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ORIGINAL ARTICLE

Recent Advances in Solar Drying System: A Review

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ABSTRACT – Research on solar dryer technology proliferates since it reduces the drying period while keeping nutritional values in agricultural products. This paper presented a review of recent advances in the solar drying system. This review is composed of working principles and classifications of solar dryers. They were classified into two main elements: airflow modes, passive or active, and the way heat is transferred: direct, indirect, mixed-mode, and hybrid. The hybrid system used several types of elements to supply additional heat in the drying system, as elaborated in this paper, such as the electrical heater, biomass, and photovoltaic system. The advantages and disadvantages of solar dryers are also being discussed in this paper.

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INTRODUCTION

Renewable energy keeps developing since it provides an alternative power source to the industries rather than fossil fuel. It is environmentally friendly since it can reduce greenhouse emissions [1] and can be regenerated. However, renewable energy is still not fully implemented in industry because of several circumstances like lack of energy technology expertise and financial issues. About 80% of the energy used worldwide is based on fossil fuels [2]. Fossil fuel is expensive and also can cause pollution due to greenhouse gas emissions. Greenhouse gases such as carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) that are trapped in the atmosphere will cause global warming. Among all the renewable energy, solar energy is commonly used in the industry [3]. In drying activity, solar energy from the sun is widely known as the primary power source to supply heat. Drying is a high energy consumption process that consumes about 10-15% of the overall world energy consumption [4].

Solar energy suits low-temperature applications at a high flow rate with a low-temperature rise process [5], for example, drying of agricultural products [6]; [7]. Drying is an essential process where the moisture from crops will be reduced so that the decaying process will be slowed, and thus, the yields can be kept for longer-term storage [8]; [9]. Other than preservation, dried products can ensure safety, easy handling, and cost-effective transportation [10].

Open sun drying is a traditional method that farmers use to dry their agricultural products such as vegetables, fruits, and herbs. However, the process is irrelevant due to several limitations. Most of the crops are lost from a long drying period which can cause product deterioration, attacks from fungi and animals, and unwanted weather conditions like rain [11]; [9]. In addition, open sun drying might need a large area to place the agricultural products and high labour costs [12]. Researches have been done to overcome the problem, and a solar dryer is invented. Solar drying is a conservation method, where it helps reduce post-harvest losses and improve products' quality associated with traditional drying that uses non-renewable energy [13]. It is proven that solar dryer is more efficient than open sun drying [9]; [12]. The solar heating system produces better quality products and reduces waste from the drying activity [14]. Solar dryers offer an ideal drying environment with a high temperature and low humidity instead of open sun drying. The drying air temperature of the solar dryer varies from 45°C to 60°C, a suitable range to dry most agricultural products [15]. In addition, precautionary steps like pre-treatment also can be done to avoid colour and aromatic from adversely affected by high drying temperature, especially for herbs and medicinal plants such as thyme [16]. Besides, osmotic dehydration is employed to partially remove water from some crops, such as cherry tomatoes before it is dried in a solar dryer. The purpose is to produce high-quality dried tomatoes with the desired colour even when the drying time is reduced [17]. Many modelling techniques have been used to develop high drying efficiency dryers so that the temperature, crop moisture content, drying rate, and quality of the crop can be predicted [18].

Sivakumar E. [19] had built a passive solar dryer which is the sides of the dryer, was made with plywood coated with white emulsion paint. The inner part of the dryer comprises a drying tray made of wire mesh. The solar dryer is constructed to compare with the traditional open sun drying method used by the farmers in Nigeria. The test was done by using harvested maize cobs with an initial moisture content of 30.3%. Results showed that the solar dryer took 3 days to dry the maize cobs to the final moisture content of 13.3 %, while open sun drying need 6 days to dry the maize cobs to 13.4%

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moisture content. Rajeshwari & Ramalingam [20] have built a solar dryer system comprise multi tray rectangular section with a flat plate collector. The temperature and drying efficiency of the system was analyzed, and it showed that the drying time of the product was reduced by 20% compared to open sun drying, and better products' quality can be achieved.

Amer, Hossain, & Gottschalk [21] designed a solar dryer with direct drying mode and a heat exchanger. The drying process operated 24 hours, where on sunny days as a solar dryer and during an unexpected cloudy day hybrid solar dryer was operated. During the nighttime, the dryer was run using the stored heat energy in water collected during daytime and with electric heaters at the water tank. The result shows that the efficiency of the solar dryer was raised by recycling 65% of the drying air in the solar dryer. Ayensu [22] has constructed a solar dryer by using local materials based on convective heat flow. The result shows that it is performed twice better than drying by open-air sun drying.

This paper presents a review of the different types of solar dryer that have been modified to improve their effectiveness in line with technological advances. In addition, this paper aims to provide ideas to the other researchers to develop a high-performance solar dryer. The remainder of the paper is organized as follows: section 2 devotes to elaborate on the working principles of a solar dryer, section 3 reviews the different classification of the solar dryers, section 4 and section 5 elucidate the benefits and drawbacks of the application of the solar dryers, section 6 exposes the recent innovations on the development of solar drying system technology, and the last section draws the conclusion of this paper.

WORKING PRINCIPLES

A solar dryer is a device that transfers heat from a heat source to products in order to dry them by removing moisture from the surface of the products to the surrounding [23]. The solar dryer usually composes three significant components: the drying chamber, solar collector, and airflow system [10], as shown in Figure 1. The drying chamber is where the drying products are stored during the drying process to make sure they are safe and clean from dirt. The solar collector is installed in the solar dryer to supply heat to the passing fluid. The targeted drying temperature can be achieved depending on the drying requirement with constant output air temperature [24]. Finally, the airflow system will ensure that the moist air from the dried products escapes to the surrounding.

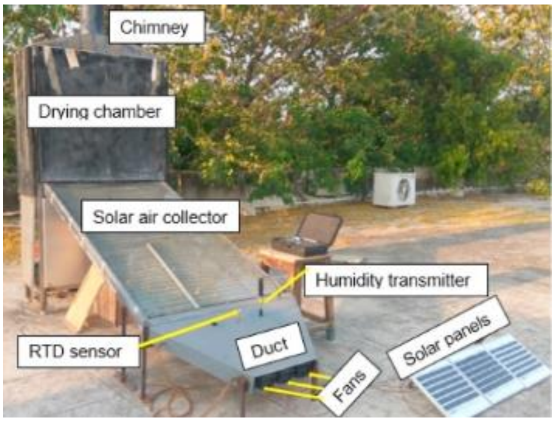

Figure 1. Solar dryer

The product is being dried by removing moisture from the inside to the surface of the product. The heated air in the solar dryer causes the vapour pressure of moisture inside the product and the moisture carrying capacity of the warm air to increase by decreasing its relative humidity [25]. Figure 2 shows drying process progression for the agricultural product where an initial heating period is first by an initial constant rate drying period and then by a subsequent falling rate drying period [9]. Temperature plays a vital role in determining the amount of moisture removed from the product's surface, where the warm air can catch more moisture than the cold air [10]. The principle can be illustrated in Figure 3.

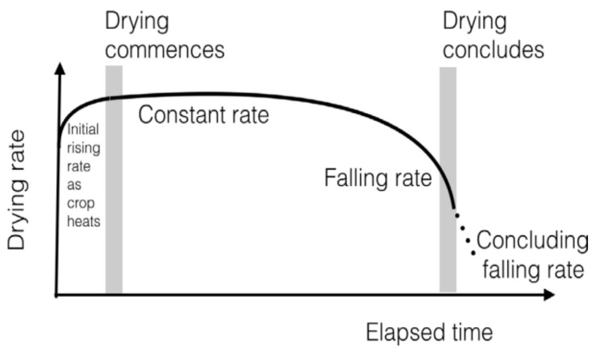

Figure 2. Drying progression [9]

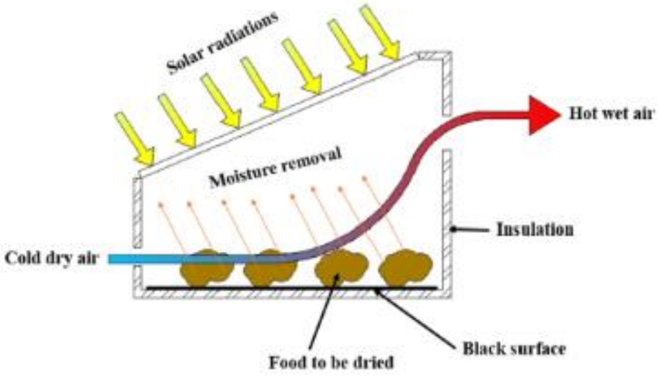

Figure 3. Principle of the solar dryer [10]

SOLAR CLASSIFICATION

Solar dryers can be classified based on a few criteria. Bennamoun [26] has stated that solar dryer is categorized into active and passive mode, and each category is divided into direct, indirect and mixed-mode types. Solar drying can also be categorized based on heating mode, direct or indirect, and how solar energy is used [27]. In this literature, the solar dryer is being categorized based on the method of airflow: either passive or active mode, and also heat transfer method from the sun to the product, which are: direct, indirect, hybrid, or mixed. Figure 4 shows solar dryer classification based on the two criteria.

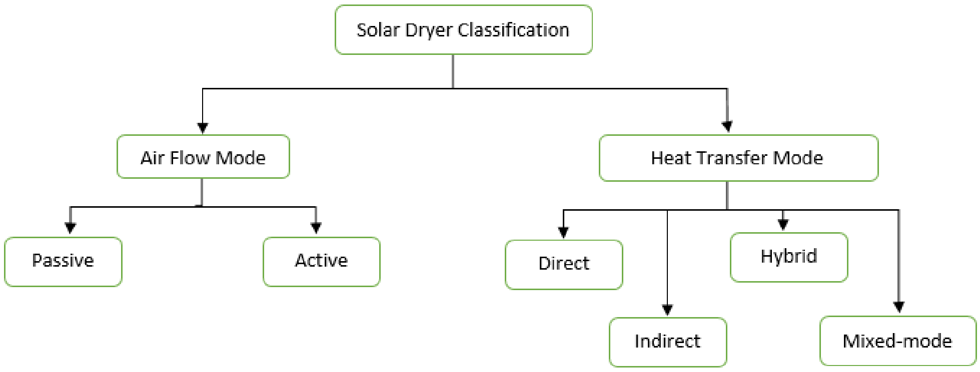

Figure 4. Solar dryer classification

H. El [10] presented a review on solar drying comprises the main components, classifications, and affecting parameters. The solar dryers are assessed according to three elements: airflow movement, mode of heat transfer, and types of drying chamber used for drying. The paper also studies the economic and environmental aspects of Lebanese cases to assess the Payback Period (PP) and CO_2 reduction.

Sharma et al [14] presented various types of solar dryer systems that are available. The paper reviewed the operational principles and the designs from the earliest natural-convection greenhouse solar dryers until the updated solar dryers in 2008. Two main groups of solar dryers have been identified: passive or natural-convection solar dryers and active or forced-convection solar dryers. The paper also presents several convenient solar dryer designs that are easy to fabricate and operated to be implemented in a rural area and small-scale industry.

Airflow mode

Solar dryers can be categorized into two groups: passive and active. The thermal energy will be transferred to the drying chamber by natural convection for the passive solar dryer. In contrast, in an active type solar dryer, fans transfer the heat from the solar collection area to the drying chamber [28].

Passive solar dyer

Passive mode solar dryer is also known as natural convection solar dryer. The efficiency of this solar dryer depends on the natural movement of air due to buoyancy force, wind pressure difference, or a combination of them [10]. The technique is widely used, especially in developing countries, due to its low initial cost and maintenance. It can be further categorized into open sun drying and natural-circulation solar energy crop drying method [3]. The crops will be spread on the ground or plate so that they are exposed to solar radiation. However, it has many disadvantages, such as waste produced and crop losses due to weather conditions and insects and rodent attacks [9]. Other than open solar drying, natural-circulation dryers also use the passive air movement mode. Heated air will flow towards the drying crops due to buoyancy force or wind pressure, or even a combination of both. Figure 5 shows the schematic of a natural convection solar dryer. However, a passive mode solar dryer has a low drying rate due to slow air movement [10].

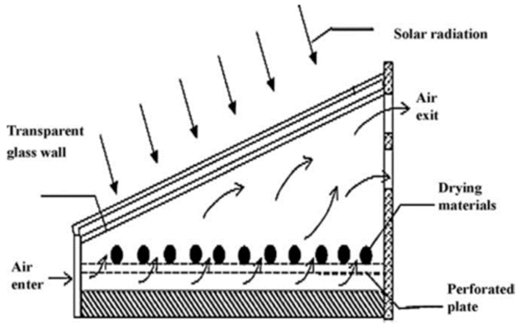

Figure 5. Schematic of Passive Solar Dryer [14]

A cabinet dryer is an example of a solar dryer that uses passive air circulation. Holes are made at the base and upper parts of the sides to allow buoyancy-driven moisture removal [29]. A chimney is added to enhance the moisture buoyancy effect in the dryer. Removing the moisture inside the system is essential to prevent the moisture from condensation inside the glass cover since it can harm the dried product. However, a cabinet dryer is suitable for drying small-batch crops, for example, banana, pineapple, mango, potato, carrots, and French beans. Discolouration may happen in the cabinet dryer because the product is directly exposed to solar radiation.

Islam, Islam, Tusar, & Limon [30] evaluated three different passive solar dryers (thin tube chimney type, attic space type, and natural draft chamber) at natural conditions. The experiments were done by drying apple, banana, pineapple and guava from 10 AM to 4 PM for several days in different seasons. The natural draft performance was the best with a 58.9% moisture removal rate, while 44.5% for thin tube chimney type and 33.3% for attic space type chamber in 6 hours drying time. The rate of moisture being removed was analyzed after 1 PM was higher than before 1 PM because of the increase of solar radiation. Davidson, Gunasekar, & Prasanthkumar [31] developed a natural convective step type solar dryer comprises 10 trays to evaluate the drying parameters of blanched and unblanched beans during sunny days. The moisture content removed was 72% to 14% for unblanched beans and 76% to 7.32% for blanched beans. The drying rate was significantly improved during drying of blanched beans; thereby, good quality dried product was obtained.

Babar, Tarafdar, Malakar, Arora, & Nema [32] designed a passive flat plate collector (FPC) with phase change material. The dryer was used to dry button mushroom, and its performance was compared to open sun drying. The dryer took only 21 hours to reduce the moisture ratio of the crop to zero, while the open sun drying reached zero after 33 hours. In addition, the drying period using the FPC dryer was reduced by 36.36% than open sun drying.

Active solar dryer

Active mode solar dryer is also known as forced convection solar dryer. The drying system uses solar energy as the heat source, and it is aided with electrical or fossil fuels to drive engines or pumps to provide air circulation [3]. The external means (engines or pumps) are used to move the solar energy in terms of heated air from the solar collector to the drying area. This mode is suitable for large-scale drying activities since it can provide higher air temperature and continuous airflow. Active solar dryers are ideal for drying crops with high moisture content like papaya, kiwi fruits, brinjal, cabbage and cauliflower slices [29]. Figure 6 below shows the schematic of a forced convection solar dryer.

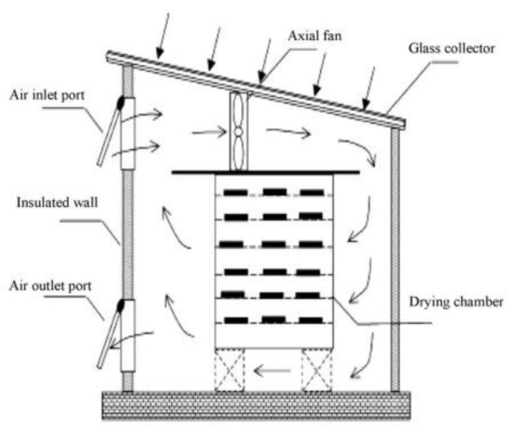

Figure 6. Schematic of active solar dryer

Demirpolat [33] investigated the drying kinetics of apple slices by using an indirect type solar dryer. A circulating fan (0.9 m^3 /h, 0.4 kW, 220 V, 50 Hz) was connected to the air inlet of the solar collector carried out by heat transfer by forced convection in the drying chamber. The author concluded that air velocity is significant since it determines the moisture removal rate from the raw material. The drying rate increased as the air velocity increased up until a specific air velocity value. After this value, it has no additional effect on drying. In addition, the air velocity is more effective in the drying phase at constant speed at the early stages of drying. Ghosal [34] fabricated a forced mode solar dryer to dry cabbage. A 12V DC fan powered by the photovoltaic module is used to create forced air circulation to channel thermal energy to the drying chamber without using grid-connected power supplies. The air temperature at the outlet dryer was 8-90°C higher than the ambient makes the drying system suitable for drying various agricultural products compared to the traditional drying method.

Veeramanipriya & Sundari [35] presented a study on the drying performance of a forced convection solar dryer aided with an evacuated tube collector and compared it with natural sun drying. The air temperature gained at the outlet of the evacuated collector was 59-108°C, more significant than the ambient temperature, which was 33.5-35.5°C. The quality of dried fruit was also better with a drying period of 5 hours, whereas open sun drying took 8 hours to reach moisture equilibrium. Etim, Eke, & Simonyan [36] constructed an indirect-active solar dryer using plywood to dry bananas. A blower was placed at the air inlet to increase the airflow rate in the drying chamber. As a result, the dryer was able to conserve 40% of the total drying time compared to open sun drying by reducing the moisture content of the products from 4.53kg to 1.57 kg within 9hours to 16 hours of drying, and moisture was reduced from 68.97% to 12.00% (wet basis).

Heat transfer mode

Solar dryers can be categorized based on their method for heat transfer as well. Those are direct, indirect, mixed-mode and hybrid solar dryer, and all of them can either in passive or active mode.

Direct solar dryer

In the direct solar dryer, the products that will be dried will be kept in a drying chamber enclosed with transparent glazing made of plastic or glass [37]. Solar radiation penetrates the transparent cover, and heat will be generated inside the drying chamber. The heat will cause the temperature inside the drying chamber to increase, and moisture from the product evaporates from its surface until it is dried. A direct dryer is very affordable and requires a low budget for construction and maintenance. However, compared to the hybrid solar dryer, a direct solar dryer has a disadvantage in operation time. Weather condition is the main factor that affects the direct dryer's performance. Windy and rainy days make the drying time of the product become longer. Besides, larger space to spread the product is required, and direct exposure to the sun may also cause product deterioration [38]. Figure 7 shows a cabinet solar dryer that uses direct mode as the heat transfer method.

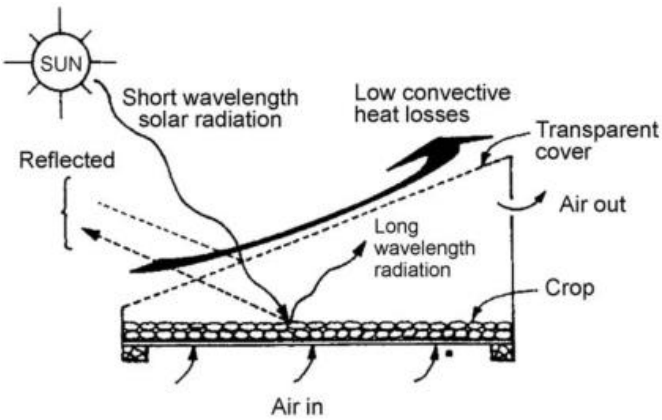

Figure 7. Cabinet solar dryer

Nabnean & Nimnuan [39] studied the performance of a direct forced convection household solar dryer for frying banana. Five batches of banana with 10kg of bananas for each batch were dried. The temperature supplied in the dryer was 35°C to 60°C between 8 AM to 6 PM. The result was compared with open sun drying. The solar dryer reduced the moisture content from 72% w.b. to 28% w.b. within 4 days, while the open sun drying reduced to 40% w.b. only in the same period. The solar dryer is more effective than the open sun drying since it can preserve high product quality and reduce 48% of the drying period. Hidalgo, Candido, Nishioka, Freire, & Vieira [40] developed a direct solar dryer integrated with a photovoltaic module for drying green onion. The performance of the dryer was evaluated under natural and forced convection modes. The forced convection showed higher performance with the average efficiencies of the solar dryer and the specific energy consumption of 38.3%, 16.4 kWh/kg, while the natural convection mode was 34.2%, 18.3 kWh/kg.

Bekkioui [41] presented a simulation on three design of direct solar dryer for drying wood. The results showed that the drying time could be shortened, and higher drying temperatures can be achieved using a larger transparent cover area to create a greenhouse effect. The double-glazing configuration produced high drying performance but increased the cost of the covers by 130% for all three designs. Meanwhile, the combination of Plexiglas-glass configuration increased by 57% in cost. However, it reduced the drying time by 25%. The drying time performance of the semi-greenhouse-type design with the combined plastic-glass configuration was comparable to that of the single glazing greenhouse-type design but with a lower cost.

Indirect solar dryer

The indirect solar dryer consists of a drying chamber, a solar collector [18] with the fan. The solar collector and drying chamber are separated, connected by a flexible insulated conduit [9]. The solar collector is preferred to be inclined rather than horizontally placed to receive a maximum amount of solar radiation. Then, air from the fan transfers the heat via ducting to a drying chamber. As a result, the products are not directly exposed to the sun, which avoids damage to the product, such as discolouration and cracking on the surface [14], while retaining vitamins in preserved fruits [9]. Compared to the direct solar dryer, the indirect solar dryer is more efficient because it has a higher drying rate. In addition, the air velocity, the temperature inside the drying chamber, and solid loading can be controlled easily [42], which will help produce better product quality. However, higher initial investment is required to construct this dryer, and its maintenance is higher than the direct solar dryer [43]. Figure 8 illustrates the principle of an indirect solar dryer.

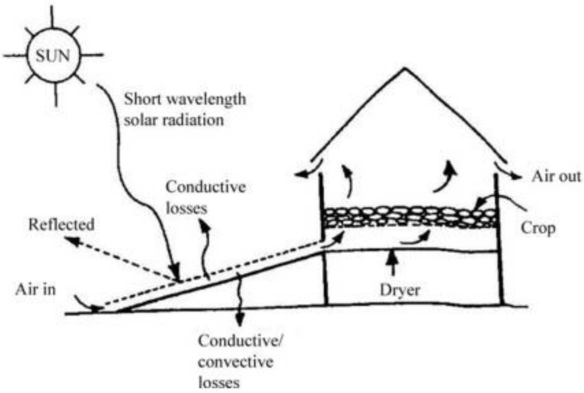

Figure 8. Indirect solar dryer

Ouaabou et al [44] investigated an indirect solar dryer by evaluating the dryer characteristic and the effect on sweet cherry drying. The authors concluded that the solar dryer was less energy-intensive and affordable. The electrical heating cost was less than 5%. The indirect forced solar dryer had no significant impact on sweet cherry fruit quality, making the drying process more efficient than open sun drying. Shalaby et al [45] constructed an indirect mode forced convection solar dryer (IMFCSD) integrated with thermal storage material, and a comparison has been made with the traditional air-drying method. The IMFCSD reduced the drying time from 60 hours to 31 hours since the dryer can still be operated during night hours. The IMFCSD was more efficient than natural air drying due to the safe drying environment and the ability to maintain the drying temperature.

An energy and exergy analysis by Mugi & Chandramohan [46] was done during the drying of okra *(Abelmoschus esculentus)* using an indirect solar dryer (ISD) with natural convection. The average efficiency of the collector was 61.49% during natural convection ISD (NISD)and 74.98% using forced convection ISD (FISD) due to a higher mass flow rate. FISD has higher drying efficiency in FISD, which was 24.95%, compared to NISD, which was 20.13% since the air velocity by the inlet fan was increased. On the other hand, the average exergy efficiency of the collector was 2.44% in NCISD and 2.03% in FCISD, since the prolonged exposure of air to solar radiation in NCISD at lower mass flow rate. In NCISD, the average exergy efficiency of the drying chamber was 55.45%, whereas, in FCISD, it was 59.32%, which is a 6.97% increase due to higher mass flow rate of air in FCISD.

Mixed-mode solar dryer

Features of direct and indirect solar dryers are combined in mixed-mode solar dryers [47]; [18] as shown in Figure 9. A separate collector will preheat the air for this type of solar dryer before it is delivered into the drying chamber. Solar radiation will penetrate the drying chamber through a transparent cover to provide heat to the product that will be dried [10]. Mixed-mode solar dryers have the highest drying rate than direct and indirect solar dryers since solar collectors and direct solar radiation are used simultaneously as the heat source. By using a mixed-mode solar dryer, the temperature will surge higher than the ambient in a shorter period which can help to attain suitable moisture level in the dried product [42]. However, such a solar dryer has a complex design, and a higher initial cost is needed [43].

Figure 9. Mixed-mode solar dryer [48]

The performance of a force convection mixed-mode solar dryer with Phase Change Material (PCM) as the thermal energy storage was analysed by Baniasadi, Ranjbar, & Boostanipour [49]. Fresh apricot slices were dried in different working conditions. It was found that the drying rate of the apricot slices at different tray level were almost identical. The PCM enhance the dryer system by extending the drying time during off-sunshine hours. The moisture pick-up efficiency and the overall thermal efficiency of the dryer are about 10% and 11%, respectively. Mixed-mode solar dryers were developed by Abubakar et al [50] with and without thermal storage material. The drying chamber was fitted with a glass cover to allow heating through the greenhouse effect. The results showed that the dryer's efficiency was increased by 13% with the use of thermal storage. It was observed that the average drying rates, collector efficiencies, and drying efficiencies of the solar crop dryers with and without thermal storage on June and August 2016 test period are 2.71×10^{-5} and 2.35×10^{-5} kg/s, 67.25% and 40.10%, 28.75% and 24.20% respectively. The solar dryer configuration results in a uniform drying rate of the dried crops.

Kolawole et al [51] designed a solar dryer using locally available materials such as plywood, translucent glass, wood, paints, and wire mesh to dry groundnut seed. The groundnut seeds are dried simultaneously by direct radiation through the transparent walls and roof of the cabinet and by the heated air from the solar collector. The average drying temperature in the drying chamber was 10°C higher than the ambient. The author also concluded that the dryer has a safe operation and relatively higher efficiency when compared with the open sun drying method. Fterich, Chouikhi, Bentaher, & Maalej [52] presented a performance study on a mixed-mode solar dryer with a photovoltaic air collector to dry tomatoes. The designed dryer comprises two compartments; the first one is a direct solar dryer with forced convection and the second one is a mixed dryer with forced convection. The prototype reduced the moisture content of the tomatoes from 91.94% to 22.32% for tray 1 and 28.9% for tray 2. On the contrary, the open sun dryer has a moisture reduction of only 30.15 %. Thus, the farmers can increase their economy by producing high-quality crops at higher drying temperature.

Karthikeyan & Murugavelh [53] designed a low-cost solar tunnel dryer to dry turmeric (*Curcuma longa*). The advantage of the mixed-mode solar dryer was the solar collector design's inclination, which effectively harnessed solar radiation. The drying time was reduced to 12 hours with the use of the solar dryer while 43 hours under the open sun drying. Another mixed-mode solar dryer was analyzed by Arina Mohd Noh & Ruslan [54]. The authors compared the new solar dryer that can be operated in two different modes (continuous mode and intermittent mode) by controlling the ventilation. The results showed that using this solar dryer in intermittent mode can increase the temperature up to 60°C, compared to continuous mode and standard dryer, 50°C and 40°C. Furthermore, intermittent mode promoted 60% electrical energy saving compared to continuous mode.

Joshua et al [48] analyze the performance of a mixed-mode solar dryer with and without phase change material (PCM). The drying efficiency of the solar dryer with the PCM was higher than without PCM, 30.34% and 23.25%, respectively, for drying banana and 30.28% and 24.26%, respectively, for pineapple. The simple payback period for the PCM based dryer was 1.6 years and the expected operation period was 25 years.

Hybrid solar dryer

Hybrid solar dryers are unique since they gain heat from more than one sources which are from the solar energy by the sun and another source such as biomass and fossil fuel [55]; [56]; [27]. The difference between hybrid solar dryers and mixed-mode solar dryers is that the mixed-mode solar dryer only depends on solar energy. In contrast, the hybrid solar dryer depends on multiple sources of energy: solar energy and other alternatives energy sources, for example, biomass [10]. The hybrid solar dryer is capable of operating in the absence of solar energy. It reduces the drying period and leads to reduce the risk of product wastage. Gudiño-Ayala & Calderón-Topete [57] studied pineapple drying using a hybrid solar dryer and a conventional solar dryer. The author reported that a traditional solar dryer requires a 31.2% longer drying period than a hybrid solar dryer. Thus, the solar dryer proves that it can reduce the drying time compared to the conventional dryer. W. Wang, Li, Hassanien, Wang, & Yang [58] presented a study on drying mango in an indirect forced convection solar dryer with an auxiliary heating device. The auxiliary heating device is used to overcome temperature fluctuation during cloudy weather. An automatic control system was employed to control the operation of the drying system, which included regulating the mass flow rate of air throughout the system. The average thermal efficiency of the dryer was between 30.9% to 33.8%. The calculated specific moisture extraction rate was 1.67 (kg water/kWh) with a drying temperature of 52°C.

1. Hybrid solar dryer (Electrical heater)

Nwakuba, Chukwuezie, Asoegwu, & Nwaigwe [59] tested a hybrid solar-electric cabinet dryer under no-load condition. An Arduino micro-processor programmable circuit board was used to control the overall operation. The solar dryer was efficient since the Arduino effectively measured the drying parameters. The time required to achieve the preset optimum drying temperatures of 50°C, 55°C, 60°C, 65°C, 70°C was determined using different air velocities. The results showed that the average minimum drying chamber heat-up times of 9.8 and 6.2 minutes were required by the electrical and hybrid heat sources at a temperature and air velocity of 70°C and 2m/s, respectively. Meanwhile, the maximum temperature gained by the hybrid and electric heat source was 92.5°C and 84°C, respectively, after 210 minutes. The authors concluded that the ambient air temperature, relative humidity and air velocity were observed to have a significant influence on the dryer heat-up time and tray temperatures.

Dorouzi, Mortezapour, Akhavan, & Moghaddam [60] developed a solar dryer that used a photovoltaic thermal solar collector to generate electrical energy for a 1000W heater and to regenerate the desiccant. It was found that both solar heat fraction and ratio of solar electricity to consumed electricity increased with decreasing the drying temperature. Using the hybrid system makes the solar dryer retain drying temperature between 60°C to 65°C and regeneration's pump activation relative humidity (RH) of 28%. The authors concluded that the temperature of 60°C and RH of 23% was recommended for the dryer since it results in the fair value of solar electricity generation and good colour qualities of the final products. Abhishek, Gowtham, Bishnoi, Swathi, & C [61] produced a hybrid solar dryer that can reduce the drying period and maintain good dried crops quality. The dryer was capable of raising the temperature 15-20°C above the ambient. The average maximum temperature gained was 57°C, which led to a shorter drying time. The organoleptic evaluation reveals that the areca nut being dried in the hybrid solar electric dryer system was completely protected from rain, insects and dust.

Taiwo Aduewa, Oyerinde, & Olalusi [62] developed a solar-powered hot-air supplemented dryer (SPHSD) with a capacity of 20 kg of sliced yam. The hybrid solar dryer was aided with a DC heater and a fan to stabilize the temperature within the drying chamber. It was compared with an indirect solar dryer, which its temperature fluctuated throughout the drying process. It can be concluded that a faster drying rate for SPHSD was achieved compared to the indirect solar dryer. Lamrani & Draoui [63] designed an indirect hybrid solar-electrical dryer of wood integrated with a latent heat thermal energy storage system. The drying system was optimized phase change material (PCM) as the storage medium and an electrical heater. The results showed that the thermal storage system enables the continuous drying process of the wood with a temperature of 4-20°C higher than the ambient during the nocturnal period.

2. Hybrid solar dryer (Biomass)

Elavarasan, Verma, & Shamasundar [64] invented a solar-biomass hybrid dryer (SBHD) using coconut husk with shell as the source of biomass. The dryer was used to dry salted soles (*Cynoglossus spp.*). With the temperature range of 35°C to 60°C, the drying efficiency gained for biomass energy and solar energy were 34.66% and 10.66%, respectively. The overall drying efficiency of the SBHD was 18.33%. Mishra, Shrestha, Sagar, & Amatya [65] integrated a biomass burning gasifier stove as an auxiliary heat source in a solar dryer to dry chilli and banana. The hybrid solar dryer was capable of providing continuous drying even though its rainy or cloudy. The moisture content of the chilli was reduced from 72.58% w.b. to 7.13% w.b. within 20 hours by using hybrid solar drying compared to 48 hours of using open sun drying. The author also concluded that this method is hygienic and can produce more quality products.

Hamdani, Rizal, & Muhammad [66] manufactured a solar dryer with biomass-fueled air heating. The experiment was conducted from 9 AM to 4 PM using solar energy, and the process continued with hot-air produced from biomass combustion from 4 PM to 6 AM. The temperature was maintained between 40°C to 50°C. After 22-23 hours of drying, the weight of the fish dropped to 12.5kg from 25kg. Manrique, Vásquez, Chejne, & Pinzón [67] developed a hybrid solar-biomass system for drying coffee beans by combining the combustion of coffee husk pellets with a PV/T system. The solar dryer reduced the moisture content of the coffee beans to 12% w.b. with 80% lower operating costs. In addition, the solar dryer can be considered environmentally friendly since the used coffee husk resulted in net-zero CO_2 emissions from combustion.

Aukah, Muvengei, Ndiritu, & Onyango [68] analysed the performance of a hybrid solar-biomass dryer by drying shelled maize using the ANSYS workbench. The test was held to find the best parameter for the solar dryer. The results showed that the ideal air velocity at the collector inlet and biomass heat exchanger outlet must be at 3m/s and 2.8m/s. As a result, the hybrid solar dyer maintained uniform temperature and airflow in the drying chamber improved the drying rate. It can preserve the quality of the dried products. Ndukwu, Simo-Tagne, et al [69] analysed a hybrid solar-biomass dryer based on energy and exergy-sustainability analysis considering all the available exergy stream of solar radiation air stream through the collector and exergy of the moisture in the product. Results showed that the hybrid solar dryer could save 10-21 hours of drying time by reducing the moisture content of 5mm thick plantain slices from 66% w.b. to 15% w.b. compared to open sun drying. The improvement potential ranged from 0.036 to 20.6W, while the waste exergy ratios and sustainability index ranged from 0.38-0.55 and 2.3–6.11, respectively. The total energy consumption for drying ranges between 5.52 and 35.47 MJ, while the specific energy consumption ranged from 4.3 to 26.2 kWh/kg. The exergy efficiency ranges from 5.6 – 95.13 % during the sunshine hours.

3. Hybrid solar dryer (Photovoltaic)

A hybrid solar tunnel dryer by combining a flat plate solar collector and solar photovoltaic system for drying peppermint was also investigated by Eltawil, Azam, & Alghannam [70]. The tunnel dryer is analysed using single, double, and three layers of mint, where it is used to protect from direct solar radiation, and the results were compared with open sun drying. The daily average efficiency of photovoltaic efficiency was 9.38%, dryer efficiency was 30.71%, overall efficiency was 16.32%, energy payback time was 2.06 years, and net carbon dioxide (CO_2) mitigation over the lifetime was 31.80 tons. Furthermore, Surendra Poonia [71] evaluated the performance of hybrid photovoltaic/thermal (PV/T) solar dryer on *ber (Zizyphus mauritiana)* fruit drying. *Ber* fruits were dried to the safe level of moisture content, 20%, in 240 hours with a drying load of 18 kg. The internal rate return and the payback period were 54.5% and 2.26 year, respectively, indicates the dryer are very cost-effective and can be promoted to a rural area with a less reliable energy source.

A hybrid PV/T for dying green chillies had been fabricated by Gupta, Das, & Mondol [72]. The authors concluded that the hybrid solar dryer was more effective than sun drying. The green chillies were dried for 8 hours, and the moisture content was reduced from 4.0 (g water/g dry matter) to 0.45 (g water/g dry matter) and 1.15 (g water/g dry matter) in the solar dryer and open sun drying. The average electrical efficiency, thermal efficiency, and overall thermal efficiency of the PVT solar dryer were 12.29%, 18.81%, and 51.18%. Ssemwanga, Makule, & Kayondo [73] built two solar dryers; a Hybrid Indirect Passive (HIP) solar dryer with a modified solar collector plate and drying cabinet and Solar Photovoltaic and Electric (SPE) dryer with an auxiliary thermal-backup system, to compare with open sun drying (OSD). The drying period of the crops were 10 hours, 18 hours and 30 hours for SPE, HIP and OSD. Drying efficiency of the improved HIP dryer was comparable to the SPE dryer and was 18% higher than the OSD method. The higher drying rate and efficiency coupled with reduced produce drying time for the HIP and SPE dryer could translate into an increased turnover of the dried food products if deployed. Therefore, both the improved HIP dryer and SPE dryers could offer faster and more efficient food drying options than the traditional OSD method.

Veeramanipriya & Umayal Sundari [74] developed a prototype of Photovoltaic Thermal (PV–T) solar dryer aided with Evacuated Tube Collector (ETC) to analyse their performance and compared with sun drying. The fabricated dryer capable of reducing the moisture content of cassava from 91.5% w.b. to 10.67% w.b. in 8 hours. Based on the analysis done by the authors, the quality of hybrid dried cassava is better in terms of physical and chemical compositions than sun-dried cassava. Therefore, the proposed hybrid solar dryer was able to produce high quality dried products for exporting.

ADVANTAGES OF SOLAR DRYER

A solar dryer can provide a faster drying period. By trapping heated air in an enclosed place, a solar dryer can secure a higher air temperature for the drying process than drying in an open-air condition. The air can be heated by allowing the solar radiation from the sun to enter the dryer through a transparent cover and traps the heat inside. Besides, the heat can be added to the drying system by enlarging the solar collection area to collect more heat [14]. The drying process can also be shortened by applying a thermal energy storage facility which will help to supply heat energy during off sunshine hours [75]; [76]; [5].

Drying using a solar dryer is efficient since the process takes a shorter drying period while reducing waste production. It can help the agricultural field in terms of economy. A more significant percentage of quality dried crops can be produced. The enclosed drying surrounding can avoid attacks from the animals and fungi, which is more hygienic than open sun drying.

The nutritional value, such as vitamins and proteins, can be maintained by drying products at an optimum temperature. In order to preserve the nutrients and properties of food products, especially fruits and vegetables, a temperature between 45°C to 60°C is needed for safe drying. Besides reducing the drying period, it can also increase the product's value, such as taste, texture, and appearance. Hence, a higher product's marketability can be achieved, leading to better financial returns for the farmers.

Mechanized dryers may have many advantages compared with open sun drying. However, the capital and maintenance are very high since it needs fossil fuel or electricity to operate. It also has rotating equipment, leading to higher maintenance costs. Therefore, a solar dryer is more preferred since it is better than open sun drying in terms of drying period and product's quality. A lower operating cost is needed compared to a mechanized dryer.

DISADVANTAGES OF SOLAR DRYER

The solar dryer is very convenient to the industry since it helps maintain the quality of the product and is environmentally friendly. However, the solar dryer, which uses solar energy as the energy source, has two main weaknesses. First, the solar dryer is intermittent by its nature and depends on the location's weather conditions [77]. At night, there will be no sunlight, and the surrounding temperature will be decreased, and it will cause the relative humidity to increase. Second, the dried product might re-absorb the ambient moisture. This process will increase the drying time, and if not taken seriously, it might ruin the product. After some study by researchers, they have proposed to use a solar dryer integrated with a backup heat source such as an electrical heater to aid the drying process. However, the heater might increase the cost of the solar dryers [43]; [78]. Besides, there is a lack of solar dryer's expertise to install a high-efficiency solar drying system due to a lack of funding and government support to develop a research program on solar drying.

RECENT ADVANCEMENT OF SOLAR DRYING TECHNOLOGY

More research on renewable energy has been focused on finding new solutions for overcoming the energy demand in recent years. Moreover, reducing the air pollution and limited use of fossil fuel resources caused clean and green energy resources [79]. Solar energy is the main root for a solar dryer which uses the solar air and solar water collector due to their ideal properties like having high thermal efficiency and simple structure that are required in thermal application [80]; [81]; [82]; [83]. Besides, several criteria must be fulfilled in order to build a high-performance solar dryer.

Optimum temperature can ensure good drying conditions, which results in better product quality. On the other hand, drying at high temperature may shorten the drying time can result in negative quality to the products [80]; [84]. Lakshminarayanan, Mahesh, Amalraj, Mithun, & Nair [85] invented a solar dryer that can help fishers dry their fishes effectively. The hexagonal solar-powered dryer made sure the dried fish did not get spoiled since they are protected from the harmful airborne dust, and only moisture is removed by the hot air of at least 65°C. Emetere, Ayara, & Obanla [86] constructed a solar dryer that used a fan to increase the airflow inside the drying system. The design increased the temperature inside the hanger chamber by an average of 16.24% within four days of operation. Lingayat, Chandramohan, Raju, & Kumar [87] investigated the drying kinetics for apple and watermelon using an indirect solar dryer. The authors found that the solar dryer was able to dry 2 to 4 kg of the fruits in 8 hours of blue-sky condition with the average collector outlet temperature of 58.63°C and 56.9°C, for apple and watermelon drying, respectively. Doğuş, Sözen, Khanlari, Amini, & Şirin [88] had analyzed a quadruple-pass solar air collector (QPSAC) which accompanied by a pilot-scale greenhouse dryer (GD) that can supply moderate hot air to dry red paper and kiwi. The paper concluded that the use of QPSAC with GD could increase the drying temperature and results in 180 minutes drying time rather than not integrating QPSAC which produced a higher drying period of 330 minutes.

Integrating the additional heat source in a solar dryer can increase the efficiency of the system. Murali, Amulya, Alfiya, Delfiya, & Samuel [89] utilized a liquefied petroleum gas (LPG) water heater as a hybrid element in their solar dryer to dry shrimp. The energy supplied by the solar system was 2,06,641 kJ (73.93%), while the LPG water heater auxiliary system provided 72,890 kJ (26.07%). The combination of both heat sources delivered a drying efficiency of the shrimp at 37.09%. Moudakkar, El, Vaudreuil, & Bounahmidi [90] have designed a crimped spiral fin-tube heat exchanger (CSFTHX) coupled with parabolic trough collectors, and flash dryer was conducted. The conducted experiments showed that the system's oil temperature and airflow rate influenced the heat exchanger performance. The authors concluded that a backup heating system is necessary for the solar flash dryer to maintain the drying condition. Using heat storage elements can also be considered as a backup heat source in the solar dryer. Ndukwu, Onyenwigwe, Abam, Eke, & Dirioha [91] have utilized glycerol as thermal energy storage in an active mix mode solar dryer that used axial fan powered by a wind air generator (AWPFS) with a passive mix-mode non-wind-powered solar dryer (PNWPS). The active solar dryer results in higher efficiency. The time is taken to dry potato slices for solar dryers that used the wind-powered axial fan and utilized the thermal storage was shorter than the passive solar dryer without using thermal storage. The drying period can be reduced from 9-16 hours with the used of the solar dryer rather than open solar drying.

CONCLUSION

The use of solar dryers in drying activity grew widely, especially in the agricultural sector. Many attempts had been made to improve this field to increase the agricultural products while maintaining their quality. Proper handling and a good preservation strategy can result in higher production and reduce wastage. This paper presented a review on solar dryers that being studied by several researchers. The working principles of the solar dryer were reported. The solar dryer can be classified based on fluid flow behaviour, passive or active type, and heat transfer method, such as direct, indirect, mixed-mode, or hybrid. Moreover, the benefits and disadvantages of using solar dryers were also discussed. The recent studies on the solar dryer were also summarized.

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