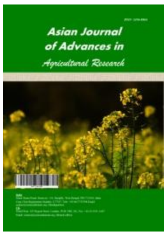

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A Comprehensive Review of the Hybrid Solar Dryers

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Authors' contributions

This work was carried out in collaboration among all authors. Author TOA did the preliminary research and finding, and wrote the first draft of the manuscript. Authors SAF and AMA worked on the detailed review of study and proofread the first draft and managed the references. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

In numerous under developed and developing countries, agrarian biological products are dried in open sun and this system of drying diminishes the exceptional quality, widespread acceptance and standard of the dried products because of hindrance from external contaminations, excessive ultra violet radiation and uneven drying rates. Decreasing petroleum derivative saves and expanding impacts of evolution global climate change environmental change because of ozone harming substance discharges have prompted a phenomenal worldwide interest in sustainable wellsprings of energy in food processing. A main competitor among these arising innovations is the change of sunlight to electric power as a substitute and steadiness for sun oriented drying framework. This process can be accomplished directly with sun powered cells (utilizing the photovoltaic impact) or indirectly by concentrating incident solar radiation to generate high-quality heat, which then supports heat production in conventional solar dryers. Various types of solar dryers have been designed and developed in different regions of the world, offering exclusive technical performances. In the hybrid solar dryers, the drying process is successful even under ominous atmospheric conditions. In this assessment paper, we reviewed unique forms of hybrid oriented solar dryers with respect to unique layout adjustments to be able to increase their effectiveness and thermal stability.

Keywords: Direct solar dryer; drying; hybrid solar dryer; solar radiation; sun.

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1. INTRODUCTION

There is various conventional drying strategies as of now accessible, yet it merits thinking about both the specialized and monetary advantages of the chance of solar based drying, alongside a significant number of commercially accessible sun powered dryers in operation today. However for a few particular cases, purposely designed solar powered dryers have likewise been developed and utilized.

The extent of hybrid solar drying system is to deliver a strong final result of a specific level of moisture content of agricultural material for instant use or for a long-term safe storage within a confined time [1-3].

This condition ought to be accomplished at a moderately steady and nonstop temperature gradient as some agricultural and biological materials to be dried might be delicate to higher and instable temperature.

Multiple approaches may be utilized to assess the specialized and technical overall performance of solar dryers however monetary and pragmatic will frequently be more significant issues in deciding their worthiness and acceptability [4].

Advances in layout methods, absorber, glazing substances and coating materials and control frameworks will all get enhancements the specialized performance of solar dryers and these will all add to the more noteworthy acknowledgment of an innovation that can assume significant part in a more economical world, especially the food creation framework.

2. REVIEW OF PREVIOUS HYBRID SOLAR DRYERS

2.1 Automated Solar Powered Hot-Air Supplemented Dryer

Inability to stabilize and regulate temperature level inside solar drying system especially during the off peak insolation period has been a major challenge in achieving uniformly dried biological material. Aduewa et al. designed and developed a solar powered hot-air supplemented dryer (SPHSD) with an automated control and data logging system [4]. The SPHSD has 3 distinct segments which are sun based authority chamber, drying chamber and warm air supplement chamber which is controlled with two 150 watt sun powered charger and one 200 Amps sun oriented battery for non-stop operation throughout horrific weather.

An electronic data logger and control unit was also developed for monitoring and controlling the temperature, air velocity and moisture content values [4]. Likewise the logger was used to record parameters at every level and location where different measuring sensors were position in the drying system as shown in Figs. 1a, 1b and 1c. The SPHSD has a capacity of 20 kg/batch, drying efficiency of 87.020%, effective moisture diffusivity value of 3.38 × (10^{-10} m^2/s), specific energy consumption 4620.571 J/kg.K, solar collector efficiency of 91.29% and thermal efficiency of 52.539% at peak operating condition.

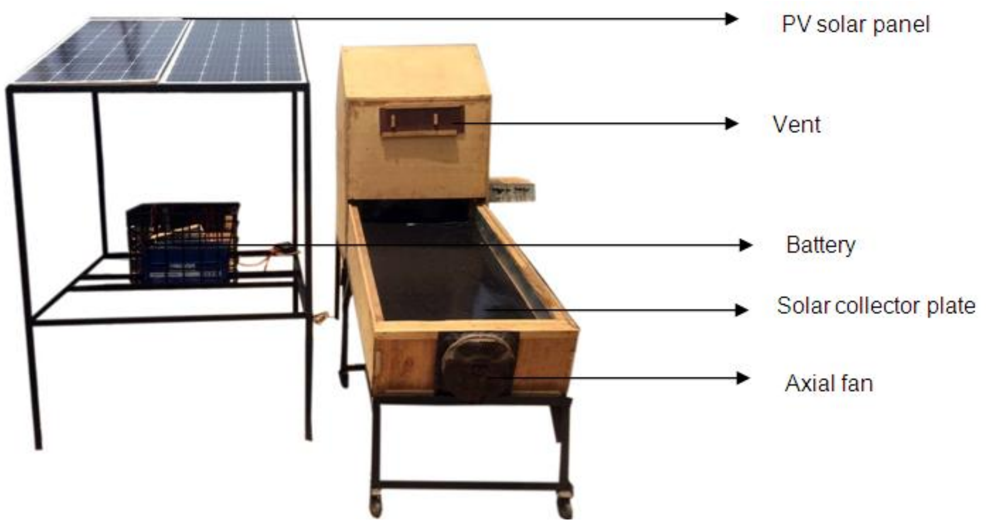

Fig. 1a. Solar powered hot-air supplemented dryer

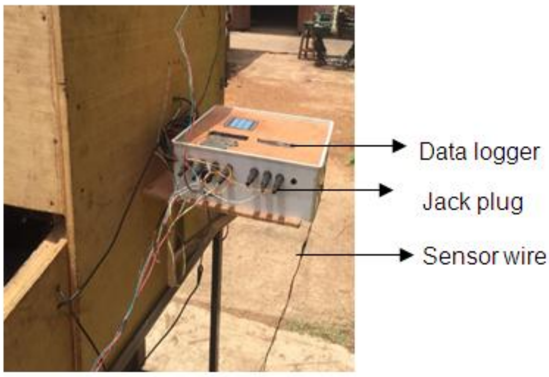

Fig. 1b. Developed data logger and control

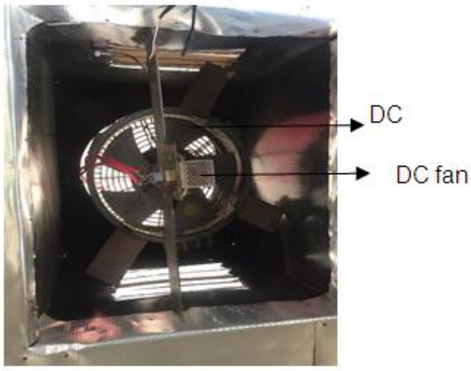

Fig. 1c. Hot-air supplement section of the dryer

2.2 Hot-Air Supplemented Solar Dryer

Aduewa et al. designed and fabricated a hot-air supplemented solar dryer for drying white yam (*Dioscorea rotundata*) slices [5]. The mass capacity of the designed hot-air supplemented solar dryer was 14 kg. The developed drying system was tested in Federal University of Technology Akure (FUTA) utilizing white yam to lay out the impact of integrating the hot-air segment into the solar based dryer which was powered using a generator.

The designed hybrid dryer has the following segments; a drying chamber, a solar collector chamber and a mechanical heating chamber. Drying experimentations were carried out using a temperature of 60°C for the hot-air supplemented solar drying process at a drying air velocity of 0.8 m/s [5]. After the trial, it was reasoned that the overall drying time used to lessen the moisture in the white white yam slices to safe storage moisture content (SSMC differs for the 2 special drying situations giving a complete drying time of 18 hours for solar dryer and 13 hours for hot-air supplemented solar dryer [5]. The average dryer thermal efficiency for the solar dryer was 31.45%, while the average dryer thermal efficiency is 42.10% at solar/mechanical drying at 60ºC, likewise, the solar collector highest efficiency was determined to be 83.28% at solar radiation intensity of 1199.46 W/m^2 and lowest efficiency of the solar collector was 23.89% at solar radiation intensity of 300.40 W/m^2 [5].

Fig. 2a. Front view of the hot-air supplemented solar dryer
Fig. 2b. Back view of the dryer

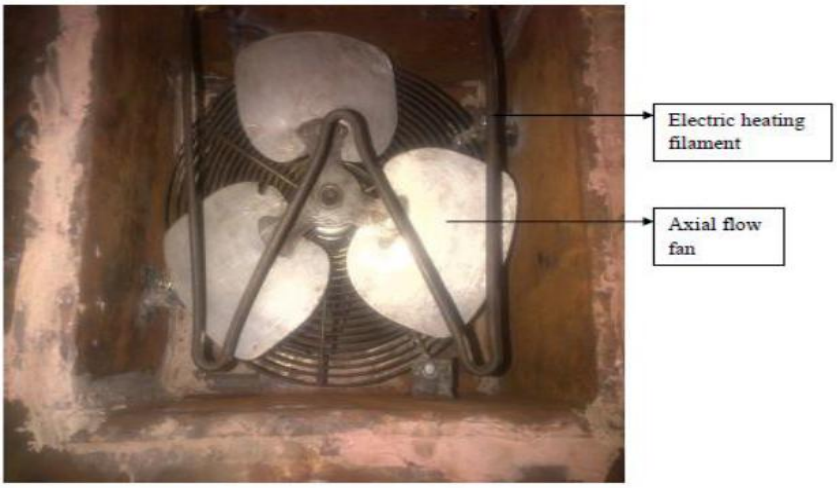

Fig. 2c. Picture of the heating element and the axial fan

2.3 Double Pass Solar Drier System

Banout et al. designed "a double pass solar drying system. Fig. 3 shows the itemized portrayal of the Double pass solar drier (DPSD)" [6]. The elements of the dryer are as follows: length 5 m, width 2 m and level 0.30 m with its sun absorber fabricated from galvanized metallic sheet painted black matt to make certain appropriate absorption of sun radiation. The heated air flows on both aspect of the absorber plate, as a result expanding the heat intensity of the surface region. Toward the start of the drier there are five DC fans which give the vital wind current through the solar absorber and drying chamber. The fans are associated straightforwardly to a photovoltaic board using a parallel connection.

As indicated by [6], trial runs for drying red chilli slices were performed utilizing DPSD and as compared with typical cabinet drier (CD) and a traditional open-air sun drying. The overall drying efficiencies of DSPD and CD to arrive at the desired moisture content of 10% (on a wet basis) were 24.04% and 11.52% respectively while the overall drying efficiency of open-air sun drying to attain the desired moisture content of 15% (on a wet basis) was 8.03%.

Further, ASTA colour value of the solar dried products from the DSPD was higher than those from CD and open-air sun drying. The DPSD suggests better overall performance as properly in all measured efficiencies and the general drying performance changed into greater and large drying proficiency was multiple times higher in the event of DPSD contrasted with CD.

2.4 Combined Solar and Mechanical Cabinet Dryer

"Bhuiyan et al. also designed and fabricated a combined solar and mechanical cabinet dryer that makes use of solar and electrical energy either independently or in aggregate form to conduct air drying" [7]. Different drying situations had been implemented by changing the heat supply source and go with the drift of air. The highest temperature reported in the drying chamber was 55°C and this was realized in two heating source and a fan condition. The temperature in upper shelf ranged from 47°C to 70°C for different heater-fan configuration. The maximum temperature was acknowledged in the upper shelf by 2 kW heater and 1 fan (70°C) and was successively followed by 2 kW heater and 2 fans (60°C), 1 kW fan and 1 fan (56.7°C) and 1kW heater and 2 fans (47°C) [7]. The temperature in lower shelf ranged from 42°C to 50°C for different operational conditions and the sequence was same as the upper shelf with respect to temperature with the exception that kW fan and 1 fan and 2 kW heater and 2 fans gave similar temperature (47°C). Bhuiyan et al. mentioned that the highest temperature (50°C) was arrived at while using 2 kW heater and 1 fan, while the lowest temperature (42°C) was given by 1 kW heater and 2 fans [7]. The variation in the temperature gradient offers the highest temperature at the upper chamber and the lowest at the lower chamber.

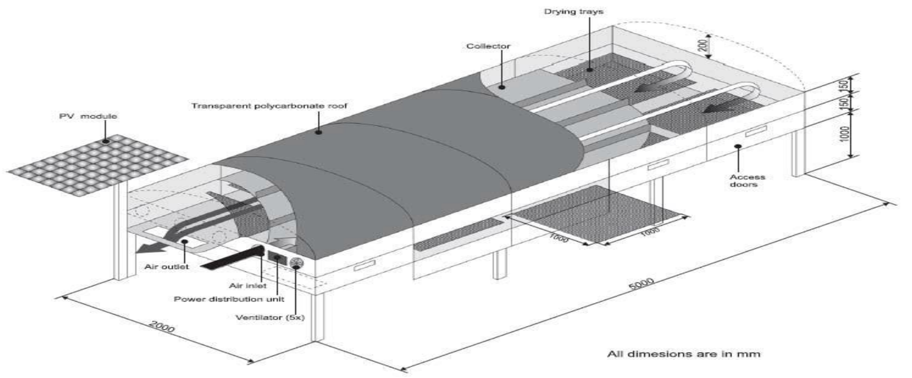

Fig. 3. Description of the Double pass solar drier (DPSD)
Source: [6]

2.5 Indirect Active Hybrid Solar – Electrical Dryer System

Boughali et al. of their studies evolved “active hybrid solar–electrical dryer in the Algerian Septentrional Sahara” [8]. The indirect active hybrid solar–electrical dryer developed by Boughali et al. “comprises of a flat plate sun collector, drying chamber, electric fan, resistance heater (3. 75 kW: accuracy ± 2%) and a temperature controller” [8]. The solar collector has an area of 2.45 m^2 that is inclined at an angle of 31° (latitude of the city of Ouargla) with the horizontal going through south all of the time, and uses matte black galvanized metal coated with a thickness of 0.002 m to absorb maximum of the incident sun radiation [8]. An experimental check with and without load had been executed in winter season so one can have a look at the thermal conduct of the dryer and the impact of excessive air mass behavior of the dryer and the effect of high air mass flow on the collector and system drying efficiency.

“The fraction of electrical and sun oriented energy commitment versus air mass stream rate was explored and investigated. It was observed that once airflow rate of the drying air extended from 0.0405 kg/m^2s (1 m/s) to 0.0810 kg/m^2s (2 m/s) the percent energy contribution by the solar air heater reduced from 25.074% to 13.22% while that of auxiliary heater increased from 74.92% to 86.78%” [8]. This increase in contribution of the auxiliary heater is due in reality to the collector outlet temperature of the air drying will be diminished essentially in high airflow rate and subsequently the air drying may be required to be heated via means of the auxiliary heater’s large temperature difference. The pictorial representation is shown in Fig. 4.

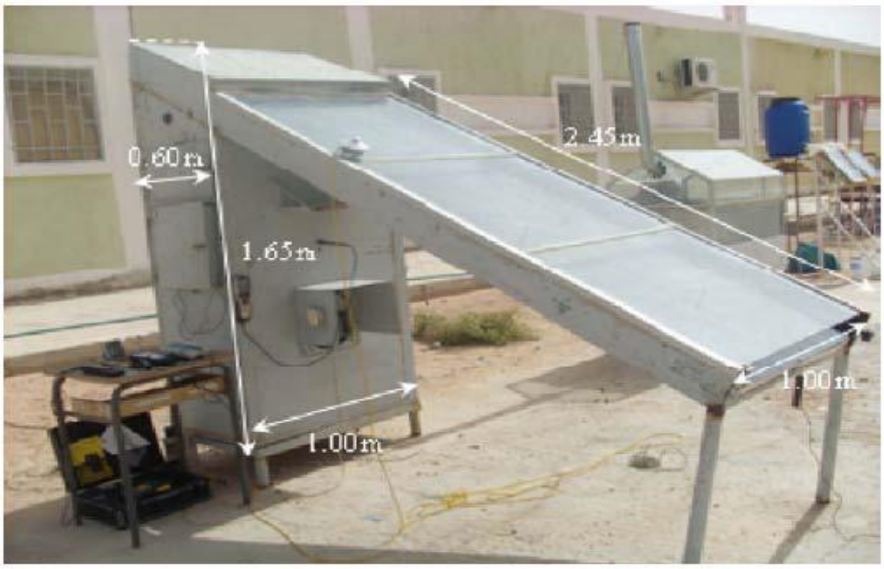

Fig. 4. Photo of an indirect active hybrid solar–electrical dryer
Source: [8]

2.6 Solar Dryer System with Swirling Flow

Gülşah and Cengiz developed a new solar drying equipment with poison of swirling flow for drying seeded grape [9]. A swirl component was introduced by the developer at the inlet channel point of the chamber to give rotating impact to the air. A new type of air solar collector, having dimensions of 940 × 1850 × 200 mm^3 was developed for supplying hot air needed for drying. To achieve an increased collector's efficiency, heat absorbing surface was fabricated in strides with 6 holes of 15 mm diameter drilled on each step for increasing turbulence effect on the fabricated expanded solar collector [9]. In the designed machine, different drying air speeds were analyzed with respect to drying periods. Drying regimes of dried grapes in the drying chamber with air solar collector and over cement ground were analyzed. Similarly, drying tests were made with air directing components introduced inside the dryer and a swirl element to the entry of drying chamber was then analyzed with respect to drying in open air under natural conditions in terms of drying time. It was reported by [9] that 200 h of drying period under natural conditions decreased to 80 h with the developed dryer having swirl element with an air velocity of 1.5 m/s.

2.7 Solar Assisted Heat-pump Dryer System

"Hawlader and Jahangeer developed a standard experimental solar assisted heat pump drying purposely for drying of green beans" [10]. The exploratory set-up involved two separate ways which are for air and refrigerant. Solar air collector, air-cooled condenser, auxiliary heater, blower, dryer unit, evaporator, and temperature and flow control gadgets were in the air way (see Fig. 6).

"Hawlader et al. made a comparison of the exhibition of an evaporator-collector and an air collector utilized in a coordinated solar system" [11]. "It was deduced that the evaporator–collector was of higher performance compared to the air collector in a solar assisted heat pump drying system" [11]. "The air collector productivity was raised as a result of higher mass flow rate of air and the usage of dehumidifier in the developed machine. The scope of productivity of the air collector, with and without dehumidifier, was viewed as around 0.72-0.76 and 0.42-0.48, respectively" [11]. "It was additionally uncovered that the potency of the evaporator-collector was beyond that of the air collector and it expanded with augmentation of refrigerant mass rate of flow. A maximum evaporator–collector efficiency of 0.87 against a maximum air collector efficiency of 0.76 was recorded" [11].

2.8 Solar Assisted Chemical Heat Pump Drying System

"A chemical heat pump (CHP) proposed as one of the possibly critical technological advances for compelling energy usage in drying was developed by Ogura and Mujumdar" [12]. "Different practical trials was carried out on the (SACHPD) machine to evaluate the performance. The overall performance of the developed machine has been investigated for various climatic conditions in the environment. Two continuous days for clear and cloudy climates were presented" [13]. The observed peak values of the solar fraction (SF) and that of the coefficient of performance of chemical heat pump (COPh) of the machine are 0.713 and 2.000 on a clear day, against the maximum values of 0.322 and 1.42 on a cloudy day. The total machine energy result of 51 kWh and 25 kWh were attained for clear and shady days, throughout 9 hours of drying period. The machine parts were shown in Fig. 7.

2.9 Solar-assisted Dehumidification System

Yahya et al. developed a solar dehumidification system for the purpose of drying medicinal herbs [14]. The machine comprises of a solar collector, an energy storage tank, auxiliary heater and adsorbent, water to air heat exchanger, a water circulating pump, drying chamber, and other equipment as shown in Fig. 8. It operates on importantly three processes which are, regeneration, dehumidification, and batch drying. During regeneration process, the ambient air outside the dryer is warmed with the heat exchanger and is passed on to the adsorbent. The air is dehumidified with the adsorbent, first and foremost, and is provided to the drying chamber as the dry air. The drying chamber's relative humidity and temperature were recorded as 40% and 35°C respectively. The overall performance indices taken into consideration to calculate the overall output of the drying device are: Pick up efficiency (ηp), Solar Fraction (SF) and Coefficient of Performance (COP) [14]. "The results shows that the maximum values of the pickup efficiency (ηp), solar fraction (SF) and coefficient of performance (COP) was found 70%, 97% and 0.3, respectively with initial and final wet basis moisture content of *Centella Asiatica L* type, 88% and 15%, respectively at an air velocity of 3.25 m/s" [14].

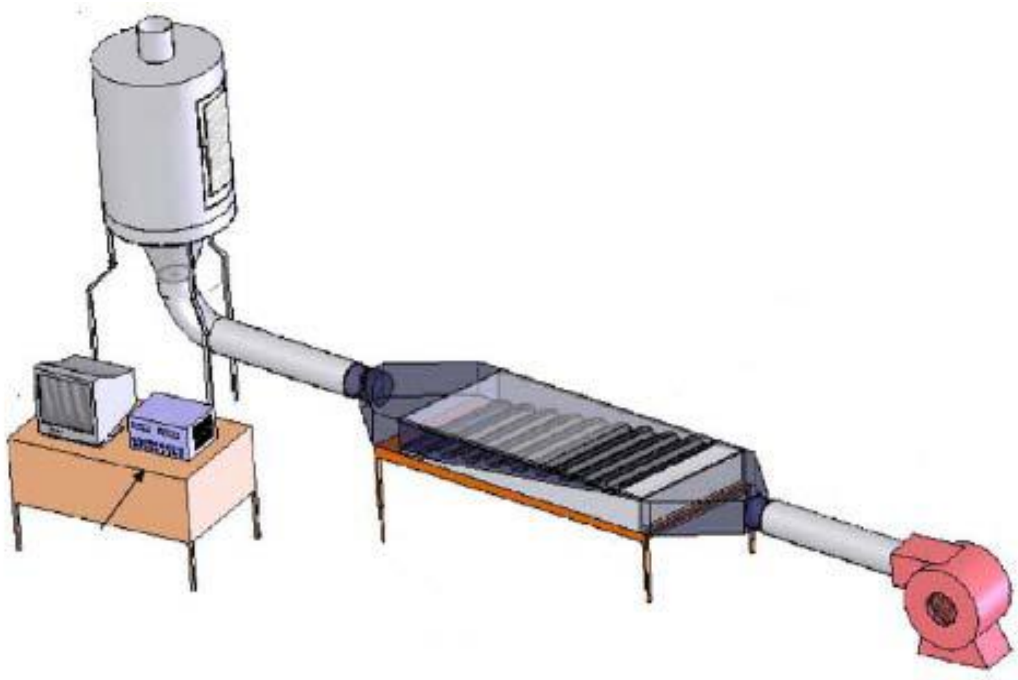

Fig. 5. Schematic view of designed experiment set
Source: [9]

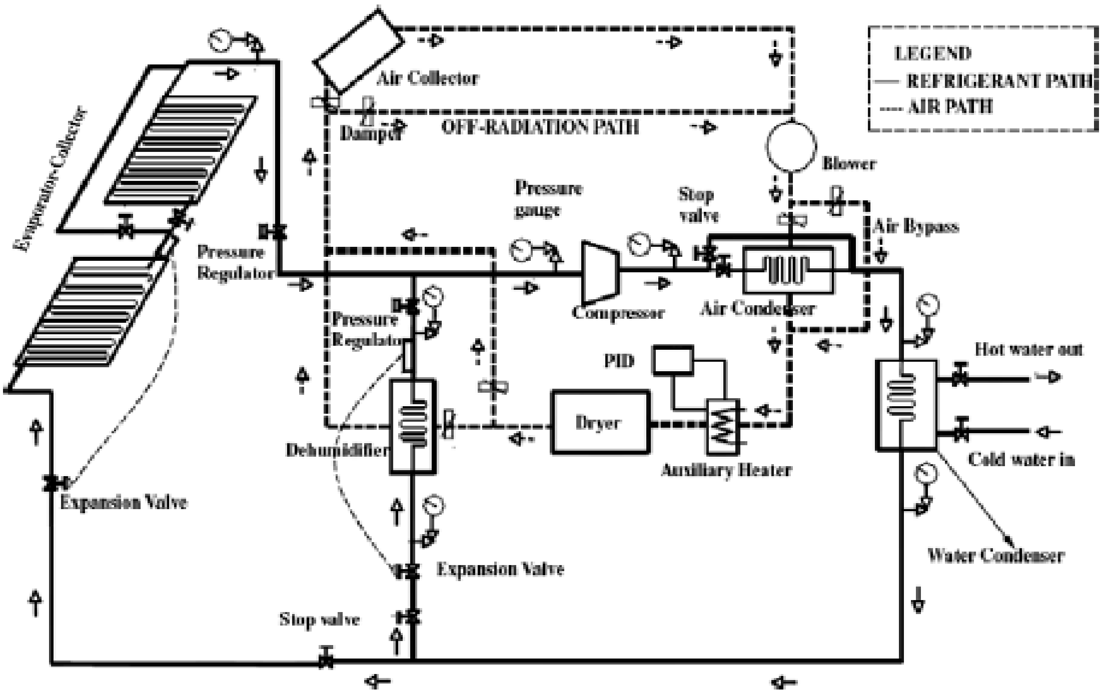

Fig. 6. Component and schematic representation of a solar assisted heat-pump drying machine
Source: [10]

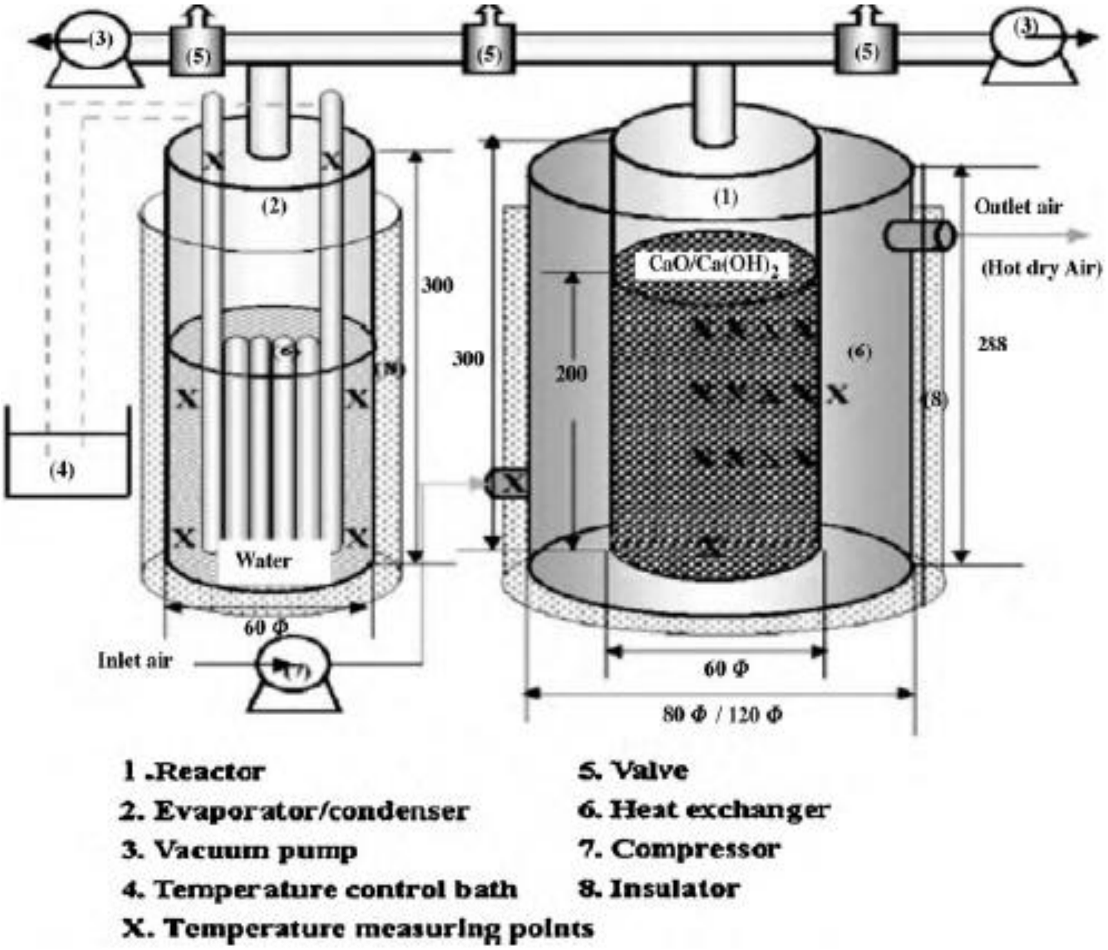

Fig. 7. Standard-type CHP unit
Source: [12]

2.10 PV-Ventilated Solar Greenhouse Dryer System

Janja et al. revealed "the exploratory performance of a PV-ventilated solar oriented greenhouse dryer for dehydration of chilies" [15]. "The designed greenhouse dryer consist of a concrete floor with an area of 5.5 × 8.0 m^2" [15]. It is protected with obvious polycarbonate plates designed within side the allegorical form to facilitate the machine development. Three fans powered by a solar cell module of 53 W were utilized to distribute air in the dryer. The structure of the greenhouse is shown in Fig. 9. To analyze its efficiency, [15] ensured that "the dryer was used to dry 4 batches of chilies with air temperature inside the dryer between 60-65°C at the noon of a clear day. High drying air temperature with sensibly low relative humidity inside the dryer compartment during practically entire time of the day showed the possibility of sun based drying inside the greenhouse dryer. The temperatures at three sections (top, middle and bottom) inside the dryer follow the same pattern" [15]. "Heat stored in the concrete substantial floor assisted with decreasing variation of drying air temperature due to the change of solar radiation. The utilization of solar cell module assists with regulating laterally the drying air temperature. The outcomes from the examinations exhibit that the drying time for drying of 100-150 kg of chilies in the dryer was essentially not exactly that expected for natural sun drying yet the drying productivity increments with stacking limit" [15].

Janjai et al. in their review introduced "the exploratory and simulated performance of a PV-ventilated solar greenhouse dryer for drying of stripped longan and banana" [16]. "While researching the trial exhibitions of the solar greenhouse dryer for drying of stripped longan and banana, 10 full scale exploratory runs were carried out. Five experimental runs were carried out for drying of peeled longan and another five experimental runs were conducted for drying of banana. The drying air temperature varied from 31°C to 58°C during drying of peeled longan while it varied from 30°C to 60°C during drying of banana" [16]. "The drying duration for peeled longan in the solar greenhouse dryer was 3 days, but 5–6 days was used for drying under natural sun for similar conditions. The duration of drying for banana in the solar greenhouse dryer was 4 days, while it took 5–6 days for natural sun drying under similar conditions. The nature of solar powered dried products as far as variety and taste was great dried items. An arrangement of fractional differential conditions portraying heat and moisture transfer during drying of stripped longan and banana in the solar greenhouse dryer was created and this arrangement of nonlinear partial differential equations was tackled mathematically using the finite difference method" [16]. "The numerical solution was programmed in Compaq Visual FORTRAN version 6.5" [16]. The simulated results agrees well with the practical data for solar drying of peeled longan and banana. The picture of the PV-ventilated solar greenhouse dryer system is as shown in Fig. 9.

2.11 Photovoltaic/ Thermal solar collector (PV/T) Drying System

"A hybrid photovoltaic thermal (PV/T) greenhouse dryer of 100 kg loading limit was developed at Solar Energy Park, Indian Institute of Technology, New Delhi), India. The developed dryer was utilized for drying Thompson seedless grapes (Mutant: Sonaka)" [17]. The hybrid photovoltaic-thermal (PV/T) integrated greenhouse (roof type even span) drying system was developed with a 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° roof slope. Two PV modules were integrated into the greenhouse dryer with (glass to glass; dimensions: 1.20 m × 0.55 m × 0.01 m; 75 Wp each) on south roof of the dryer. The PV module generates DC power which powers a DC fan (inner diameter = 0.080 m, outer diameter = 0.150 m) for forced convection operation and also for greenhouse environment's thermal heating.

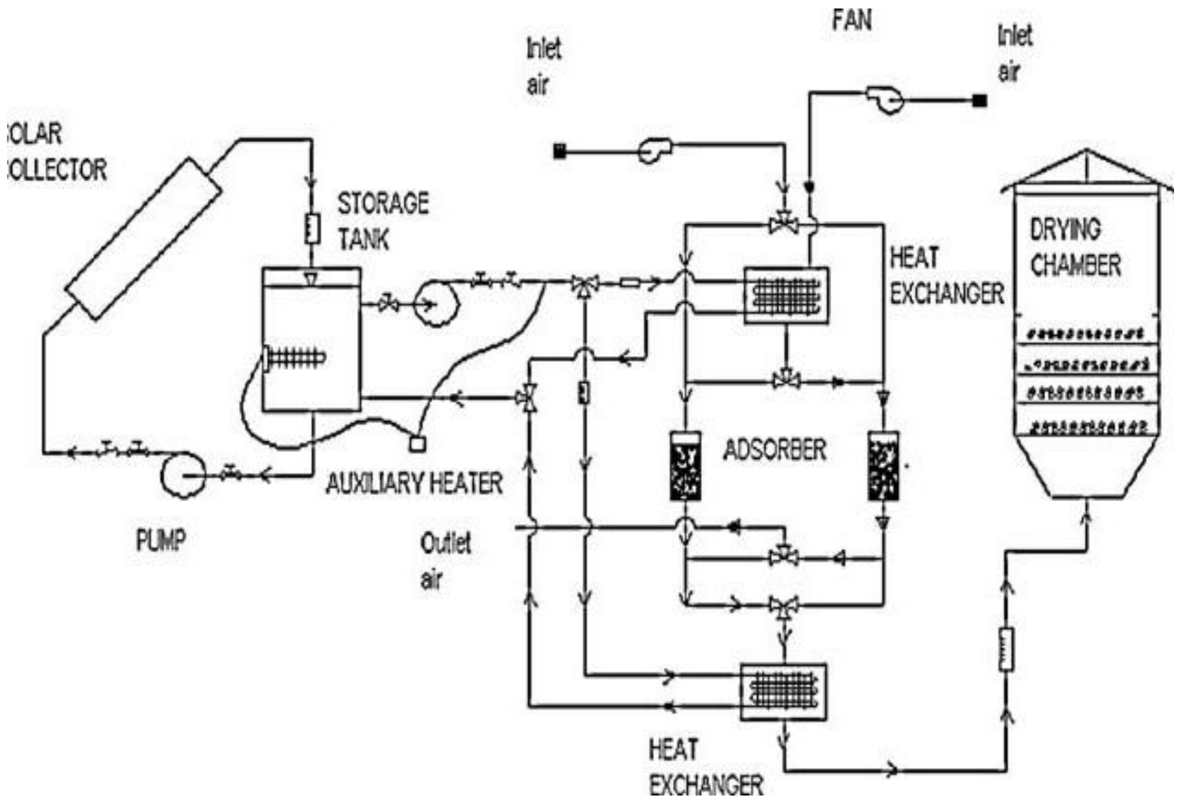

Fig. 8. Schematic diagram of the solar assisted dehumidification system
Source: [14]

Fig. 9. The greenhouse solar dryer
Source: [15]

"Different hourly trial information in particular moisture dissipated, grape surface temperatures, surrounding air temperature and stickiness (humidity), greenhouse air temperature and moistness, and so on were recorded to assess heat and mass exchange for the developed machine. It was deduced that the value of the convective heat transfer coefficient for grapes (GR-I) is between 0.26 and 0.31 W/m^2K for greenhouse and 0.34–0.40 W/m^2K for open conditions, respectively and that for grapes (GR II) lies between 0.45–1.21 W/m^2K for greenhouse and 0.46–0.97 W/m^2K for open conditions, respectively" [17]. The Pictorial representation of the hybrid photovoltaic-thermal (PV/T) integrated greenhouse dryer designed by Barnwal and Tiwari is shown in Fig. 10.

Fig. 10. Hybrid photovoltaic-thermal (PV/T) integrated greenhouse dryer
Source: [17]

2.12 Biomass Hybrid Solar Dryer

“Drying of Cashew nut is one of the most energy-sapping cycles of cashew nut process industry. Based on this, Saravanan et al. designed and fabricated a hybrid dryer consisting of a solar flat plate collector, a biomass heater and a drying chamber as shown in Fig. 11” [18]. “40 kg of Cashew nut with initial moisture of 9% is used in the trial test. The performance evaluation of the dryer is carried out in two series of operation: hybrid-forced convection and hybrid-natural convection. Drying time and drying proficiency during these two methods of activity are assessed and contrasted and the sun drying. The machine is capable of reaching drying temperature within 50º and 70ºC. In the hybrid forced drying, the expected moisture content of 3% is accomplished in something like 7 hours and the typical machine productivity is assessed as 5.08%. In the hybrid natural drying, the expected moisture content is acquired in 9 hours and the typical machine productivity is 3.17%” [18]. The fuel utilization during the drying system is 0.5 kg/hr and 0.75 kg/hr for forced convention and natural mode, individually. The drying process in the hybrid forced method of activity is two times quicker than the sun drying. The dryer can be subjected to any climatic circumstances: as a sun based dryer on normal radiant days, as a biomass dryer at evening and as a hybrid dryer on shady days. In light of the exploratory review, it is reasoned that the created hybrid dryer is appropriate for small range cashew nut cultivators in country areas of agricultural nations.

2.13 Advantages of Hybrid Solar Dryers

“Drying, a phenomenon mostly considered to be an energy- based and economically effective method that can be universally used to improve the shelf life of numerous agricultural and biological products. In order to minimize the amount of moisture present in agricultural materials, likewise to hinder the possibility of microorganism growth and also inhibit deterioration caused from enzymatic reactions, non-enzymatic browning, and oxidation of lipids and pigments, most efficient solar drying system should be considered” [17,19]. Among numerous available methods, hybrid solar dyer is the most professional and economical means of drying biological materials mostly by commercial farmers [20,21]. In order to derive a highly desirable dried products, several hybrid drying systems such as the greenhouse dryer [15,22,23,24,17] and the hybrid solar dryer [4,25,26,5,18] have been introduced. These machines are quicker, more proficient, and more clean, bringing about lower crop misfortunes comparative with the conventional outside sun drying and Indirect and direct sun oriented drying techniques [27,28,29,30]. To get the ideal quality and guarantee a decent return for the fabricators, be that as it may, the machines should be appropriately developed and scaled to meet the prerequisites of explicit agricultural and biological produce and likewise environmental conditions.

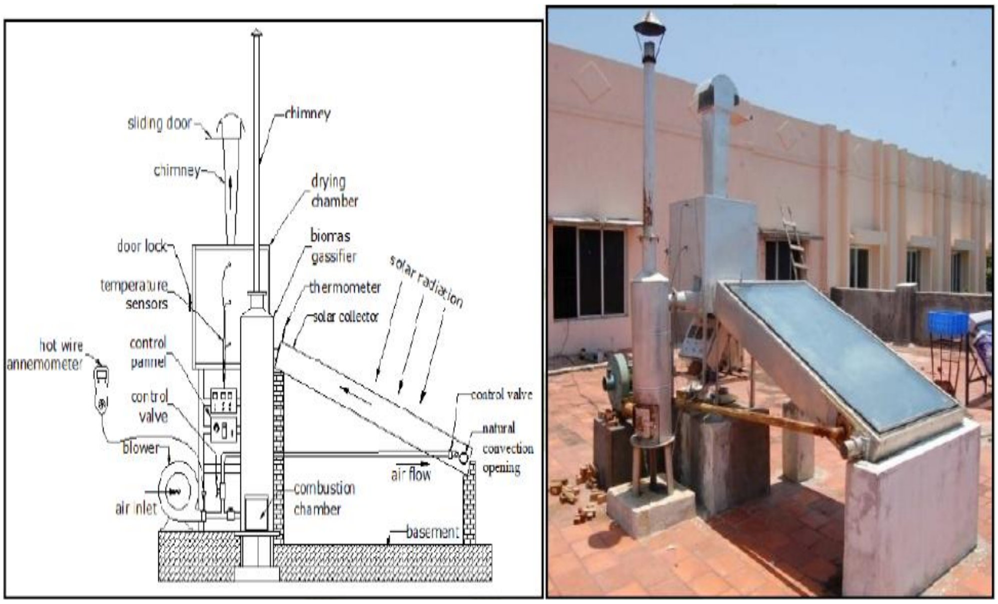

Fig. 11. Biomass hybrid solar dryer
Source: [18]

3. CONCLUSION

This review paper focused on hybrid solar dryers. A comprehensive study of how hybrid solar dryers fare compared to other dryers, various design modifications and enhancement techniques applied to them is done. In this paper, various new improvements to hybrid dryers are also discussed. The Hybrid dryers are the most cost-effective type of dryers and are mostly easy to fabricate and use. Hybrid solar dryers uses auxiliary equipment and protects the products from external contamination and it can use in unfavorable weather condition and also it is used in night time. These are the simplest form of dryers and are easy to fabricate, use and cost-effective.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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