Review Article

A REVIEW ON TREND DEVELOPMENT ON HYBRID SOLAR DRYER

Abstract

The objective of this paper is to present a review on hybrid solar dryer and its modification for further research. Energy is not evenly distributed in the world, developed countries have more than enough while developing countries are facing it inadequacy. Rural areas where agricultural activities are taking place largely have no access to power supply to power drying equipment. Large amount of farm produce of about 30% were damaged due to lack of drying facilities. This has been resolved with the application of evolution of solar dryer and to a better level, use of hybrid solar dryer of exponential value over open air sun drying. It was found that the drying efficiency of hybrid solar dryer was 35%, while the maximum drying temperature was 80^{o}C. Retention time in drying chamber was found to be between 2 – 3 days, it indicate the sustainability of hybrid solar dryer for drying high moisture farm produce. Various design of solar dryer and hybrid solar dryer were reported in the literature thus for is presented. Hybrid solar dryer could be developed further with the inclusion of dehumidifier as a system aiding drying.

Key words :Solar Drying System ,Agricultural Produce, Photovoltaic, Heat Exchanger

Introduction

Sun as the only source of energy to the planets in the solar system is fundamentally essential to their functions. Earth being placed fourth in the solar system has a good positioning for the development of all relief in support of habitants, relative to their survivor (Ahmed 2010). Globally increase in demand for energy in human activities as made it a priority to find an alternative of other source of energy, most importantly a renewable source of energy to complement or substitute non-renewable sources of energy (Khan *et al*. 2011). The rate of depletion of fossil fuel, discharge of carbon monoxide, chloro-floro carbon CFC, deterioration of ozone layer, has become a great challenge to us all, and requires bringing together all parties in technical innovation and energy management. (Kazem, 2011). This gave rise to a holistic practical approach in dealing with this herculean task. Several renewable energy sources have been named, solar, wind, biofuel, etc. are all alternative sources with high level of reliability. It abundance state and friendliness to the environment has made it recommendation encouraging to the global world. Unequivocally, non-renewable energy is less harmful and with zero level of emission of hazardous gasses (Duffie *et al*. 2013).

It has been advised to shift towards annexing maximum potentials of solar energy. Solar is sub divided into two solar photovoltaic PV and thermal collectors (Maor and Appelbaum 2012). Photovoltaic is used to produce electrical energy which is either supply directly for final use of stored in a battery cell (Gan *et al.* 2017). Thermal collector is being used in two forms, heat accumulator in drying chamber of solar dryer system and heat exchanger. Advantages of distinct characteristics in solar energy makes it differ, abundance, free-cost and no emission (Hernandez *et al.* 2014). Uses of solar energy is known in the residential community, commercial for small and medium enterprise and industrial at various stratum of production. Many electronic application of solar energy system are water pumping system, residential solar heat exchanger, pre heating for industrial purpose, solar assisted heat pump (Chauhan 2015). Several electronic device were powered by solar energy, this include but not exhaust the following, sound system, touch light, grinding machine, iron, water heater, printing machine etc. Nowadays; transport system are now powered by solar energy, this cut across air transport system, road and rail transport system and water transport system (Slimani *et al.* 2017). In recent years this approach on solar energy maximization has reduce dependency on fossil fuel and enhancing clear, safer and better environment (Li *et al.* 2019).

Solar energy is the largest available renewable energy supply, it conversion to electrical energy is subjected to law of conservation of energy, "energy can never be created nor destroyed but can be trance form, from one form to another" (Cheema 1978). Solar insulation which is in form of radiant light energy is being converted to electrical energy with the use of photovoltaic panel PV. Photovoltaic plate is made of crystalline silica, unit cells, junction box, backplane, and cable that the cells to form a complete circuit (Yahya *et al*., 2016). The tempered glass cover is to protect the main body of power generation and the selection of light transmission: transmittance must be high about 91% and super white tempered treatment. Cells have only one function which is the most important – to generate electricity. Waterproof tendency in the panel and insulation, sealing are all functions of the backplane. Aluminum alloy protect the laminate, play a certain role in sealing and resist aging. Junction box functions as a protector to power generation system and act as a current transfer station. Silica gel as its name implies, functions as seal between the component and the aluminum frame inclusion of the junction box (Kuan *et al*., 2019). Though; in some occasion double sided tap or foam were used instead of silica gel. All these material used must be resistant to aging, some solar panel manufacturing company do issue 25 years warranty.

On the other hand, solar for thermal power is being used in heat engines, domestic water hot heater, drying, cooking etc. in the case of dying several form of solar dryer is being developed, further innovation gave rise to hybrid solar dryer to complement the efficiency of solar insulation in solar dryer (Elangovan and Natarajan 2021). Several heat sources have been incorporated, electrical heat source, heat pump and coal. Composition of solar dryer are sola collector, glass lase, black metal sheet with high heat capacity, suction or axial fan to direct air convention, drying chamber, chimney and other heat source in the case of hybrid solar dryer (Jangde *et al.*, 2021). A number of tray are placed in the drying chamber, but dependent of the type of produce to be dried, grains, fruits, vegetables, sliced tubers, and crops. Moisture content of produce also affect the agreement of trays in the drying chamber, inclusion of heat and mass transfer rate (Janjai *et al*., 2009). Drying rate was dependent of some drying factors like, temperature, humidity, air velocity, which were put in consideration while designing solar dryer.

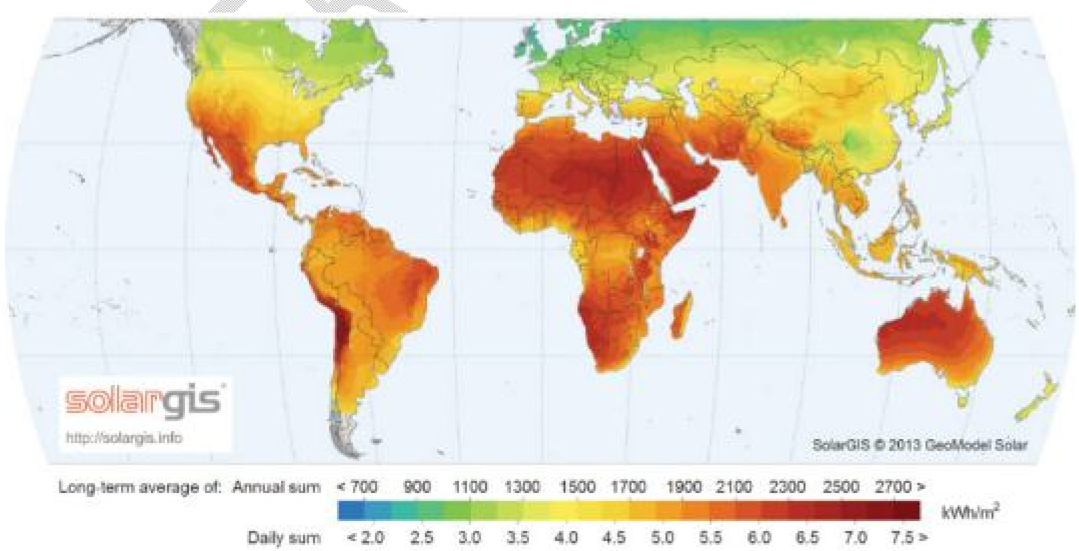


Figure 1. World map of global horizontal irradiation

Agricultural produce are product with high moisture content, though; it varies base on class and family of the produce. Post-harvest operation takes place immediately after harvest, processing harvested produce further by different level and steps of processing operation. Grains, fruits and vegetables are agro produce that are known for their richness in vitamins, high concentration in moisture, fiber and low fat (Fellows 2017). These are seasonal in production and are mostly available in their fruiting season. Despite increase in production of grains, fruits and vegetables human demand has not been met. Damages of produce after harvest is responsible for this inhibition which arises from mechanical factors during harvest, biological and biochemical actives (Sendhil *et al.,* 2022). Most damage occurred at the fresh state of produce or unconducive storage condition. Poor handling, bad transport system, lack of accuracy and precision in harvesting device and unorganized market system could also responsible for this damage. Innovation and development should be made to improve the technicalities of food processing, adaptive modification of machines and handling processes will reduce losses in agricultural production. Packaging of goods should be given utmost priority to prevent quick damage and elongate shelf life of produce (Assadeg *et al.,* 2020).

Drying is one of numerous ways of improving and preserving agricultural produce. Sun drying has been known from time immemorial, but still the most common method of drying in countries in tropical and sub-tropical part of the world. It has merit of no or low capital or cost of maintenance, expertise of no significance is required (Mendoza-Miranda *et al.,* 2016). Open air sun drying is possible in countries where weather condition allows dry immediately after harvest. On the contrary, protection of drying produce in sun drying from rain, wind, dust has been a difficult issue, has well as that of birds, rodent, insect and other animals, causing deterioration to the quality and quantity of produce (Atul *et al.,* 2013). Some produce are not fit for sun drying, volatility content and color do change to the extent of losing large nutritional value and economic value in domestic market and international market. Great deal of challenges in open air sun drying can be solved with the use of solar dryer (Lin *et al.,* 2022). Conditions in tropical countries allows the use of solar dryer and makes it attractive, productive and environmentally sound. Dryers have been developed and used to dry produce, preserve it and improve it shelf life. Remover of moisture in agric produce and reduction in size and volume are important for further processes (Huy 2018). Dryers are powered by electrical source which comes at an expensive rate. Solar dryer is an alternative means of drying which is cheaper and can be handled by rural farmers without any difficulties. Nowadays solar dryer has come in different forms to the extent of fabricating hybrid solar dryer.

Types of solar drying system.

There are three major types of solar drying system known, significations direct solar dryer, indirect solar dryer, force circulation solar dryer. In direct or natural convective dryer, products are placed in shallow layers or tray, with black end closure and a transparent cover (Zomorodian *et al*., 2004). Solar insulation are directly falling on the agricultural produce, absorption of solar radiation is dependent of the nature of the produce. The food produce is heated up and moisture from the product evaporates, rate of evaporation also influenced by heat emission from the blackened end. Evaporated moisture moved out through natural convective circulation. Indirect dryer has a drying chamber where the food produce is placed. It has a solar collector where air is heated by solar radiation and blown into the drying chambers. In some cases drying product receive heat from the sun and also heated air from solar air heater collector (Mohanraj and Chandrasekar 2007). In peculiarity with this type of solar dryer, manipulation of drying factors like temperature, humidity and drying rate is allowed to a certain extent. Force circulation dryer was designed to allow continuous blowing of hot air over the food product. The retention time of produce in this dryer is short, loading and unloading of food is done at intermittent rate. Comparatively the thermodynamic efficient of this dryer is high and can be used to dry big size product and of large volume. It design has no definite form as well as the heat flow pattern, sometimes cross-flow type, concurrent flow type, in some counter flow type (Hossaina and Bala 2006).

Advantages of solar drying system

Drying rate in solar dryer is greatly dependent of high temperature, air velocity, and humidity rate and sun intensity. Product can be left in the drying chamber of the dryer without interference of wind, rain and flies. Drying process could continue over night from the day sun solar drying without any contact with dust, dew, mist or frog which could contaminate the quality of food (Majid *et al*., 2009). Quality and quality of produce in this drying system is maintained, while the colour remain attractive and stand for value at any level of marking. Harvesting at early stage is allowed and reduction in field losses was minimized if not eradicated. Planning of harvesting season is now well organized and allowed all year round since drying as a means of processing could be done at any time. Quick deterioration and spoilage in storage facility is being averted, since drying is process of elongating shelf life. Produce are better handled in dried state than wet, therefore easy handling was enhanced by this unified drying. Cost and mode of transportation of dried material are more easer and safe (Yahya 2016). Economic value of produce was increased and farmer or manufactures are making more money than their prediction.

Disadvantages of solar drying

A distinct demerit of solar drying system is the limited time of solar isolation in the day time. It is not influenced by variation in the length of day and night, weather longer day nor shorter night the duration of isolation is between 9:00 am and 5:00 pm daily. Longer retention time of drying of some agricultural produce was not precisely overcome, hence there could be need for hybridization (Msomi *et al.*, 2017). Contamination of produce though, low in significance, but still need to be taken seriously in achieving better condition of drying. Quantum of heat energy required is in variance with the predicted value of drying capacity. Cost invested in design and fabrication of solar drying system is very high.

Development of Solar Dryer to Hybrid Solar in a Periodical Array.

El-Amin *et al.* (2006) in their research work on natural convention solar dryer of box-type cabinet dryer mode was design and constructed. The component of this dryer was solar collector, drying chamber combine in a unit system. The solar collector area was 16.8 m^2 and is expected to dry 195.3kg of fresh mango and 100 kg of sliced mango from initial moisture content of 81.3% to final moisture content of 10% in two solar day drying time under ambient condition. A prototype dryer with 1.03 m^2 solar collector area was constructed to conduct an experiment on drying. The average ambient temperature obtained was 30oc and relative humidity of 15% with air flow rate of 0.0903 $kgs\text{-}^2$ and daily global solar radiation incident on horizontal surface of about $232\ wm^{-2}$ for drying time 10 hours per day.

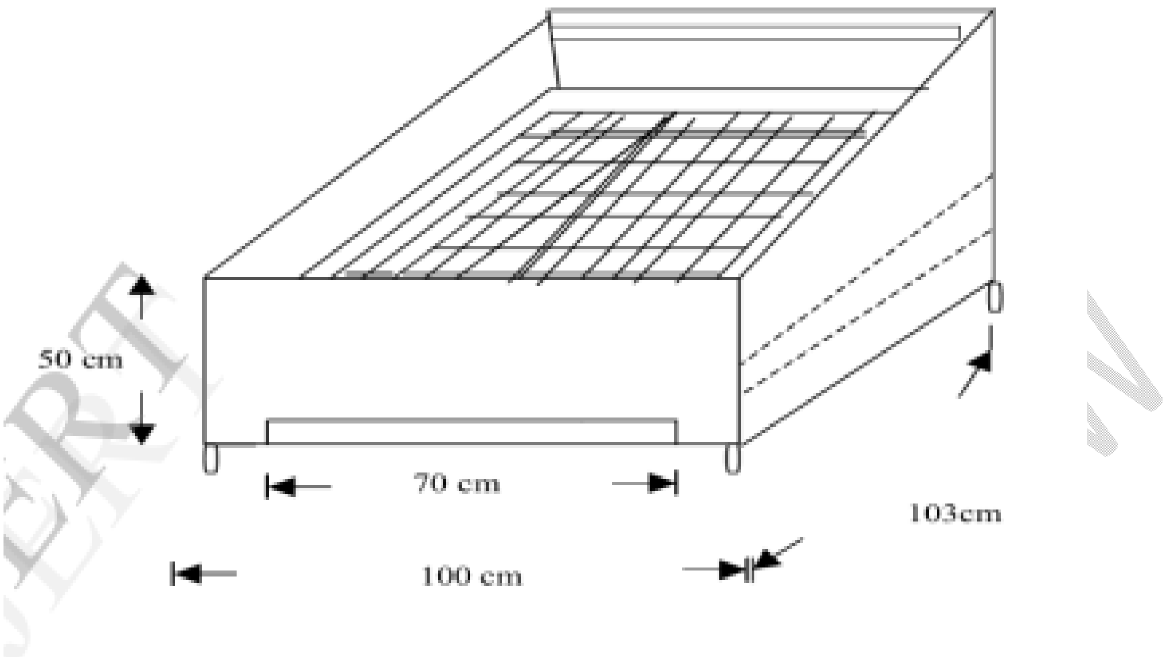


Figure 2. Isometric view of constructed solar dryer

Mohanraj and Chandrasckhar (2007) developed a force convective solar dryer in their research of drying copra under Indian climate conditions. During this period maximum solar intensity of 932 wm^{-2} was obtained. Average relative humidity of about 68 % and drying temperature at inlet point of dryer was 43^{o}C while maximum air drying temperature obtained was 63^{o}C. The outlet point of drying chamber has different values of drying factors, the relative humidity at this part was 90% at initial instant f drying though reduced gradually as drying process proceeded. Relative humidity of 34 % was now recorded at final stage of drying. Average moisture content of coconut was reduced from 51.8% to 7.8% and 9.7% in the bottom and top tray respectively after 82 hours of drying. Moisture content reduction in the first two days of drying was recorded to be about 33% and 20% respectively. Thermal efficiency of solar air heater was reported to be 24%. It was finally reported in their report that force convention solar drier is far better in performance, producing high quality copra for small scale holders. High quality copra of about 75% was produced from force convective solar dryer. Further development of force convective solar dryer was hybridized solar dryer, revolution of innovations in solar drying systems was a transition in food processing and storage.

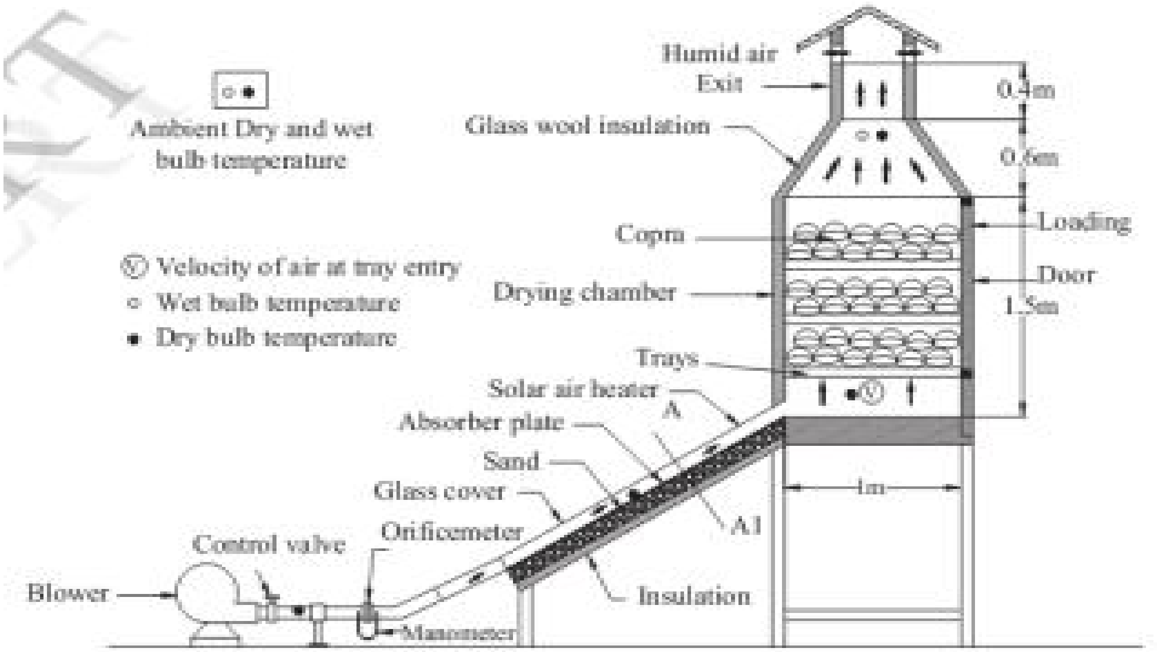


Figure 3. Sectional view of solar drying system used for copra drying

Rathore and Panwar (2007) conducted research work on solar dryer using hemi cylindrical walk-in type of solar tunnel dryer for drying grapes. It was design for large volume drying, majorly for industrial use. Peak thermal capacity permissible inside the dryer was 65^{o}C coupled with average solar radiation 2.3MJm^{-2}h^{-1} within a 10 hour drying duration per day for drying 320 kg of grapes. Specific heat capacity of air 1.012 kJkg^{-1}k^{-1} allows the reduction of moisture content initial stage of 85% to final stage of 16% in a range of 7 days drying time using tunnel dryer with 30% dryer efficiency.

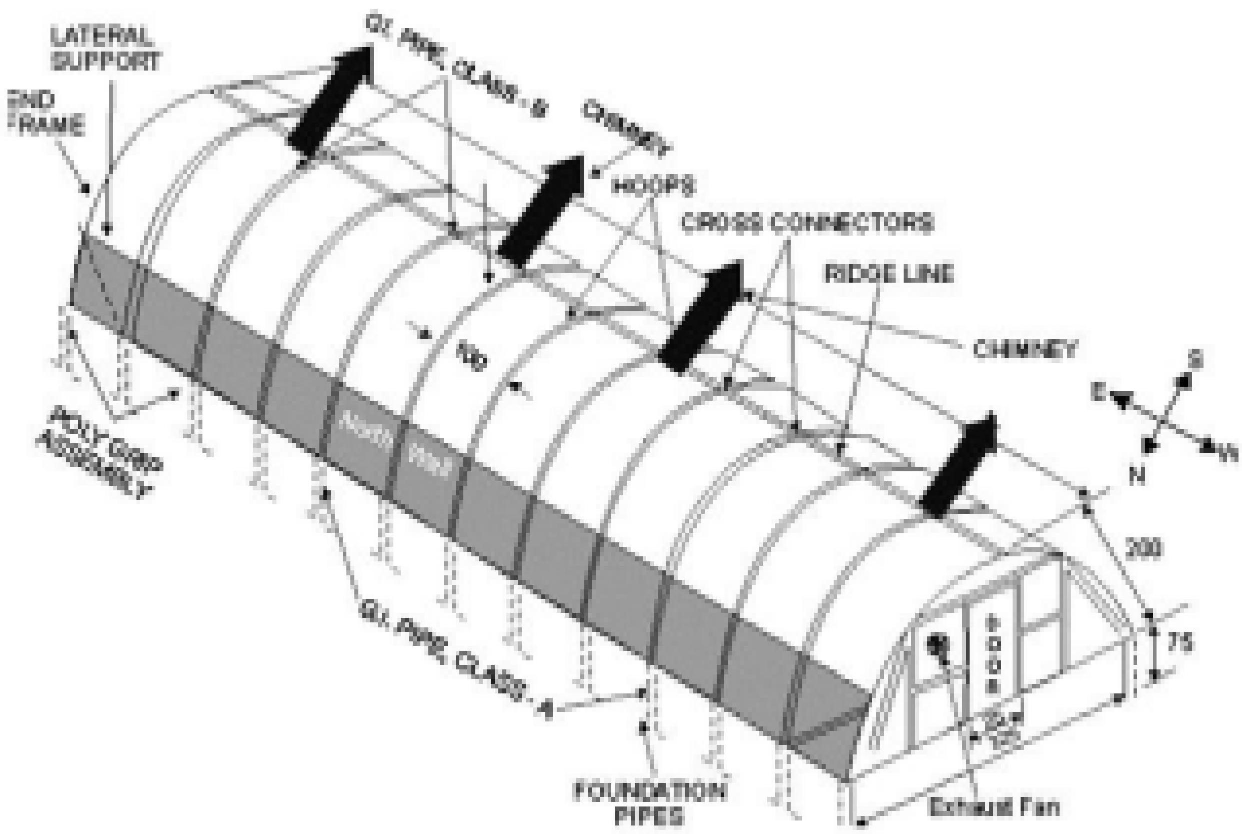


Figure 4. Isometric view of hemi-cylindrical solar dryer

Ahmed (2010) developed a solar drying system of cylindrical section system; thermal analysis was conducted as part of the performance and efficiency of the dryer. It contains a cylindrical drying chamber, with three layers of tray. It has a solar collector of length 1.10 m and width of 1.10 m drying chamber, inclusion of an axial fan designed for the purpose of 70 kg of bean crop. Performance evaluation of solar air collector using three air flow rate was tested. The highest temperature of 71.4^{o}C of solar collector outlet was obtained at 11:00 am. He further reported radiant intensity was 750wm^{-2} for air flow rate of 0.041 kgs^{-1} was recorded while minimum temperature of 40^{o}C was obtained while the air flow rate was 0.0675 kgs^{-1} at radiant intensity 460 wm^{-2}. Maximum thermal efficiency of 25.64% of solar air collector was achieved at air flow rate 0.0675 kgs^{-1} and minimum average thermal efficiency of 18.63% at air flow rate 0.0405 kgs^{-1} was obtained. Initial moisture content of beans was 70% while flow rate was 0.0405 kgs^{-1} while the finial moisture content was 14% at air flow rate of 0.0765 kgs^{-1}.

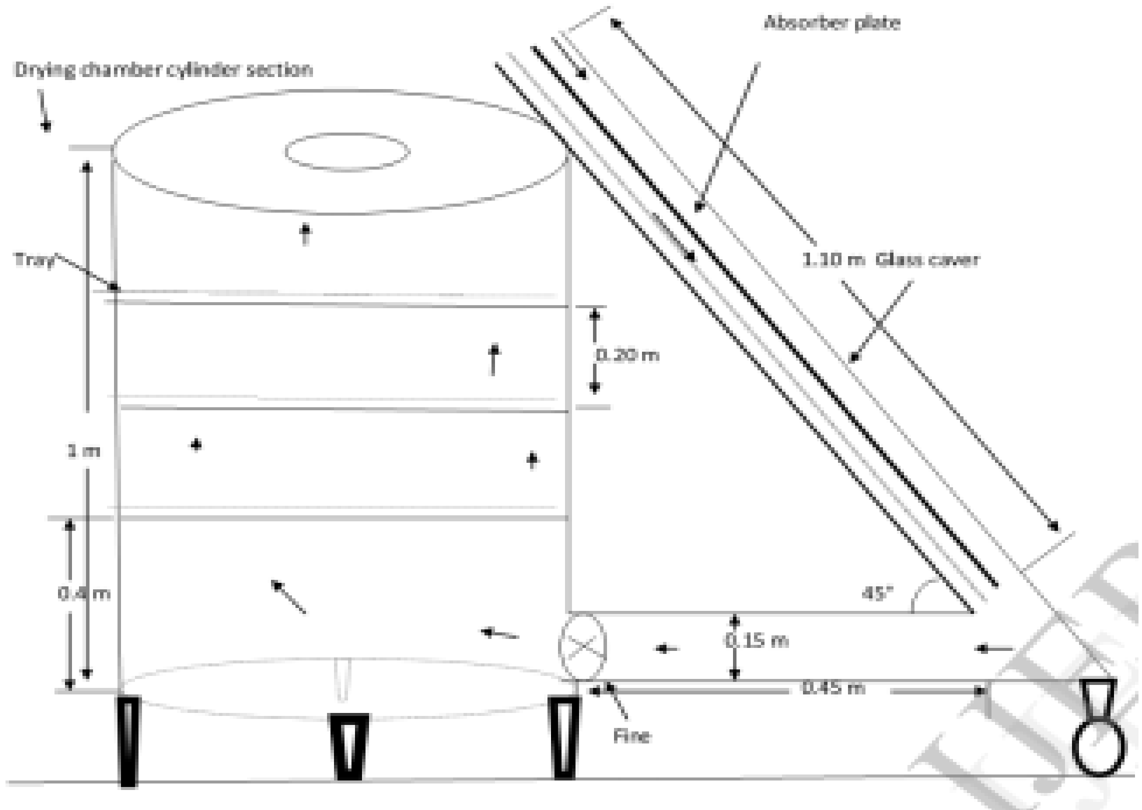


Figure 5. Sectional view of cylindrical section of solar dryer

Amer *et al.* (2010) developed a hybrid solar dryer, designed and fabricated using direct solar energy and heat exchanger as alternative source of heat. Efficiency of the soar dryer was optimized by recycling hot fluid from the heat exchanger in multiple times. Heat loss was minimized to the outside air with little exhaust integrating the efficiency to 65%. Hot air temperature could be raised above the ambient temperature in Mid-European summer from 30^{o}C to 40^{o}C. Dying capacity of dryer was predicted to be 30 kg of sliced banana for 8 hours in sunny day. In all; initial moisture content of 82% w.d was reduced to final moisture content of 18% w.d, while open air sun dry could only dry to 62% *wet basis* wb moisture content. An advantage of hybrid solar dryer over other forms of solar dryer manifest in the experimental work.

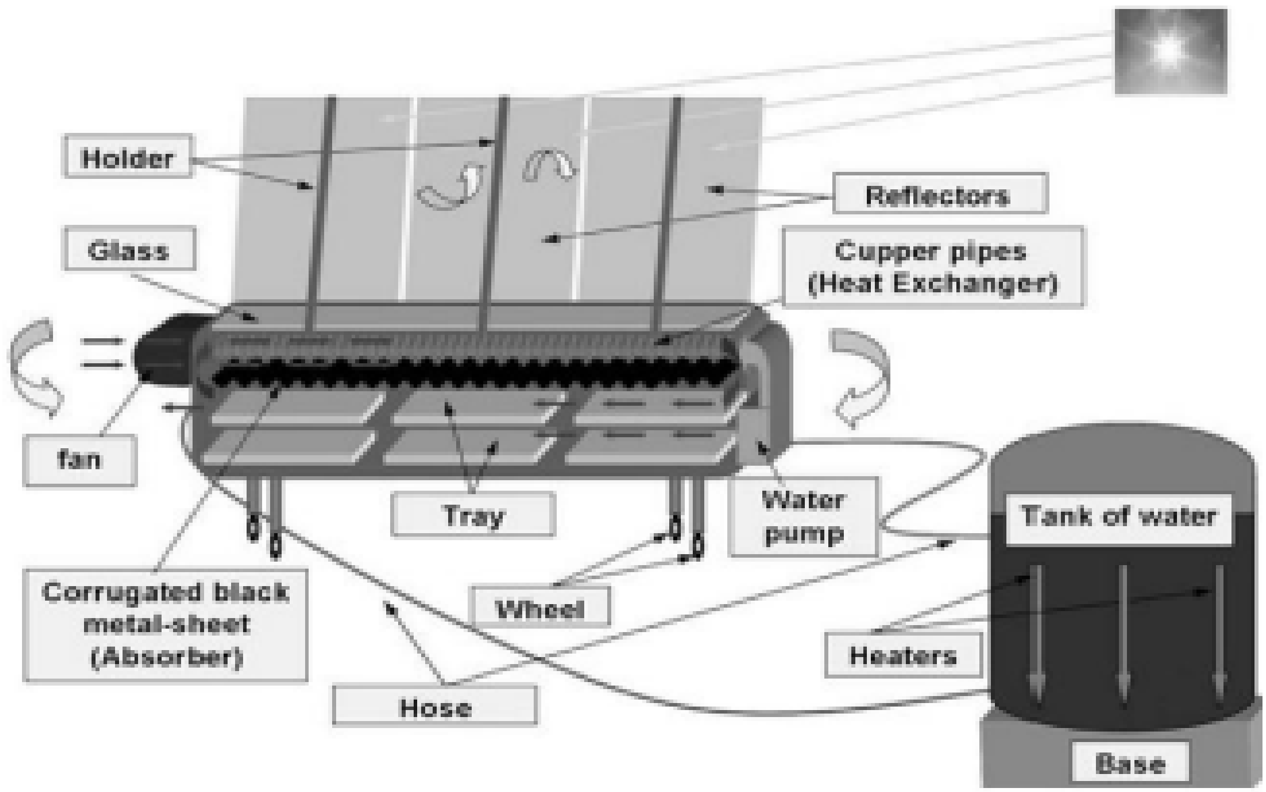


Figure 6. Heat exchanger assisted hybrid solar dryer

Drying of some cash crop requires high temperature due to possession of hard cover, which necessitate energy intensive process. Saravanan *et al.* (2015) designed, fabricate and evaluate a hybrid solar dryer consisting of solar plate, solar collector, biomass heater and a drying chamber. A 40 kg load of cashew nut with initial moisture content of 9% was used for the performance evaluation of the biomass heater solar hybrid dryer. Drying process was sub divided into two modes of operation, hybrid-force convective drying system and hybrid-natural convective drying system. Drying parameter like drying time, drying efficiency of force convective and natural convective drying system were compared with sun drying. Temperature of drying was between 50^{o}C and 70^{o}C in the hybrid force drying while a moisture content of 3% of the cashew nut was attained within drying duration of 7 hours. The required moisture content was attained in a longer time of drying in natural convention, retention time of 9 hours. Fuel usage in biomass during drying process was 0.5 kghr^{-1} and 0.75 kghr^{-1} for force mode and natural mode respectively. This dyer could reduce the drying time and increase drying efficiency if the following modification was made on it: providing parabolic reflector on both side of the collector, increasing the absorptivity of the absorber plate by replacing copper plate with aluminum one, increasing air flow rate and providing electric heating coil. The developed cashew nut dryer is move suitable and recommended for cashew nut farmers in rural areas of developing countries.

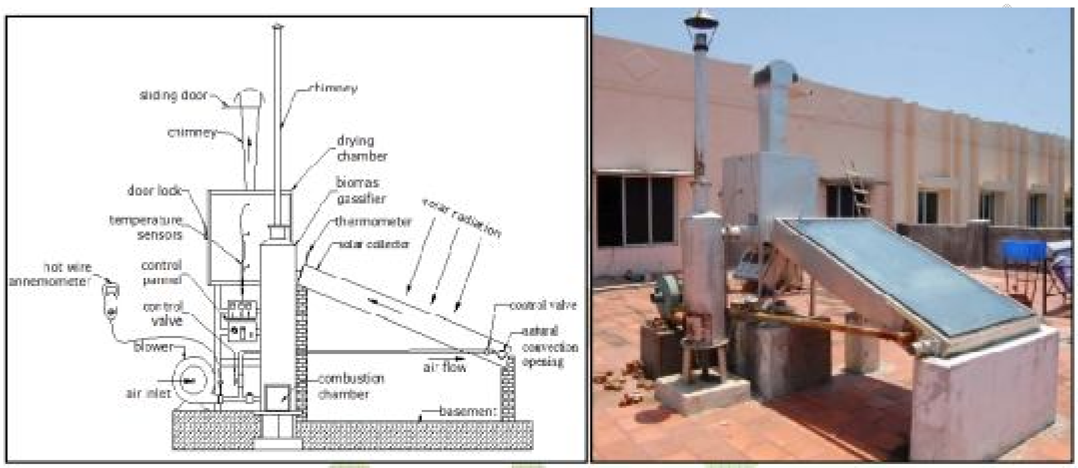


Figure 7. Biomass heater hybrid solar dryer

Further research on hybrid solar dryer is still on going, Yahya *et al*., 2016 design soar assisted heat pump dryer for cassava. Component part of solar assisted heat pump dryer SAHPD are solar collector with other sub component like, transparent cover glass material, absorbent finned plate made of aluminum coated with black opaque colour. Angular iron frame interior and exterior part coated with 1 mm thickness aluminum and insulation using fiber glass materials. Two solar collector of area 1.8 m^2 each were connected in series. Heat pump component are evaporator, condenser, compressor and expansion valve. Performance evaluation of solar dryer (SD) and solar assisted heat pump dryer (SAHPD) for drying of cassava chips was conducted. SD and SAHPD decreased the mass of cassava from 30.8 kg to 17.4 kg with in 13 and 9 hrs at average temperature of 40^{o}C and 45^{o}C, respectively. Moisture content of cassava chips was reduced from 61% w.b to 10.5% at a mass flow rate of 0.124 kg/s. average thermal efficiency of SD and SAHPD was 25.5%and 30.9% respectively. During drying the average drying rate and specific moisture extraction rate were 1.33kg/hr and 0.38 kg/kWh respectively in SAHPD while SD as 1.93 kg/hr and 0.47 kg/kwh respectively. The zenith efficiency varied for SD in their experiment was 3.9% to 65.3% while SAHPD has was between 15.9% and 70.4%, both had an average value of 39.3% and 43.6% respectively. Solar fraction of SD and SAHPD were 22% differ, situated at 66.7% and 44.6% respectively. Coefficient of performance of heat pump ranged from 3.23 to 3.47 with an average value of 3.38, below is the schematic diagram of the solar assisted heat pump dryer.

Figure 8. Solar assisted heat pump dryer (SAHPD)

Hybrid solar dryer has been a potential method of annexing solar usage for drying and further developed for optimized efficiency. Houhou *et al*. (2017) develop a solar heat pump dryer directly driven by photovoltaic panels. The outcome of the result affirm that temperature of drying air is crucial external parameter compared to the velocity. Increase in drying temperature from 45°C to 55°C reduced the moisture content from 0.75% to 0.3%. Component part of this solar heat pump dryer is divided into two main part drying chamber and heat pump system.

There are some other components made up the heat pump: condenser, evaporator, compressor, and the expansion valve. Two major cycles are involved in the performance of this dryer; the vapor-compression refrigeration cycle and drying air cycle. Functions of the vapor compression refrigeration cycle depends on four steps compression, condensation, throttling and evaporation.

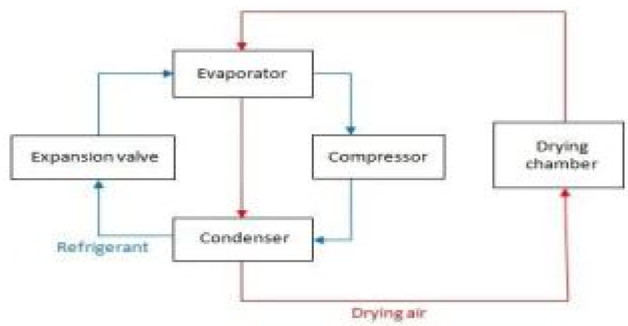


Figure 9. Description scheme of the heat pump dryer system

Aremu *et al*., 2020 in their research work in the design, fabrication and performance evaluation of hybrid solar dryer. The hybrid solar dryer was integrated with solar panel, using solar energy and electrical energy. A solar collector, drying chamber, and three trays of dimension 1.30 x 1.4 m. four photovoltaic cell PVC modules powered the heating element and charging of 200 AH tubular battery for the purpose of operating the DC fan. This model is design to serve as solar dryer and solar hybrid dryer. Evaluation of dryer was carried out using 10.5 kg of fresh yam slices, it drying rate was compared with direct open sun drying under same atmospheric weather condition. From the outcome of their result ambient temperature at 2 pm was 36.5°C while the solar collector and drying chamber was 64.5°C and 51°C respectively. Moisture content of freshly sliced yam reduced from 89% to 33% in ten hours of drying at drying rate of 0.8776 Kh/hr in open air drying. Moisture content reduce from 89% to 20 % in 10 hours at drying rate of 0.9056 kg.hr in solar drying, while hybrid solar dryer recorded decrease from 89% to 7% in ten hours, with drying rate of 0.9258 kg/hour. This result indicate that hybrid solar drying is faster and better than open air drying in multiple of times. Solar drying is of good efficacy but hybrid solar drying is far better in capacity and efficiency. The overall efficiency of the hybrid solar dryer was identified to be 66.7%.

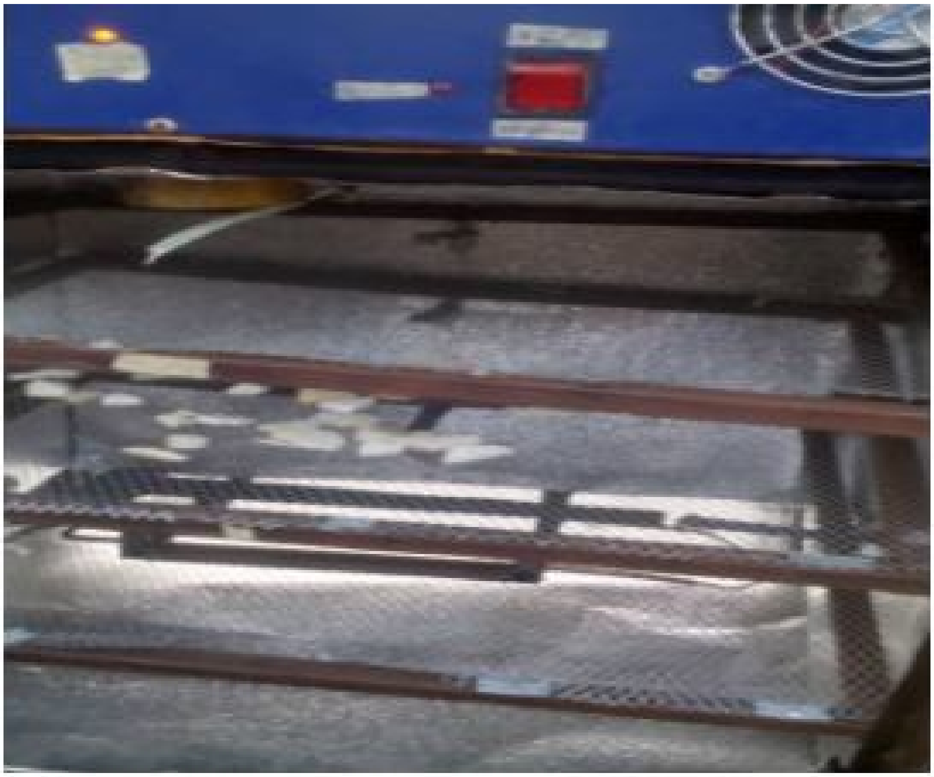


Figure 10. Hybrid solar dryer coupled with electrical heating element

In 2021 Pimpam *et al*. conduct a research work on fabrication and testing of double – sided solar collector for drying banana. The solar collector was inclined at angle of 15^o to the ground with a receiving surface of 7 m^2. Banana chips took 5 days for it drying time, reduced the moisture content from initial stage of 68.5% w.b to final moisture of 17.4% in the dryer and 27.3% in the open-air sun dry. From their result, highest drying temperature of 62.7% was attained in the drying chamber, while the average drying temperature was 54.1%, this was 13.6% higher than open air sun drying system. The drying rate of the solar collector dryer reduced the banana moisture content from 1.3 to 1.5 times faster than that of sun drying. Thermal efficiency for the dryer was 13% while that of solar collector was 21.9%. The efficiency of drying chamber id dependent of solar collector's capacity. The component part of this solar dryer are double solar collector, drying chamber and chimney, all perform different distinct significant functions. Bananas of 10 kg weight was assumed to be the testing weight during the experimental work. Daily drying time predicted was between 9:00 am to 5:00 pm to attain the predicted bone dried moisture content for the banana.

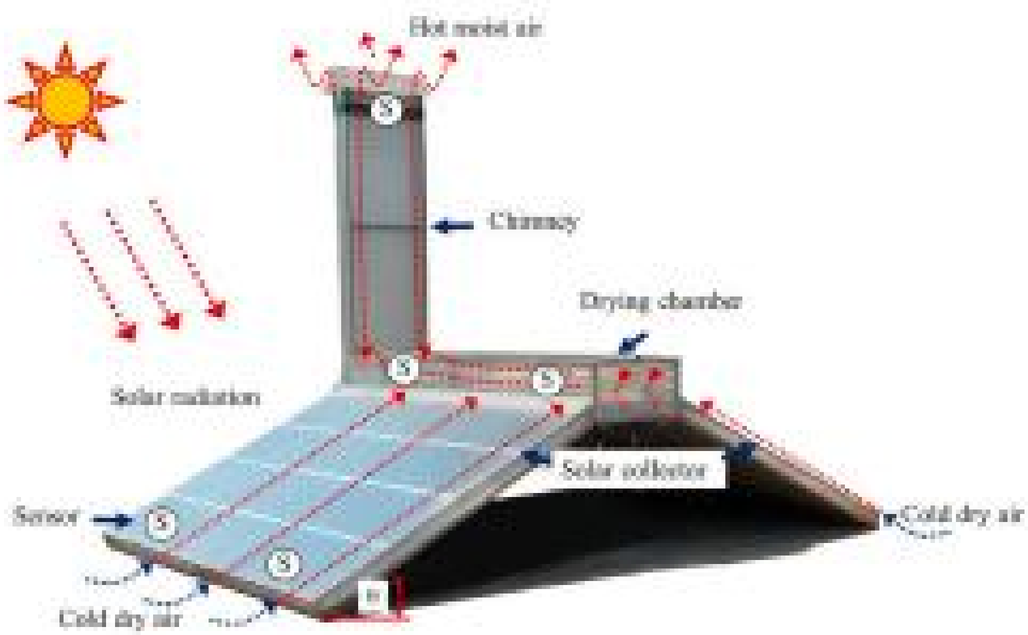
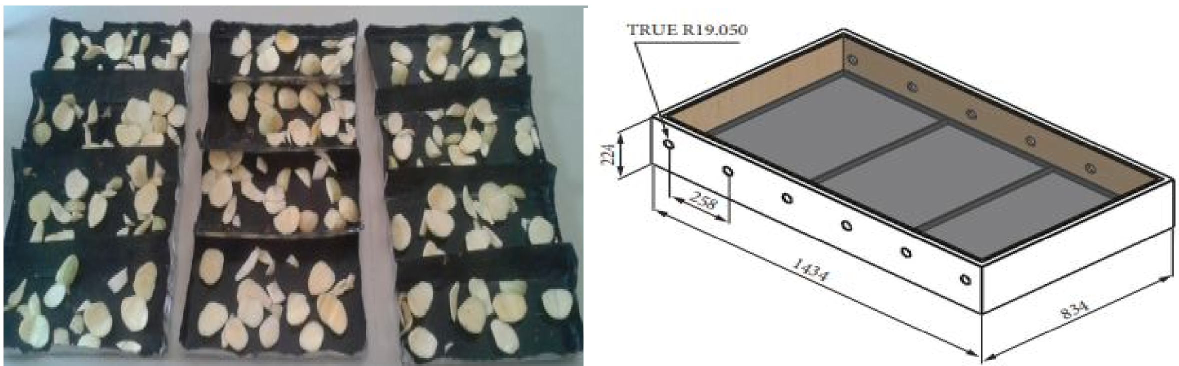


Figure 11. Double-sided solar collector dryer

Kumred *et al.* (2022) design a solar dryer to reduce rate of damage in agricultural produce, simplicity of design is very crucial to designer most importantly the final user accessibility. Their solar dryer was constructed with just four components, each has a distinct function. The plywood box was made and painted black, being a bad conductor it heat capacity is very low, and required no insulation. A glass component functions as a cover, it transparency allow much insulation, though; some light beam was reflected. It is directly placed on the drying chamber and captures solar radiation. Trays made of aluminum and coated black were used to increase the absorptivity. All drying product were place on the trays and were insert into the drying chambers. There were braze bars on the tray to prevent free flow of the drying produce while placed at an inclined angle in the drying chambers. Thermocool functions as insulator in the solar dryer and is placed on the external surface of the dryer to reduce heat loss. Holes of about 1.5 inches were constructed on the drying chamber made of wooden box to allow air circulation and optimum heat and mass transfer. Black paint were used on the trays and drying chamber since black colour absorb more radiant heat than other colours and will aid drying process faster.



(A) **(B)**

Figure 12(A-B). Solar dryer designed for drying fruit and vegetable

Agricultural process in the rural area requires urgent attention in the area of food processing to avert rate of losses of agricultural produce. Gunawan *et al*. (2022) considered the huge economic loses coming from damages of food as a consequence of inadequate drying facilities. Moisture content of farm produce are mostly higher than 45% which must be reduced to bone dried level for the purpose of preservation and increase shelf life of produce. Drying process must be continuous to attain good outlook and quality to gather economic value at both local and international market. Solar dryer for day functions could not spring up this projection, hybrid solar dryer of exponential heating power must be able to enhance continuous drying systems. In their research in drying, a solar dryer dome similar to a greenhouse was constructed. The height of the dome was 3.5 m, area of 6 m x 8 m and volume of the dome is approximately 125 m^3. It was made Smart Solar Dome SSD by considering the energy required for operational purpose. Power that was needed for it operational motive are internal ambient conditioning, sensing external environmental condition, energy stored for night time usage, close control system, data processor all these are mechatronics components. Solar smart dome must position in a technical manner to align with North-South axis of the globe.

Figure 13. Solar dryer dome design

The present modification in solar dryer evolved hybrid solar dryer after considering all drying parameters that are required in both internal and external impact of these parameters. Deficiencies in hybrid solar dryer which is largely on volume of drying chamber was further research. An outcome of new innovation on drying equipment was establish, hybrid greenhouse solar dryer became a form of dryer to look into in the field of drying. Effect of modification on various heat transfer parameters like heat transfer, drying time, drying efficiency, relative humidity etc. were studied and encapsulate for further research and improvement (Singh and Gaur 2022). It was reported that most hybrid dryers have drying temperature of about 65^o- 80^{o}C in their drying chamber. This is a positive indication in capacity of hybrid solar dryer to dry high moisture farm produce. Retention time of drying was about 2-3 days, shows the fast rate of moisture remover during drying process. Many literatures reviewed, it was unequivocally stated that the maximum drying efficiency in hybrid solar dryer was 35%, which was later improved by the advent of hybrid greenhouse dryer.

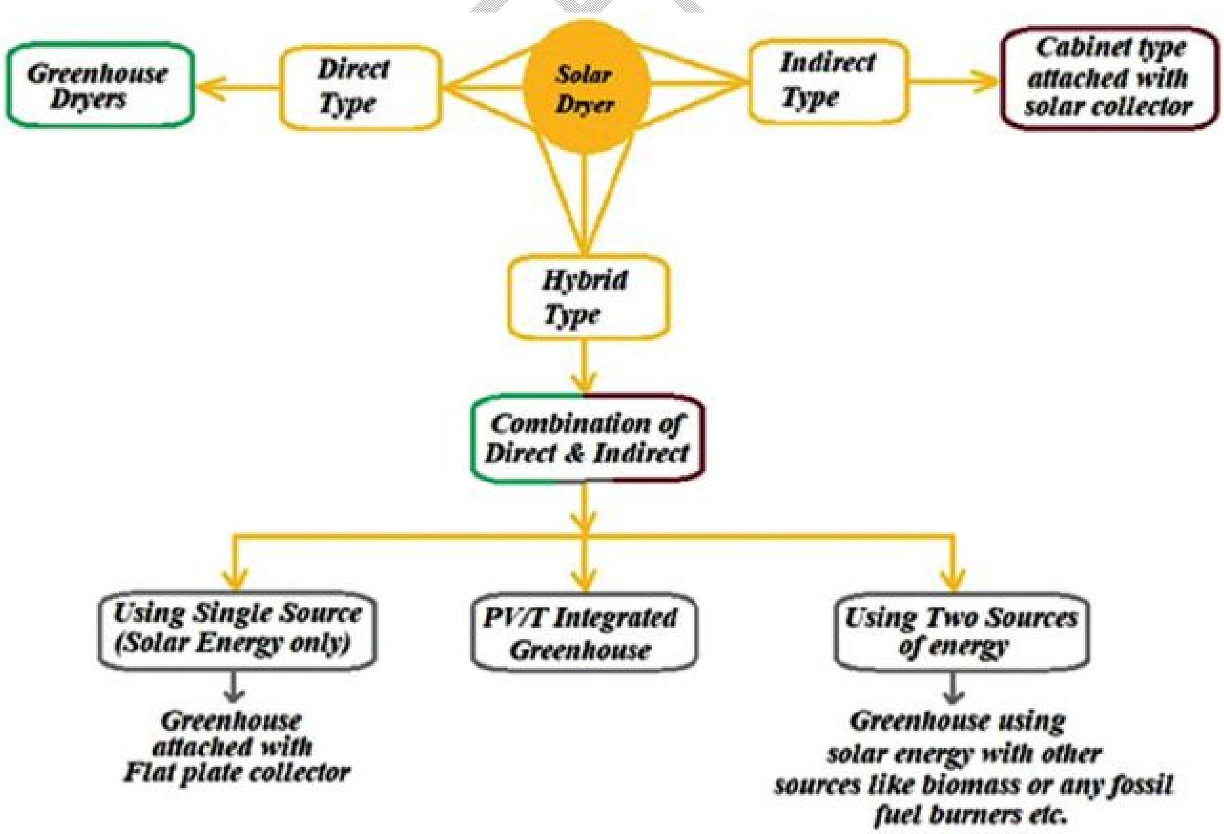


Figure 14. Flow chat of hybrid solar dryer construction system.

Table 1. Different solar dryer for drying different agricultural produce at different drying rate and moisture ratio.

DRYER	SAMPLE	REMARK	DATE
Double Pass solar dryer V-groove DPSD(V)	Herbal tea	Moisture reduction from 87% to 54 % (wb), air flow rate: 15.1 m^3/min, Drying temperature 50^{o}C, solar collector area 15 m^2	2011
Solar assisted chemical heat pump drying system (SACHPDS)	Lemongrass	Moisture content reduction from 85% to 13 %(wb), COP 2, Air flow rate 1-3ms-1, Drying Temperature 55^{o}C	2022
Solar-Assisted Dehumidification System (SADS)	Medical Herbs	Relative humidity:40%, temperature: 35^{o}C, Air velocity: 3.25ms^{-1} Efficiency:70% cop:0.3	2020
Double Pass Solar dryer with fins DPSD(F)	Seaweed	Solar collector area 11.52 m^2 Drying Temperature 50^{o}C, Air Flow rate 15.1 m3/min, moisture content reduction from 90% to 9%(wb)	2010
Indirect active hybrid solar-electrical dryer system (IAHSDE)	Sliced tomato	Air flow rate 1.8, 2.82 and 3.7 m^3/min, Drying temperature 65^{o}C, Solar collector area 2. 45 m^2	2020

Table 2: Some research done on hybrid solar dryer in some countries of the world

Fruit and vegetable	Type	Major findings	reference	country
Corn	Solar assisted heat pump in store dryer	- To reduce the moisture content of the corn from 16.6% to 14.5% (w.b), elapsed drying time was 240 hr. - Power consumption per grain ton to reduce the moisture content by 1 % was 1.24 kWh and the value was much lower than the official standard (2.0 kWh).	Li *et al*. 2011	India
Pegaga leaf	Solar assisted dehumidificat ion dryer	- The colour of solar dried pegaga leaf did not become darker due to the lower air temperature and Rh used (T< 56°C, RH< 36%). - Pegaga leaf dried at 65°C using hot air became darker	Yahya *et al*. 2016	India
India	Solar air dryer -	A protease activity of 2655 units/g was obtained at pH 5.5 and 285 units/g only at pH 9.0	Macalood *et al*. 2008	Span
Rice	Mixed mode passive solar dryer	- Higher degree of whiteness was found in solar dried rice than sun dried rice. - Similar flavour was found in both sun dried and solar dried sample	Mehdiza *et al.* 2009	Malysia
Green Leaves	Indirect solar dryer	Solar dried sample showed higher losses of β-carotene and ascorbic acid as compared to hot air cabinet drying upon storage because of prolonged drying time. - Chlorophyll loss was also higher in solar dried sample. - Faster drying conditions showed better retention of the quality parameters of leafy green vegetables	Negi and Roy 2001	Arkansa s
Carrots	Solar cabinet dryer	- Longer drying time leads to higher loss of β-carotene - Exposure to light resulted to oxidation. - Low rehydration ratio was observed due to greater shrinkage in solar dried samples	Prakash et al. 2004	India
Turmeric	Solar biomass dryer	Dried turmeric rhizomes resulted from solar drying by two different treatments viz. water boiling and slicing were found similar in terms of physical appearance. - Open sun dried sample was found having lesser volatile oil	Prasad et al. 2006	India
Cocoa beans	Indirect and direct type solar dryers	- The dried beans from the direct solar dryer were more brittle and higher in acidity than the open air and indirect solar dryers. - Dried beans from the indirect solar dryer showed the highest overall quality.	Bonaparte et al. 2006	Malaysia
Plums	Greenhouse Drye	- Both solar and open sun drying of plums pre-treated by combination of 1% potassium hydroxide and 60°C dipping temperature or by combination of 1% sodium hydroxide and 60°C dipping temperature ensued in relatively higher values of redness and yellowness as compared to hot air drying. - The combined effect of solar radiation and these pre-treatment combinations reduced the darkish colour of plums during solar drying and open sun drying	Tarhan 2005	Turkey

Coffee	Solar dryer with black transpired air solar collector	Coffee bean dried faster in the solar dryer with good quality and no significant defect. Absence of browning, highest retention of natural colour were observed.	Chapman *et al.*2006	Thailand
Wild coriander	Direct cabinet solar dryer and indirect cabinet solar dryer	Oil from dried samples in indirect solar dryer was similar in composition to those obtained from oven or fresh one.	Banout *et al.* 2010	Peru
Olives leaf	Indirect forced convention solar dryer	The value of L parameters of the solar dried oliver leaves increase compared to the fresh one. Luminance of the leaves was improved by solar drying but the greenness of the leaves reduced. Olive leaves dried at 40oC (1.62 m3/min) exhibited the lowest DPPH radical scavenging activities.	Bahloul *et al.*2009	Tunisia
Grapes and figs	Indirect and direct solar dryer	Vitamin C content of solar dried fruits was low due oxidation, especially when the samples were either scalded or sulfurized. The colour of solar dried grapes showed high acceptance as compared to the natural dried sample (medium acceptance). The texture and colour of figs dried using mixed solar dryers showed better acceptance than the sun dried samples	Gallali et al. 2005	Malaysia
Vanilla	Solar greenhouse dryer	Export quality standard (Grade A) with vaniline content of 2.36% was obtained. Average drying time for vanilla pods was between 49 to 53.5 hr with drying temperature ranging from 33°C to 65°C and RH of about 34% during day time	Abdullah *et al.*,2006	Indonesia
Pistachio nuts	Direct solar dryer	Both solar and sun dried samples showed splendid taste as compared to hot air dried sample. - No aflatoxin was found in both sun and solar dried pistachio nuts.	Ghazanfari *et al,* 2011	Malaysia
Sweet potato	Green house solar dryer	Solar dried sample showed negligible losses in total carotenoids as compared to sun and hot air dried samples. - Sun dried sample showed the lowest retention value.	Bechoff et al. 2022	Uganda
Henna, rosemary, Marjoram and Moghat	Unglazed transpired solar dryer	Oil obtained from medicinal plants dried in the solar dryer were higher in quantity as compared to the traditional drying methods. - Higher test scores for sensation were obtained for the solar dried plants (marjoram, moghat and rosemary) in terms of colour, odour, and taste	Hassanain 2020	Nigeria
Cocoa beans	Direct solar dryer	Overall quality evaluation (flavour, acidity, fermentation index, appearance and odour) indicated that loading of 20 kg cocoa beans is optimum. - At this load, drying time was shorter	Hii et al. 2021	Morroco

		and this reduces the risk of putrefactive development in the beans due to unfavourable weather condition.		
Lemon slices	Solar dryer associated with the PV Module	Dried lemon samples with bright colour were observed under complementary solar drying using gradual temperature increment (36°C-52°C). - Lesser browning was observed in solar dried samples with comparison of hot air dried sample at 60°C.	Chen et al. [22]	Taiwan
Indian gooseberry	Forced Convective solar dryer	- Flaking treated sample retained maximum ascorbic acid (76.6%) because of reduced exposure of the sample in the drying air. - Flaking and pricking treatments showed minimum loss of taste and flavour.	Verma and Gupta 2013	India
Chilli	Solar assisted biomass drying	Overall drying efficiency of the system was estimated at 10.08% as compared to solar cabinet drying at 7.4% and sun drying at 4.3%, respectively.	Leon and Kumar 2016	Canada
Thyme	Solar dryer using wire baske	- The essential oils extracted from the oven dried and solar dried samples were 0.5% and 0.6% (per 100 g dry wt), respectively. - The oleoresin and ash content were 27% for both drying methods and 1.6%, 2.03% and 2.25% for the fresh, oven dried and solar dried samples, respectively	Balladin and Headley 2012	Malaysia

Conclusion

Hybrid dryer is the next phase of drying systems, it remove all forms of drawback of conventional dryers both in direct and indirect form of dryer, also improve it drying rate and efficiency. The use of high thermal capacity and heat energy storage engineering material in hybrid solar increases it drying time during sun day time. Inclusion of auxiliary heating element powered by AC or DC current in hybrid solar dryer can actualize reduction of retention time and increase in capacity. Drying rate and drying time in hybrid solar dryer is dependent of convective parameters coefficient. Heat transfer coefficient in hybrid solar dryer was in multiple ratio higher than another conventional dryer. Optimization of air flow rate is crucial since it affect the evaporation rate from crop surface to room air. Cost incur on hybrid solar dryer is high compared to conventional dryer, though; it has lengthy payback time which could be 2 to 3 years. Development and modification led to the transition from open air sun drying to solar drying, as well from solar drying to hybrid solar drying, up to the recent with the use of greenhouse solar dryer. Further modification could be in the inclusion of dehumidifiers into hybrid solar dryer to boost capacity and efficiency.

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