Greenhouse Drying System

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Drying via solar energy is an environmentally friendly and inexpensive process. For controlled and bulk level drying, a greenhouse solar dryer is the most suitable controlled level solar dryer. The efficiency of a solar greenhouse dryer can be increased by using thermal storage. The agricultural products dried in greenhouses are reported to be of a higher quality than those dried in the sun because they are shielded from dust, rain, insects, birds, and animals. The heat storage-based greenhouse was found to be superior for drying of all types of crops in comparison to a normal greenhouse dryer, as it provides constant heat throughout the drying process.

greenhouse dryer thermal storage no-load condition load condition

1. Introduction

Globally, in 2018–2019, fruit production was estimated to be 392 million tons, and vegetable production was estimated to be 486 million tons. Due to post-crop or post-harvest handling, nearly 30–40% agricultural produce is damaged or spoiled [1]. Among developing countries, India is the second-largest producer of vegetables and fruits; however, 35% of the crop is nevertheless lost post-harvest. The factors responsible for these losses include improper handling, poor production methods, and inadequate storage facilities. This results in the approximate annual financial loss of 104 million US dollars [2]. Spoilage mainly occurs due to microorganisms, as a high percentage of water is present in fruits and vegetables.

To keep the agricultural product preserved, the removal of moisture content is essential. The most economical process of food preservation involves drying foodstuffs in the sun, a method which has been practiced for 5000 years. The dehydration of agricultural products takes place due to heat treatment, either via a natural or artificial process. The heat can be generated via a natural method, such as solar radiation, or via an artificial method, such as the generation of electricity by burning fossil fuels. The entire world faces the issue of an energy crisis due to the limited availability of fossil fuels and the rapid increase in the consumption of oil and natural gas. Electricity is either unavailable to many farmers or too expensive. Moreover, the supply of electricity is exceptionally erratic; therefore, dependence on its supply is an unreliable prospect for many farmers. To run the farm machinery on fossil fuels, on a large scale, is not financially prudent and it can significantly impede the management of the farm [3].

One of the most important and all-encompassing phenomena is global warming, as it affects flora and fauna across the globe. The diverse ways in which humans are broadly affected by global warming include rises in air temperature, rises in sea level, and changes in climate. These disturbances occur due to the high melting rates of snow/ice, the distinct differences in geographical distribution norms, and the extinction of animals and plants. The environmental system is degrading due to the ill effects of greenhouse gases [4].

The weather pattern is therefore affected. There is an uneven distribution of rain, and some parts of the world are left dry and arid. Renewable energy sources are the ultimate solution to deal with these unavoidable problems. The sun is the ultimate source of renewable energy, and it is the best renewable energy source to capitalize upon. Solar concentrators, solar collectors, and solar dryers utilize solar radiations for drying applications; farmers and small stakeholders find these to be the most flexible options for obtaining energy [5].

1.1. Solar Drying

Since ancient times, the solar drying method has been used by mankind to dry fruits, seeds, plants, wood, meat, fish, and other agricultural and animal products. The sun provides a free and renewable energy source for drying purposes. Several scientific research methods have been applied in order to improve solar dryers for the preservation of forest and agricultural products. Solar radiation is used to evaporate the moisture that is present in the product during the natural sun drying process; nevertheless, there is seasonal variation with regard to the intensity of sunshine, which can cause uneven drying, thus resulting in the under-drying and over-drying of products [6]. Solar energy is used to heat the air, and this heated air is able to flow over the product, thereby removing the moisture and carrying away the vapor released from the product. The equipment that harnesses the solar energy to heat the air and dry the food products has acquired the term, “Solar Dryer”. The solar dryer mitigates the limitations of natural sun drying by improving the quality of the dried product. During the solar drying process, solar energy is used as the only energy source, or it is augmented by adding hybrid energy sources. Natural or forced convection airflow can be generated by the solar dryer [7].

During the drying process, the product may be subjected to preheated air as a result of convection, or the product may be directly exposed to heat due to solar radiation. The vaporization of moisture occurs as a result of the heat being absorbed by the agricultural product. Moisture is vaporized from the moist surface of the product when the heat is absorbed. This vaporization increases the temperature of the agricultural product, which results in the enhancement of the agricultural product’s vapor pressure in comparison with the surrounding air. The ability of moisture to diffuse into the crop’s surface from the interior depends on the size of the product, the moisture content, and the nature of the product. Solar drying usually occurs when agricultural products are available in abundance. Solar drying technologies provide an opportunity to sell dried products during off-season periods. Moreover, the products can be sold at higher prices during harvesting seasons because of its superior quality.

There are various types of solar drying technologies, with each having their own merits and demerits. The use of the solar dryer depends upon the metrological conditions of the crop. The rate of drying inside the solar dryer is always higher in comparison with the drying rate in the sun. Additionally, the crops that are dried inside the solar dryer contain a higher amount of Vitamin A and Vitamin C. The solar dryer also minimizes crop losses that are caused by rain and dirt. The solar dryer is mainly categorized into three modes that are based on drying (i.e., open, direct, and indirect drying) [8].

1.1.1. Open Sun Drying

With open sun drying, the short wavelength of solar radiation descends on the rough surface of the agricultural crop. The surface absorbs part of the short wavelength radiation, depending on the color of the exposed crop, and the remaining part is diffused. There is an increase in the temperature of the crop due to the absorption of solar radiation as it converts solar radiation into thermal energy; this results in the loss of long-wavelength radiation from the surface of the agricultural product to the ambient surroundings through moist air.

Wind blowing over the surface of the crop also adds to the convective heat loss. The crop is dried as the evaporation of moisture takes place in the form of evaporative losses. **Figure 1** illustrates the open-air drying process.

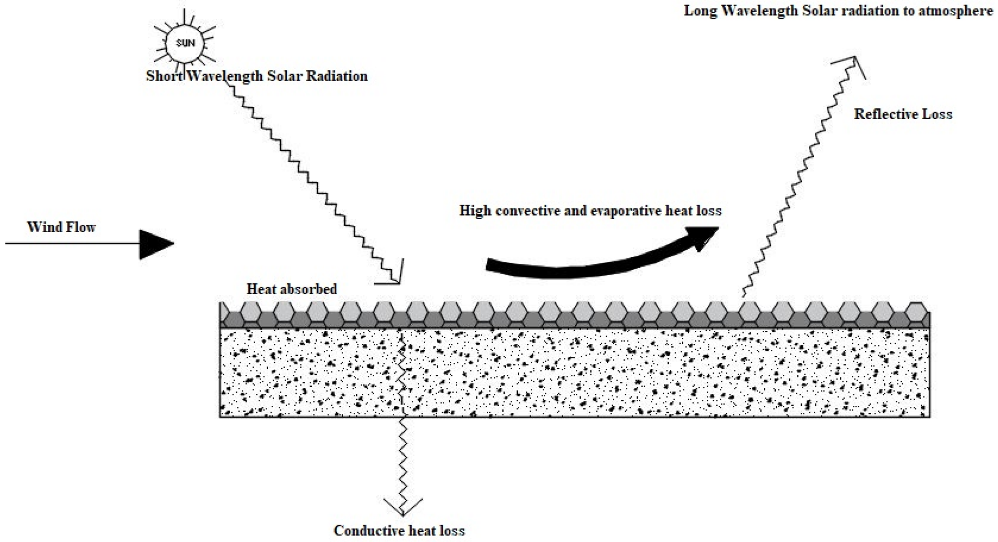

Figure 1. Open sun drying [9].

Open sun drying is the cheapest and simplest method of drying; however, many drawbacks are associated with this method. The prominent economic concern regarding this method is that open sun drying fails to maintain a standardized international quality, therefore, products obtained from this method remain out of the global market [10]. With the realization that the quality of the product obtained from open sun drying is deficient, a technically improved solar energy utilization method emerged; this is called solar or control drying [11].

1.1.2. Direct Solar Drying

Solar radiation incidents on the transparent glass cover are easily transmitted into the cabinet of the dryer. Most of the radiation is transmitted into the cabinet of the dryer, and the remaining part of the radiation is reflected back. The crop surface reflects part of the radiation, and the remaining part is absorbed by the crop surface, which thus increases the temperature of the crop. The heated crop starts emitting long-wavelength radiation, but the long wavelength radiation cannot escape into the atmosphere due to the presence of the glass walls and cover; thus, the presence of both the incidental and reflected radiation within the chamber further increases the temperature to be higher than that of the crop [12]. **Figure 2** illustrates a direct solar drying system.

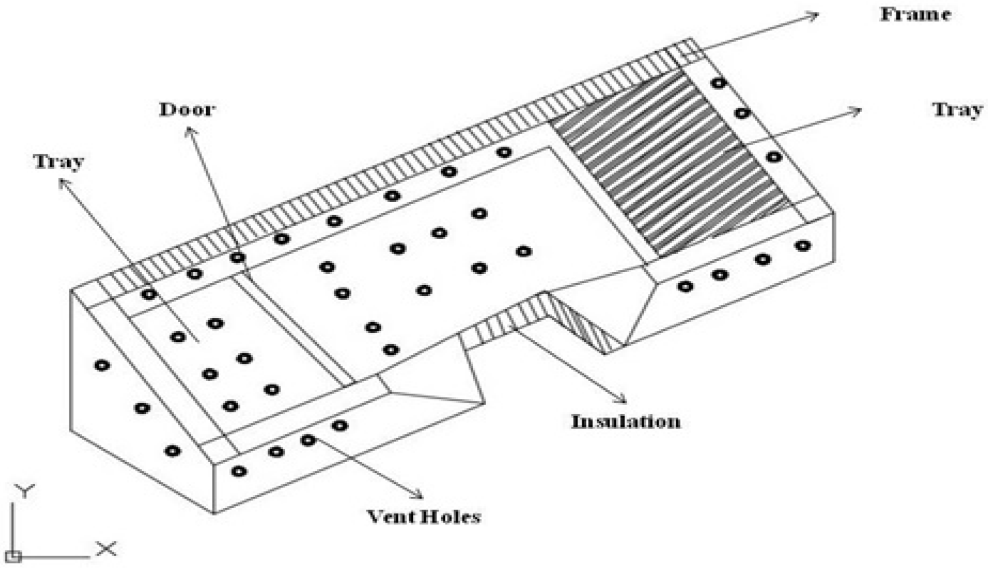

Figure 2. Direct solar drying [9].

1.1.3. Indirect Solar Drying

The indirect solar drying process occurs when the crops in drying chamber are not exposing to solar radiation. In the indirect solar dryer, a solar heater is used to dry the air, which is then passed through the drying chamber, either via natural or forced convection. The black painted absorption surface of the simple solar air heater absorbs the solar radiation and transmits it in the form of thermal energy (heat) to a working fluid [13]. **Figure 3** represents an indirect solar drying system. The dryer's chamber is connected to an absorber panel. The temperature of the air that is present inside the drying chamber is increased due to the decrease in solar radiation on the flat plate collector; this heated air passes through the drying chamber via natural circulation or forced circulation. The airflow rate can be controlled (increased) by using a drying chamber with a chimney or by providing a wind operated ventilator situated on the upper portion of the chamber. To further regulate the temperature of the unit, a fueled heat source is also installed, along with an indirect solar dryer [14].

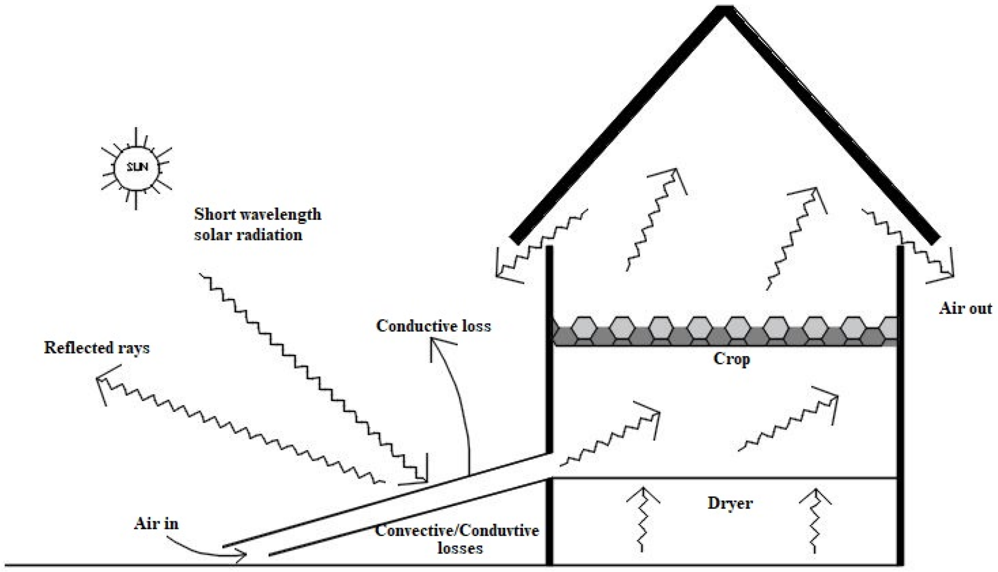

Figure 3. Indirect solar drying [9].

An assessment of the energy required for drying the agricultural products can be conducted using the initial and final moisture content for individual crops.

2. Greenhouse Dryer for Different Products

Using a greenhouse dryer is one way in which to conduct direct solar drying. The greenhouse effect is the underlying principle upon which the greenhouse drying system is based [15]. With regard to the greenhouse effect, the solar radiation received by the earth is trapped, thus increasing the overall temperature within the atmosphere. The atmosphere consists of gaseous matter and suspended particles, and it allows most of the incoming solar radiation to enter. The moment this radiation strikes the earth, part of it is immediately absorbed. Some of the energy is reflected back into the atmosphere, in the form of infrared rays, by the earth's surface [16]. Carbon dioxide (CO_2), water vapor, methane (CH_4), and nitrous oxide (N_2O) are the gases present in the atmosphere which absorb these infrared rays. The infrared rays that strike atmospheric particles are partially absorbed and partially redirected toward the earth; these rays are also absorbed. The greenhouse effect is the composite effect resulting from the earth's atmosphere absorbing infrared rays; this effect causes an increase in atmospheric temperature [17]. This natural phenomenon, where in heat is trapped by the earth's atmosphere, maintains a certain temperature range on earth in order to support life [18]. **Figure 4** represents a greenhouse drying system.

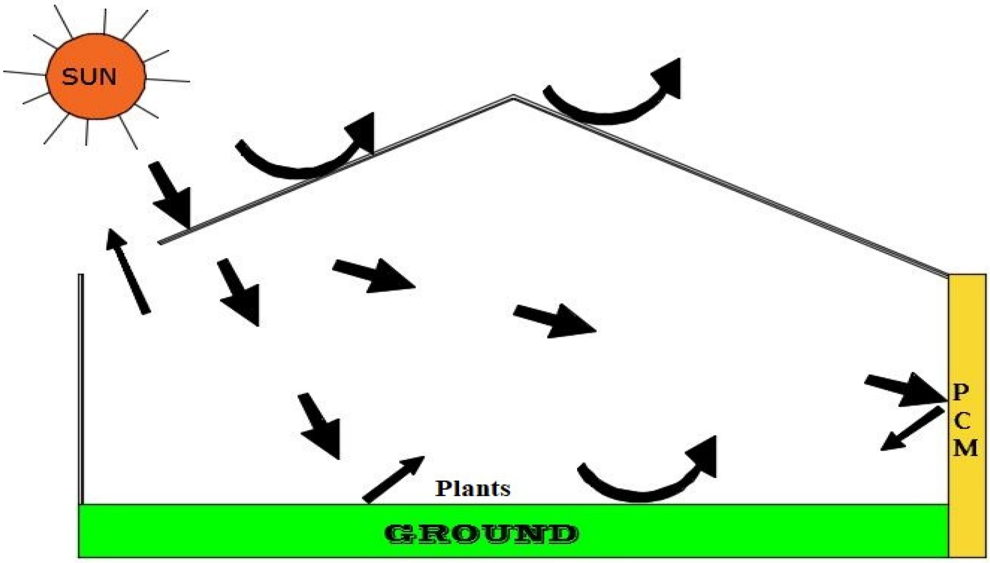

Figure 4. Greenhouse dryer with a PCM on the north wall [19].

The solar radiation consisting of short infrared wavelengths easily enters the transparent roof and walls of the dryer. It is partially absorbed by the object inside the dryer, which increases the temperature of the product. The heated object emits longer wavelengths, which is relative to its feeble intensity, and it is incapable of penetrating the transparent glass walls and rooves of the greenhouse [20]. The heat energy remains entrapped within the enclosure of the transparent glasshouse. This phenomenon, where in the temperature increases, is known as the greenhouse drying system, which is utilized for drying applications. It regulates the controlled environment; hence, it is also known as a controlled environment greenhouse [21].

2.1. Importance of Greenhouse Drying

The open sun drying technique is the most widely practiced method for the preservation of agricultural products in developing countries. This method does not provide satisfactory results under unfavorable weather conditions, and it can lead to the degradation of the quality and reliability of the product [22]. These losses mainly occur due to the dust and dirt, as well as bacteria and insects. Alternative methods can avoid these losses by drying the agricultural products in a cheaper and more economical way. Using the greenhouse dryer could be the best alternative method to avoid the disadvantages of open sun drying [23].

In the GHD, crops are kept inside the trays in the enclosed structure, and the moisture removal process takes place either via a natural or forced convection mode. The mode of heat transfer depends on the removal of exhaust air from the dryer. The main advantages of using a GHD are:

(i) The fabrication cost is low.

(ii) The structure of a GHD can be used throughout the year, which helps to increase the production of a dried crop.

(iii)Using a GHD improves the use of solar energy in terms of efficiency.

2.2. Greenhouse Dryersfor Different Products

2.2.1. Red Chili

Khawale and Khawale (2016) conducted an experiment by using a solar dryer (double pass) when drying red chili. The results show that the average value of solar radiation is 566 W/m^2 and the air flow rate is 0.071 kg/s. The product moisture content was reduced from 80% to 9.1% by using a double pass indirect dryer. This process took 24 h, not including the evening hours. When the red chili was dried in the open sun, the process took 58 h. In this work, the collector efficiency and system drying efficiency were found to be 38% and 59.6%, respectively. The evaporative capacity of the system was observed to be in the range of 0.14–23 kg/h [24].

Dhanore et al. (2014) evaluated the solar tunnel dryer’s performance. This process was used for drying a sample of 5 kg of red chili. The moisture content was reduced to 5% from 75% during this process. The chamber and the ambient temperature were 51.68 °C and 39.1 °C, respectively. The solar radiation ranged between 250 W/m^2 and 850 W/m^2, and the air velocity was maintained at 0.5 m/s [25].

Fudholi et al. (2013) evaluated a red chili product being dried in both open sun and solar drying conditions. The drying performance of the product was observed during this process. The experimental results showed that the product dried in 30 h and the moisture content reduced from 80% to 10%. In open drying conditions, the product took 65 h to dry. In solar drying conditions, the time taken for the product to dry reduced by 49%. The average evaporation capacity and the average solar intensity were maintained at 0.97 kg/h and 420 W/m^2, respectively. The Specific Moisture Extraction Rate (SMER) was observed to be 0.19 kg/kWh [26].

In Thailand, Kaewkiew et al. (2012) evaluated the drying of red chilis in a large-scale greenhouse solar dryer. The sheets in the dryer were made of polycarbonate and they were parabolically shaped. The concrete floor area was 8 m × 20 m, and nine D.C fans were installed for ventilation purposes. The moisture content of the red chilis was 74%, and they were dried in open dryer for three days. The solar radiation intensity during the drying process was observed as ranging between 390 W/m^2 and 820 W/m^2. The color of the red chili was better maintained in the greenhouse dryer compared with the open sun dryer. The payback period of the large greenhouse dryer was found to be two years; this period must contend with numerous technical and economical parameters [27].

Banout et al. (2011) investigated the open, cabinet, and solar dryers (double pass) in terms of their performance when drying red chili. Regarding open sun drying, the process took 93 h; the process took 73 h in the cabinet dryer; and the process took 32 h in the double pass solar dryer. The chilis used had 10% moisture content. When compared with open sun and cabinet solar dryers, the solar dryer (double pass) has a higher ASTA (American Spice Trade Association) color value and low Vitamin C deterioration was observed. The construction cost of this dryer was greater compared with the cabinet dryer, but the drying rate per kg was less [28].

Mohanraj et al. (2009) evaluated the forced solar dryer design. The capacity of the dryer was 50 Kg, and it had graves for the heat storage of red chili. For 24 h, the red chili was dried, and the moisture content was reduced from 72.8 to 9.1%. The maximum solar intensity was observed to be 950 W/m^2, and the average temperature in the dryer was 50.4 °C. The efficiency of the dryer was found to be 21%. The specific moisture extraction rate was recorded at 0.87 Kg/kWh. The humidity was higher at the exit of the dryer, and it gradually decreased as the drying time increased, and at the final stage of the process, it became constant [29].

Hossain et al. (2013) examined are designed solar tunnel dryer, with a capacity of 80 kg, in order to dry fresh red chili. The drying time for the improved solar dryer was 20 h. It reduced the moisture content of the chili from 2.84 kg/kg to 0.04 kg/kg. Compared with the unimproved dryer, it took 32 h to reduce the moisture content from 0.41 kg/kg to 0.08 kg/kg. Green chili took 35 h to reduce the moisture content from 0.70 to 0.1 kg/kg using the traditional drying method; however, it took 22 h to reduce the moisture content from 7.5 kg/kg to 0.05 kg/kg using the improved dryer. Moreover, the quantity and pungency of the product can be improved, and the drying time can be reduced with blanching. The solar dryer's temperature was constant, and it recorded more than just the atmospheric temperature, which was 21.63 °C. Blanching the red chili improved the color value [30].

2.2.2. Turmeric

Karthikeyan and Murugavelh (2018) worked on a mixed mode solar tunnel (forced convection). In order to harness the solar intensity effectively, inclination is the key factor. The moisture content was reduced from 0.779 kg/kg to 0.07 kg/kg of water/dry matter. The process of drying the product took 12 h compared with open sun drying, which took 43 h. The dryer's exegetic efficiency was found to be 48.11%, and energy utilization varies between 9.94% and 32.97%. Mathematical models were used in this experiment to observe the behavior of the turmeric [31].

Borah et al. (2015) designed and studied the performance of solar turmeric dryer. Inside the dryer, the temperature was found to be between 38 and 50 °C, and the ambient temperature was recorded and found to be between 24 and 27 °C. Both solid and sliced turmeric was used for the experiment, and the final moisture content was found to be between 6.37% and 15.49% for the solid turmeric, and 78.65% for the sliced turmeric after 12 h. The average effective moisture diffusivity was recorded to be 1.455×10^{-10} m^2/s for the solid turmeric and 1.852×10^{-10} m^{-2}/s for the sliced turmeric. In each batch of turmeric powder, the curcumin content varied. During the heat processing of the turmeric, the curcumin content was found to be between 27 and 53%, and there was a maximum loss in pressure cooking for 10 min. The sliced turmeric drying rate was faster than the drying rate for the whole turmeric. For both the sliced turmeric and whole turmeric, the rates of drying were found to be similar, at 62%. Sliced turmeric requires a 25.5 h drying process. During the open sun drying process, the sliced turmeric is affected by white patches of fungal growth. When using a solar collective dryer, no fungal growth was observed, and a Page model was found to be effective for the analysis [32].

Gunasekar et al. (2020) investigated the performance of solar drying for drying turmeric. Biochemical constituents in turmeric, such as oleoresin, the total protein content of boiled turmeric, volatile oil, and curcuma, may vary. The quality of the turmeric may result in varying levels of moisture due to these biochemical constituents. Due to the boiling and drying processes of turmeric, the curcumin content was found to be intensified. During the open sun drying process, the drying time was 96 h, and it was 63 h during the solar drying process. The solar dryer temperature ranged between 28 and 88 °C. The moisture content of turmeric was reduced from 79.04 to 7.14%

over 12 days during the open sun drying process. The curcuma content varies non-linearly with respect to moisture content. Initially the moisture content in turmeric was found to be 2.89 g per 100 g at 78.04%, and it varied between 2.88 g and 4.55 g per 100 g sample during the open sun drying process. A small variation in volatile oil content was shown during the open sun drying process. The volatile oil content before the drying process was found to be 5.9 mL/100 g of sample, after the drying process it was found to be 5.26 mL/100 g for the sun-dried sample, and it was 5.21 mL/100 g for the solar dried sample. The oleoresin content after the drying process was found to be 8.97 g/100 g of sample for the open sun drying process and it was 9.21 g/100 g of sample for the solar drying process. The boiled turmeric initially had aoleores in content of 1.24 g/100 g of sample, and it also decreased linearly by 1.15 g/100 g of sample during the solar drying process, and by 1.77 g/100 g of sample during the sun drying process. By drying the product in a solar dryer, more proteins were obtained from the sun, and this is beneficial both biologically and theoretically [33].

Lakshmi et al. (2018) investigated the mixed mode solar dryer’s (forced convective type) performance. This process is used for sliced turmeric samples that are integrated with the heat storage. In this process, 35 kg paraffin wax was used as the thermal storage during the liquid stage. The moisture level was reduced from 73.4 to 8.5% over 18.5 h in a mixed forced solar dryer, and in open sun drying conditions, it took 46.4 h. A moisture level of 12% was found after using the solar dryer, and when it was equipped with a solar air heater, the efficiency was calculated to be 25.6%. The mixed mode solar dryer saved time by 60%. The total flavonoids content for the solar dryer operating in a mixed mode was found to be 7.58 mg/g of sample, and it was found to be 1098 g and 8.08 g for fresh turmeric and solar dried turmeric, respectively. A high medical agriculture value was found after using the mixed mode solar dryer [34].

2.2.3. Copra

Yahya et. al., (2018) evaluated the solar air dryer’s (double pass) performance using a finned absorber for drying copra. During this drying process, the moisture level was reduced from 52.68 to 10.73% over 23 h, and in open sun drying conditions, it took 67 h. The air flow rate and the average rate of drying was maintained at 0.084 kg/s and 0.054 kg/h, respectively. For open drying and solar air drying, the average rate of drying was 0.191 kg/h. The efficiency of the system was found to be 39.47%, and the improved potential rate was 87.98 J. In Indonesia, open sun drying and smoke-drying processes are used for drying coconut; this has disadvantages such as debris, rain, and insect infestation [35].

Ayyappan et al. (2010) studied the copra drying process in a solar tunnel dryer. Under full load conditions, the natural conventional solar dryer took 57 h for the moisture content to reduce from 52.8 to 8%, and under half load conditions, it took 52 h. Compared with the open sun drying process (53%), good quality copra was obtained in the solar tunnel dryer (54.66%). The average efficiency was found to be 21%, and the solar intensity was found to be 860 W/m^2 [36].

Mohanraj et al. (2008) worked on a forced convective solar dryer, which involved designing, manufacturing, and testing it. Regarding its different levels, the moisture level was reduced from 51.8 to 7.8% on the bottom level, and it was reduced to 9.7% on the top level. The thermal efficiency of this system was found to be 24%. The kiln drying process was the alternative method to the open sun drying method for drying copra. In India, via direct contact with smoke, copra is dried, and the possibility for smoke deposition emerges. Copra with a high quality of 78% was achieved by using this dryer, and a thermal efficiency of 25% was achieved; the copra was left undamaged [37].

2.2.4. Grapes

The numerical model for the greenhouse solar drying of grapes was studied by Hamdi et al. (2018). The moisture level was reduced from 5.4 to 0.23 (g water/g dry matter) within 128 h. The temperature in the solar dryer was 55.98 °C compared with the ambient temperature that was found to be between 24.55 °C and 35.72 °C. The simulation of the mathematical model was conducted using TRNSYS software [38].

Ramos et al. (2015) developed a mathematical model based on the explicit finite difference. It was integrated with the heat and mass transfer model. The model incorporated the effective moisture diffusivity parameter, which caused changes in terms of shrinkage and the reliance on thermal properties in water [39]. The simulation model predicted accurate times. The hemi cylindrical solar dryer's temperature was maintained between 55 and 80 °C. On the first day, the moisture content was reduced from 84% to 69%, and on the seventh day, it was further reduced to 16.5%. The pre-treatment process reduced the moisture content in less time [40].

Fadhel et al. (2005) revealed that greenhouse drying has zero running costs. The time taken to dry grapes in a solar greenhouse dryer, and via open sun drying, took 78, 120, and 205 h, respectively [41].

Yladiz et al. (2001) studied the regression model and estimated the coefficient and effect of an electric fan on air temperature. The moisture content in grapes was reduced to 0.15 kg water/kg of dry matter from 2.5–3.2 kg water/kg of dry matter. During the first 34 h of drying time, an air velocity of 1.0 m/s was recorded, and after 35 h, the air velocity was 1.5 m/s. The coefficient of regression and the R2 was 0.98 and 4.10×10^{-3}, respectively [42].

2.2.5. Peanuts

Ester Y. Akoto et al. (2017) developed a solar dryer in order to improve peanut quality. The reduction in moisture content was 5.42% and 31.8% from 25.84% after single layer drying, and it was reduced to 4.24% after four layers drying, respectively [43].

The development of the dryer not only accelerated the drying of peanuts, thus enabling an evaluation of the quality of peanuts. Noomhorn et al. (1994) discovered that at 10 rpm, at a 75 °C temperature, and at a feed rate of 9 kg/min, the optimal quality was obtained. At higher temperatures, peanuts have poor quality index uniformity and a greater drying time because of the pressure of the sand. The drying time was reduced by reducing the feed rate and changing the rpm of the drum [44].

Bunn et al. (1972) studied an empirical equation related to high moisture content. It was tested in a drying environment, and it was also compared with frequently used drying methods [45].

2.2.6. Fish

Abdul Majid et al. (2015) experimented on 10 kg batch size solar dryer, studying silver cyprinid fish over 12 h. The moisture content was reduced to 18% from 72%, whereas in the open sun it took 20 h. The efficiency of the system and the collections were 12% and 9.4%, respectively. The bottom, middle, and top tray of the dryer maintained constant rate i.e., 0.145, 0.145, and 0.147 respectively [46].

Bassanio et al. (2011) designed the solar tunnel dryer to accommodate 50–110 kg. Half of the tunnel's base was used for drying and air heating for 30 h; the moisture content was reduced to 15.6% from 66.6%, and the efficiency of the dryer was 29.8%. The fish quality was enhanced in terms of flavor, food value, brightness, color, and taste [47].

Bhor et al. (2010) evaluated the solar tunnel dryer and found that the drying rate was higher compared with open sun drying. The temperature was maintained at 53.8 °C and the moisture content of the fish without salt was reduced to 19.04% over 33 h and 20% over 36 h for the upper and lower trays, respectively. In the case of sun drying, the moisture content reduced to 19.68% over 40 h. The salted fish's moisture content was reduced to 19.5% over 36 h and 19.6% over 38 h for the upper and lower trays, respectively [48].

3. Classification of the Greenhouse Drying System

3.1. Natural Convection Solar Greenhouse Dryer

With this type of dryer, the incidental radiation is transmitted through the canopy of the system, which results in the heating of the crops. The temperature of the crop increases because solar radiation is absorbed. The principle of the thermosiphon effect works in the natural convection solar greenhouse dryer [49]. Ventilation is provided at the top of the dryer which enables humid air to be released from the dryer. The buoyant forces are responsible for the circulation of heated air through the crop when using this type of system. The movement of air within the drying chamber is called the passive mode and a dryer operating under such a convection mode of operation is termed as a natural convection solar greenhouse dryer [50]. **Figure 5** shows the pictorial view of a natural convection solar greenhouse dryer.

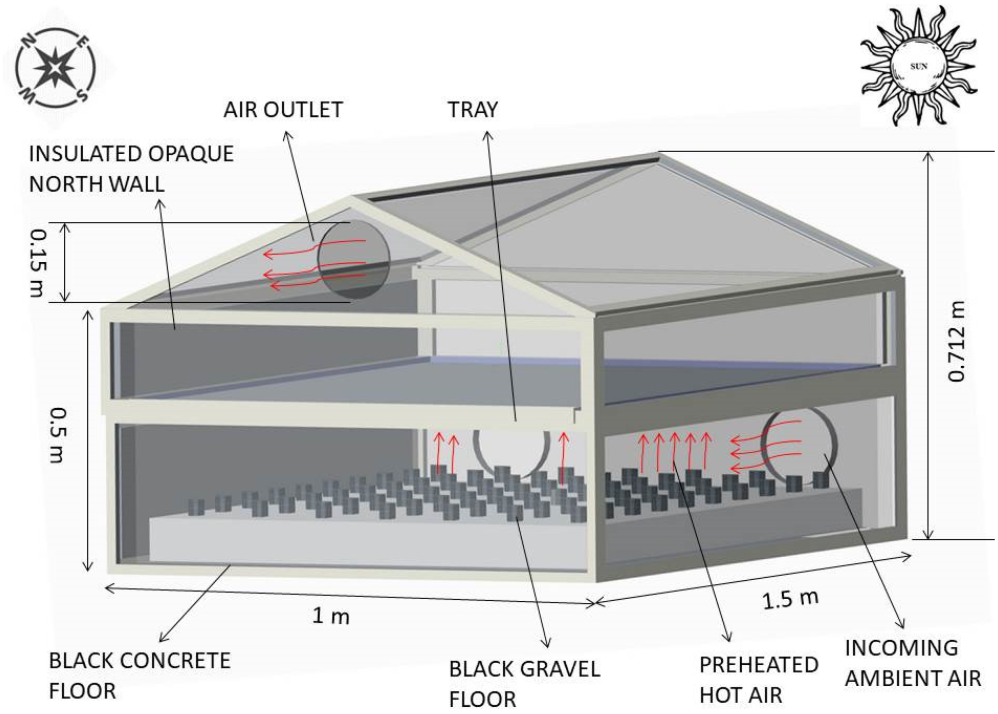

Figure 5. Pictorial view of a natural convection solar greenhouse dryer [51].

Natural circulation greenhouse dryers are used for drying agricultural products at the farm level because of the non-availability and erratic power supply in remote rural areas. It consists of an inclined collector coupled with a drying chamber, which contains trays to hold the agricultural products. The air circulation within the drying chamber takes place due to the differences in density; this occurs as a result of the buoyant forces [15].

However, due to high air resistance, airflow is not possible through the thin layer using natural convection; therefore, to increase the airflow, ventilators or chimneys are installed. Rodents and rain do not damage the dried products in the natural convection solar dryers during the drying process. Moreover, the drying time is minimized when compared with the open sun-drying process.

Natural circulation greenhouse dryers are modified forms of regular greenhouses. For a controlled airflow, vents of appropriate sizes and positions are incorporated into the dryer. The earliest types of passive solar greenhouse dryers are characterized by a large transparent cover of polyethene with an inclined glass roof to help allow direct solar radiation to cover the product [52]. The problems that arise from using natural convection greenhouse dryer include the holding capacity of the dryer, which results in low productivity; there is a risk of the air circulation failing, thus causing the drying products to spoil; and the exposure to solar radiation may result in vitamin loss and decolorization. Ahmad and Prakash (2019) designed and built a greenhouse dryer that uses natural convection. The bed of the drying chamber was covered with sensible heat storage materials. Four distinct types of bed were chosen for the comparative heat transfer assessments of the proposed setup: a gravel bed, ground bed, concrete bed, and a black painted gravel bed. The black painted gravel bed provided conditions that produced the highest heat gain, which was 53%, whereas the corresponding values for the concrete bed, gravel bed, and ground bed were 33%, 49%, and 29%, respectively. As a result, a black-painted gravel bed is strongly advised for optimal heat storage [53]. From studying the literature, researchers may conclude that only forced ventilation systems containing a blower or a fan helps in the proper removal of moist air.

3.2. Forced Convection Greenhouse Dryer

In order to regulate the temperature and moisture evaporation, an optimum airflow is required for the greenhouse dryer throughout the drying process; this is achieved by observing the changes in the weather conditions [54]. An exhaust fan is installed on the west wall to eliminate the humid air [55]. The GHD airflow is regulated by the use of a blower or fan; this is called a forced convection solar greenhouse dryer [50]. **Figure 6** shows the pictorial view of a forced convection solar greenhouse dryer.

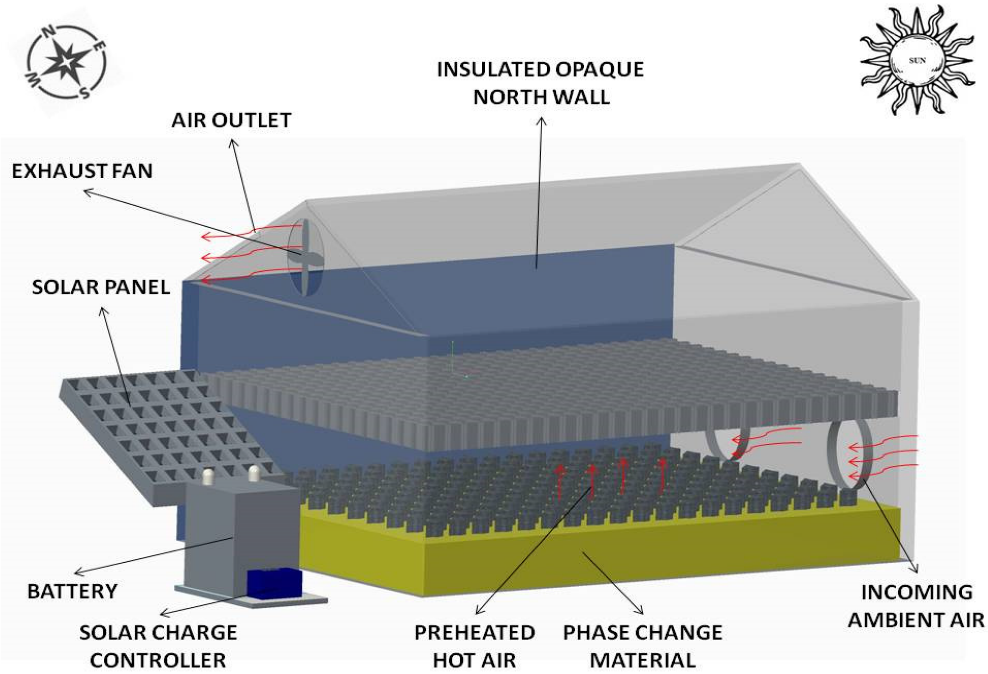

Figure 6. Forced convection solar greenhouse dryer.

Movement of the hot air from the drying chamber occurs as a result of the fans in the forced convection greenhouse dryers. For high moisture content products, such as tomatoes, papaya, grapes, chilis, kiwis, bitter-gourds, cabbages, brinjal, and cauliflower, forced convection greenhouse dryers are the most suitable [50].

The five basic components of a forced convection greenhouse drying system are: a drying chamber; a tray to contain the product that needs drying; an inlet hole; an outlet hole adjusted with a fan or blower for air circulation; and for a continuous steady power supply, a battery charging system is required. The heated air passing over the wet product facilitates moisture evaporation due to the convective heat transfer mode [56]. The difference in moisture concentration between the crop surface and dry air causes drying [57].

3.3. Solar Hybrid Greenhouse Dryer

The solar drying system is mainly divided into three modes of operation; direct mode, indirect mode, and hybrid mode. Regarding the hybrid solar dryer, the combination of two sources of energy is supplied for drying purposes. The combination of two sources can be wholly renewable or non-renewable [58]. The types of hybrid solar dryers are: (i) hybrid solar dryer assisted by geothermal energy; (ii) hybrid solar dryer assisted by biomass energy; (iii) hybrid solar dryer assisted by ocean/wind energy; (iv) hybrid solar dryer assisted by renewable energy; and (v) hybrid solar dryer assisted by solar air heater. In a hybrid greenhouse dryer, the dryer is assisted by other energy supplies [59]. Moreover, the hybrid dryer should have the ability to work in both an active and passive mode depending on what is required. **Figure 7** represents the hybrid greenhouse dryer.

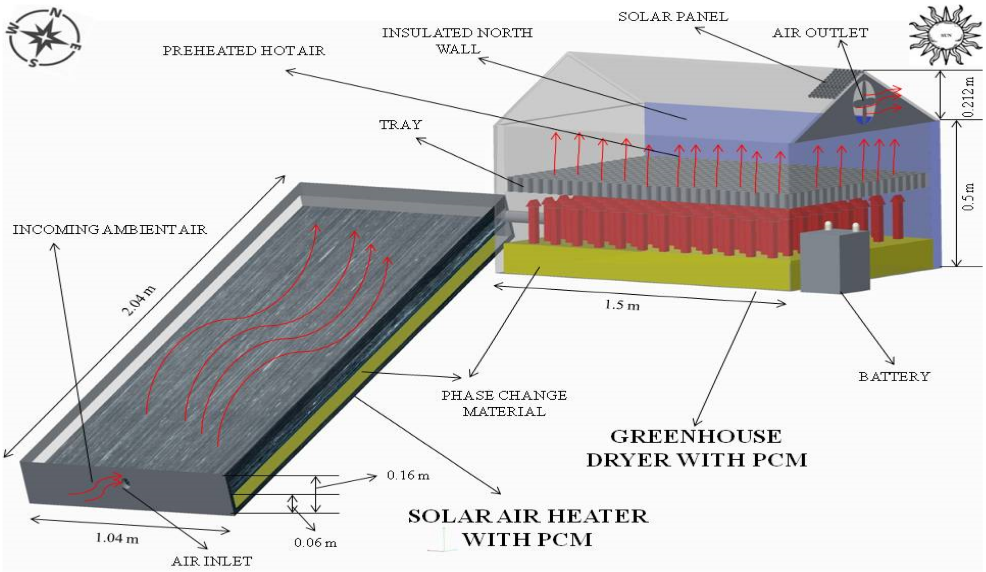

Figure 7. Hybrid greenhouse dryer.

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