VOL. 10, NO. 8, MAY 2015 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

A REVIEW ON INDIRECT SOLAR DRYERS

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ABSTRACT

Solar drying is one of the most ancient and simplest forms of drying known to mankind. Even today, most of the agricultural produce such as grains, spices, fruits and vegetables are dried under the sun. However, drying these products directly under the open sun has many drawbacks such as debris, rain, blowing wind, insect infestation, human and animal interference etc. which leads to contamination of the products. By the use of solar dryers, such problems can be easily overcome. Thus, there is a need to make the solar dryers more efficient and cheaper. There are various types of solar dryers developed and are classified based on the mode of air circulation, such as, natural circulation and forced circulation solar dryers; based on the type of drying, like, direct solar drying, indirect solar drying and mixed mode solar drying; material to be dried; types of operation e.g., batch or continuous, etc. In case of direct type solar dryers, the products are exposed directly to solar radiation which reduces the quality of the products. Also, the drying rate is very low in direct type solar dryers. These disadvantages are overcome by indirect type solar dryers. In this paper, we did a comprehensive review of various new technologies in indirect type solar dryers. We reviewed how these dryers fare against open sun drying and against each other and also, all the different enhancement techniques applied to them, in order to improve their efficiency and reduce the drying times.

Keywords:solar dryers, indirect type,forced circulation,natural circulation.

INTRODUCTION

In developing countries, majority of population is engaged in farming activities. Almost 80% of the total food products are cultivated by small farmers. These farmers use conventional means of drying (open sun drying) for their produce. Open sun drying is still the most common and the oldest method to preserve agricultural produce. But, this type of drying has many drawbacks like contamination problems, uneven type of drying, and uncontrolled moisture content in end products, causing degradation in the quality of the products. Solar dryers have thus been developed to overcome these problems of open sun drying.

The major barrier in adoption of solar dryers is their cost. Tara Chandra Kandpal, Atul Kumar and Pallav Purohit [32] analyzed how solar dryers fare economically compared to open sun drying and found that solar drying of agricultural products appears to be financially attractive for cash crops and it may even be possible to justify the use of high cost solar drying systems. However, for drying highly perishable products, it is extremely important to develop low cost systems [32]. Today it is possible to develop low cost solar dryers from local materials. Atul Sharma *et al*. [33] reviewed some easy-to-fabricate and easy-to-operate low cost dryers that can be suitably employed at small-scale factories or at rural farming villages while A. Fudholi *et al*. [34] gave examples of several solar driers and their possible prices for local manufacture.

Another barrier in the use of solar dryers is that the drying can only be carried out during sun shine hours. Thus use of solar dryers depends largely on the availability of the sun which reduces their functionality. To overcome this barrier, new technologies are being developed using desiccant units and thermal storage systems to make them functional even during off- sunshine hours. By the use of these technologies and efficient designs, continuous solar dryers are developed. Lalit M. Bal *et al*. [35] reviewed solar dryers with thermal energy storage systems thus facilitating continuous use of dryers. S.M. Shalaby *et al*. [36] did a comprehensive study on solar dryers with PCM while Lalit M. Bal reviewed solar dryers with latent heat storage systems and concluded that PCM reduces heat losses and improves the efficiency of the system.

The most important advantage of the solar dryers is that they work on renewable energy and are pollution free. Also, solar dryers can be easily constructed from local materials. It is successfully proved how solar dryer technology is key element to climatic and environmental protection as well as sustainable development [37].

Direct solar drying is the easiest method of solar drying; however, it has many disadvantages such as:

a) Direct exposure to solar radiation reduces the quality of the products and reduces the vitamins and nutrients from them.
b) Drying rate is very slow.
c) No control over rate of drying.
d) Products are directly exposed to uneven climatic changes and poor solar conditions.

These disadvantages are taken care of indirect type solar dryers. Indirect solar drying is the new and more effective technique of product drying. In this type of drying, the products are not directly exposed to the sun but, the solar radiation is used to heat the air which then flows through the product to be dried. Thus, moisture from the product may be lost by convection and diffusion. The indirect type solar dryers are classified into natural convection (passive) type and forced convection (active) type depending upon the method used to pass the air over the products.

In natural convection indirect type solar dryers, the products are stored in the cabin or hot box units. Solar collector is used to absorb the incident solar radiation and heat the air which passes over the stored products. As the air is heated, its density gets reduced and it flows into the drying section naturally. Since, in this case, the flow of air is by density difference only, these are called natural convection solar dryers.In forced convection solar dryers, the heated air is forced into the drying cabinet by means of an external device, (eg. blower, fan, etc.). Thus they offer better control over drying, but, require more power.

The objective of this study is to review new innovations and technologies in indirect type solar drying and different modifications and assessment techniques applied to them in order to improve their effectiveness.

SOLAR DRYER CLASSIFICATION

Solar dryers are classified depending upon the mode of air circulation, such as natural circulation and forced circulation dryers; or based on type of drying, like, direct solar drying, indirect solar drying and mixed mode solar drying. They are also classified depending upon the construction of the drying section. Figure-1 indicates the classification of solar dryers and drying modes [38].

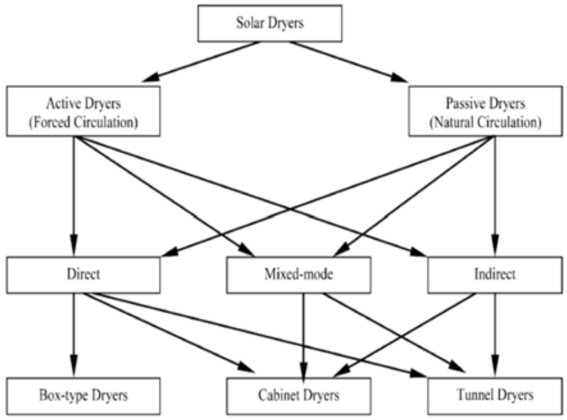


Figure-1. Classification of solar dryers drying modes [39].

INDIRECT TYPE NATURAL CONVECTION SOLAR DRYERS

A. Madhlopa *et al*. [1] developed an indirect type natural convection solar dryer integrated with collector-storage and biomass-backup heaters (Figure-2). The major components of the dryer were biomass burner (with a rectangular duct and flue gas chimney), collector-storage thermal mass and drying chamber (with a conventional solar chimney). They tested the dryer in three modes of operation (solar, biomass and solar-biomass) by drying twelve batches of fresh pineapple, with each batch weighing about 20 kg. They concluded that the thermal mass was capable of storing part of the absorbed solar energy and heat from the burner. It was possible to dry a batch of pineapples using solar energy only on clear days. In case of solar-biomass mode of operation, drying proceeded successfully even under unfavorable weather conditions. In this operational mode, the dryer reduced the moisture content of pineapple slices to 11% (db) and yielded a nutritious dried product. The average values of the final-day moisture pickup efficiencies were 15%, 11% and 13% in the solar, biomass and solar-biomass modes of operation respectively.

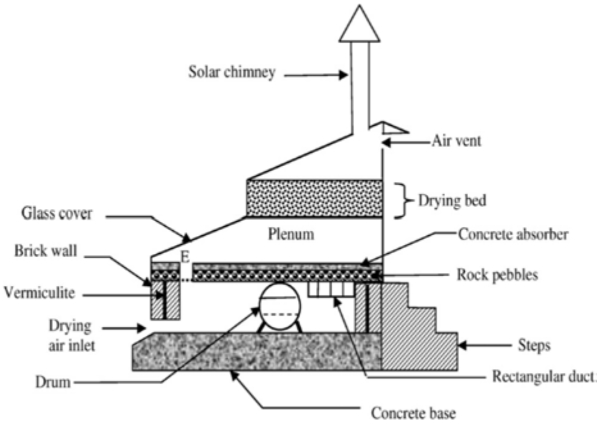


Figure-2. Cross-sectional view of the solar dryer through the burner, collector, drying chamber and solar chimney [1].

Subarna Maiti *et al*. [2] designed and developed an indirect, natural convection batch-type solar dryer fitted with north-south reflectors (Figure-3). They concluded that with the help of reflectors, the collector efficiency without load was enhanced from 40.0% to 58.5% under peak conditions during a typical day. They dried 'papad' - a popular Indian wafer with desired extent of drying (ca. 12%, wet basis) which could be achieved within 5 h in this static dryer having 1.8 m^2 area of the collector and computed loading capacity of 3.46 kg. However, they concluded that the design of operation with reflectors may need to be suitably modified as it may cause case hardening in case of certain food items.

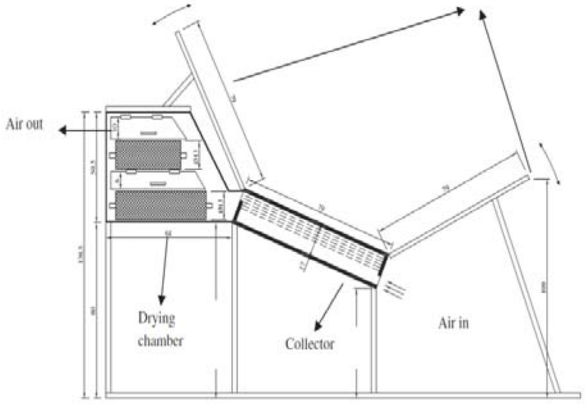


Figure-3. Schematic view of the constructed indirect natural convection solar dryer (dimensions in cm) [2].

Othieno *et al*. [3] developed an indirect solar maize dryer (Figure-4). The dryer consisted of a single glazed passive solar air heater with 1 m^2 single flat-plate collector. The air heater was connected to an insulated drying cabinet equipped with a chimney. The entire dryer assembly was made from hardboard. To improve the efficiency, air heater was modified with a wider air gap (15 cm) to accommodate three layers of wire-mesh absorber between the glazing and the flat-plate absorber. The dryer was capable of drying 90 kg of wet maize from a moisture content of about 20% wet basis to 12% within 3 days on a sunny day.

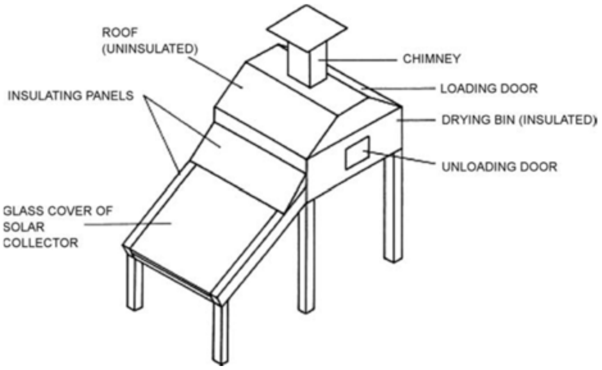


Figure-4. A distributed-type natural-circulation solar maize dryer [3].

A.A. El-Sebaii [4] designed an indirect type natural convection solar dryer (Figure-5). The system consists of a flat plate solar air heater connected to a cabinet acting as a drying chamber. The air heater is designed to be able to insert various storage materials under the absorber plate in order to improve the drying process. Sand is used as the storage material. They conducted drying experiments with and without storage materials for drying various fruits. They found that the equilibrium moisture content for seedless grapes was reached after 60 and 72 h when the system is used with and without storage material, respectively. Therefore, the storage material reduced the drying process by 12 h. In order to accelerate the drying process, they divided products into pieces and then chemically treated them by dipping the samples into boiling water containing 0.4% olive oil and 0.3% NaOH for 60 s. However, the required time to achieve required moisture for the chemically treated seedless grapes, when the system is used with sand as a storage material, is drastically reduced to 8 h. They finally concluded that system is capable of drying 10 kg of chemically treated grapes or green peas during 20 h of sunshine.

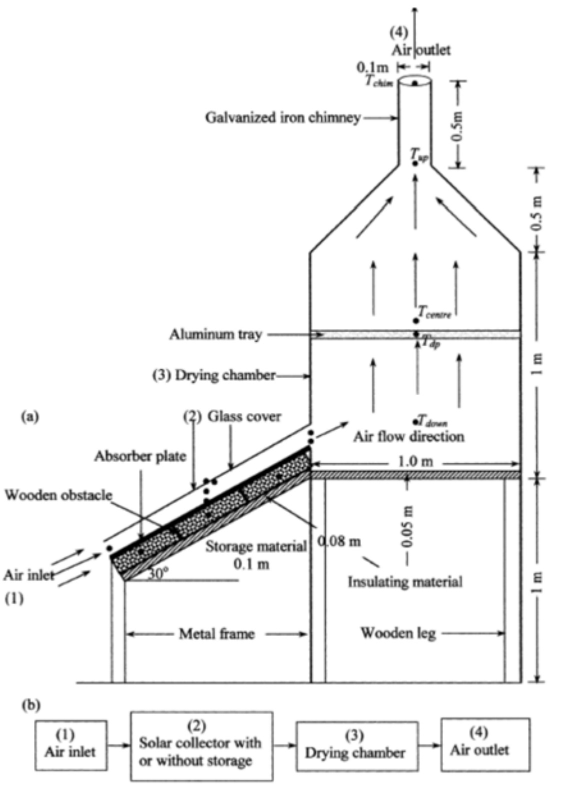
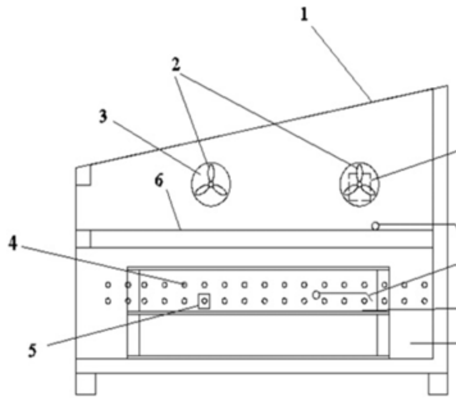


Figure-5.(a) Cross-sectional view of the indirect type natural convection solar dryer; (b) Air flow diagram. [4].

K.P. Vijayakumar *et al*. [5] developed and tested a new type of efficient indirect natural convection solar dryer (Figure-6). In this dryer, the product was loaded beneath the absorber plate, which prevented the problem of discoloration due to irradiation by direct sunlight. Two axial flow fans, provided in the air inlet, were used to accelerate and control the drying rate. They loaded the dryer with 4 kg of bitter gourd having an initial moisture content of 95%, and concluded that the final desired moisture content of 5% was achieved within 6 h without losing the product colour, while it was 11 h for open sun drying. They did a detailed performance analysis of the dryer with three methods namely 'annualized cost method', 'present worth of annual savings' and 'present worth of cumulative savings'. They calculated the cost for

1kg of bitter gourd as Rs. 17.52, while, in case of an electric dryer it was Rs. 41.35. The life span of the solar dryer was assumed to be 20 years and its payback period was calculated as 3.26 years. They finally concluded that the quality of the dried products were on par with the branded products available in the market.



1-Glazing; 2-Fans; 3-Air inlet; 4-Exit of air; 5-Humidity probe; 6-Drier absorber plate; 7-Velocity probe; 8-Temperature sensors; 9-Perforated tray; 10-Drying cabinet

Figure-6. Schematic diagram of indirect natural convection of solar dryer [5].

A. O. Adelaja *et al*. [6] developed a natural convection indirect type solar dryer and performed thermal and drying analysesto obtain someperformance evaluation parameters for the system (Figure-7). They tested its efficiency and effectiveness by drying some plantain fillets. Through analysis and testing, they found the collector efficiency to be 46.4% while system efficiency was 78.73%. The collector had moisture removal efficiency of 77.5% that was achieved in 20 hours. They estimated the cost of the dryer to be $195.00 which proved it to be affordable for the small- and medium-scale enterprises as well as for private usein domestic applications.

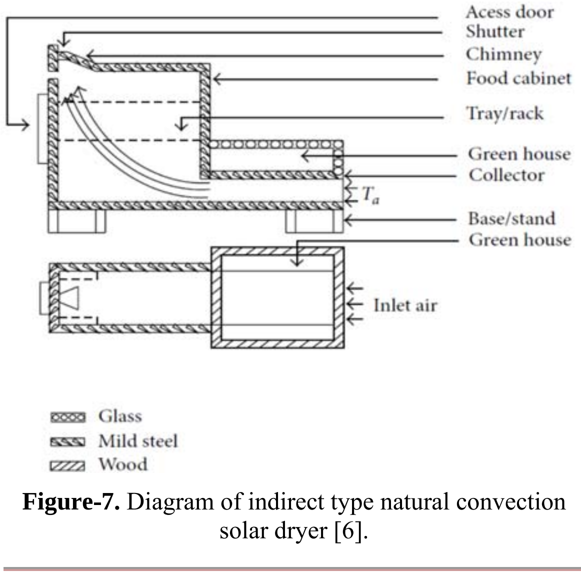


Figure-7. Diagram of indirect type natural convection solar dryer [6].

J. E. Berinyuy *et al*. [7] designed and constructed a double pass solar tunnel dryer integrated with heat storage using local materials and evaluated it for drying leafy vegetables and other agricultural products (Figure-8). The dryer was faced southwards with an inclination of 6º, and the solar radiation falling on the dryer surface was estimated to be 12.13 kJ/m^2 per day. They also used heat storage system, due to which, the temperature inside the dryer remained 5ºC above the ambient temperature even at sunset. The dryer was capable of drying 17 kg of sliced cabbage from 95% moisture content wet basis down to 9% in five days. They concluded that the overall dryer efficiency obtained was 17.68%, with a moisture extraction efficiency of 79.15% and airflow of 9.68 m^3/hr. They tested the dryer on other high moisture products and found that the dryer could reduce the drying time by 30 to 50% depending on the product.

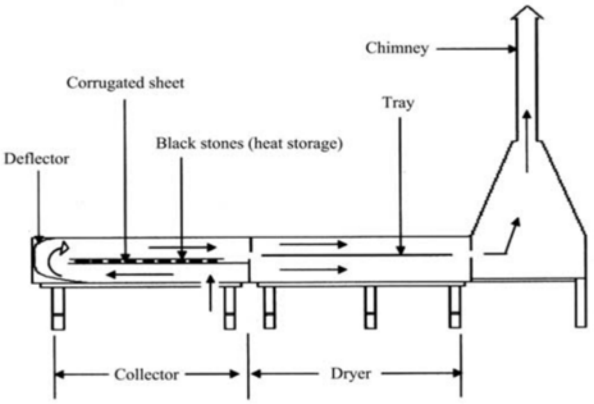


Figure-8. Double pass natural convection solar tunnel dryer integrated with heat storage [7].

I.N. Simate [8] developed a comparison of optimized mixed-mode and indirect-mode natural convection solar dryers for drying maize (Figure-9). The models are run under variable solar conditions in order to optimize the dryers and compare their performance. The optimization gave a shorter collector length for the mixed-mode solar dryer than for the indirect mode dryer of the same grain capacity. Through optimization, the author concluded that, the drying cost, annual cost and initial cost of the mixed-mode dryer are lower than those of the indirect-mode. The drying costs were 12.76 and 16.05 US$/ton for mixed-mode and indirect mode solar dryers.

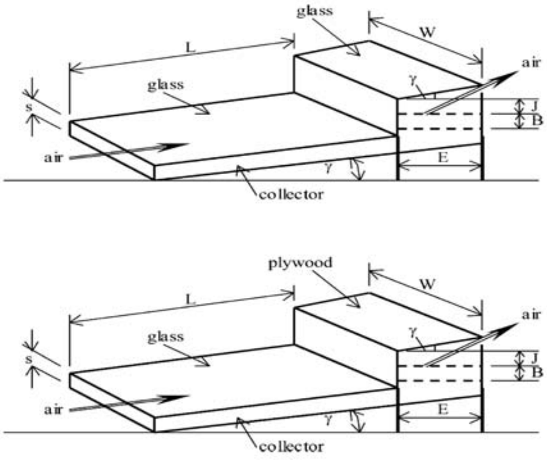


Figure-9. Geometry of the mixed-mode and indirect-mode natural convection solar dryers.

INDIRECT TYPE FORCED CONVECTION SOLAR DRYERS

M. Mohanraj *et al*. [9] developed an indirect forced convection solar dryer incorporated with sensible heat storage material for drying chilies (Figure-10). They concluded that the dryer integrated with heat storage material enables it to maintain a consistent air temperature inside the dryer. The chili was dried from an initial moisture content of 72.8% to the final moisture content of about 9.2% in the bottom tray and about 9.7% (wet basis) in the top tray. The inclusion of heat storage material (Gravel) also increases the drying time by about 4 hours per day. They estimated the thermal efficiency of solar dryer to be about 21% and specific moisture extraction rate to be about 0.87 kg/kWh.

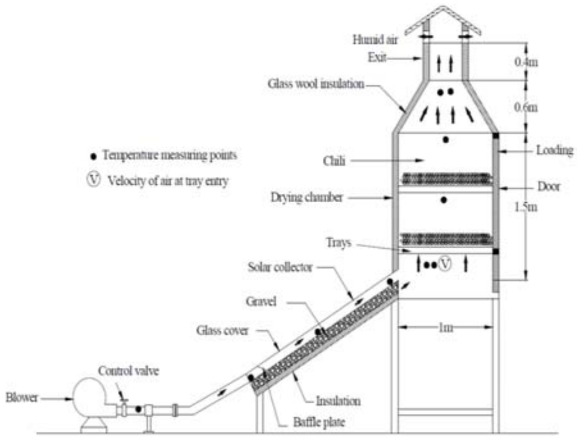


Figure-10. Experimental setup of indirect forced convection solar dryer incorporated with sensible heat storage material [9].

S.M. Shalaby *et al*. [10] developed an indirect type solar dryer using PCM as heat storage material for drying medical plants, Ocimum Basilicum and Thevetia Neriifolia (Figure-11). The model was tested under no load with and without PCM at a wide range of mass flow rates (0.0664-0.2182 kg/s). They found that after using the PCM, temperature of the drying air was higher than ambient temperature by 2.5-7.5 ^{0}C after sunset for five hours at least. It is observed that this novel design successfully maintained the desired temperature for seven consecutive hours every day. In addition, the solar dryer with PCM provides a drying air temperature, after 2:00 pm, 3.5-6.5 ^{0}C more than when it was free of PCM. They achieved final moisture content of O. basilicum and T. neriifolia in 12h and 18h in the case of implementing PCM. During their experimentation, they observed that the mass flow rates of 0.1204 and 0.0894 kg/s give the peak values of the drying temperature when the ISD is operated with and without PCM, respectively.

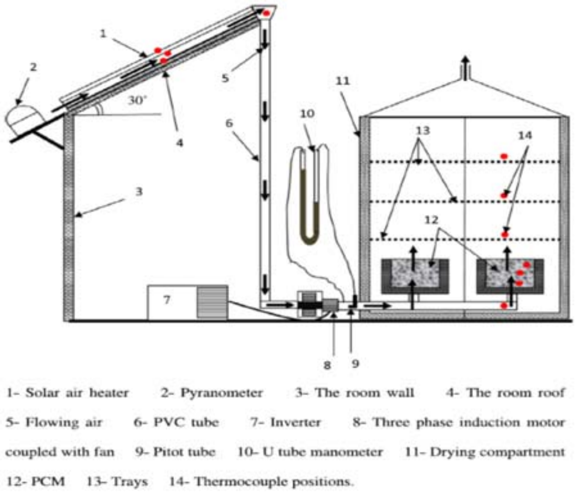


Figure-11. Experimental setup of novel indirect solar dryer (ISD) with PCM [10].

R. Velraj *et al*. [11] developed a phase change material based thermal storage system for heating air used in a dryer (Figure-12). They used HS 58, an inorganic salt based phase change material to store excess heat which was then recovered during off sunshine hours. It is observed that at high mass flow rates, the collector efficiency is also higher due to the reduction in heat losses. They also observed that by selection of the phase change material with suitable phase change temperature, avoids overheating of air during the peak sunshine hours, thereby, avoiding the spoilage of food products due to excessive heating. They concluded that by supplying air at lower mass flow rate during the discharging process, maximum capacity of the storage system can be utilized and uniform supply of heat for a longer duration of time during off sunshine hours can be achieved.

Figure-12. Experimental setup of PCM based solar air heater used for solar drying application [11].

Gutti Babagana *et al*. [12] designed and constructed forced/natural convection solar vegetable dryer with heat storage and compared their performances. The collector efficiency was 45% and the useful heat of 48.9 W/m^{2}K was used for about 6 hours in drying even during the night because of heat storage system.They observed that when using the forced convection mode, the drying time of tomato, onion, pepper, okra and spinach were 14 hrs, 15 hrs, 12 hrs, 11 hrs and 1 hr respectively, and when using the natural convection mode, the drying times were 24 hrs, 27 hrs, 25 hrs, 21 hrs and 2 hrs respectively. It was concluded that the forced convection system has higher drying capabilities as compared to natural convection system. Also, the airflow rate can be controlled as needed, not as in natural mode whose airflow rate depends on ambient climatic conditions. However, forced convection mode requires a source of motive power for the operation (battery) which is an added cost.

Ghatrehsamani S.H. *et al*. [13] developed an indirect type forced circulation solar dryer for apricot drying and compared the results of indirect solar drying with the mixed mode solar drying. It is observed that drying rate of apricots in the mixed-mode is higher than that in the indirect mode of solar drying. Through the application of mathematical model, it was seen that this 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.

Amina Benhamou *et al*. [14] did a simulation of solar dryer performances with forced convection dryer. The aim of their study was to determine the drying curve and the change rate of drying by solar energy on two plant materials, olive pomace, and colocynth, depending on solar radiation. Their study allowed them to monitor effects of some parameters influencing solar drying. They concluded that, increasing temperature of drying air, which is most influential parameter leads to increased humidity in the dryer and therefore reduced drying time.

Alireza Azimi *et al*. [15] used an indirect forced convection solar dryer to study the kinetic drying of eggplant. From drying curves, they observed that the main part of drying process took place in the falling drying rate period. The collector raised the ambient temperature more than 45°C in the peak of the solar intensity at noon. They concluded that an evaluation of the effectiveness factor and collector efficiency illustrated an inverse relationship between them in most of the drying processes. According to performed mathematical modeling on the drying curves, they concluded that the Midilli and Kucuck model could present drying behavior of the product for both indirect solar drying and open sun drying methods.

S.M. Shalaby *et al*. [16] evaluated thermal performance of an indirect forced convection solar dryer to dry mint and thymus (Figure-13). They tested fourteen mathematical models of thin layer drying & found that Midilli and Kucuk model is convenient to describe the thin layer solar drying of mint. However, the Page and modified Page models were found to be the best among others for describing the drying curves of thymus. Based on the results obtained for the solar drying of thymus and mint, they found that the drying times of thymus and mint depend on the mass of the drying product and temperature of the drying air. They also inferred that the abnormal drying behavior of thymus needs further study at different mass flow rates and various temperatures of the drying air. Finally, they observed the cost of drying mint and thymus in the indirect-mode forced convection solar dryer to be 0.025 €/kg and 0.087 €/kg, respectively.

Figure-13. Photograph of the experimental setup developed by S.M. Shalaby and A.A. El-Sebaii [16].

Jan Banout *et al*. [17] developed a unique forced convection double-pass solar dryer (DPSD) (Figure-14) and compared it with a cabinet type natural convection solar dryer and traditional open-sun drying (OSD) to dry bamboo shoots. They recorded mean drying temperatures and relative humidity in the drying chambers to be 55.2°C, 23.7%; 47.5°C, 37,6%; 36.2°C, 47.8% in DPSD, natural convection solar dryer and OSD, respectively. They concluded that, the fastest drying process was in DPSD where the required humidity was achieved after 7 hours, compared to OSD where it took 16 hours. They found that the overall drying efficiencies were 23.11%, 15.83% and 9.73% in case of DPSD, natural convection solar dryer and OSD, respectively. The DPSD resulted in the lowest moisture content 16.6% (w.b.) of bamboo shoots.

Although the construction of DPSD was very much costly compared to natural convection solar dryer, but the drying costs per kg of bamboo shoots were 42.8% lower than that of natural convection solar dryer, so the payback period for both the dryers were more or less similar. However taking into the consideration the life of both dryers they found that the payback period of DPSD is preferable.

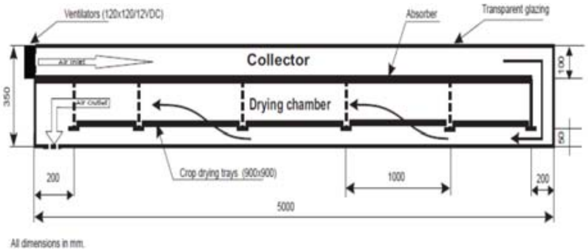


Figure-14. Description of double-pass solar dryer developed by Jan Banout and PetrEhl [17].

V. Shanmugam *et al*. [18] incorporated a $CaCl_2$ based regenerative solid desiccant bed into the dryer for drying green peas (Figure-15). The results of their tests have shown that the integration of desiccant unit with solar dryer continues the drying of products in the off-sunshine hours and improves the quality of drying product. At a given air flow rate of 0.01, 0.02 and 0.03 kg/m^{2}s the product dries to its equilibrium moisture content at about 22, 18 and 14 hours, respectively. Also, more uniform drying of product in all the trays is achieved during desiccant drying. They modified the design further and incorporated a reflective mirror to improve the regeneration of the desiccant and tested it to dry green peas and pineapple [19] (Figure-16). The test results were then conducted with and without the inclusion of the reflective mirror. They concluded that, with the inclusion of a reflective mirror on the desiccant bed the drying potential increases considerably. The useful temperature rise of about 10 ^{0}C was achieved with mirror, which reduced the drying time by 2 hours for green peas and 4 hours for pineapple slices.

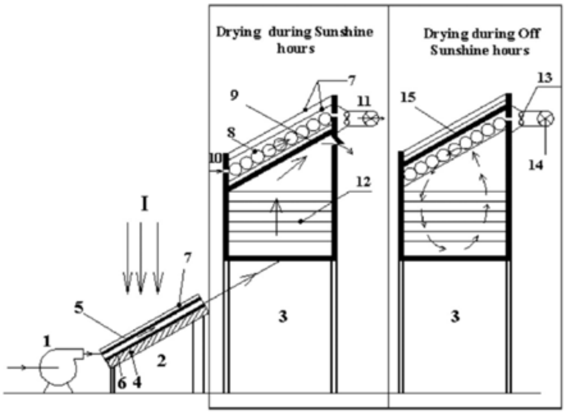


Figure-15. Schematic view of the desiccant integrated solar dryer [18].

Figure-16. Pictorial view of the desiccant integrated solar dryer with reflected mirror developed by V. Shanmugam and E. Natarajan [19].

Abdul Jabbar N. Khalifa *et al*. [20] investigated the performance of a typical solar drying system and a system equipped with an auxiliary heater as a supplement to the solar heat to dry beans and peas (Figure-17). They compared the performance of both to that of natural drying. They conducted tests with four different flow rates of 0.0383, 0.05104, 0.0638, and 0.07655m^3/s. They found that drying times for both beans and peas were reduced from 56 hours for natural drying to 12-14 hours for typical solar drying and 8-9 hours for combined (solar and auxiliary) drying. Also, it was concluded that the efficiency of the solar dryer with auxiliary heater was increased by 25% to 40% compared to that of the typical solar drying system. They observed that the drying time was reduced by 33% for peas and 36% for beans due to the use of auxiliary heat which resulted in an increase in the energy consumption by 22% for peas and 30% for beans.

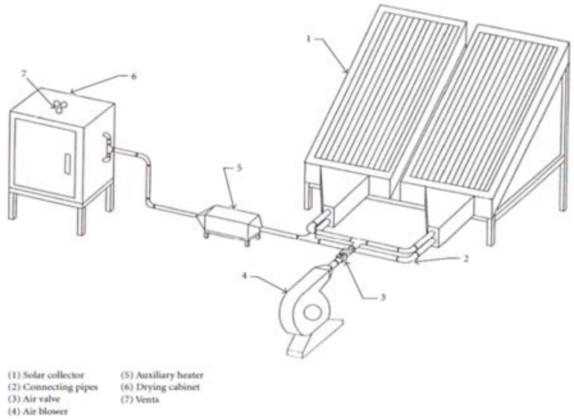


Figure-17. Schematic diagram of solar dryer with auxiliary heater [20].

S.K. Amedorme *et al*. [21] designed and constructed a simple and inexpensive forced convection indirect solar dryer for drying moringa leaves. The total cost of the dryer was calculated to be 200GH ₵. Locally available materials were used in the construction of solar dryer to dry a batch of moringa leaves, 2 kg by mass, with an initial moisture content of 80% wet basis from which 1.556 kg of water was required to be removed to have it dried to a desired moisture content of 10% wet basis. It was recommended to test the dryer under full load conditions. The tests about nutritional values of moringa leaves when sun dried and solar dried were not undertaken.

R.K. Aggarwal [22] developed an indirect solar dryer for drying of hill products (Figure-18). The solar dryer of 25kg capacity was attached with a solar cell for running the fan. Bulbs were also provided in the solar collector for heating air during cloudy days, evenings and mornings for faster drying, thereby reducing the drying time. He also compared the market value of the dried products.

Figure-18. Actual setup of indirect type solar dryer developed by R.K. Aggarwal [22].

Kamlesh Kumar Tekam *et al*. [23] developed a forced convection indirect solar dryer integrated with P.V cells to run the electric fan (Figure-19). The system consisted of two main parts as heat collector unit and food dryer chamber. Electric motor was used to let the smoother air flow in/out of the food drying chamber and was run directly from PV cells. The experiments were performed to dehydrate apples and concluded that the developed system is capable of drying most of the agricultural products. The results were compared with that of open drying and concluded that, solar dryer system resulted in a reduction in the drying time to an extent of 43.46% in comparison to open sun drying.

Figure-19. Solar drying system with PV module [23].

Sirinuch Jindaruksa *et al*. [24] performed evaluation of a silica gel based desiccant bed solar dryer (Figure-20). They used three silica gel beds (SGBs) on top, east and west. Each SGB had width of 0.55 m, length of 0.95 m. and thickness of 0.01 m. Each silica gel was used for operation and then was exposed to solar radiation for regeneration as shown in the chart below:

Table-1. Operation schedule of silica gel beds [24].

Direction of SGB	**Morning** (06.00-12.00)	**Afternoon** (12.00-18.00)	**Night** (18.00-6.00)
West	Dehumidification	Regeneration	-
East	Regeneration	Dehumidification	-
Top	Regeneration	Regeneration	Dehumidification

The solar dryer was thus used for continuous drying process. Based on the results, it was concluded that the top SGB had highest adsorption rate, next was the west SGB and the last was the east SGB. It was observed that the parameter that affected the adsorption rate of silica gel were air temperature which, inverse proportional to the adsorption rate and humidity ratio of humid air which, directly proportional to the adsorption rate. Finally, they analyzed how the system fared compared to non-dehumidification system and found that the drying time of with-dehumidification system was up to 20.83 % shorter than without-dehumidification system. Also, it was inferred that the solar dryer with dehumidification system has higher collector efficiency, chamber efficiency and more energy efficiency than the drying process without-dehumidification system.

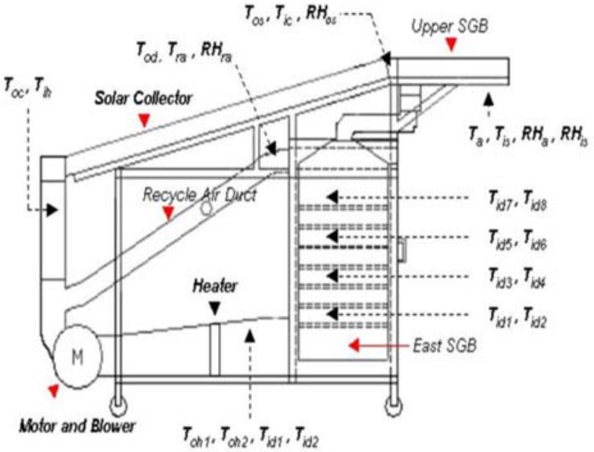


Figure-20. Design of solar dryer with dehumidification system [24].

S. Youcef-Ali *et al*. [25] studied the effect of airflow turbulence on calorific losses in foodstuff dryers through an indirect forced convection dryer (Figure-21). The drying process is delayed due to various losses through the dryer walls. They also considered the turbulence effect produced due to the flow of air as it is passed over grills. They studied the influence of various losses and presented a comparative study between various models, those that take into account and those that ignore these losses. They used a mathematical model for dryers in forced convection. From the experimental approach, they found the Nusselt number to be $Nu=0.165Re^{0.9}Pr^{1/3}$, when the airflow is disturbed due to the presence of pierced grills. They concluded that this Nusselt number form can be generalized for air in forced turbulent flow inside the dryer, with established profiles of temperature and velocity and for a Reynolds number ($17 < Re < 1500$). They also suggested another form of Nusselt number $Nu=0.65Re^{0.9}Pr^{1/3}$ which can be used in theoretical models that determine the drying kinetics of such dryers with pierced grills in the same conditions.

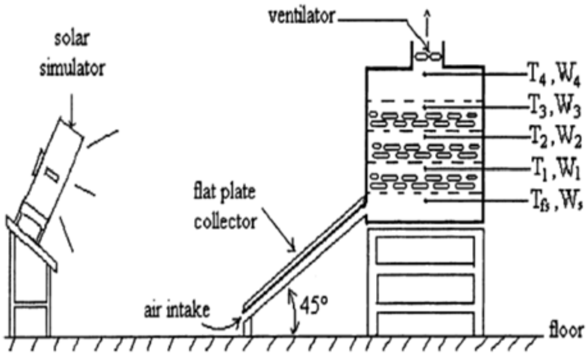


Figure-21. Layout of the experimental model [25].

A.F. Nassar *et al*. [26] developed two identical prototypes of solar dryers (direct and indirect) having the same dimensions to dry whole mint. They operated both these under natural and forced convection modes and compared their results. It is observed that the drying rate of mint under forced convection was higher than that of mint under natural convection, especially during first hours of drying. For forced convection dryers, it was observed that the rate of drying was more or less the same in both direct and indirect type drying. They also used empirical models to fit the drying curves and found that nine of them successfully represented the solar drying behavior of mint. From these models, they inferred that for forced convection, Verma *et al*. model was the best model for thin layer solar drying of mint for both direct and indirect drying.

A. Sreekumar [27] designed a roof-integrated solar air heating system for drying fruits and vegetables. The solar air heater had an area of 46 m^2 and recorded a maximum temperature of 76.6 ^{0}C. He loaded the dryer with 200 kg of fresh pineapple slices with an initial moisture content of 82% which was reduced to the desired level of 10% within 8 hours. He also concluded that the cost of drying 1 kg pineapple worked out to be Rs. 11 which was roughly half of that of an electric dryer while the payback period worked out to 0.54 year, that was much less than the life of dryer which was estimated to be 20 years.

D.S. Roosevelt *et al*. [28] developed a forced convection indirect type solar dryer set-up with an electrical back-up for drying of leathers (Figure-22). They did a comparative study on characteristics of leather by three different drying processes namely, open, solar and electrical drying. The data includes physical properties, surface texture, thickness variation and area reduction of leather. They concluded that, Open sun dried leather exhibits higher order bursting and grain crack strengths due to their relatively smoother and damage-free surface texture while, electrically dried leather exhibits higher order tensile strength. Solar drying of leather gives their strength characteristics in between that of open- and electrical-dried leathers. They finally proved that solar drying of leather can be a cost-effective proposition for large scale leather drying.

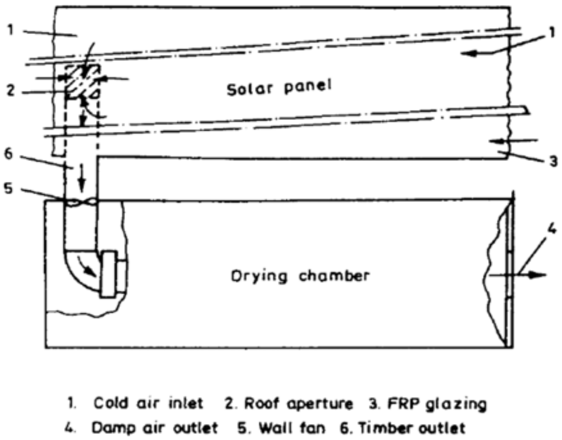


Figure-22. Schematic illustration of the solar-dryer set-up for drying of leather [28].

E. Kavak Akpinar [29] performed modeling and performance analysis of an indirect forced convection solar dryer for drying of mint leaves and compared the results with open sun drying. They analyzed the drying data by using ten different mathematical models. From the results, they concluded that Wang and Singh model was the most suitable for describing drying curve of the thin layer forced solar drying process and open sun of mint leaves. They also calculated the energy utilization ratio (EUR) of the drying cabinet and concluded that its value varies between 7.826% and 46.285% and the value of improvement potential varied between 0 and 0.017 kJ/s. These parameters were dependent on the drying time and ambient temperature.

S. Shanmugam *et al*. [30] performed modeling and experimental studies on oscillating inclined-bed forced convection solar dryer (Figure-23). The dryer was dryer capable of oscillating its bed while kept at an inclined position with respect to vertical and was connected to a double-pass flat plate collector. They dried Sunflower seeds with the bed of the dryer tilted at different angles and oscillated at different frequencies. They compared the results of the physical model and the mathematical model and concluded that the percentage of the average error and the standard deviation for the dryer thermal efficiency was 0.78% and 1.33%, respectively.

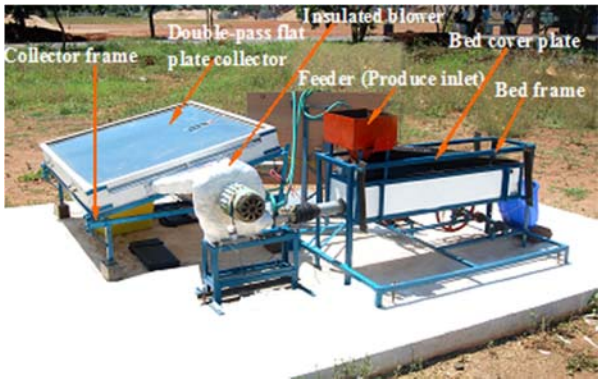


Figure-23. A view of the oscillating inclined-bed forced convection solar dryer solar dryer [30].

P.N. Sarsavadia [31] developed a forced convection dryer with recirculation of air to study the effect of airflow rate, air temperature and fraction of air recycled on the total energy requirement of drying of onion slices (Figure-24). For drying of onion sliceswithout using recirculation of air from initial moisture content of about 86% (wet basis) to final moisture content of about 7%(wet basis), the energy required per unit mass of water removed was found between 23.548 and 62.117 MJ/kg water. They concluded that by doing recirculation of exhaust air, the maximum saving in total energy up to 70.7% was achieved and energy required per unit mass of water removed was found between 12.040 and 38.777 MJ/kg water.

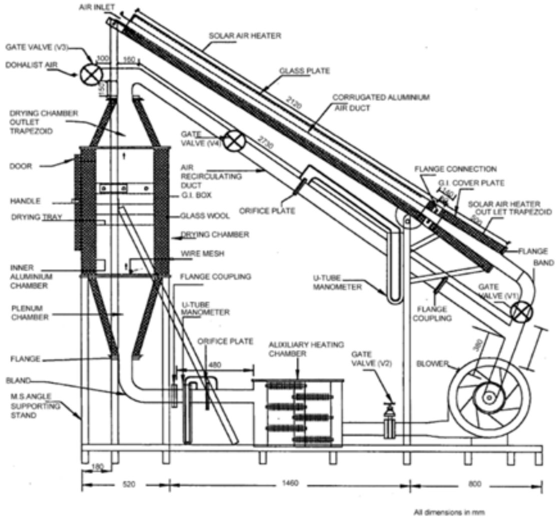


Figure-24. Schematic of forced convection solar dryer with recirculation of exhaust air [31].

CONCLUSIONS

This review paper is focused on indirect type solar dryers. In this paper a comprehensive study of how indirect solar dryers fare against other types of dryers as well as open sun drying and various design modifications applied to them has been performed. This paper also presented some low cost, easy to fabricate and operate dryers that can be suitably employed in small scale industries or at farming villages.

Although, mixed mode solar dryers are more efficient, but, they have disadvantage of exposing the products to solar radiation. The natural convection solar dryers are easy to fabricate and are low cost as well as self sufficient, as they require no other power consuming equipments. However, since air is flown due to natural convection, there is still no control over drying rate unlike forced convection dryers. The forced convection indirect dryer offers proper control over drying rate as the air flow can be regulated, protects the products in a better way for longer duration as they are not exposed directly to the solar radiation and reduces the drying time required for the products, however, they consume more power which is an added cost.

Various kinetics studies, mathematical models and enhancement techniques have been applied to the indirect type solar dryers to improve their effectiveness. From the heat transfer analysis of the dryer and drying kinetics of various products, much better understanding of drying rates in the dryer is obtained. Also through the use of enhancement techniques in the dryer like: efficient collector designs, heat storage units, desiccant materials, recirculation of air, PV cells and auxiliary heating techniques, the indirect type solar dryers are able to function even during the off-sunshine hours.

However, to further improve the effectiveness of these dryers and to keep them continuously operational, a combination of such different techniques must be developed in one single unit while keeping the overall cost minimal.

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