Improper preservation of seasonal agricultural products and depleting energy reserves cause considerable loss, thereby reducing the food supply significantly. Therefore the preservation of food becomes essential to make it available throughout the year. Drying is a post-harvest preservation technique to reduce loss of seasonal surplus and yield more profit during demand. A large variety of solar dryers have been designed and developed in the recent past. This paper attempts to present the current research in the field of solar drying in developing countries. Exhaustive research and development have been carried out in order to make solar drying economical and eco-friendly. Solar drying with desiccant bed is capable of drying agricultural products at late evening and the efficiency of the solar dryer designed using evacuated tube collector is better compared to other solar dryers for drying agricultural products during cloudy days.

KEYWORD: Agricultural Products, Moisture Content, Solar Dryer, Desiccant Bed, Evacuated Tube Collector.

Food preservation is essential for keeping fruits, vegetables, meat and marine products for a long time with good quality. Most of the agricultural products contain high moisture of 70% at the time of harvest. Due to this excess water, the growth of microorganism is very fast in the crops and may spoil the foodstuff and reduce the nutrient content of the product. Therefore, it is necessary to remove the moisture in the crops for its long time preservation [Chaudhari and Salve, 2014]. Several processes have been employed to preserve food products. Among these, drying is a simple process for removing excess water content from agricultural products.

Drying involves the application of heat to vaporize moisture and removal of water vapor after its separation from the food products. It is thus a combined and simultaneous heat and mass transfer operation for which energy must be supplied. The removal of moisture prevents the growth and reproduction of microorganisms like bacteria, yeasts and moulds causing decay and minimizes many of the moisture-mediated deteriorative reactions. Sun drying is the most common drying technique used to preserve agricultural crops. But the crops suffer undesirable effects of dust, dirt, atmospheric pollution, insect and rodent attacks. Due to this, the quality of the product is reduced. This disadvantage can be eliminated by using a solar dryer [Sontakke and Salve, 2015]. The advantages of using solar drying technologies are enormous than the fossil fuel product drying. The most important advantage is pollution free and reducing carbon particles in atmosphere [Patel et.al., 2013].

PRINCIPLE OF SOLAR DRYERS

Heat is generated by absorption of solar radiation on the product itself as well as on the internal surfaces of the drying zone. The basic principles of solar dryer are:

- Converting light to heat: Any black absorbing material inside a solar dryer will improve the effectiveness of absorbing and turning light into heat.
- Trapping heat: Isolating the air inside the dryer from the air outside the dryer makes an important difference. Using a clear solid, like a plastic bag or a glass cover, light is allowed to enter and converted to heat. But once the light is absorbed and converted to heat, the plastic bag or glass cover will trap the heat inside. This makes it possible to reach similar temperatures on cold and windy days as on hot days.
- Moving the heat to the food: Due to convection, the heat is moved to the food, which enables to remove the moisture present in it [Dadi et.al., 2016].

CLASSIFICATION OF SOLAR DRYERS

Solar dryers can broadly be categorized into direct, indirect and specialized solar dryers [El-Sebaii and Shalaby]. The three modes of drying are: (i) open sun, (ii) direct and (iii) indirect in the presence of solar energy. In indirect solar dryers, solar radiation is not directly incident on the material to be dried. Air is heated in a solar collector and then ducted to the drying chamber to dry the product [Gutti et.al.]. The working principle of these modes mainly depend upon the method of solar-energy collection and its conversion to

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useful thermal energy [Sharma et.al., 2009]. The performance of solar dryer depends on the condition of the weather. Under sunny conditions the drying time is short and extends during the winter or rainy conditions. The capacity of the dryer can be calculated from the difference in drying time during weather conditions. Figure 1 shows the broad classification of solar dryers.

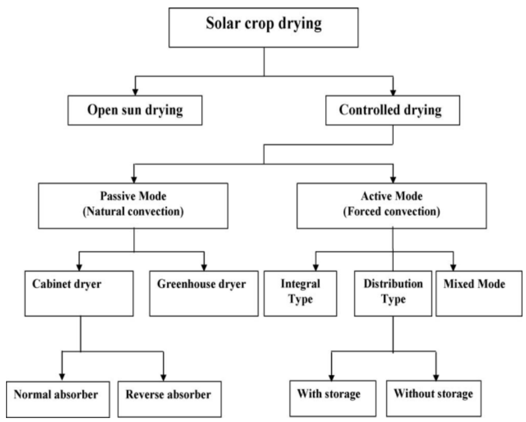

Figure 1. Classifications of solar dryers.

Open Sun Drying

Sodha et al., 1985 investigated the open sun drying. Short wavelength solar radiation falls on the uneven surface of crop. Some part of the energy is reflected back and remaining is absorbed by the surface of the crop. The absorbed radiation from the sun is converted into thermal energy and the crop temperature starts to increase. There is a long wavelength radiation loss from the crop surface to ambient air through moist air and convective heat loss due to the blowing wind through the moist air over the crop surface. The moisture of the product evaporates and consequently the crop becomes dry. In addition, a part of absorbed thermal energy is carried into the interior of the product. Due to this absorbed thermal energy, temperature increases and the formation of water vapor forms inside the crop and then it diffuses towards the crop surface, finally thermal energy losses in the form of evaporation. The moisture content removal is very fast in the initial stage, as the presence of excess moisture on the surface of the product presents a wet surface to the dry air. Consequently, drying depends upon the rate at which the moisture within the product moves to the surface by the process of diffusion. The disadvantage of the open sun drying process is contamination of external materials like insects, dust, dirt and microorganism. Also the discoloring is the main drawback due to direct UV radiation. Figure (2) shows the process of sun drying.

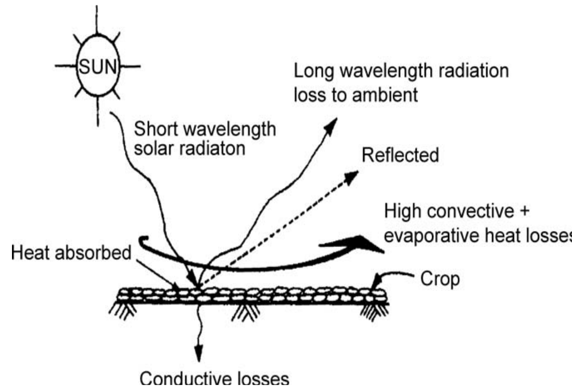

Figure 2. The working principle of open sun drying.

Greenhouse Dryers

Prakash et al., 2016 conducted annual energy and exergy analysis of the modified greenhouse dryer (MGD) under active mode (AM) and passive mode (PM). The experimental results show that the payback period of MGD under passive mode is 1.11 years and active mode was 1.89 years. The heat utilization factor for PM and AM are found to be (0.12 – 0.38) and (0.26 – 0.53) respectively. The coefficient of performance range for PM is (0.55 – 0.87) and (0.58 – 0.73) for AM. The MGD under AM is more effective than MGD under PM for high moisture content crops like tomato and capsicum, and both dryers show similar performance for medium moisture content crop (photo chips). The results suggest that MGD dried crops are more nutrient than the open sun drying.

Janjai et al., 2011 developed a large scale solar greenhouse dryer (SGD) covered with polycarbonate sheet. The reduced moisture content (RMC) of banana is 68% (wb) which took 5 days to reach the desired moisture content in the greenhouse dryer whereas natural sun drying took 7 days under same weather condition. The RMC of chilli is found to be 75% (wb). The designed dryer took 3 days to remove the moisture but natural drying took 5 days to dry the same sample. Also RMC of coffee is 52% (wb) which was dried within 2 days in the designed dryer while sun drying required 4 days. The result of SGD exhibited good quality products as compared to natural sun dried products.

Natural Convection Dryers

Jain and Tewari, 2015 investigated the performance of indirect natural convection solar crop dryer developed with packed bed phase change thermal energy storage used to maintain continual herb drying. During the sunshine hours, the phase change material stores the thermal energy and releases latent and sensible heat used to operate the dryer for next 5 – 6 hours effectively after sunset. The temperature of drying chamber was 6 ^{0}C higher than the ambient temperature till the midnight during the month of June at Jodhpur. The results show that the high outlet temperature of 50 ^{0}C indicates good natural convection maintained throughout the drying process. The mass flow rate was observed to be 0.02 – 0.04 kg/s. The experiment over the night suggest good performance and the drying thermal efficiency was found to be 28.2% based on the total evaporation of water.

Adelaja et al. developed a cost effective natural convection solar dryer for drying plantain chips in the tropical and sub – Saharan African countries. The results show that the collector and system efficiencies are 46.4% and 78.73% respectively, while the percentage of moisture removal of 77.5% was achieved at the 20th hour in order to give a final moisture content of 15.75% in the dried product. The cabinet temperature was 52 ^{0}C which is the optimum temperature for drying fruits and vegetables.

George et al. designed a model of natural convection solar dryer (NSD) with twin collectors and was tested with and without load under the climatic conditions of Maseno, Kenya for drying of vegetable kales. The moisture content reduced from 84.1% to 10% (wb) in 15 hours. Open sun drying has a lower value of drying rate as compared to solar dried kales. The quality test results suggest that 76% of Vitamin C were retained in solar dried kales, with 75% carbohydrate, 91% protein and 100% minerals. The quality and appearance of the solar dried kales were good as compared to open sun drying.

Solar Tunnel Dryers

Arun et al. carried out the analysis of solar tunnel greenhouse dryer with biomass backup heater for drying copra. The moisture content of copra reduced from 53.84% to 7.003% (wb) in 44 hours. Ten different modeling was used for determining the theoretical moisture ratio of copra. Mathematical analysis of drying characteristics of copra in the designed dryer shows best result with very minimum values of Chi square and Root Mean Square Error (RMSE).

Gokhan et al. Conducted the characteristic analysis of a solar tunnel dryer for drying of Rio grand type tomato. 12 different types of mathematical models available in the literature were compared using the coefficient of determination. The results suggest that two – term drying model show a better fit for drying tomato with the highest coefficient R^2 of 0.9967 as compared to other models under the conditions of Izmir, Turkey.

Agbossou et al. developed a new type of solar tunnel dryer under the conditions of Gape – Kpodzi, in Southern Togo for drying maize. The result exhibit two – term drying model as the best fit for the experimental drying of maize with he highest coefficient of determination (R^2) of 0.9975 compared to other drying models. This developed solar dryer can be used for dehydration of maize crops under the meteorological conditions of Southern Togo.

Ayyappan et al. developed the natural convection solar tunnel dryer for drying copra under the meteorological conditions of Pollachi, India. The results from the investigations suggest that the moisture content reduced from 52.2% to 8% (wb) in 57 hours under full load conditions and 52 hours under half load conditions. The estimated efficiency of solar tunnel dryer was 20% which shows a better quality of copra as compared to the open sun drying.

Srisittipokakun et al. manufactured a new type parabolic – shaped solar tunnel dryer for drying of Andrographis paniculata in Nakhon Pathom Thailand. The moisture content of Andrographis paniculata varied from 75% (wb) to 7% (wb) within 2 – 3 days. Also the drying air temperature varies between 35 – 75 ^{0}C under the meteorological conditions of Nakhon. The dried products are completely protected from rain, animals and insects which ensure that dried products are of high quality.

Forced Convection Dryers

Mohanraj et al. fabricated and tested the forced convection solar dryer integrated with sensible heat storage for drying copra. The performance of the dryer is compared with sun drying. The moisture ratio reduced from 52% to 9.2% (wb) in 24 hours of designed dryer and 66 hours for sun drying. The moisture content increased by 0.1-1% due to desorption during off sunshine hours. 25% of copra product has been affected by bacterial infection. The results show that poor quality copra was obtained in the sun drying. The forced convection solar dryer is most suitable for copra drying. Figure 3 shows a forced convection solar dryer.

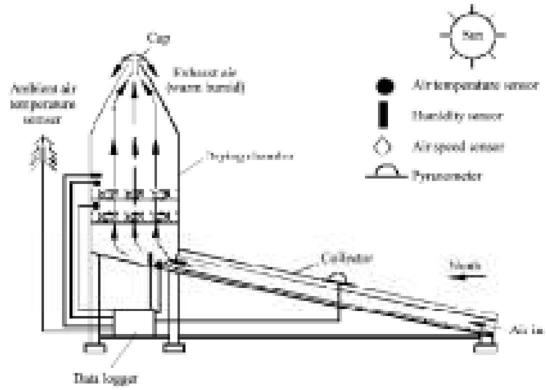

Figure 3: Forced convection dryer.

Mohanraj et al. designed an indirect forced convection solar dryer integrated with sensible heat storage material for drying chili under the meteorological conditions of Pollachi, India. The heat storage material increases the drying time about 4 hours per day. Moisture content of chili reduced from 72.8% to 9.2% in 24 hours. The drier efficiency and specific moisture extraction rate were estimated to be 21% and 0.87 kg/kWh respectively. Comparative study shows that the forced convection solar dryer is more suitable for producing high quality dried chili for small-scale holders.

Rajendra Patil et al. developed a two cabinet solar dryer for tomato drying in natural and forced convection method under the meteorological conditions of Chandwad (India). The moisture content reduced from 94% (wb) to 10% (wb) in 9 hours for forced convection and 12 hours for the active convection mode. The collector efficiency of cabinet solar dryer was found to be 32.96% and 17.12% in forced and natural convection mode respectively. The comparative study concluded that forced convention drier is more suitable for producing high quality dried tomatoes.

Hybrid Solar Dryers

Hossain et al. designed a prototype Hybrid solar dryer for drying tomato under different weather and operating conditions. The performance of the hybrid solar dryer is better as compared to natural sun drying method. The tomato halves were pretreated with UV radiation, acetic acid, citric acid, aschoric acid, sodium metatrisulphate and sodium chloride. Sodium metabisulphate can be used to prevent the microbial growth at lower temperature (45 ^{0}C). The results suggested that the efficiency of the designed dryer varies from 17% to 29% under different operating conditions, which exhibited a better quality of dried tomato.

Anna Hubackova et al. developed a drying model compared to the conventional drying in electric oven for selected Cambodian fish species. The experimental data of moisture ratio versus drying time were fitted with various drying models. By the method of mathematical modeling, it is observed that reduced chi square test ranges from 0.008 to 0.0239, co – efficient of determination (R^2) ranges from 0.9464 to 0.997 and the test of Root Mean Square Error (RMSE) ranges from 0.00036 to 0.00221. Higher values of (R^2) indicate a good fit for drying fish. The two models of drying, the logarithmic and two – term models described the drying kinetics of marine species. The results show best score of appearance, odor, flavor, texture and overall sensory quality in all tested categories compared to natural sun drying. In this point of view, solar drying confirms the acceptable technology for fresh water species in Cambodia.

Srinivasan et al. made a comparative study between open sun drying and forced type (mixed mode) solar drying using bitter gourd. The result shows that during the day the temperature inside the dryer and the solar collector were much compared to the ambient temperature. The results show that time required for forced convection (mixed mode) type SD (10 hours) is better than the open sun drying (17 hours).

Jude et al. investigated and constructed a low cost direct absorption solar dryer under controlled conditions of drying. This dryer was fabricated with a hot box and glass roof from the available local materials and it was tested under the actual environmental conditions of Ohinugwu, Nigeria. The recorded ambient temperature was 33 ^{0}C and the average temperature was 59 ^{0}C. The direct absorption solar dryer used, prevents the adverse effect of UV radiation on agricultural products due to UV stabilized polythene sheet covered on the glass roofs. This also increases the quality of dried product.

Samira et al. investigated the performance of locally designed forced convection integrated hybrid solar dryer for drying of sliced potatoes under the conditions of Saharan of Algeria. The experiment was conducted in two ways such as hybrid drying using solar energy and hybrid drying using conventional electric power and PV (photo voltaic) modules. The results show that the air flow speed is 0.51 m/s in 2 hours 45 minutes for hybrid drying (solar energy) and 0.5 m/s in 1 hour 15 minutes for hybrid drying (conventional electric power). The hybrid drying with PV modules provide the best operating conditions, best efficiency, low drying time and high quality product.

Desiccant Solar Dryers

Wisut et al. investigated the performance of the solar dryer with and without dehumidification system for drying chili. To decrease air humidity, silica gel beds were used as desiccant bed. The collector and chamber efficiency are observed to be 42.1% and 13.8% respectively for drying chili with dehumidification system and took 19 hours, whereas the collector and chamber efficiency are 39.6% and 10.9% without dehumidification system and took 24 hours for dying chili.

Misha et al. conducted the performance analysis of a solar-assisted solid desiccant dryer for drying crushed oil palm fronds. The drying time for reducing the moisture content of crushed oil palm from 69% to 29% (wb) is 4 hours for solar – assisted solid desiccant dryer while the open sun drying takes 30 hours 40 minutes. The results show that the performance analysis of the combination of desiccant and solar dryer produces good quality crushed oil palm fronds. Also the drying performance is much improved with the consumption of low energy as compared to open sun drying.

Famurewa et al. investigated the drying kinetics of thin-layer fluidized bed dryer for drying of cassava. The models were compared on coefficients of determination (R^2), reduced chi-squares, Root Means Square Errors (RMSE) and Mean Bias Error (MBE). Based on this, 12 different mathematical models were fitted to the data of nonlinear analysis. Modified Henderson and Pabis model were found to be best model describing the drying kinetics of cassava chips due to highest value of R^2, least value of chi square, RMSE and MBE.

Solar Dryer with Evacuated Tube Collector

Umayal et al. designed and fabricated a solar dryer using evacuated tube collector with and without heat storage materials (gravel) for drying chili under the climatic conditions of Thanjavur, India. The moisture content was reduced from 87.36% to 3.4% in 10 hours with heat storage materials whereas it took 12 hours for the dryer without gravel and 32 hours in natural sun drying. The efficiency of the dryer with, without storage material and natural sun drying are found to be 34.23%, 22.03% and 9.23% respectively. The quality of dried chili is higher in terms of color, odor and flavor.

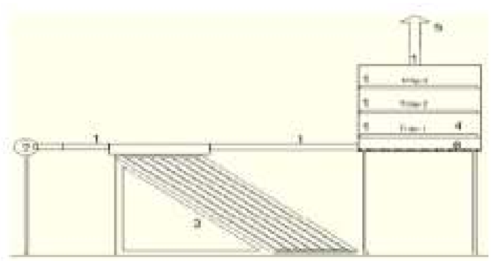

Figure.4. Solar dryer with Evacuated Tube Collector.

Ubale et al. designed and fabricated solar dryer with the evacuated tube collector in the forced convection mode for drying of Thomson seedless grapes. The moisture content was reduced from 77% to 19% (wb) in 36 hours. The average collector efficiency of forced convection solar dryer was 23.4% and produced high quality raisins (dried grapes).

Vijaya sankar et al. designed and fabricated solar dryer with evacuated tube collector using locally available materials and evaluated the performance of the dryer under natural and forced convection mode for drying copra. The temperature of the chamber varies from 35.8 ^{0}C to 67.2 ^{0}C. The moisture content of copra reduced from 84.33% to 55.13% during 4 hour intervals in forced convection. The maximum temperature for natural and forced convection obtained was 51.9 ^{0}C and 67.2 ^{0}C respectively. The result shows that the designed dryer reduces the cost of energy usage and the high quality of dried copra can be obtained as compared to open sun drying.

Rajagopal et al. fabricated an indirect forced convection solar dryer with evacuated tube collector for drying copra under the conditions of Coimbatore, India. The temperature of drying chamber can be obtained as 78 ^{0}C for forced convection and 32 ^{0}C for natural convection solar dryer. The moisture content reduced from 52.3% to 7%. The forced convection solar dryer takes shorter time than the natural convection dryer.

Umayal et al. designed a forced convection solar dryer with an evacuated tube air collector for drying bitter gourd under the meteorological conditions of Thanjavur, India. The moisture content reduced from 91% to 6.25% in 6 hours as compared to 10 hours in natural sun drying and the quality of the dried bitter gourd using solar dryer with an evacuated tube collector is higher than the natural sun drying.

Satis et al. designed an indirect type forced convection solar dryer with an evacuated tube collector for drying copra under the condition of Coimbatore, India. The drying chamber temperature is 78 ^{0}C for forced convection and 32 ^{0}C for natural convection solar drying. The forced convection dryers take less time than the natural convection.

CONCLUSION

Solar dryer is the best alternative technology to avoid disadvantages of natural sun drying methods. This paper has made a detailed investigation and reviewed various designs, constructions and operational principles of different types of solar dyers. The design parameters and the performance of the dryers are also analyzed. This investigation can be employed in small-scale factories or at rural farming villages. Such low-cost food drying technologies show minimal spoilage with enhanced food quality and nutrient content. Solar drying with desiccant bed is capable of drying agricultural products at late evening and the efficiency of the solar dryer designed using evacuated tube collector is better compared to other solar dryers for drying agricultural products during cloudy days.

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