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A Review of Solar Dryer Technologies

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Abstract- *Drying* is very important process applicable for agricultural and industrial products. Drying is the moisture removing process from the products. Drying reduces the bacterial growth in the products. It will helpful for preserving the products for long time. Solar drying is the oldest method of products drying. Open air solar drying method is used frequently to dry the agricultural products. But this method has some disadvantages. Therefore to avoid disadvantages it is necessary to use the other solar drying methods. Different solar drying methods are direct solar drying, indirect solar drying, and mixed mode solar drying. The device used for drying process with application of solar energy called the Solar dryer. Solar dryer are also classified with mode of air circulation. In this paper, we studied the various modes of solar drying and classification of solar drying techniques.

Index Terms -Solar drying technologies, Natural circulation solar dryers, Forced circulation solar dryers, Green house dryer, Solar tunnel dryer.

1. INTRODUCTION

Drying is a simple process of removing excess water content from an agricultural or industrial product [36]. It is oldest method of food preservation. Most of the agricultural products contain the higher moisture of 25–80% but generally for agricultural products around 70%. This value of moisture content is very much higher than the required for long preservation. Due to this moisture content bacterial and fungal growth is very fast in the crops. Bacteria and enzymes may spoil the foodstuff and reduces the nutrient content in it. Moisture content of crops to a certain level slows down the bacterial, enzymes, and yeasts effect [36]. Therefore it is necessary to reduce the moisture content in foodstuff for its long preservation. Another case of drying is to remove the total moisture content from food. These dehydrated foods regain its original conditions after re-watering whenever necessary to use.

Using solar drying technologies are very much advantages than using fossil fuels for product drying. Most beautiful advantage is pollution free method and reducing emission of carbon particles in atmosphere. Solar drying technologies are broadly classified in to three modes direct solar drying, indirect solar drying and mixed mode solar drying [1, 7, 8, 21, 24, 27, 34, 36]. Solar dryer are the device used for product drying with proper application of solar energy. Solar dryers are classified by air movement in the drying chamber. It is generally classified according to natural circulation and forced circulation [7, 8, 10, 22, 36].

A. A. El-Sebaii et. al. presented a comprehensive review of Solar drying of agricultural products with detailed fundamentals and previous work performed on solar dryer (2011) [1]. Atul H Patel et. al. reviewed the different types of solar dryer with detailed development and performance (2013) [7]. Babagana Gutti et. al. presented how the solar dryer technology effective for agricultural products preservation and also discussed the various evaluation methods for solar dryers (2012) [8]. B. K. Bala and Nipa Debnath presented comprehensive review of solar dryer developments and potentials for drying of fruits, vegetables, spices, medicinal plants, and fish (2012) [10]. D. R. Pangavhave and R. L. Sawhney presented the review article of different solar drying technologies with detailed development and performance for grape drying (2002) [12]. O.V. Ekechukwua and B. Norton discussed the review of solar drying technologies for application of each design type for rural farmers in developing countries (1997) [27]. S. VijayaVenkataRaman et. al. presented comprehensive review of various solar drying technologies with design, development and performance evaluation also discussed the drying in off sunshine hours by using different desiccant materials (2012) [34]. V. Belessiotis and E. Delyannis presented comprehensive study of different solar drying technologies with fundamental principles and parameters (2010) [36].

2. METHODS OF SOLAR DRYING TECHNOLOGIES

2.1 Direct Solar Drying

Direct solar drying is the conventional way of drying the products. In this method the products are directly exposed to the solar radiation and reduce the moisture content to atmospheric air. The air movement is due to density difference. It is broadly classified into two categories:

(1) The outdoor open air solar drying.
(2) Through a transparent cover which protects partly the foodstuff from rain and other natural phenomena i.e. a passive solar drying method [36].

This technique involves the thin layer of product spread over large space to expose to solar radiation [36]. This process for a long time until the products will dry to a required level. The surface floor made from the concrete or particular area of soil is making applicable for Outdoor direct sun drying. This type of drying method is useful for grains. Material is led on outdoor floor for a long time, usually 10-30 days. It is easiest method product drying but it has following disadvantage [14, 20, 37];

(1) It depends on climate conditions and requires a large surface and long time of exposure to the sun.
(2) Final product condition is on observations of unskilled human being.
(3) Final condition of dried product will never control scientifically.
(4) Product may loss quantity wise on attack of birds, animals and rodents.
(5) Product may expose to all kinds of weather changes.
(6) Drying rate is very low for direct solar drying.
(7) The direct exposure to sunlight can greatly reduce the level of nutrients such as vitamins in the dried product.

2.2 Indirect Solar Drying

Indirect solar drying or convective solar drying is the new technique of product drying. It is very efficient method than the direct type of solar drying. In this method the atmospheric air is heated in flat plate collector or concentrated type solar collector. The heating process is either passive or active. This hot air then flow in the cabin where products are stored. Therefore moisture from the product may lost by convection and diffusion. This method of drying is used to avoid direct exposing to the solar radiation. This method mainly reduces the disadvantages of direct solar drying.

2.2.1 Advantages and Disadvantages of Indirect Solar Drying [36]:

(1) Drying rate is high as compare to direct solar drying.
(2) Final condition of product after drying can be controlled scientifically.
(3) Losses in product are avoided on the circumstances of natural phenomena.
(4) Floor surface area required is very low for the same quantity of material in direct solar drying.
(5) Same dryer can be used for different seasonal products.
(6) Preserve the nutrient content in product as avoiding direct exposure to solar radiations.
(7) Main disadvantage of indirect solar drying is the high initial cost.

2.3 Mixed Mode Solar Drying

It is combination of direct and indirect solar drying method. Product may dry with both direct exposure to solar radiation and hot air supplier on it. Air may heated in solar energy collector first then pass to the chamber where products are stored. In this process product may dry according to convective moisture loss. The same chamber is partially or totally covered with the transparent material to exposure the products to solar radiation. Fig.1 shows Schematic views of the mixed mode natural convection solar crop-dryer (MNCSCD). System is divided into three main components: an air-heater, drying chamber, and a chimney. Air-heater through which the drying air is heated as it flows over and under an absorber plate that is heated in turn by direct absorption of incident radiation. Crop to be dried is placed in drying chamber. The moist air flows through chimney and escapes into the surrounding. Mixed mode natural convection solar crop-dryer presented by F.K. Forson et. al.(2007). Solar energy is incident on the planes of the primary collector and the drying chamber. The governing equations were derived with respect of the drying air temperature, humidity ratio, product temperature and its moisture content [13]. O.V. Ekechukwu and B. Norton represent the various designs of mixed-mode natural-circulation and forced circulation solar dryers. Fig.2 shows various schematic views of mixed mode solar dryer.

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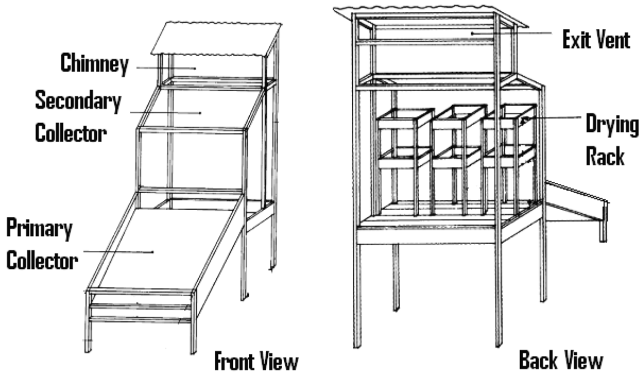
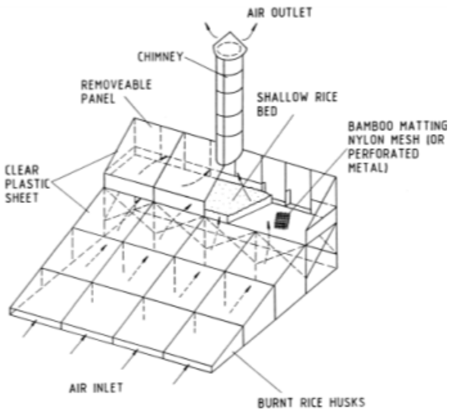
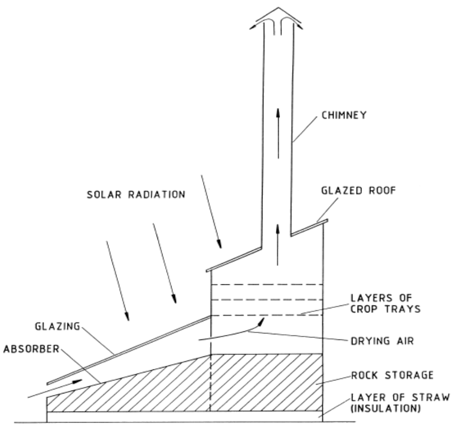


Fig.1. Schematic views of the Mixed Mode Natural Convection Solar Crop-Dryer (MNCSCD) [13].



(a)



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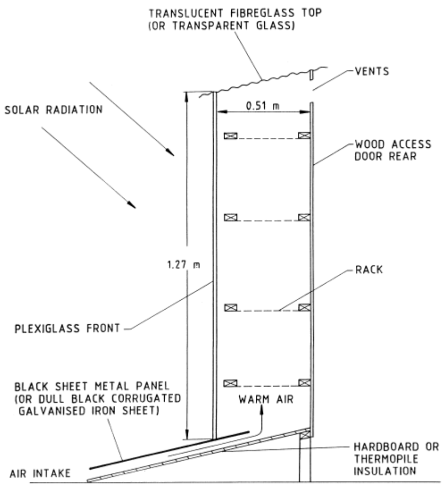

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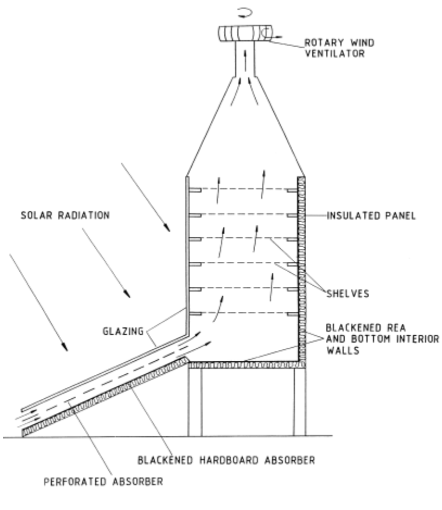


(d)

Fig.2 Schematic views of a Mixed-mode solar dryers a) Natural-circulation solar rice dryer; b) Natural-circulation solar-energy dryer with thermal storage; c) Multi-stacked natural-circulation solar-energy dryer; d) Wind-ventilated solar dryer [27].

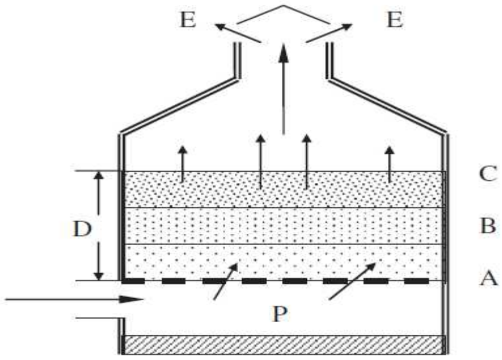


Fig.3 Deep bed drying zones of grains. D: bed height; P: plenum chamber; A: lower zone; B: middle zone; C: upper zone of grain and E: exhaust of humid air [36].

2.4 Thin Layer Drying and Deep Bed Drying

Drying rate mainly depend upon some factors, these are moisture content of product, temperature of air, velocity of air, relative humidity of surrounding air apart besides that the type and size of products also affect the drying rate. Therefore fruits vegetables are dried with thin layer and agricultural grains, beans, seeds, nuts etc. dried in deep bed. Fig. 3 shows three different zones of drying grains. Lower zone dried very rapidly than upper zones. The removed moisture content from lower zone accumulates in the upper zone. Therefore temperature and moisture content gradients form in the zones. The final moisture content is calculated as average moisture content of the three zones. This will limits bed height in the chamber [36].

3. SOLAR DRYER

Solar dryer is the simple devices used to collect the solar radiations and transfer that radiation in the form of heat energy and this heat energy then transfer to product for drying.

3.1 Classification of Solar Dryer

Solar dryers configure with many modes of heat transfer and construction. Therefore it is difficult to classify the solar dryer. Solar dryer are classify with drying process, mode of heat transfer, air movement, material to be dried, types of operation e.g., batch or continuous, etc. Ekechukwu and Norton (1999) present a complete classification according partly to the type of dryer. Babagana Gutti et. al. also represent the complete classification of solar dryer (2012). Solar dryer broadly classified by mode of air movement in the collector and drying chamber;

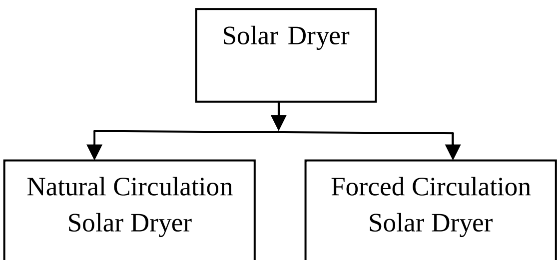


Fig. 4 Classification of Solar Dryer

3.2 Natural Circulation Solar Dryer

In natural circulation solar dryers the product are stored in the cabin or hot box units. Where heating method is either direct or indirect type depend on the final product quality. Heating takes place by natural convection, solar radiation through the transparent cover or in a solar air heater. The natural circulation type solar dryers are inexpensive in constructions, easy to install and operate.

3.2.1 Cabinet Type Natural Circulation Solar Dryer

D. R. Pangavhave and R. L. Sawhney (2002) represent the simplest cabinet type solar dryer shown in fig.5 a). This is a small box generally made from easily available wooden material. Front, Side and rear panel are provided with holes for circulation of air. The base of box is made from the wire mesh wooden trays [11, 26]. O.V. Ekechukwu and B. Norton (1999) represent the modified cabinet dryer shown in Fig.5 b). It equipped with a wooden plenum to guide the air inlet and a long plywood chimney to enhance natural-circulation [27].

A. Saleh and I. Badran were designed, developed and tested the domestic solar dryer with transparent external surfaces. Thin-layer drying method used to describe the drying phenomena regardless of the controlling mechanism. The experimental set up used to estimate the drying period for several products. The performance was tested under different operational conditions and the drying characteristics were experimentally investigated. Experiments were conducted on two local herbs, Jew's mallow and mint leaves. System was use the solar tracking mechanism [6]. A.R. Celma and F. Cuadros presents energy and exergy analyses of the drying process of olive mill wastewater (OMW) using an indirect type natural convection solar dryer are presented shown in Fig. 6. Using the first law of thermodynamics, energy analysis was carried out to estimate the amounts of energy gained from solar air heater and the ratio of energy utilization of the drying chamber. Also, applying the second law, exergy analysis was developed to determine the type and magnitude of exergy losses during the solar drying process. Two operating days' time was needed to make the final moisture content of OMW [5].

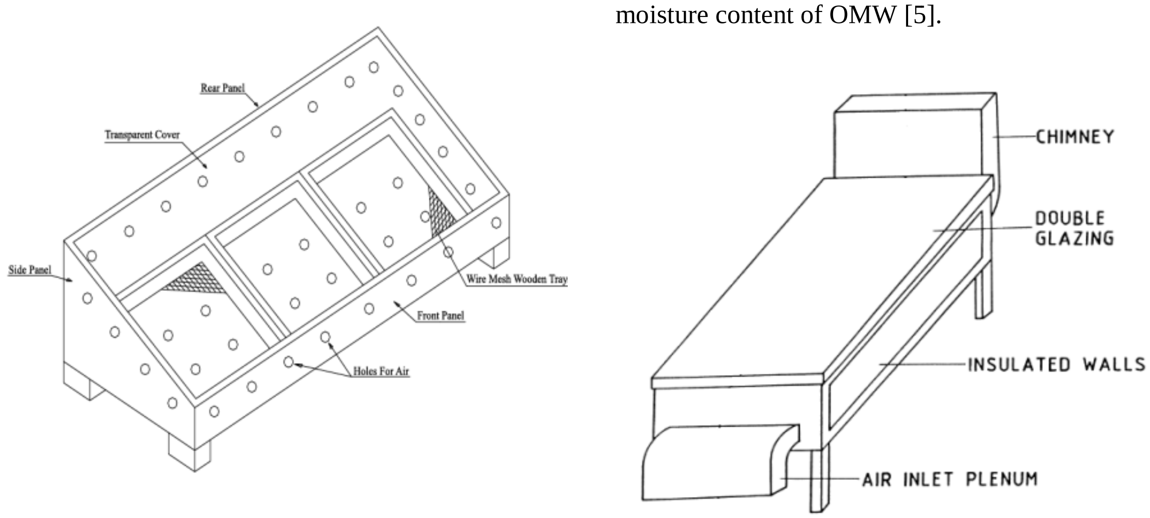
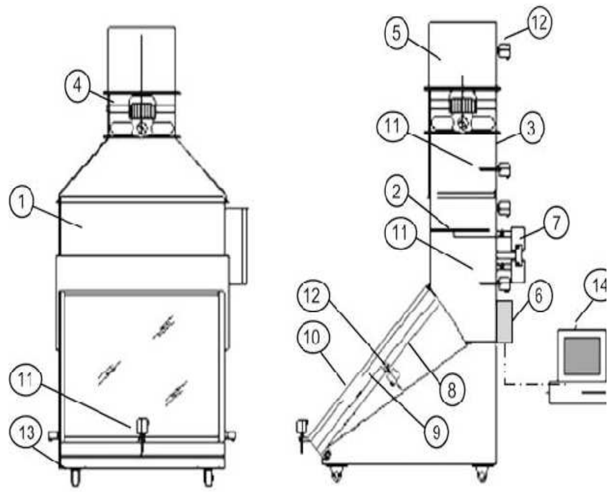


Fig.5 a) Simple design of Cabinet Solar Dryer [12]; b) Modified Cabinet Solar Dryer [27].



(1) Drying chamber
(2) Tray
(3) Load door
(4) Optional Fan
(5) Chimney
(6) Control panel and data transmission
(7) Load cell
(8) Polystyrene plate
(9) Black aluminium plate
(10) Cover
(11) Temperature and relative humidity sensors
(12) Flux controlling sensor
(13) Support wheel , (14) Computer

Fig.6 Experimental set up developed by A.R. Celma and F. Cuadros for olive mill wastewater (OMW) [5].

J.K. Afriyie et. al. (2009) tested chimney-dependent direct-mode solar crop dryer for different angles. For that a laboratory model of a direct-mode dryer was designed and constructed with three replaceable drying-chamber roofs, each at a different angle with respect to the vertical plane. Roof angles 810, 640 and 510 were used. The width of the drying chamber was 440 mm and the length was 420 mm. The total height of the chamber was 530 mm. The base of the chamber was made of wood (40 mm thick) with the top surface painted black to serve as absorber in the drying chamber. Such types of solar dryers are suitable for low humid air. For high humid air condition, it is necessary to provide certain amount of preheating to the air. The results showed that the solar chimney can increase the airflow rate of a direct-mode dryer especially when it is well designed with the appropriate angle of drying-chamber roof [21, 34].

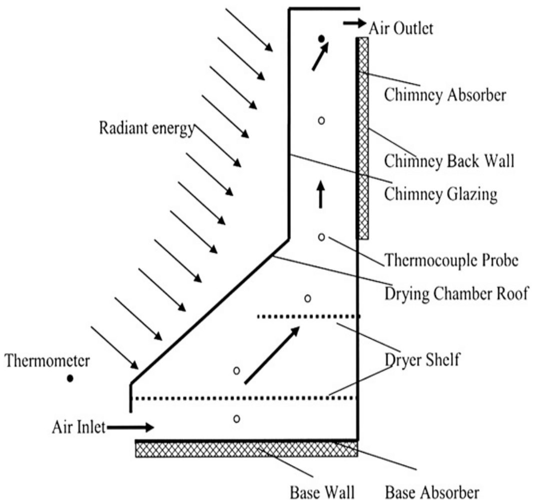


Fig.7 Functional architecture of the chimney-dependent direct-mode solar crop dryer [21].

3.2.2 Green House Type Natural Circulation Solar Dryer

Green house type solar dryers are used for large quantity products drying. Fig.8 a) shows the Glass roof green house type of solar dryer. Here cold atmospheric air passes from two side walls and circulate on the product. House consist of length wise two parallel rows of drying platforms made up of galvanized iron wire mesh surface. It was laid over wooden beams. Glass roofs allow passing solar radiation over the product. Side walls was black painted improves solar radiation absorption. Exit vent was provided on top most position. Fig.8 b) shows the tent type natural circulation solar dryer. It was made from locally available bamboo framework. Front side facing to the solar radiation and upper half portion of backside covered with transparent plastic cover. Back colored plastic covers the remaining bottom half portion of back side and also lies on the floor of tent to increase the solar radiation absorption. Small vent was providing at top of one triangular side of tent for air movement [27].

P. Gbaha et. al. (2006) develops direct mode type solar dryer with chimney. Fig.9 shows experimental set up. It was constructed from local materials (wood, blades of glass, metals). The drying chamber made up of dimensions 1.34 m x 0.936 m x0.45 m. The surface on which the product to be dried is exposed is 1.24 m x 0.81m dimensions and represents a drying area of 1m2. The solar chimney assembled on the cover of the drying chamber contains an absorber, velocity regulator of natural convective flow. The length of the solar chimney base is fixed at 0.20 m x 0.50 m high. It was tested experimentally in foodstuffs drying (cassava, bananas, and mango). Also presents an experimental approach which consists in analyzing the behavior of the dryer. The study relates mainly kinetics and establishment of drying heat balances [29].

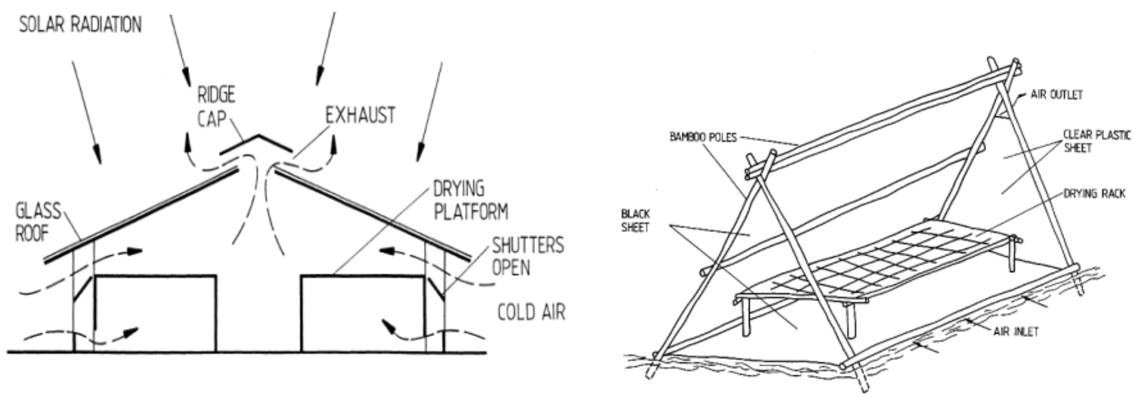


Fig.8 a) Glass roof green house type of solar dryer; b) Tent type natural circulation solar dryer [27].

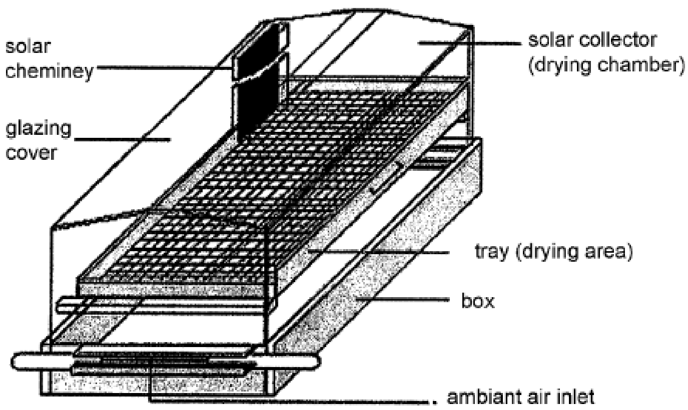


Fig.9 Direct solar dryer using a thermal circulator [29].

3.3 Forced Circulation Cabinet Solar Dryer

3.3.1 Cabinet Type Forced Circulation Solar Dryer

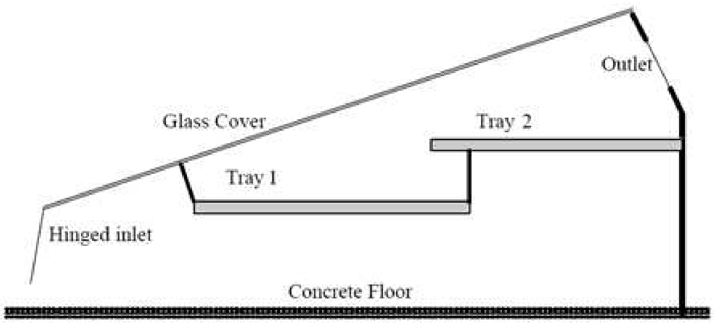


Fig.10 Schematic view of cabinet type forced circulation solar dryer [3].

Ahmad Ghazanfari (2002) develops a prototype forced circulation cabinet solar dryer shown in Fig.10 for pistachio nuts drying. The drying chamber was made up of dimensions with length of 170 cm; width of 210 cm; front height of the chamber is 30 cm and the back height of 65 cm. Four trays were used of sliding type of dimensions 80 cm x 70 cm x 10 cm. It was fitted in the chamber. The final moisture content of the nuts was 6.0%. This final moisture content reached in 36 sunshine hours [3].

Performance study was presented by Medugu, D. W. for two designs of solar dryers (chimney and cabinet). Both dryers were used to perform experimental test in drying 50kg of tomatoes, pepper and bitter leaves. Chimney provided at the top with DC fan and hole provided at the side of the system of cabinet solar dryer. Chimney type solar dryer gives reduced drying time than cabinet type [24].

3.3.2. Chamber type forced circulation solar dryer

Experimental study presented by Alireza Azimi et.al. (2012) on Eggplant drying with an Indirect forced convection solar dryer. Fig.11 shows schematic and pictorial views of solar dryer for eggplant drying. Performance of solar dryer is determined by defining the efficiency of collector and an effectiveness factor as the ratio of the drying rate in the indirect solar dryer to the drying rate in

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the open sun. Drying behavior of eggplant was performed on kinetics study [4]. Dattatreya M. Kadam and D.V.K. Samuel (2005) develop forced convective system for cauliflower drying shown in Fig. 12. Flat plate collector consists of absorber plate of GI sheet (22 gauge) with channel fins. Collector used with dimensions 1m x 2 m and total collector area is of 8 m^2. The forced airflow allows a better hot air distribution through the trays. The relation between moisture ratio and drying time was found and drying constant K was calculated from experimental data for different pretreatment [11]. Ghatrehsamani S.H. et. al. (2012) develops indirect type forced circulation solar dryer for apricot drying and compare results of indirect solar drying with the mixed mode solar drying. It can be said that the drying rate in the mixed-mode of solar drying is higher than the indirect mode of solar drying in every air flow velocity. The increase in the drying rate could be due to the values of higher temperature in the mixed-mode because of direct solar radiation on product in cabinet in addition to the heated air by solar heaters [15]. New solar dryer systems with swirling flow for drying seeded grape designed and develop by Gülşah Çakmak and Cengiz Yıldız (2009). Fig.13 shows the schematic diagram of experiment set designed for drying seeded grapes grown around Elazığ region. It is examined for drying time compared to that of natural drying. Also it is examined for drying rate with air velocity [16]. Gutti Babagana et. al. present design and construction of forced or natural convection solar dryer with heat storage. The drying tests were conducted for drying tomato, onion, pepper, okra and spinach and results compared between forced and natural circulation modes [17]. Jan Banout and Petr Ehl present design and details of the double-pass solar drier for drying (DPSD) of bamboo shoots in Vietnam. The performances of a forced convection DPSD have been compared with those of a typical conventional dryer and a traditional open air sun drying for drying of bamboo shoots. DPSD shows better performance than other types of dryer for bamboo shoots drying.

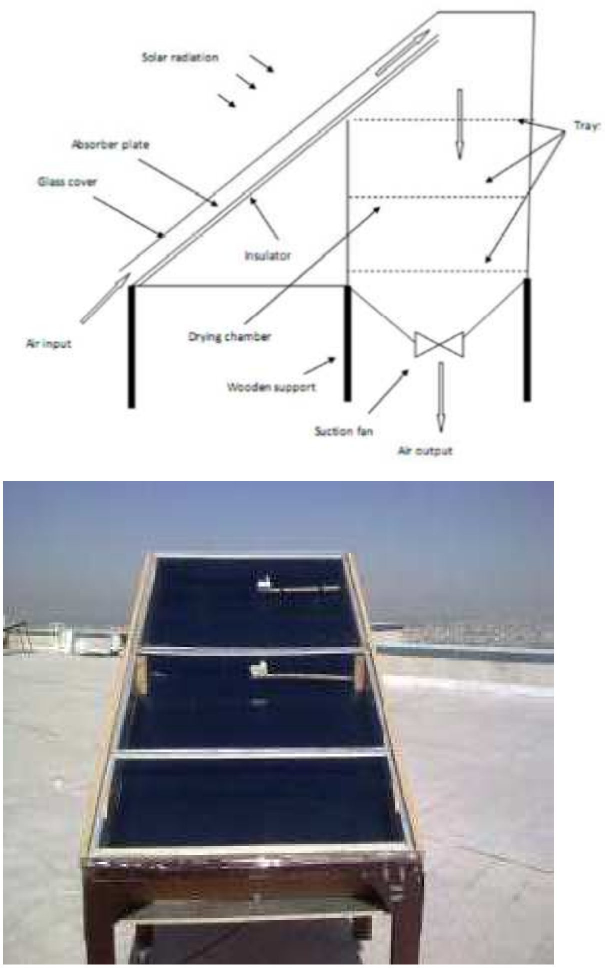


Fig.11 a) Schematic view and b) Pictorial view of an indirect forced convection solar dryer for Eggplant drying [4].

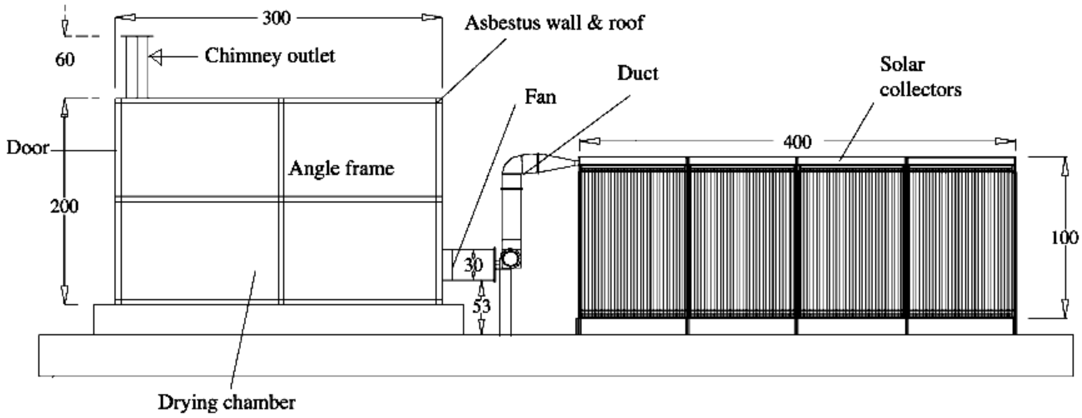
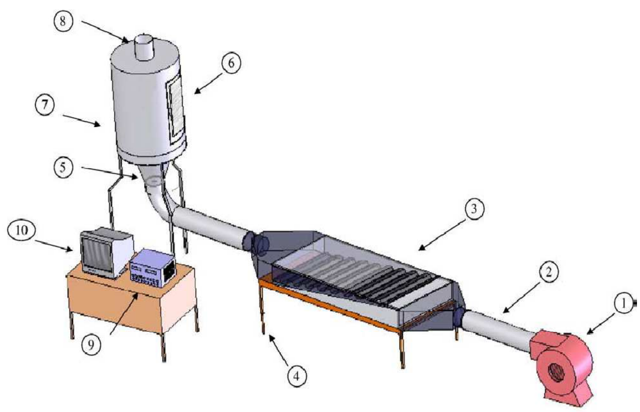


Fig.12 Side view of forced circulation solar dryer and front view of the flat-plate solar heat collecting panels developed by Dattatreya M. Kadam and D.V.K. Samuel for cauliflower drying [11].

Fig. 14 shows the description of Double-pass Solar Drier (DPSD) [19]. Kumar Tekam et. al. designed and developed prototype forced circulation solar dryer system operated on PV module shown in Fig. 15. Electric fan operated by PV module. Set up consists of solar collector unit and food dryer chamber. The dryer chamber was closed fitted by aluminum pipe and aluminum plate which was painted with black color Experimental set is evaluated for apple drying and calculations were compared with open air solar drying [22]. M. Mohanraj and P. Chandrasekar (2008) develops the cabinet type forced circulation solar dryer for Copra drying shown in Fig.16. They Investigates the variation of moisture content, ambient temperature and air drying temperature as function of drying temperature. The drying rate of copra in the solar dryer was high compared to open air solar drying [23]. Mustafa Aktaş et. al. designed and developed the heat pump and solar dryer for determination of drying characteristics of apples. It was recommended that the system with combination of both dryers considered being more efficient. The drying process can be continued with solar energy in the daytime and a heat pump dryer can be used at night [25]. Panna Lal Singh (2010) develops forced convection type solar dryer for Silk cocoon drying shown in Fig. 16. The dryer (50 kg/batch) consisted of cabinet type drying chamber, drying trays, solar air heaters, hot air ducts, blower and electrical backup. Overall size of the drying chamber was 1000 x 1500 x 1500 mm. It was provided with 30 numbers of the drying trays to load the cocoons to avoid direct exposure of UV radiations on silk cocoons. Size of the each tray was 0.57 x 0.82 m. Collector area of the solar air heaters was 16 m^2. There were eight solar air heating panels (size: 1 m x 2 m) arranged in series and parallel combinations. The drying time for a batch of raw cocoons were 16–19 sunshine hours depending upon intensity of sun and ambient temperature [29].



1- Fan; 2- Duct

3- Solar energy collector;

4- Support frame;

5- Swirl element;

6- Door ;7- Drying Chamber with air directing elements;

8- High humid air exhaust;

9- Control panel;

10- Computer.

Fig.13 Schematic view of experiment set up with swirling flow solar dryer for seeded grape drying [16].

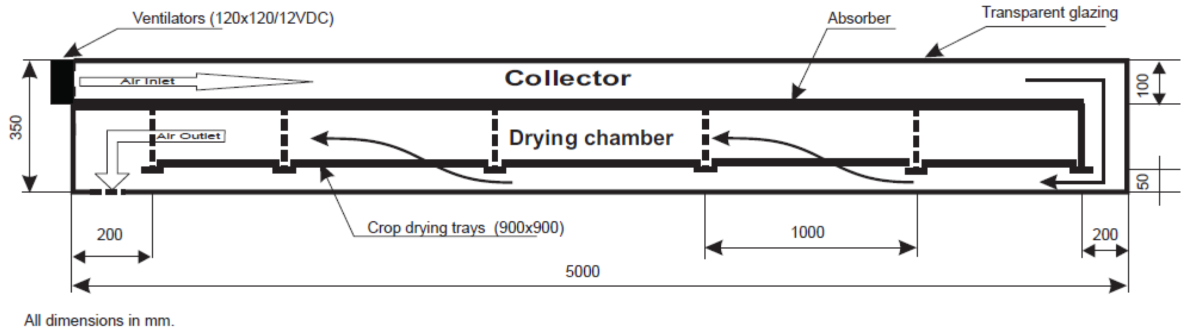


Fig. 14 Description of Double-pass Solar Drier (DPSD) [19].

Fig.15. Pictorial view of forced circulation solar dryer system operated with PV cell [22].

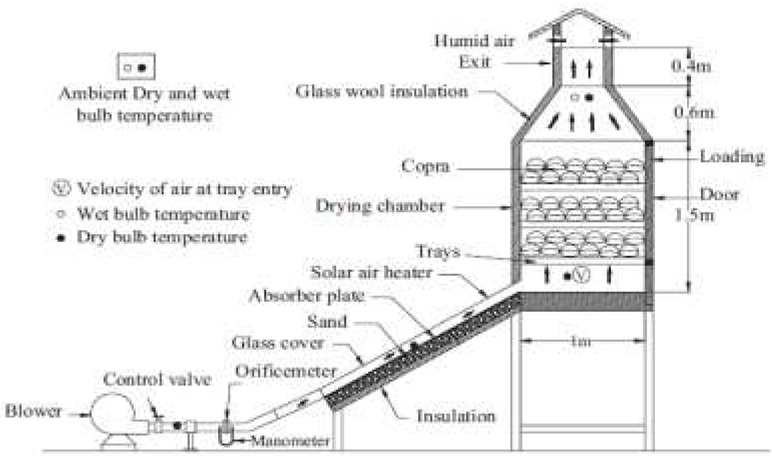


Fig.16. Schematic view of the solar drier used for copra drying [23].

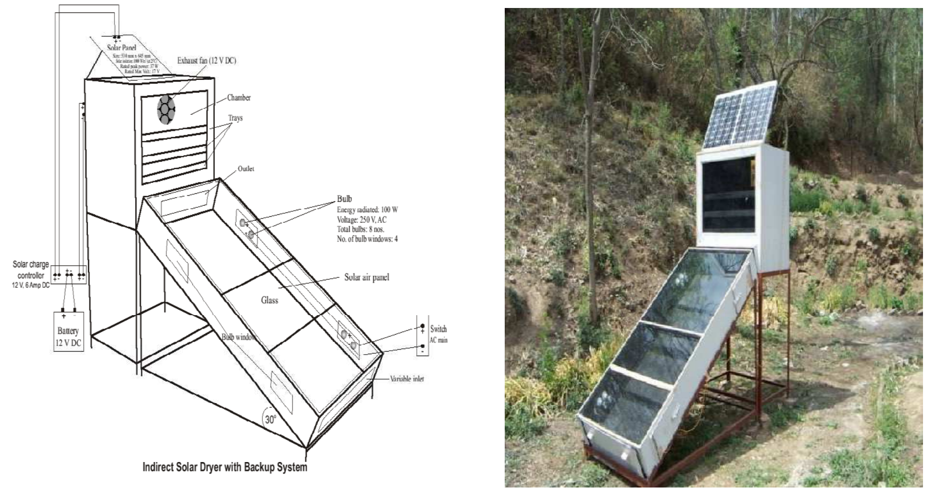


Fig.17. a) Schematic view b) Pictorial view of forced circulation solar dryer for hill products [30].

R. K. Aggarwal (2012) designed and developed the indirect forced circulation solar dryer for hill products. Fig. 17 shows the schematic view and photo of dryer. Solar collector with a glass area of 2.4 m^2 and volume is $0.693m^3$. The drying chamber with dimension of 1.1m x 0.7m x1m has three removable trays. The eight bulbs of 100 W each are provided in the solar collector for heating during rains and after sunset to reduce the drying time. A DC fan is provided at top of the drying chamber for air circulation. A solar battery has been attached with the drying chamber to run the fan. Also present survey report about of uses of solar dryer in the hill area [30]. Systematic design and construction of indirect forced convention solar crop dyer for drying Moringa leaves presents by S.K. Amedorme et. al.(2013). The tests were performed for geographical orientation in Kumasi is 6.7^o N, 1.6^o W [33]. S. Youcef-Ali and J.Y. Desmons (2007) present effect of aerothermic parameters and the product quantity on the production capacity of an indirect forced convection solar dryer. Experiments were studied for the drying potato. The solar collector equipped with offset plate fins placed in the dynamic air passage below the absorber [35].

V. Shanmugam and E. Natarajan (2005) present the experimental investigation of forced convection and desiccant bed integrated solar dryer. Fig.18. a) shows schematic view of the desiccant integrated solar dryer. The system consists of a forced circulation flat plate solar air collector, drying chamber and a desiccant unit. Desiccant bed is a mixture of 60% bentonite, 10% calcium chloride, 20% vermiculite and 10% cement by weight. This bed provides better drying effect during off sun shine hours. System is studied for green peas drying for different air flow rates [37]. Same experimental set up was examined for Experimental study of regenerative desiccant integrated solar dryer with and without reflective mirror by V. Shanmugam and E. Natarajan (2006). The desiccant material is increased by 20% of earlier set up [38].

3.3.3. Green house type forced circulation solar dryer

J. Kaewkiew et. al. presents the experimental investigation of the performance of a large-scale greenhouse type solar dryer for drying chilli in Thailand. Fig.19 shows the pictorial view of dryer. The verified chilli consist initial moisture content of 74% (WB), this value reached to 9% (WB) in 3 days. Green house made in parabolic shape and it was covered of polycarbonate. The dimensions of green house were width of 8.0 m, length of 20.0 m and height 3.5 m and floor was made from the concrete. Nine DC fan installed in dryer operated on three 50-Watt solar cell modules. Capacity of dryer was 1000 kg of fruits. Fig.19 shows pictorial view of green house solar dryer used for chilli drying in Thailand [20].

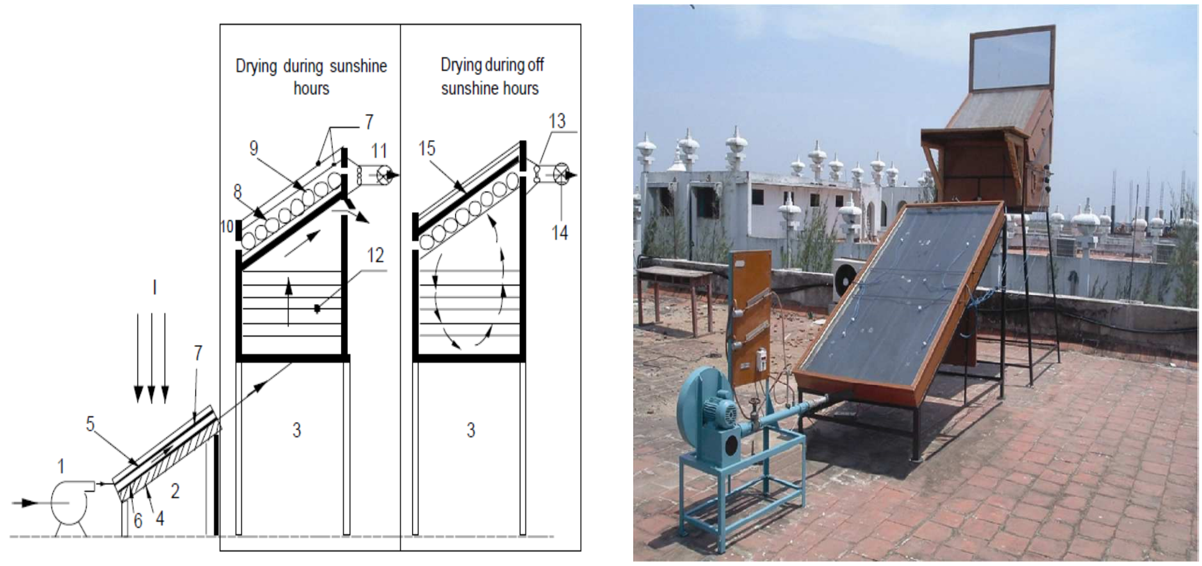


Fig.18. a) Schematic view of the desiccant integrated solar dryer: b) pictorial view of the desiccant integrated solar dryer with reflected mirror developed by V. Shanmugam and E. Natarajan [37, 38].

Fig.19 Pictorial view of green house solar dryer used for chilli drying in Thailand [20].

Serm Janjai develops and disseminates the use of a greenhouse type solar dryer for small-scale dried food industries. Developed solar dryer shows same characteristics of previous explained solar dryer by J.Kaewkiew et. al. For continuous drying operation a 100kW-LPG gas burner used in green house to supply hot air to the dryer during cloudy or rainy days. For dissemination purpose other two green house solar dryer developed and installed at different places in Thailand shows satisfactory result [31]. Serm Janjai et. al. develop the large-scale solar greenhouse dryer using polycarbonate cover for a tropical environment of Lao People's Democratic Republic. Solar dryer Developed with same characteristics of previous explained solar dryer by J.Kaewkiew et. al. Dryer was tested One thousand kilograms of banana with the initial moisture content of 68% (wb), hundred kilograms of chilli with the initial moisture content of 75% (wb) and Two hundred kilograms of coffee with the initial moisture content of 52% (wb). Banana was dried within 5 days compared to7 days required for natural sun drying with the same weather conditions. Chilli was dried within 3 days while the natural sun drying needed 5 days. Coffee was dried within 2 days as compared to 4 days required for natural sun drying [32].

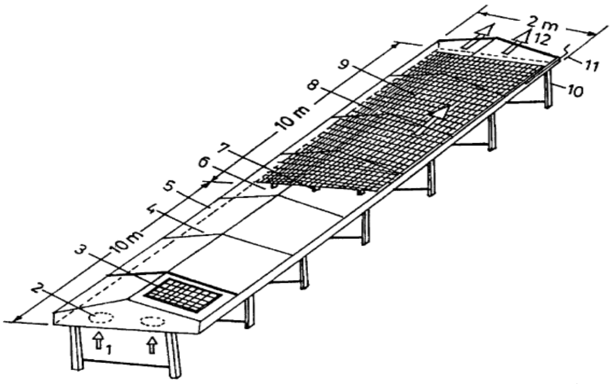
3.3. Solar Tunnel Dryer

The solar tunnel drier was installed for Pineapple drying at Bangladesh Agricultural University, Mymensingh, Bangladesh B.K. Bala et. al. The drier consists of a flat plate air heating collector, a tunnel drying unit and a small fan to provide the required air flow over the product to be dried. Both the collector and the drying unit are covered with plastic. The air at the required flow rate is provided by two DC fans. Heat is transferred from the absorber to the air in the collector and heated air from the collector while passing over the products absorbs moisture from the products. Solar radiation also passes through the transparent cover of the drier and heats the products in the drier. This enhances the drying rate and the temperature in the drier rises in the ranges of 34.1–64.0°C for a change in solar radiation from 0 to 580 W/m2. Experiment is carried for Pineapple drying of quantity 150 kg [9].

H.P. Garg and R. Kumar (2000) studies thermal performance of collector semi-cylindrical solar tunnel dryers shown in Fig. 21. These studies mainly compare the natural circulation and forced circulation of air through dryer. All experiments carried for Delhi climate (28.58 N Latitude). The proposed design of solar tunnel dryer has two components viz., air collector and drying chamber and both are connected in series. The air is forced in the collector either by air blower or due to the natural convection. Air is heated throughout the collector length and is passed in the drying chamber to evaporate the moisture from the product [18]. N. Srisittipokakun et. al. (2012) design and develop parabolic shaped solar tunnel dryer for Andrographis paniculata drying shown in Fig.22. Andrographis paniculata is an annual plant with characteristic white-purple or spotted purple flowers that flourishes in South-East Asia, China and India. It has been valued for centuries by herbalists as a treatment for upper respiratory infections, fever, sore throat and herpes. The solar tunnel dryer consists of a solar collector, drying tunnel, and three radial flow fans to drive the moist air out of the drier. The product to be dried is placed as a single layer inside the drying tunnel. Andrographis paniculata contains of 75% (wb) moisture in initial stage. Two experiments were carried out 100 kg of Andrographis paniculata can be dried in 2 days [26].

Garima Tiwari et. al. presents Comparative study of commonly used Solar Dryers in India. Comparison was based upon the parameters such as maintenance and purchase cost of dryers, drying capacity, range of crops, quality of dried product, adaptability to local condition and efficiency. Comparative studied for chili, mushroom, groundnut, maize, pepper and yam drying [14].

A. Fadhel et.al. present study of the solar drying of grapes by three different processes. Comparative consist of open air, natural and solar tunnel drying. Solar tunnel greenhouse drying was found to be satisfactory and competitive to natural convection solar drying process [2].



1- Air Inlet;
2- Fan;
3- Solar Module;
4- Solar Collector;
5- Side Metal Frame;
6- Outlet of the collector;
7- Wooden support;
8- Plastic net;
9- Roof structure for supporting the plastic cover;
10- Base structure for supporting the tunnel drier;
11- Rolling bar;
12- Outlet of the drying tunnel.

Fig. 20 Solar tunnel drier for pineapple drying [9]

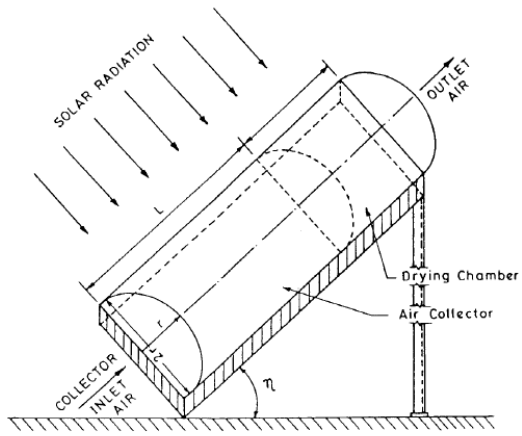


Fig.21 Schematic view of semi-cylindrical solar tunnel drying system [18].

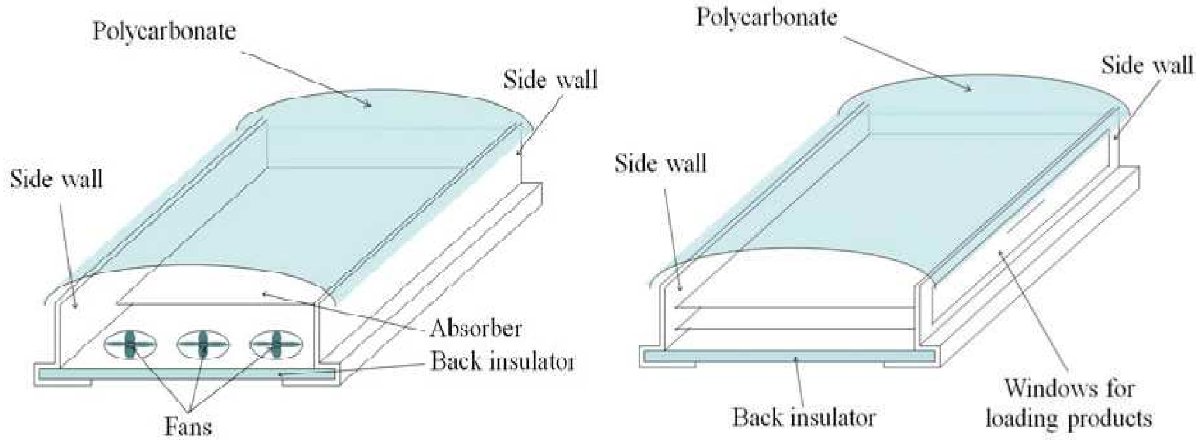


Fig.22 The characteristics of solar tunnel dryer (a) Solar collector and (b) Product container [26].

4. CONCLUSION

Solar dryer is the best alternative technology to avoid disadvantages of conventional drying methods. Solar dryer is designed for a particular crop and atmospheric conditions of location. Various types like mixed mode, natural circulation, forced circulation, green house type and tunnel type of solar dryer are reviewed with design parameters and performance. In mixed mode of drying the product may dry in less time compared to direct and indirect mode drying. But indirect mode of product drying will essential whenever requires avoiding direct exposure of product to the solar radiation. Forced circulation solar drying shows better result with reduced drying time than open air solar drying and natural circulation solar drying. But natural and forced circulation solar drying should use for limited quantity of product. For large quantity of product drying, it is better to use the green house type solar dryers.

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