Review on global solar drying status

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Abstract: Solar drying system is applied to dry food and other crops, which is superior in quality and save the consumption of the valuable conventional fuels. A state of art review of the various designs, details of constructional features and operational principles of wide variety of practically realized drying systems, which works on solar energy. The engineering aspect of the solar dryers is also discussed along with drying characteristic analysis of the crop. Some very recent developments in solar drying technology are highlighted. Fruit dryers and characteristics of various fruits while drying is also presented in this communication.

Keywords: solar drying system, dry food, solar energy, conventional fuels.

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1 Introduction

In many rural locations in Asian and African continent, grid-connected electricity and supplies of other non-renewable sources of energy are either occupied and it not affordable to many cultivators. The large initial and running costs of fossil fuel powered dryers present such barriers that it is rarely adopted by small- scale farmers. Climatic conditions have a great influence one extent of crop losses and deterioration during open sun drying. If weather is warm and dry, crops can be dried in natural drying. For this to be practical, the ambient relative humidity during the drying period must be low enough so that partial vapor pressure difference between crop surface and ambient must maintain. Meteorological data even for the most favored areas, show that this is not always feasible (McLean, 1980). The basic essence of drying is to reduce the moisture content of the product to a level that prevents deterioration within a certain period of time, normally regarded as the "safe storage period" (Ekechukwu, 1987). Drying involves the removal of moisture from the product by heating and the passage of air mass around it to carry away the moist vapor.

Food is the basic comfort and necessity of human beings. The critical problem is retaining balance between production and consumption food product. Increase of food supply and limitation of population growth are cited as two solutions for the imbalance of food. But both the solutions require a considerable amount of capital and time to achieve. A third and most viable solution to the world's food problem involves reducing the food loss, which occurs due to various reasons (Esper and Muhlbauer, 1998). Solar dryers can also be used for industrial drying processes. It can be realized a useful device for energy conservation; saves drying time, minimized drying area and enhance the quality of dried product, which also reduce carbon emission.

Solar dryers circumvent some of the major disadvantages of natural drying. Solar energy drying

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systems is used for the whole drying process or for supplementary to industrial drying. Therefore it minimizes the load on conventional source of energy.

The goal is to address the above issues by informing technical and commercial knowledge in solar drying—design, fabrication, full-load operation, and economical feasibility— for a variety of crops and a number of suitable geographical regions. It is surprising that a process used as commonly as solar drying has received so little technical development. It is not unreasonable to believe that annual saving in the millions of dollars might be realized through lowering the costs of drying, improving the quality of the products, and reducing losses by spoilage, deterioration, transport delays, and other factors(Lof, 1964). Solar drying can be an effective means of food preservation since the product is completely protected during drying against rain, dust, insects and animals (Esper andMuhlbauer 1998). Ekechukwu (1999) presented a comprehensive review of the fundamental principles and theories governing the drying process, along with basic definitions. Low cost drying technologies suitable for rural farming areas were presented by Chua and Chou. A brief introduction on each of the drying technology considered namely fluidized and spouted bed, infrared drying, solar drying, and desiccant drying were presented followed by some technical details on their working operations (Chua and Chou, 2003). Sharma et al.(1994) gave a preliminary economic analysis for an indirect type solar fruit and vegetable dryer. The analysis stressed that the most significant economic parameters in the lifecycle costing of the system were the payback period and internal rate of return. And the important and influential parameters, namely, initial investment, fuel price, interest on fuel price, etc.. Solar dryer are used to common farming, in agriculture process. Artificial drying is high energy intensive and expensive process. It raised the cost of final product.

A systematic approach for the classification of solar energy dryers were also evolved, identifying two generic groups, namely, passive or natural circulation solar energy dryers and active or forced convection. Drying is a two stage process —constant (first stage) and falling (second stage) drying rate. The constant drying rate takes place when moisture remove from surface of the crop while during falling rate moisture diffusion takes place from core to surface. The condition of the second stage determined by the properties of the material being dried (Can, 2000). Open sun drying is the most commonly used method to preserve agricultural crop. It leads to losses in the quantity and quality of the dried product (Pangavhane et al., 2002). It is fertile to get infected from foreign particles, rain, and beast. Therefore, it is important to develop solar dryer in third world countries to avoid the shortcoming of natural drying (Yaldiz et al., 2001). Solar drying process can be classified on the basis of energy used to remove the moisture which is transferred to the product (Furlan et al., 1983). Significant developments of the past decade in the area of solar crop drying were reviewed by Muhlbauer, stating the fact that solar energy is considered more applicable to low-temperature in-storage drying systems and it has gained more importance in the last decade for drying grain (Muhlbauer,1986). Purohit et al. (2006) developed a simple framework to facilitate a comparison of the financial feasibility of solar drying as against open sun drying, having presented the results of some exemplifying calculations and a brief discussion about the same (Purohit et al., 2006).

Present communication is based recent advancement in the field of design and performance evaluation of solar drying systems for the different crops. The eventual objective of employing these appropriate drying technologies is to significantly improve the agricultural returns for farmers in appreciation of the hard effort they have devoted in crop cultivation.

2 Global status of solar drying technologies

The conventional method of solar drying in the Asia-Pacific region is by open air drying where the product to be dried is showing directly to the sun. Ong (1999) studied the several designs accessible for solar drying for various countries. Three types of solar dryers—cabinet, indirect and greenhouse dryer—

considered by Ong as having the best possible for development in Asia-Pacific region(Ong, 1999).Vecchia et al.(1980) described the attitude followed and the main results of a study, which was limited to thermal forms of energy consumptions, performed under the contract for the Commission of the European Communities. An quantity on the possibilities of diffusion of solar technologies in European countries in the sectors, namely, rural houses (space heating and hot water production), protection heating, hot water productionfor animal husbandry, greenhouse heating and crop drying were also given. The application of solar drying systems wasintroduced in Nepal for the conservation of food and income generating activities. A nationwide survey revealed that three types of solar drying systems were in common use, namely, cabinet type for domestic use, racks type for profitable and tunnel type for industrial purposes. Modification in design, construction materials and capacity were done by Joshi et al. 2000 to match the local need sand improve the performance of these three types of dryers. Solar thermal devices have been used in the West Indies islands for over a century. Usually, crops such as rice or cocoa have been dried in the sun on drying floors. Solar water heater becomes commercially viable technology in the Barbados and Jamaica since last two decade. Other solar thermal applications-solar still, dryer, cooker and absorption chiller have also been developed and used for domestic/commercial/industrial purpose (Headley.,1998). Lawrence et al.(1990) designed and tested solar crop dryer based on thermal storage system for climatic conditions of Papua New Guinea. Research and development work in solar drying conducted in Thailand in the past 15 years was reviewed by Somchart and Soponronnarit (1995) and the technical and economic results indicated that solar drying for some crops such as paddy, multiple crops and fruit is feasible. Current and projected food conservation and solar crop dryer availability were given by Mabrouk and Belghith (2000), along with potential renewable energy sources in Tunisia. Roman presented a concise survey about solar crop drying with explanations about the conventional, industrial drying and the drying techniques. The solar drying in Chile and its practical advantages were presented (Roman., 1984). Prakash and Kumar (2013) have reviewed the historical solar dryer as well present trend in solar dryers. The moisture content of various fruits and vegetables are presented in Table 1.

Table1 Moisture content, temperature and diffusivity

S.No.	Material	Moisture content ,kg/kg, d.b.	Temperature ,°C	Diffusivity, m^2/s
1	Alfalfa stems	3.70	26	2.6×10^{-10} - 2.6×10^{-9}
2	Animal feed	0.01 - 0.15	25	1.8×10^{-11}- 2.8×10^{-9}
3	Apple	0.10 - 1.50	30 - 70	1.0×10^{-11} - 3.3×10^{-9}
4	Avocado	-	30-58	$3.3\ \times10^{-10}$ - 1.2×10^{-9}
5	Banana	0.01 - 3.50	20 - 40	3.0×10^{-13} - 2.1×10^{-10}
6	Beef raw (freeze dried)	0.127	25	3.07×10^{-11}
7	Beet	-	65	1.5×10^{-9}
8	Biscuit	0.10 - 0.60	20 -100	8.6×10^{-10} - 9.4×10^{-8}
9	Bread	0.1-0.75	20-100	2.8×10^{-9} - 9.6×10^{-7}
10	Carrot	0.01 - 5.00	30 - 70	1.2×10^{-9} - 5.9
11	Cauliflower	11.5 - 0.05	60-90	2.54×10^{-12} - 3.8×10^{-12}
12	Coconut (albumen)	0.2-0.6	45-110	4.6×10^{-11} - 6.6×10^{-10}
13	Coffee extra	0.08-1.5	30-70	1.0×10^{-11} - 3.3×10^{-10}
14	Corn	0.04-0.4	10-90	1.0×10^{-12} -1.0×10^{-10}
15	Egg liquid	-	85 -105	$1.0\ 10^{-11}$ - 1.5×10^{-11}
16	Fish muscles	0.05 - 0.30	30	8.1×10^{-11} - 3.4×10^{-10}
17	Garlic	0.2-1.6	22-58	1.1×10^{-11} - 2.0×10^{-10}
18	Garlic	0.06-1.89	40-70	1.3×10^{-10} – 3.2×10^{-9}
19	Grain (sorghum)	0.021	55	2.8×10^{-11}
20	Glucose	0.08 - 1.50	30 - 70	4.5×10^{-12} - 6.5×10^{-10}
21	Lentil	0.1-0.2	30-50	2.8×10^{-11} - 2.8×10^{-9}
22	Milk (dry)	0.13	25	2.1×10^{-11}
23	Muffin	0.10 - 0.95	20 -100	8.5×10^{-10} - 1.6×10^{-7}
24	Onion	0.05-18.7	60-80	2.3×10^{-10} - 6.6×10^{-9}
25	Cauliflower	11.5 - 0.05	60-90	2.54×10^{-12} - 3.8×10^{-12}
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Note: Source: Jangam et al., (2010).

3 Appraisal of solar dryers

Various researchers have systematically classified solar dryers (Fudholiet al., 2010; Belessiotis and Delyannis, 2011). Murthy (2009) reviewed a variety of aspects of solar dryers applied to drying of food products at small scale and the popular types of dryers found in the Asia-Pacific region and new types of dryers with improved technologies were discussed. The concert evaluation of the dryer was discussed in detail and it was found that there is a shorter way of estimating the performance of a dryer. Sharma et al. (1995) offered an experimental investigation of three different types of solar dryers based on the principle of natural, forced convection and mixed mode of heat transfer. The efforts were made to select the most appropriate design to be used on a household, farm or on an industrial scale (Sharma et al., 1995). Different types of active air type solar collectors were examined by Henriksson and Gustafsson (1986), for two main applications namely drying of agricultural crops and heating of animal houses. It was found that there are benefits if the solar collector is integrated in to the building and the types of dryers which have been tested have the potential to compete economically with oil as a heat source. Suspended-plate solar air heaters were installed on farms in Tennessee to supply heat for grain and crop drying. The heaters were telemetrically monitored by Womac et al. (1985) to determine thermal performance and to allow succeeding analyses of economic feasibility. Results of the thermal analysis revealed that solar air heaters will successfully provide a suitable air temperature rise during most crop drying conditions. Tiwari et al. (1994) have presented energy balance equations for solar crop dryer with shallow bed under passive mode. A reflector placed over the wall of the chimney. It was observed that drying time is significantly reduced due to increase in thermal energy on the collector by the reflector.

4.1 Direct mode solar dryer

A direct-type natural convection solar dryer and a simple biomass burner were combined by Bena and Fuller (2002). It is demonstrated to drying fruits and vegetables in rural area. A direct type natural convection solar dryer was designed, constructed using local materials (wood, blades of glass, and metals) and then tested experimentally in foodstuffs drying (cassava, bananas, and mango) by Gbaha et al (2007). The behavior of the dryer and its analysis have taken done based on its experimentation as shown in Figure 1.

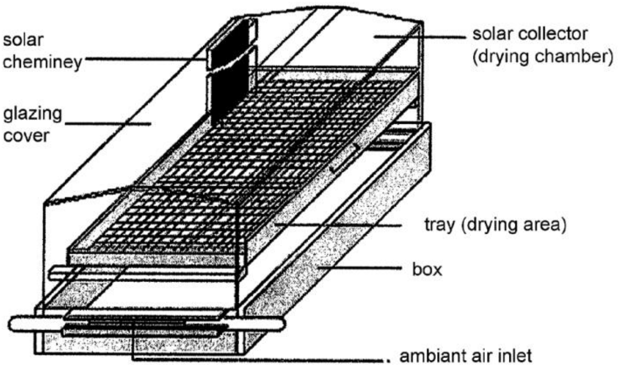

Figure 1 Direct Solar Dryer (Gbaha et al., 2007)

From last two decade, researchers have done analysis and used greenhouse as dryer for low and medium drying in large scale (Kumar and Tiwari, 2006a; 2006c; 2007; Jain and Tiwari, 2004). Prakash and Kumar (2014a) have reviewed various existing greenhouse dryers. Kumar et al (2006) have reviewed various applicationof greenhouse. In order to effectively utilise greenhouse dryer, researchers have conducted experimentation in no-load conditions for greenhouse dryer under both natural and forced convection mode (Kumar et al., 2013; Prakash and Kumar, 2013b; 2014c; 2014d; 2014e; Barnwal and Tiwari, 2008). Researchers have also reviewed the various state of art applications0of greenhouse as dryers and others [41-42].

Greenhouse dryer minimizes the shortcomings of the cabinet dryer such as capacity of full load operation, expenditure, and moisture condensation under the glass surface. It is a direct solar dryer. Several researchers have made an attempt to minimize the various losses and enhance the drying rate [43-45]. The design of greenhouse depends upon the latitude of the place and the requirement of crop. Greenhouse dryer is operated in either active or passive mode as shown in Figure 2 and Figure 3.

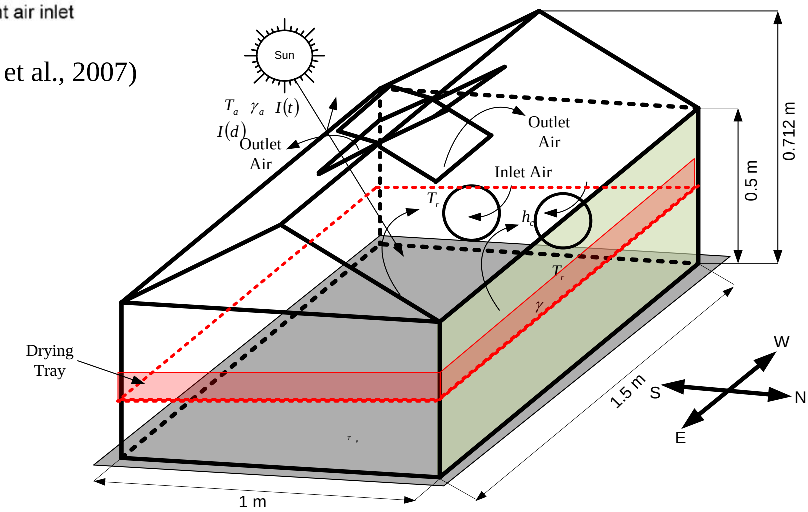

Figure 2 Greenhouse dryer under passive mode (Prakash and Kumar, 2014)

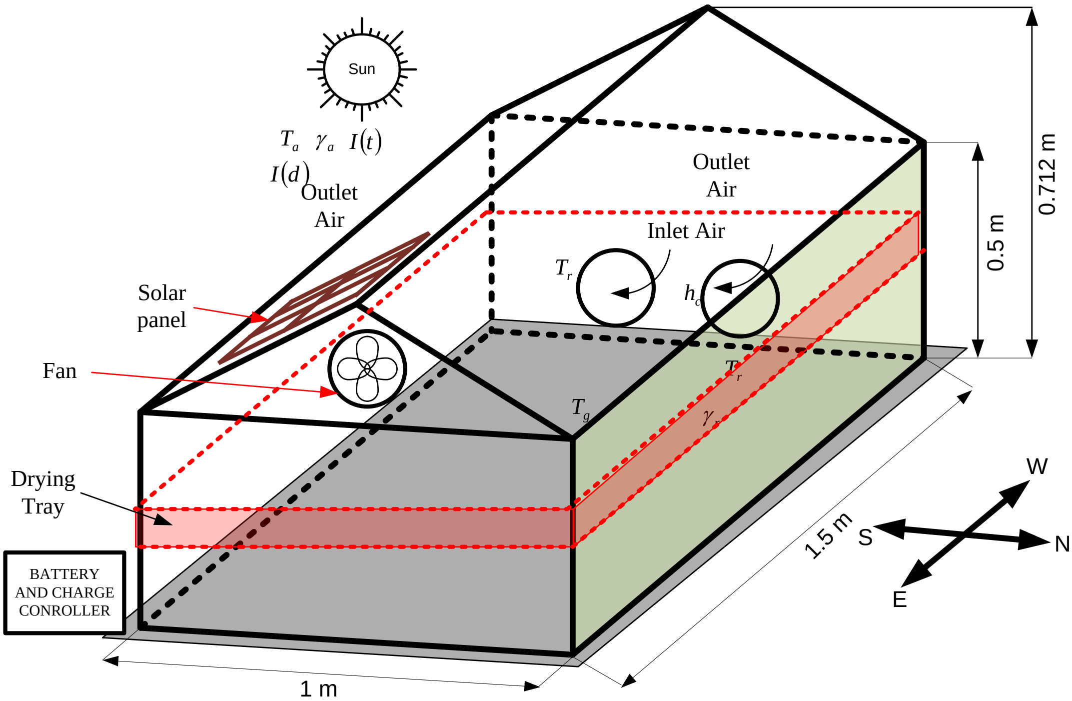

Figure 3 Greenhouse dryer under active mode (Prakash and Kumar, 2014)

A study of convective mass transfer coefficient and rate of moisture removal from cabbage and peas under open sun and greenhouse drying was performed by Jain and Tiwari. The convective mass transfer coefficient was found to be lower for greenhouse drying under natural convection mode as compared to open sun drying. And its value was doubled under the forced mode of greenhouse drying compared to natural convection mode in the initial stage of drying [46]. The study of drying of red pepper in open sun and greenhouse drying at constant laboratory conditions were carried out by Kooli et al (2007). The greenhouse drying were conducted in the wind tunnel and 1000W lamp was used as substitute of sun.Jain presented a transient analytical model to study the application of a greenhouse with packed bed thermal storage to crop drying. The proposed model is tested to dry onion (Jain, 2005). Janjai et al. (2009) presented the experimental and simulated performance of a PV-ventilated solar greenhouse dryer for drying of peeled longan and banana. A system of partial differential equations describing heat and moisture transfer during drying of peeled longan and banana in the solar greenhouse dryer was developed and this system of non-linear partial differential equations was solved numerically using the (FEM) finite difference method.

A transient analysis of a cabinet-type solar dryer was carried out by Dutta et al.(1988) with simplified but practical assumptions and the model predicts the instantaneous temperatures inside the dryer, the moisture content and the drying rates. The analysis was done for no load, and for loads ranging from 10 kg to 40 kg of drying product. The reverse flat-plate absorber is a non-concentrating collector, which can collect solar energy at elevated temperature. The concept of a reverse flat plate collector was used by Goyal and Tiwari (1999) as a heating medium of air for drying agricultural products in a cabinet dryer. The cabinet dryer is mounted on top of the absorber maintaining a gap of 0.03 m for air to flow above the absorber. The incoming air will be heated and enters the dryer from the bottom. The thermal performance of reverse flat-plate absorber dryer was evaluated by solving the various energy balance equations and compared with that of a conventional cabinet dryer. It was found that the reverse flat-plate absorber dryer gave the better performance. Evaluation performance studies of solar cabinet dryer were reported by (Mojolo, 1987; Ampratwum and Dorvlo, 1998; Minka, 1986). Sharma et al. (1990) and Mursalim et al.(2002) evaluated a modified cabinet dryer with natural convection system. The dryer is with a single transparent plastic cover and sawdust was used the insulator. The drying chambers walls was build of plywood painted black with dimensions 120 cm × 80 cm × 40 cm. For airflow, 12 holes were providing with 1 inch pipe at the bottom.

Low cost solar tunnel dryer was kept in an east-west direction to make the solar radiation incident more efficient. The main purpose of this dryer to provide protection from dust, beast, rain, wind and reduce the drying time as compared to open sun drying (Elicin and Sacilik, 2005). Usub et al. (2008) studied an experimental analysis to survey the performance of a mixed-mode type forced convection solar tunnel dryer, which was used to dry silkworm pupae under tropical weather conditions of Mahasarakham, Thailand. Hossain and Bala (2007) developed a multi-function solar tunnel dryer. It can be used to 80 kg of fresh chilies. It reduces the dying time in comparison to natural drying and enhances the quality of dried product. The inside temperature is raised by about 22^{o}C above the ambient temperature.

A large scale integral type natural-circulation solar-energy crop dryer suitable to use in the tropics was presented by Ekechukwu and Norton (1998). In the wet atmospheric season is not all suitable for drying due to lack predictable nature of atmosphere. The integral-type natural-flow solar crop dryer was simulated by Onyegegbu et al. (1994). In this simulation, it includes the effects of varying ambient conditions of air temperature and humidity and diffuses and beam components of solar radiation. Study revealed that operating the dryer at conditions of minimum entropy generation yields a useful criterion for choosing dryer dimensions and is compatible with the desire to maintain allowable limits on crop temperature. An inexpensive integrated solar collector cum storage system using rocks as a sensible heat storage medium was designed and made-up to provide low grade heat (Sharma et al., 1991). It is used to provide heat to enhance drying.

Ferreira et al. (2008) studied the feasibility of a solar chimney in solar dryer to dry agricultural products. Theoretical and experimental study proofs its practical applicability in the field of drying. Das and Kumar (1989) proposed a low cost solar dryer along with a vertical flat plate collector chimney was tested for drying of post harvested high moisture paddy. The experiment was conducted during the winter season and study reveals that the average increase in the air temperature of 20.8^{o}C and 27.1^{o}C for the inclined and the vertical collectors, respectively as compared to ambient temperature.

4.2 Indirect mode solar dryer

An indirect type natural convection based solar dryer with integrated collector-storage and biomass-support heaters was developed and evaluated by Madhlopa and Ngwalo (2007). The proposed dryer was constructed with locally available material and operated in the three modes of drying: solar, biomass, and solar–biomass. It is tested to dry twelve batches of fresh pineapple (Ananas comosus), with each batch weighing about 20 kg. Results showed that the thermal mass was capable of storing part of the absorbed solar energy and heat from the burner. Sami et al., (2011) have developed mathematical model for the indirect solar dryer and it is validated with the experimental result. The schematic diagram is presented in Figure 4.

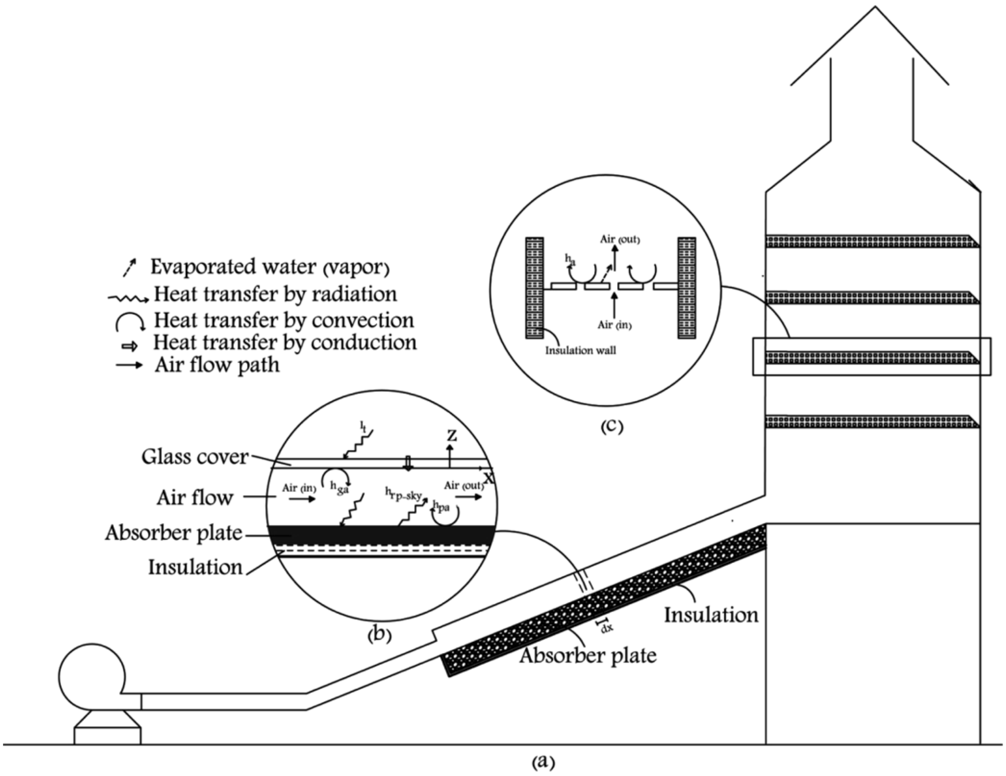

Figure 4 Indirect Solar Dryer (Sami et al., 2011)

Sharma et al. (1993) described the design and performance of an indirect type solar fruit and vegetable dryer developed and the experimental results suggested that even under unfavourable weather conditions, the unit is capable to produce good quality products and low investment required. This solar dryer is applicable for small farm. The performance of indirect passive solar dryers tends to be rather poor because of the low air flow rates which occur through such dryers. Two ways to improve the performance of such dryers are either to use the waste fuel to increase the buoyancy forces by heating the air in a chimney attached or to optimize the gap between the transparent cover and absorber plate of air heating collector. Bassey et al.(1994) presented the results of an experimental study in which the effects of heating the air in a chimney fitted to the dryer and the effects of varying the collector gap on the dryer performance were measured and the results indicated that the performance of the dryer can be improved if temperatures in the chimneys are maintained over 50°C above the ambient for more than 4 h and if the chimney is at least 2 m high and the mean drying rates in the dryer can also be improved by reducing the collector air gap height which should not be greater than 4 cm.

Singh et al. (2004) developed a solar dryer, which has a multi-shelf design with midway heating, passive, integral, direct/indirect and portable solar dryer, to enable farmers to add value to their produce by drying it at the farm itself and can also be used in cottage industries in remote places, with a novel feature of drying the product under shade or otherwise as per requirement. To overcome the problem of reduction in efficiency on second and third drying day, a semi-continuous mode of loading was investigated. So efficiency remains constant during drying period. The development and testing of a new type of efficient solar dryer, with two compartments: one for collecting solar radiation and producing thermal energy and the other for spreading the product to be dried, particularly meant for drying vegetables and fruit, was described by Sreekumar et al. (2008). A detailed performance analysis was done by three methods, namely ‘annualized cost method’, ‘present worth of annual savings’, and ‘present worth of increasing savings’ and the drying cost for 1 kg of bitter gourd was calculated as

Rs. 17.52, whereas it was Rs. 41.35, in the case of an electric dryer.

The double-pass solar collector with absorbent media in the lower channel provides a higher outlet temperature as compared to single-pass collector and leads to higher thermal efficiency. A experimental and theoretical model of double-pass solar collector was designed and developed by Sopian et al..(2009). Study reveals that due to absorbent porous media, thermal efficiency of the collector increases because of high outlet temperature. Jain and Jain (2004) presented a passing analytical model for an inclined multi-pass solar air heater with in-built thermal storage and attached with the deep-bed dryer and evaluated the performance of this for drying the paddy crop. It was observed that the bed moisture content decreases with the time of the day and relative humidity of air and the drying rate increases with the increase in the depth of drying bed.

A new solar dryer, which consisted of a solar air heater and a drying chamber, was developed by Tiris et al. (1996), for drying food products. It was shown that the use of this type of solar dryer reduced the drying time considerably and essentially provided better product quality. Industrial drying can be demonstrated to cost effective if solar thermal energy storage system is incorporate with basic solar dryer. Therefore, drying system can be worked during off sunshine periods

A simple system of such type was evolved by Khanna and Singh (1967), where a reservoir of water and heat exchanger were integrated into the drying system. Solar heat collection and its storage were affected by thermo-siphon action with water and depending on the mode of heat transfer, viz. natural or forced convection. This system can be used either for space heating or indoor industrial drying. A multi-purpose low cost and simple solar crop dryer, consisting of a small fan, solar air heater and a tunnel, was design and developed by Lutz et al.(1987), for drying various agricultural products. The solar dryer was successfully tested in Greece, Yugoslavia, Egypt, Ethiopia, and Saudi Arabia drying grapes, dates, onions, peppers, and several medicinal plants.

4.3 Mixed mode solar dryer

A mathematical model, consisting of the air-heating process model, drying model and scientific performance criteria model, for drying agricultural products in a mixed-mode natural-convection solar crop dryer using a single- pass double-duct solar air-heater was presented by Forson et al. (2007). The governing equations of the air drying temperature, humidity ratio, crop temperature and its moisture content, and performance criteria indicators were derived. Results of simulation runs using the model were presented and compared with the experimental data and it was shown that the model can predict the performance of the quite accurately. Singh and Kumar (2011) have developed and tested the mixed mode solar dryer as shown in Figure 5.

Figure 5 Mixed mode solar dryer (Singh and Kumar, 2011).

A mixed mode natural-convection based solar crop dryer designed and used for drying cassava and other crops in an enclosed structure was presented by Forson et al (2007). A prototype of the proposed dryer was constructed and used in experimental drying. A mathematical model—air-heating process, drying, technical performance criteria— for in a mixed-mode natural-convection solar crop dryer using a single-pass double-duct solar air-heater presented by Forson et al. (2007) The governing equations of the drying air temperature and humidity ratio, the crop temperature and its moisture content, and performance criteria indicators were derived. Results of simulation were presented and compared with the experimental data. It was shown that the model can predict the performance of the properly and therefore can be used as a design tool for prototype development.

Ahmad (2001) proposed a simple solar air heater, which is covered by cheap plastic film with air bubbles. It is used for various drying operations on a farm (grain, fruit, fish, etc.). A considerable raise in the inside temperature (10°C) of the airflow was obtained.

The development of solar heated drying kilns in recent decades shows that there have been a series of modifications to optimize their drying and thermal efficiency. Luna et al.(2009), have presented various dryer and its components for solar heated drying kilns focusing on changing trends in industrial systems. Based on this analysis, some future adaptations were suggested.

5 Solar drying system with heat storage

A thin layer drying bed coupled with water heater dryer was proposed and analyzed by Tiwari et al. (1997), for making the whole system operate throughout the year. The system can be used to provide hot water when the drying system is not in use. The water heater which is below the air heater would act as a storage material for drying the crop during off sunshine hours. A prototype solar fruit and vegetable dryer was developed by Akyurt and Selcuk (1973). It consists of a glass covered flat plate collector containing metal chips, a dryer with transparent walls, and an insulated tunnel, joining the two. Bell peppers and sultana grapes were dried to commercially acceptable moisture levels in various kinds of weather conditions and at various air velocities. An economic analysis was undertaken to examine the possibility of using various heat sources as a secondary heating system, which when integrated with the prototype, will enable all-weather operation.

6 Desiccant based drying systems for night operation

An indirect forced convection solar dryer with integrated desiccants was built and tested by Shanmugam and Natarajan (2007). The system was operated in two modes— sunshine hours and off sunshine hours. The drying experiments were conducted with and without the integration of desiccant unit. The effect of a deep mirror on the drying potential of the desiccant unit was also tested. The study showed that the use of reflective mirror on the desiccant bed causes faster renewal of the desiccant material. An indirect forced convection and desiccant integrated solar dryer, consisting of a flat-plate solar air collector, drying chamber and a desiccant unit, was designed and fictitious by Shanmugam and Natarajan (2006) to investigate its performance under the hot and humid climatic conditions of Chennai, India, with green peas. An adsorption unit of silica gel was designed by Hodali and Bougard (2001) to integrated in a crop solar dryer. It consists of a direct flat-plate forced convective solar dryer connected in similar to solar air collector. It is numerically selected and applied for the drying of apricots in Morocco under real climatic conditions. Result revealed that it has improved the quality of dried product and reduced the drying by 44-52 h as compared to open sun drying.

6 Solar drying system for various agriculture produces

The optimum method for using a solar air collector joint coupled with a grain drying system was investigated by Radajewski et al (1987). It is of two types of solar collectors: uncovered and covered. A computer model was built-up to minimize the cost of drying and optimize the geometry of the collector.

Sarsilmaz et al (2000)., investigated the drying of apricots in a newly developed rotary column cylindrical dryer (RCCD) equipped with a particularly designed air solar collector (ASC) to find the optimum drying air rate and rotation speed of the dryer and to preserve uniform and hygienic drying conditions and also minimize the duration of drying. A hybrid solar dryer was designed and constructed using direct solar energy and a heat exchanger by Amer et al. The efficiency of the solar dryer was raised by 65% and was tested for drying of ripe banana slices. Field level experiments on solar drying of pineapple using solar tunnel dryer were conducted at Bangladesh Agricultural University, Mymen singh, Bangladesh by Bala et al (2003). The pineapples dried in the solar tunnel dryer were completely protected from rain, insects and dust, and its quality as comparable to sun dried products. The proximate analysis was also indicated that the pineapple dried in the solar tunnel dryer was of a quality suitable for human consumption.

6.1 Grape drying

Barnwal and Tiwari (2008) studied to dry grape by using hybrid photovoltaic–thermal (PVT) greenhouse dryer. The hybrid PVT integrated greenhouse dryer has been developed having floor area of 2.50 m ×2.60 m, 1.80 m central height and 1.05 m side walls height from ground and 30^o roof slope. The greenhouse dryer has been integrated with two PV modules on south roof of the dryer. The PV module produces DC electrical power to operate a DC fan for forced mode operation. The air moves from bottom to top through three-tier system of perforated wire mesh trays. The UV stabilized polyethylene sheet has been fitted over the structural frame of the dryer. Pangavhane and Sawhney (2002a) have reviewed solar dryers for grape drying. Pangavhane et al. (2002b) developed a multipurpose natural convection solar dryer. They reported that the drying airflow rate increased with increase in ambient temperature by the thermal buoyancy in the collector. Grapes is to used to dry in the proposed system and it save the drying time significantly and produced better quality of product.

6.2 Onion drying

The natural and greenhouse drying of onion flakes was performed by Kumar and Tiwari (2007), to study the effect of different mass on convective mass transfer coefficient. It is observed that there is significant effect of mass on convective mass transfer coefficient under both mode of drying. The rate of moisture removal in case of greenhouse drying is more than that open sun drying during the off-sunshine hours due to the stored energy inside the greenhouse. El-Sebali et al. (2002) reported that moisture content (M_t) decreases from its initial value M_o (85%) to 57% and M_t (6%) after 48 h and 32 h for the full size and cut samples, respectively, under the same conditions of the chemically treated onions.

6.3 Potato type solar dryers

The determination of temperature dependent drying parameters namely drying constant, lag factor from drying kinetic curves of food product was proposed by Tripathy and Kumar (2008), using a laboratory scale mixed-mode solar dryer. It consists of an inclined flat-plate solar collector connected in series to a drying chamber glazed at the top to perform natural convection drying experiments with potato cylinders. The thin-layer drying equation describing the drying behavior of food products is derived from Fick's law of diffusion. The analysis exposed that both drying constant and lag factor increase with sample temperature. The application of artificial neural networks (ANN) for prediction of temperature variation of food products solar drying was investigated by Tripathy and Kumar. Data on potato cylinders and slices obtained with mixed mode solar dryer for 9 typical days of different months of the year were used for training and testing the neural network.

6.4 Mango dryer

Madhlopa et al. (2002) reported that sliced fresh mangoes having an initial moisture content of 85% can be dried at 31.7^{o}C–40.1 ^{o}C for 20 h to a final moisture content of 13% in an indirect type natural convection solar dryer. It was found that the dryer was suitable for conservation of mangoes and other fresh foods. Toure and Nkembo (2004) reported that mango having an initial moisture content of 84 % can be dried with maximum temperature allowable at 40.8^{o}C for 15 h to final moisture content of 27.6% in type of natural convection solar dryer.

6.5 Copra solar dryer

A forced convection solar drier designed, fabricated and tested to dry copra by Mohanraj and Chandrasekar (2008). They reported that the drying methodology is more suitable for producing high quality copra for small holders. About 75% of high quality copra could be produced by the proposed dryer. Drying of copra in the drier reduced its moisture content from about 52% to 8% and 10% in 82 h for trays at the bottom and top, respectively. The maximum drying air temperature recorded during peak sunshine hours was 63^{o}C. The average temperature reduced to 31^{o}C outside the hours of sunshine and during the night.

6.6 Tomato type solar dryers:

El-Sebali et al. (2002) reported that moisture content (M_t) decreases from its initial value M_o (95%) to 85% and M_t (7%) after 36 h and 28 h for the full size and cut samples, respectively, under the same conditions of an indirect type natural convection solar dryer. Movagharnejad and Nikzad (2007) have studied on drying of tomatoes at different variables—heater power, air velocity. The experimental results were modeled by ANN and other standard analytical drying models like Page, Newton, Henderson and Pabis etc. Result revealed that ANN model predict the moisture ratio more accurately than other mathematical models.

6.7 Banana solar dryers

Smitabhindu et al. (2008) performed simulation and optimization of solar assisted drying system for drying bananas. The simulation model was validated by comparing with experimental results. The optimum values of the collector area and recycle factor were found to be 26 m^2 and 90% respectively with a minimum drying cost of 0.225 USD per kg.

6.8 Apple solar dryer:

Elicin and Sacilik et al. (2005) has been developed a solar tunnel dryer capable of dehydration of the apples. The proposed drying set up saves 4 h of drying period as compared to open sun drying to reduce the moisture content from 82% to 11%.The apple dried in the solar tunnel drier was completely protected from rain, insects, dust, bird, and the dried apple was a high quality in terms color and hygienic.

6.9 Jaggery solar dryer:

Kumar and Tiwari (2006a, 2006b, 2007) have proposed the thermal modeling of the drying behavior of jaggery in the roof-even type greenhouse dryer under natural and forced convection. Model is validated by the experimental result. Study revealed that result predicted by the modeling is in good agreement with the experimental result. Prakash and Kumar (2013, 2014) have presented the ANN and Adaptive neuro fuzzy inference system (ANFIS) model for the drying of jaggery in the greenhouse dryer under passive model. Model was validated with experimental result.

7 Other vegetables drying

An indirect type natural convection locally made solar dryer, was investigated experimentally and theoretically by El-Sabaii et al. (2002), for the drying of fruits and vegetables such as seedless grapes, figs, green peas, tomatoes and onions. Linear correlations between drying constants and drying product temperature were found to satisfactorily describe the drying curves of the materials under study. The characteristics constants c and n of Henderson’s equation were resolute for the selected crops and a simple mathematical model was presented for the drying chamber based on the energy and mass balance equations. An experimental study was performed by Sacilik (2007) to determine the drying characteristics of hull-less seed pumpkin in solar tunnel dryer and natural drying. It was found that among the various models (Page, Henderson and Pabis, logarithmic and two-term models) tested to interpret the drying behavior of hull-less seed pumpkin, one was selected which presented best numerical indicators.

8 Heat and mass transfer and drying characteristic model for solar greenhouse drying system

8.1 Analysis of heat and mass transfer for solar Greenhouse Drying System

Prakash and Kumar have done heat transfer analysis of the modified greenhouse dryer under active mode in no-load conditions(2014d).

(i)Evaluation of convective heat and mass transfer coefficient

The convective transfer coefficient (h_c) under active mode is calculated as Equation 1

$h_c=(K`\times C`(Re.Pr)^n)/X`$

$Nu=C`(Re.Pr)^{n`}$ (1)

By taking logarithm on both side of equation then Equation 1 can be written as Equation 2

$\ln(Nu)=\ln(C`)+n`\ln(Re.Pr)$ (2)

This is in the form of a linear straight line Equation 3

$y=mx+c$ (3)

Here Equation 4 and Equation 5

$y=\ln(Nu)$ and $x=\ln(Re.Pr)$ (4)

with $m=n`$ and $c=\ln(C)$ gives $C=e^c$ (5)

From Equation 5, the value of 'C' and 'n' is evaluated by the help of simple regression analysis.

$h_e=0.013h_c$[107]

Where h_e is the evaporative loss.

(ii) Evaluation of instantaneous efficiency loss factor

Here the heat loss through canopy is very small, hence it can be ignored. The instantaneous efficiency loss factor is calculated directly through outlet of the dryer. This can be calculated as Equation 6

$\eta`=(0.33N\,V_e\,(T`_r-T`_a))/(I(t)A`)$ (6)

(iii)Evaluation of electrical efficiency

The Equivalent thermal efficiency of PV solar cell is evaluated as Equation 7

$\eta_{ete}=((0.8IV)/(A_cI_p*0.38))\times 100$ (7)

And Electrical load efficiency is evaluated as Equation 8

$\eta_{ele}=((I`_{lf}V`_{lf})/(A_cI_p))\times 100$ (8)

(iv) Determination of the rate of ventilation/infiltration

The rate of ventilation or infiltration losses from the outlet of the greenhouse dryer is evaluated as Equation 9

$Q`_{loss}=0.33NV_g\,(T`_r-T`_a)$ (9)

(v) Calculation of number of air exchange per hour

The calculation of number of air exchange per hour from the dryer through the ventilation is calculated as Equation 10

N= $(V_o\times A_c/V_g)\times 3600$ (10)

8.2 Drying characteristic model for solar drying system

In order to evaluate the evaluate the drying performance of the crop dried in solar dryers; various researchers have proposed mathematical models (Movagharnejad and Nikzad, 2007). Seven different such models are presented in Table 2.

Table2Various types of mathematical models tested on tomato (Movagharnejad and Nikzad, 2007)

S. No	Model No	Name of Model	Equation of Moisture Ratio
1	1	Newton	exp(-kt)
2	2	Henderson and Pabis	a*exp(-kt)
3	3	Page	exp(-kt^n)
4	4	Logarithmic	a*exp(-kt)+c
5	5	Two-Term	a*exp(-k$_o$t)+b* exp(-k$_1$t)
6	6	Wang and Singh	1+at+bt^2
7	7	Modified Henderson and Pabis	a*exp(-kt)+b* exp(-g*t) +c* exp(-h*t)

These models describe the natural drying behavior of the crop. The moisture ratio of the crop is calculated as Equation 11

$$MR=\frac{M_i-M_{emc}}{M_o-M_{emc}} \qquad (11)$$

9 Conclusions

Solar dryers like natural convection and forced convection dryers, direct and indirect type dryers, integral dryers, greenhouse dryers, cabinet dryers, tunnel dryers, mixed mode dryers are reviewed with respect to their design, development and performance. Special attention is given to the heat transfer models, drying characteristic solar drying technologies, which facilitate the drying of crops in the off-sunshine hours. A desiccant based solar drying system was one such technology briefly discussed. Solar dryers designed specifically for a particular crop like grain dryers, grapes dryer, onion dryers, potato dryers, etc. were reviewed with their design, performance evaluation and the results of simulation of the systems.

This paper are also present some easy-to-fabricate andeasy-to-operate dryers that can be suitably employed at small-scale factories or at rural farming villages. Such low-cost food drying technologies can be readily introduced in rural areas of developing and developed country to reduce spoilage, improve product quality and overall processing hygiene. In addition, at the same time conserve the crude oil and precious conventional fuels and protect the degradation of the environment.

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Notation

A= Area of solar cell (m^2)

A_c= Cross sectional area of the ventilator (m^2)

C`=Constant

h_c=Convective heat transfer coefficient of the air ($W/m^{2o}C$)

I_p=Global solar radiation on the solar cell (W/m^2)

I_s= Short current for the solar cell (A)

I`(t)= Solar intensity inside the modified active greenhouse dryer (W/m^2)

$I`_{Lf}$=Load current of exhaust fan (A)

K`=Characteristic dimension of the modified greenhouse dryer

M_i= Instantaneous moisture content

M_o =Initial moisture content

M_{emc} = Equilibrium moisture content

n`= Constant

Nu= Nusselt Number

N= Number of air exchange per hour

Pr=Prandtl number

Re= Reynolds number

$T`_r$= Temperature inside the modified greenhouse dryer (^oC)

$T`_a$= Ambient temperature (^oC)

V_e=Velocity of exhaust air (m/s)

V_g= Inside volume of the greenhouse dryer (m^3)

V_{Lf}= Load voltage of the exhaust fan (V)

V_o= Open circuit voltage of the solar cell (V)

X= Characteristic constant