GHDs with Solar Technologies

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Greenhouse dryers (GHDs) are simple facilities that can provide large capacities for drying agricultural products. The solar GHDs (SGHDs) are classified as passive and active systems. The passive SGHDs have a heat transfer through natural convection, whereas, SGHDs having a heat transfer through forced convection are called active dryers. Active SGHDs can be integrated with different solar technologies, including photovoltaic (PV), photovoltaic-thermal (PVT), and solar thermal collectors. Additionally, solar-assisted greenhouse dryers (SGHDs) can be integrated with heat pumps and thermal energy storage (TES) units and presented in hybrid configuration considering their integration with other renewable energy sources with the aim of improving the thermal performance.

Keywords: agricultural products ; solar drying ; greenhouse dryers ; energy storage ; performance enhancement

1. Introduction

The world's population is growing steadily and is projected to reach up to approximately 8.6 billion by 2030, 10.1 billion by 2050, and 12.7 billion by 2100. Therefore, an increase in food production is inevitable to satisfy the basic needs of livelihood [1][2][3]. Along with the increase in productivity, the reduction in food grain wastage, post-harvest losses, and losses incurred at various stages of the food supply chain will play a major role in dealing with food insecurity. According to a report released by the Food and Agriculture Organization (FAO) in 2020, about one-third of the produced food (almost 1.3 billion tonnes) is lost every year [4][5]. In developing countries, about 30–40% of total food production is lost mostly at post-harvest and processing levels, while in developed countries the same value is lost *at* retail and consumer levels [6][7][8]. Post-harvest losses are significantly restricted via the drying of raw food crops. Preservation of agricultural products for a long time entails reducing their moisture content in a way to keep their essential nutrients [9][10].

Agricultural crop drying is an energy-intensive process in which both heat and mass transfer occur. From primitive times, "*sun drying*" has been a common traditional practice to preserve cultivated crops. However, to satisfy the ever-increasing population's food demand, an increase in the use of conventional energy sources at different stages of the food supply chain is inevitable [11][12]. It has also been reported that the global energy demand will increase about 40–50% by 2030 to meet the global food demand [13][14]. An indicative diagram in **Figure 1** shows the scenario of energy utilization at different stages of the food supply chain. The figure reveals that energy utilization at the stage of post-harvest food processing comprises a significant percentage share of the total energy utilization in the whole food supply chain [8][15].

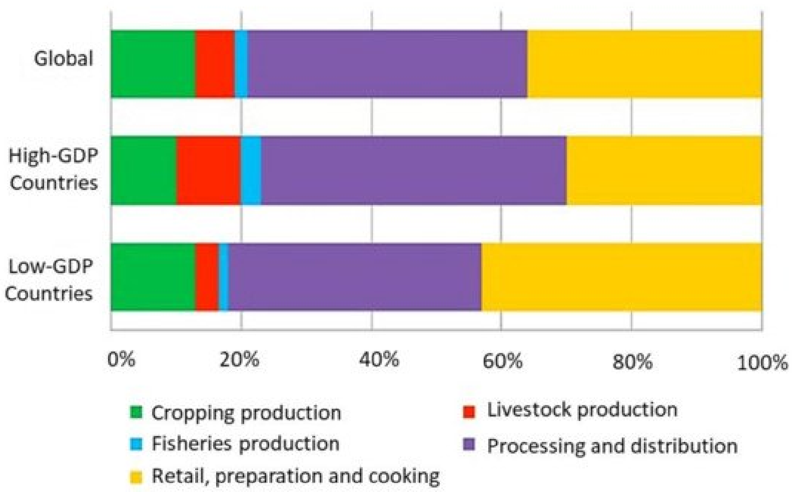

Figure 1. Utilization of energy at different stages of the whole food supply chain, adapted with permission from [16].

Among several existing procedures, open-air sun drying is widely used due to its low cost but encompasses the major drawback of losing considerable thermal energy, resulting in poor utilization of heat during the process. Consequently, the drying process gets affected, causing the production rate to be lowered, which results in a long drying period [17][18]. Other than the lower thermal efficiency of this process, some other factors affect the sun drying's productivity, such as climatic conditions, rain, wind, birds, pests, and rodents. Additionally, there is a large possibility of food contamination and food-linked diseases because of fungus growth in dried food crops due to uncontrolled external parameters [19]. In this regard, modern and advanced drying systems that are newly conceptualized and proposed can overcome the aforesaid problems of the drying systems. These advanced dryers help to enhance the overall energy efficiency of the systems, quality of the dried food, drying period, and hygiene of the food corps [20][21]. Out of various types of globally developed dryers, greenhouse dryers (GHDs) are easy to install and have higher load capacities [22]. With the growing concern on the depletion of fossil fuels, environmental pollutions, and global warming, the use of renewable energy sources (RESs) to power agricultural operations and the food supply chain processes is in the limelight [23][24]. The use of renewable energies in agriculture and food production systems will release the burden on the environment. In this context, solar drying as a renewable-based post-harvest food processing method can reduce the use of conventional fossil fuels and considerably mitigate adverse impacts caused by greenhouse gas (GHG) emissions from this sector [12][25].

Among various solutions, solar greenhouse dryers (SGHDs) [26][27][28][29] and hybrid solar drying systems [30][31] are the most widely suggested remedies found in the literature. It is a well-known fact that solar energy is the primary RES while the other forms of renewable energies are indirect conversions of solar energy. Thus, solar energy-based advanced agricultural crop drying systems and their various aspects need extensive discussion to develop a sustainable food supply chain mitigating food insecurity in economic and environment-friendly ways. Therefore, the drying systems require a careful and proper design and analysis before installation to achieve the anticipated productivity and efficiency. For this, various parameters such as drying kinetics, effective energy interactions and utilization, and different techniques for energy loss reduction need appropriate consideration.

2. Solar-Assisted Dryers for Agricultural and Marine Products

In recent decades, several types of solar dryers have been developed to decrease post-harvest losses and improve the quality of agricultural products. The utilization of solar energy for drying agricultural and marine items is the most appealing and economical solution [32]. Solar drying under controlled conditions of temperature and moisture removing rate confirms perfect drying and the required quality of the final product. However, only a few designs of solar dryers are deployed on scales other than demo projects or used at the industrial level [19][33]. The classification of solar dryers for agricultural and marine products is mainly performed according to the size of the dryer, design of the system, and solar energy consumption mode. **Figure 2** depicts passive, active, and hybrid solar-powered dryers considering techniques for air circulation (natural or forced) and methods of heat transfer (direct or indirect).

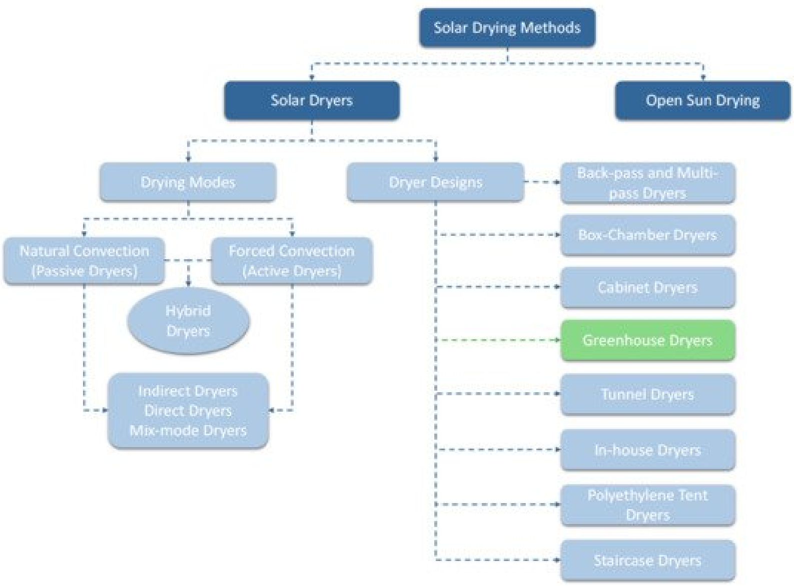

Figure 2. Categorization of solar-powered dryers, adapted from refs. [19][33][34].

2.1. Open Sun Drying

Figure 3 illustrates the functioning of the open-sun-drying method in which solar radiation is directly incident the surface of the crop. A portion of the received solar radiation is absorbed by the drying product depending upon the surface structure and color of the crop, while the remaining part is reflected in the environment. The solar radiation is absorbed and converted into heat and causes the temperature of the crop to increase. Further, due to the elevated temperature of the crop, longwave radiation is lost from the crop surface to the ambient, while the longwave convective heat loss occurs due to natural convection and blowing wind via moist air over the crop surface. The evaporation of moisture from the crop results in evaporative losses. Drying of the products depends on some external parameters, including the intensity of solar radiation, ambient temperature, wind velocity, and relative humidity, as well as internal parameters like rate of moisture transfer within and to the surface of the product by the diffusion process that depends on the type of the drying product [35].

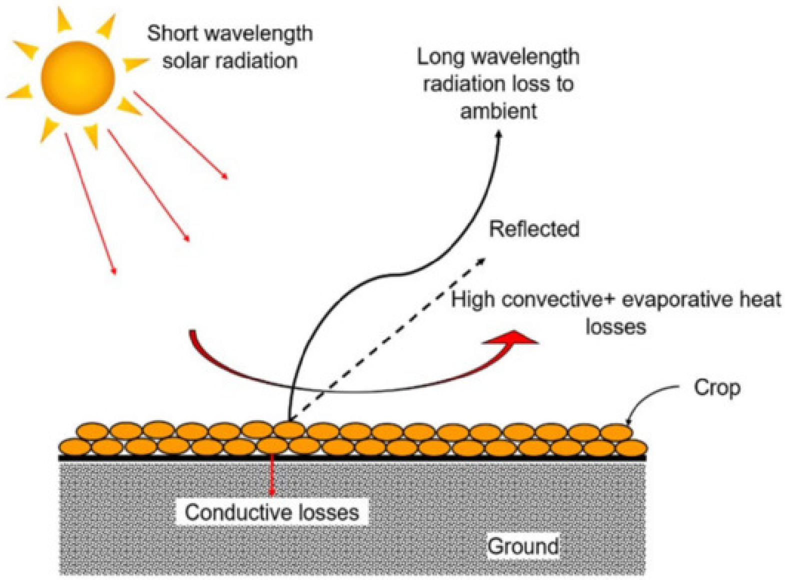

Figure 3. Basics of the open-sun-drying method, adapted with permission from [19].

In the open-sun-drying process, substantial losses occur because of numerous factors including birds, rodents, insects, and micro-organisms, while unpredicted storms or rain worsen the condition. Further, excess/insufficient drying; impurities due to external contaminants such as dirt, dust, insects, and micro-organisms; and color fading by ultra-violet (UV) radiation are characteristics of open-sun-drying [33]. Additionally, open-sun-drying is a sluggish process that can lead to significantly huge losses. Products dried under open-sun-drying usually fail to meet international standard quality [36].

2.2. Passive Solar Dryers

Direct passive solar dryers with natural convection have simple and low-cost construction. The drying chamber of a passive solar dryer typically contains a thermally insulated box of a transparent sheet made of glass/polyethylene/polycarbonate with inlet and outlet openings [28][37][38][39]. The air heated by received solar radiation flows across the crops either by buoyancy forces or pressure gradients, or a combination of both [40][41][42][43][44][45]. Throughout drying, a part of solar radiation reflects the ambient while the remaining is transferred to the cabinet and absorbed by the drying product. The typical drying efficiency of a passive solar dryer has been reported as 20 to 40%, depending on the type of the drying product, airflow rate, and location [37]. The efficiency of a dryer is defined as the ratio of the energy utilized for heating the sample from moisture evaporation to the total consumed energy.

The indirect passive solar dryer with forced convection comprises a drying chamber and a solar air collector. A low-pressure solar air collector is used to heat the air that enters the drying chamber and passes over the drying tray via an air duct. Air vents or a chimney at the top of the drying chamber expel the moist air out [46][47]. The average drying efficiency of indirect passive solar dryers ranging from 13 to 25%, which is smaller than direct solar dryers [37]. However, it is stated that, unlike a direct passive dryer, this approach faces the issue of cracking and facilitates the protection of vitamins and color since drying products are not exposed directly to solar radiation [40][43]. **Figure 4** represents passive direct and indirect solar dryers. The passive dryers are recommended for operation in small batches for fruits and vegetable drying [48].

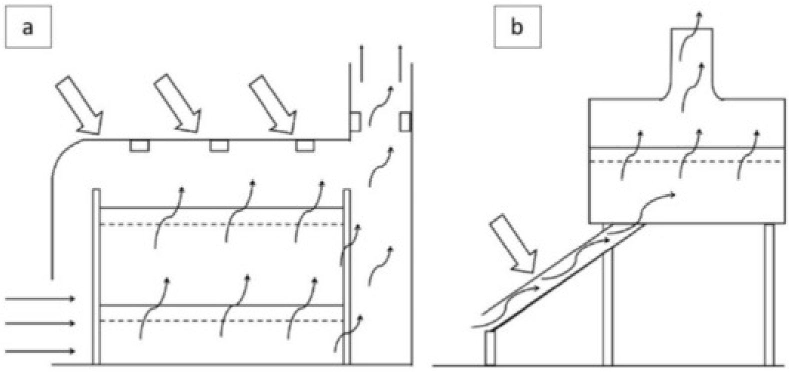

Figure 4. Schematic of passive solar dryers, adapted with permission from [49]; (**a**) direct type; and (**b**) indirect type.

2.3. Active Solar Dryers

Active solar dryers consist of an air circulation system to circulate the heated air in the drying unit or flow from the solar air heater to the drying unit (**Figure 5**). An external arrangement is made for circulating the air in the drying chamber. Fans or blowers run by electricity produced with the help of a photovoltaic (PV) panel or grid circulate the air for drying [43]. An exhaust fan is used for moving the air, and these types of solar dryers can be used in large-scale commercial drying operations. These dryers have been introduced to be more appropriate to dry crops with high moisture content such as kiwi, papaya, cabbage, and cauliflower than passive solar dryers [48][50][51]. The active dryer needs more capital cost than a passive dryer, and its operating and maintenance costs are also higher to attain high product quality as well as drying efficiency, where optimum air mass flow rate and temperature are required for regulation [50].

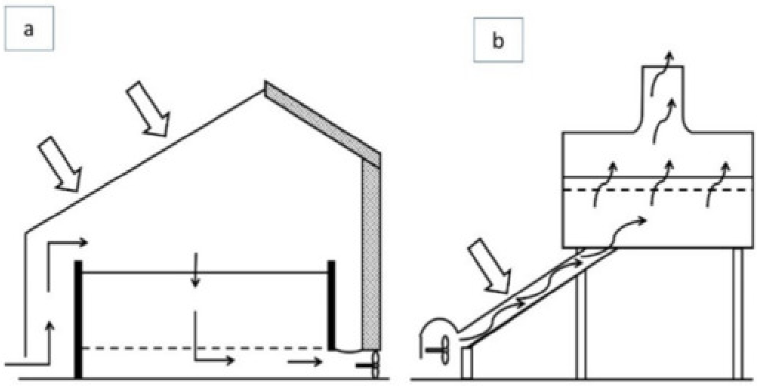

Figure 5. Schematic of active; (**a**) direct-type solar dryer, and (**b**) indirect-type solar dryer, adapted with permission from [49].

2.4. Hybrid Solar Dryers

In a hybrid solar dryer, the agricultural products are dried under direct solar radiation and/or backup energy or stored heat when sunlight is not available. These types of dryers are utilized in single and mixed modes of drying. The hybrid dryer could decrease microbial infestation in drying products [51][52][53]. Lamrani and Draoui [54] presented a simulation study on wood drying via a hybrid solar electrical dryer integrated with thermal energy storage (TES) system. The application of the TES ensures that uninterrupted wood drying and temperature of the drying chamber are greater than that of the ambient air by about 4–20 °C during the night. Mohammed et al. [55] conducted an economic analysis and evaluated the drying performance of novel hybrid active and passive-mode solar dryers for drying fruits in East Africa. A passive hybrid improved solar dryer (ISD) and improved PV-assisted hot air dryer using an active hybrid solar dryer 'Solar Photovoltaic and Electric (SPE)' were built as low-cost methods to dry fruits in Uganda. The results indicated that ISD and SPE dryers perform better than the open-sun-drying method. Additionally, the economic analysis indicates that drying costs were found to be low for the products dried using the ISD than SPE dryer. Comparably, the pay-back period (PP) for the SPE was 2.4 times longer than that of the ISD dryer. Hybrid solar dryers have been utilized for a variety of crops such as mushrooms [56], pineapples [57], and cashew nuts [58]. These kinds of dryers are appropriate for the fast drying of crops to provide high product quality.

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