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A review of solar drying design and architecture: Direct, indirect and mixed-mode solar dryer

Permana Andi Paristiawan[1], Ihwan Ghazali[2,*], Dwi Aryanti[3], Budiarjono[3], Ayu Amanah[3], Muhammad Idris[4], Dhany Hermansyah[5,6], Esam Abu Baker Ali[7,8,9]

[1]Research Center for Metallurgy, National Research and Innovation Agency, South Tangerang, Banten, 15314, Indonesia

[2]Fakulti Teknologi Kejuruteraan Mekanikal dan Pembuatan, Universiti Teknikal Malaysia, Melaka, Hang Tuah Jaya, Durian Tunggal 76100, Melaka, Malaysia

[3]Faculty of Engineering, Universitas Bung Karno, Jl. Kimia No. 20. Menteng, Jakarta 10320, Indonesia

[4]PT PLN (Persero), Engineering and Technology Division, Jakarta, Indonesia

[5]Department of Agro-Industrial Technology, Faculty of Agriculture Technology, IPB University, Bogor, 16680, Indonesia

[6]National Food Agency, Jakarta, 12550, Indonesia

[7]School of Mechanical Engineering, Universiti Teknologi Malaysia, 81310, Johor Bahru, Malaysia

[8]Faculty of Engineering, Omar Al-Mukhtar University, Libya

[9]General Electricity Company of Libya (GECOL)

***** Corresponding Author**:** ihwan@utem.edu.my

Abstract

Solar energy is available in abundance. It is considered an effective energy source for drying agricultural products. Although it is affordable, open sun drying suffers from both qualitative and quantitative issues caused by unexpected environmental conditions (rain, dust), animals (insects, birds, rodents), and over- or under-drying. Therefore, it is important to introduce a better drying technology to preserve solar energy without deteriorating the quality of the drying product. For that reason, solar dryers have been developed to produce higher drying temperatures and lower relative humidity that will eventually lead to superior drying rates and reduced final moisture contents compared to the conventional open sun drying method. Therefore, not only does the solar dryer meet the requirements of agricultural products, but it also saves energy, time, and money. The study reviews recent studies on direct, indirect, or mixed dryers design which focus on several aspects of solar drying, including: advantages and disadvantages and comparative evaluation for each type of solar drying design. Furthermore, this review paper contributes to the recent literature about such a significant findings of solar drying technologies for food conservation.

Keywords:
Keywords: Solar drying; Direct solar dryer, Indirect solar dryer; Mixed-mode solar dryer.

1 Introduction of a solar dryer

Recent development in alternative energy such as progress in biofuel [1-3] and electric vehicles [4, 5] has brought many benefits to mankind. Food preservation plays a substantial role in food security [6]. Hundreds of millions of people all over the world are malnourished [7]. For that reason, global food security can be overcome by applying technological innovation in the agricultural sector. Technology involvement is of importance to prevent post-harvest losses of an agricultural product after peak season ends [8, 9].

When foods are dried, their inherent physical state is changed, causing alterations in the quality of the food materials. In these regards, solar dryers can maintain the ‘acceptable to first grade’ edible status of agricultural products possessing valuable components such as vitamins, proteins, vitamins, and probiotics, which are considerably important for humans and animals. Drying requires the removal of moisture content from the food until a desired percentage is obtained, at which no or minimum chemical, physical, or micro-biological responses take place. The driers are specified based on how heat is distributed or what the medium of drying is. For example, solar dryers, heat pump dryers, super-heated steam dryer, and microwave dryer [10-13].

Different drying rates might have different effects on the biological or physical changes that might influence the degradation of food quality. The drying with high drying rates involves elevated temperature processes including drum, spray, hot-air tunnel, spouted bed, fluidized bed, super-heated steam, and heat-pump drying. However, another drying process, which involves low drying rates with higher processing times, undergoes lower temperatures. This includes solar drying, vacuum, freeze, atmospheric freeze, and microwave drying. To obtain enhanced product quality, higher efficiencies, shorter processing times, and lower production costs; a combination of drying methods is frequently used, such as spray–freeze drying, microwave vacuum drying, and microwave–convection drying [14-16].

Solar drying is one of primordial method of food conservation, yet recently the numerous improvements and development have been taken place to make it improved in terms of quality of product, drying time and efficiency of system. The improvements and development in solar dryers have been investigated and reviewed by various researchers. The investigation provided the knowledge of researches that focused on both review and research article which elaborate the detail implementation of solar drying for food conservation.

Lingayat et al. [17] reviewed the performance of various indirect type solar dryers and also presented the use of energy storage in indirect dryers. Singh and Gaur [18] reviewed how solar dryers are suitable from a sustainability point of view. Lamidi et al. [19] presented a review on the advancement in solar drying in the context of agricultural product drying. Hidalgo et al. [20] studied on the history of the solar dryers, their social impacts, and recent trends going on solar drying. Mishra et al. [21] presented a review on drying of commodities in greenhouse solar dryers.

Regarding to the dried product, many studies investigated various of dried product such as fruits, beef, fish, plants, leave, and vegetable. The observations provided the findings of the performance of drying system and how good the drying quality. Mewa et al. [22] evaluated the beef drying by five models. The model found the best for the drying behavior of beef. Beside beef product, other references mentioned for fish drying [23] by Richa et al. Etim et al. [24] investigated drying system for fruit (banana) and observed the dryer efficiency. Other references also studied the fruit dried product such as mango [25], tomato [26], chilly[27], coffee [28], grape [29], and date [30]. Different to the previous mentioned, Hage et al. [31] assessed technical, economic and environmental aspect for solar drying.

The paper presents studies on direct, indirect, or mixed dryers design which focus on several aspects of solar drying, including:

recent studies, benefit and drawbacks and comparative evaluation for each type of solar drying design, challenges, and future direction. Furthermore, this review paper outlines contributes to the recent literature about such a significant findings of solar drying technologies which can be used as an alternative for food conservation, particularly by optimizing the environmental and energy resources.

2 Fundamentals of a solar dryer

2.1 Benefits of a solar dryer

Solar drying technology has been used for food preservation because of its many advantages. The first and foremost advantage is undoubtedly the enhancement in the preservation against infective bacteria and microbiological decompositions, thus extending the shelf life of the food. In addition, the storage capacity will increase because of a considerable reduction in moisture content. Since moisture is significantly reduced, microbial growth can be further minimised, while at the same time the storage and transport system will improve owing to a significant decrease in weight and size of the drying product because of water loss. Another benefit of solar drying technology is the elimination of cooling equipment for food preservation, thus avoiding cooling systems and energy costs. Besides all the benefits mentioned above, solar dryers also facilitate food diversification, resulting in various types and flavours of food products available in the market.

However, compared to advanced drying equipment, the investment costs of solar drying technology are still lower. In countless rural regions of most developing countries, the electricity supply is often limited and expensive. Drying systems that use modern facilities are unsuitable due to the unaffordable investments and operating costs. Therefore, the development of solar dryers can meet the needs of farmers in rural areas.

2.2 Drawbacks of the solar dryer

Note that radiation from solar energy alternates, thus irregularity is the main problem as it works only during the sunshine. Solar drying technology is also more expensive than open sun drying. In some cases, a number of parts of material should be imported, thus increasing the capital cost.

2.3 Challenges of a solar dryer

Despite its promising application, a number of challenges hinder the adaptation of solar drying technology. First, funding and government support are scarce, inhibiting the progress of solar dryer research and development. The high-priced initial investment is another barrier. The lack of technical know-how in the design, production, and installation is also common, particularly in an advanced and high-efficiency solar drying system. Most importantly, farmers and average people are not aware of the significance and advantages of solar dryers, which prevents the application of solar drying technology, especially in most rural areas in developing countries. Although the quality of the final drying product can be improved by reducing harvest losses using a suitable drying technique, it is important to remember that there is currently no standard or merely a marginal difference in the price between low- and high-quality drying products. This will further affect the acceptance of solar drying technology in the market. However, if these barriers can be overcome, the application of solar dryers will certainly be able to contribute to the economic development in rural areas in the majority of developing countries where the lack of electricity is prominent.

2.4 Component of solar dryer

Normally, solar drying equipment comprises three major components: (1) the drying chamber, (2) the air heater, and (3) airflow system. The drying chamber is the insulated place in which the products are placed to protect the food from external disturbance. The solar heater or the solar collector is a dark colour box with a transparent and clear cover. It heats the ambient air by increasing the temperature by 10-30 K. The last component is the airflow system whose function is to release moist air to the nearby area [32, 33].

3 Direct Solar Dryer

Using a geothermal water heat exchanger as a complementary energetic supply, Sandali et al. [34] aimed to improve the performance of a direct solar dryer. With an integrated heat exchanger, the highest drying air temperature was reported to be 58°C, whereas the lowest was 46°C.

Tuncer et al. [35] examined a quadruple pass solar collector supplemented with a greenhouse dryer. The results were analysed numerically and experimentally for the drying of red pepper and kiwi with performance tests carried out at a flow rate of 0.008 and 0.010 kg/s. The mean thermal efficiency was found to be between 71.63% and 80.66%. The authors concluded that by integrating a quadruple-pass solar collector, a greenhouse dryer was able to significantly reduce drying time. In terms of numerical results, the maximum deviation was reported to be 10% between the experimental results and the CFD. Fig. 1 shows the distribution velocity of two different solar collectors; triple- and quadruple-pass collectors.

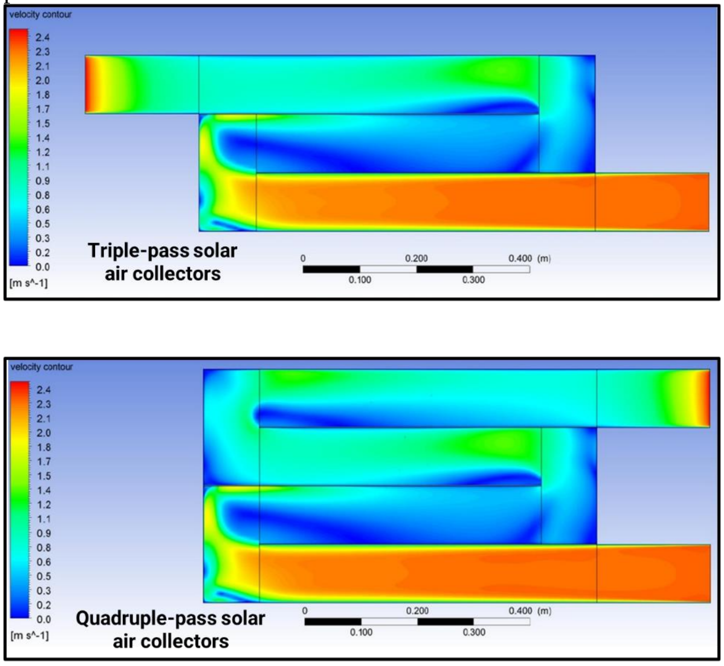

Fig. 1. Distribution Velocity of solar air collectors, adapted from [35].

Overall, their velocity characteristics depict comparable contours with pressure loss of only 3.8 and 4.5 Pa for triple- and quadruple-pass, respectively, showing an insignificant rise in fan power consumption.

Nabnean and Nimnuan [36] investigated the performance of a direct forced convection solar dryer to dry bananas. A parabolic cover with polycarbonate plates was used to decrease the heat losses while allowing the solar radiation to diffuse into the dryer, as shown in Fig. 2. It was found that the drying air temperature varied between 35 and 60°C during the day. The final moisture content reached 28% wet from an initial value of 72% (wb) in four days (Fig. 3). For comparison over the same period, the final moisture content of the open sun-dried banana only dropped to 40% (wb). A 48% reduction in drying time was also observed in the solar dryer compared to open-sun drying. The solar dryer's payback period was estimated to be 1.1 years.

Téllez [37] compared a cabinet-type direct convection solar dryer operating with indirect forced convection to dry Stevia leaves.

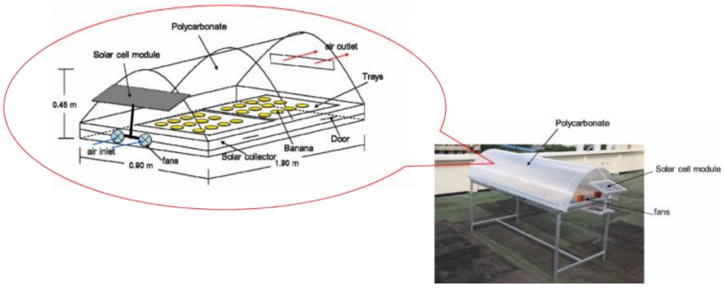

Fig. 2. Direct and forced convection solar drying technology with a parabolic cover of polycarbonate plates for drying banana, adapted from [36].

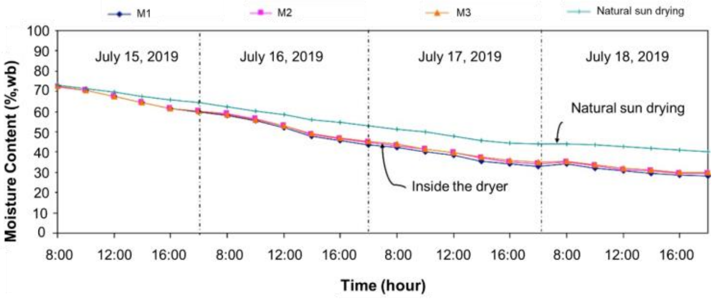

Fig. 3. Comparison of moisture contents between solar and natural sun drying, adapted from [36].

The results showed that the indirect solar dryer provided a better result with reasonable drying times and superior protection. For the direct solar dryer, the best predictive drying kinetics model was found to be the Weibull and two-term exponential models, whereas the best model for the indirect solar dryer was reported to be the Weibull model as depicted in Fig. 4.

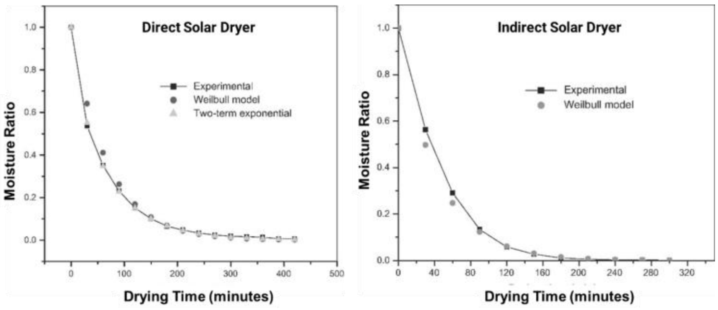

Fig. 4. Best-fit predictive drying kinetics model for direct solar dryer and indirect solar dryer, adapted from [37].

4 Indirect solar dryer

Vijayan et al. [38] analysed the environmental impact of an indirect forced convection solar dryer for bitter gourd slices. The average pickup efficiency was found to vary from 17.12 to 54.29% and the exergy efficiency varied from 28.27 to 40.68% for 0.0141–0.0872 kg/s. The effective moisture diffusivity (D_{eff}) of the bitter gourd slices also varied from 8.6293×10^{-10} to 12.9585×10^{-10} m^2/s. The mitigation of carbon dioxide mitigation & received carbon credit received were reported to be 33.52 tons and INR (Indian Rupee) 10894 to 43576, respectively.

A solar dryer with indirect forced convection integrated with supplementary heating equipment was conducted by Wang et al. [39] Page's model was found to be the most suitable model for mango solar drying. Chaouch et al. [40] compared an active direct and indirect solar dryer for the drying of camel meat. Compared to open sun-dried experiments with deteriorated hygienic and physicochemical quality, both drying methods showed satisfactory results to meet Algerian legislation.

El Khadraoui et al. [41] designed and manufactured an indirect solar dryer with forced convection using phase change material (PCM) to investigate the charging-discharging behaviours of the storage of the PCM cavity (Fig. 5). The drying chamber temperature of the solar dryer with PCM was found to be higher than that of the ambient at 4 to 16 ° C at night. In addition, the relative humidity inside the chamber was reported to be 17–34.5% lower compared to the ambient.

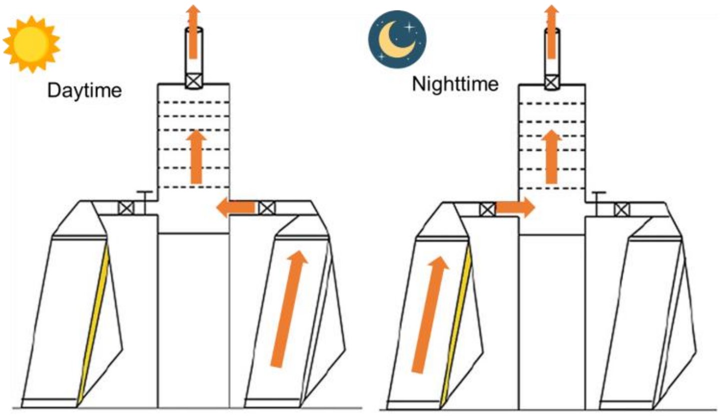

Fig. 5. Working principle of indirect solar drying technology with PCM, adapted from [41].

Ortiz-Rodrguez et al. [42] compared the characteristics of a direct and indirect solar dryer for the drying of natural rubber sheets. The moisture content was found to decrease from 45.8 to 0.59% dry (db) for the direct solar dryer, while that of the indirect solar dryer reduced from 49.7 to 0.33%. Thirteen thin layer models were also used to examine the drying characteristics, with the Pabis and changed Henderson giving the best fit for both the direct and indirect solar drying systems. Overall, the direct solar dryer with greenhouse type was suggested for small-scale producers, while the indirect solar dryer with tunnel type was recommended for larger scale with greater and nonstop production. Fig. 6. shows the representation of an indirect tunnel-type solar dryer.

Kong et al. [43] developed a solar drying system equipped with a photovoltaic collector. Two types of solar cells integrated with the air collector were compared as shown in Fig. 7. For the amorphous silicon collector, the results showed that the average electrical efficiency, average thermal efficiency, and comprehensive utilization efficiency were 5.7%, 46.8%, and 54.4%, respectively, whereas, for the polycrystalline silicon collector, the values were 6.8%, 40.7%, and 55.4%, respectively.

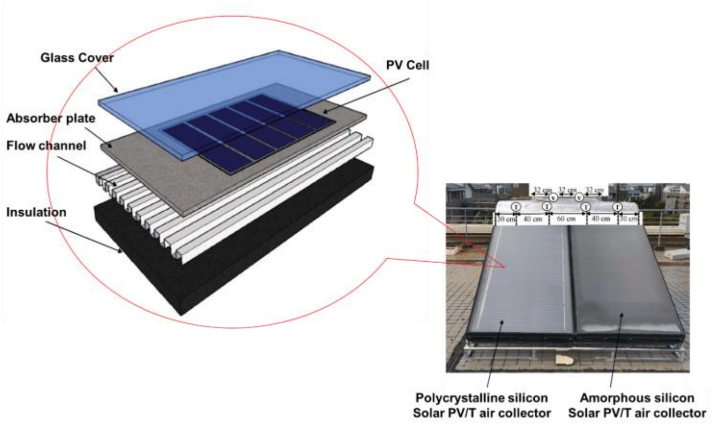

Fig. 7. Structural diagram of a solar photovoltaic collector and its photographic view, adapted from [43].

Rabha et al. [44] developed an indirect forced convection solar tunnel dryer integrated with a shell and tube heat storage module to dry sliced ginger and ghost chili pepper. Exegetic efficiency was found to improve with a shorter drying time, with high energetic efficiency observed in the last hours of the drying experiments, as shown in Fig. 8.

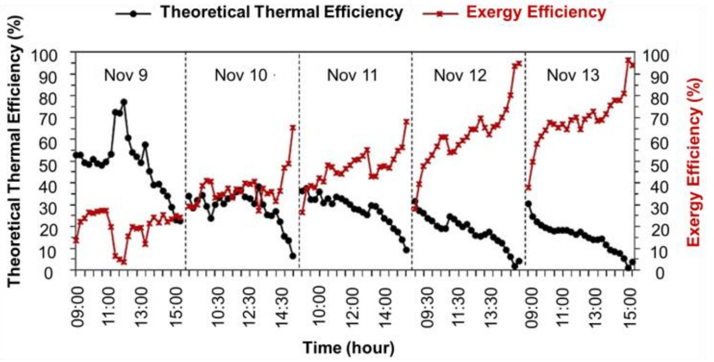

Fig. 8. Variation in the thermal and exergy efficiencies of the drying process, adapted from [44].

Slimani et al. [45] developed a hybrid PV/T solar collector for an indirect solar dryer as shown in Fig. 9. The thermal efficiency of the hybrid collector was found to increase by nearly 31% from the basic configuration. The air temperature supplied by a double-pass photovoltaic/tetrahedral (PPT) collector was believed by the authors to be exceptionally appropriate for solar drying applications.

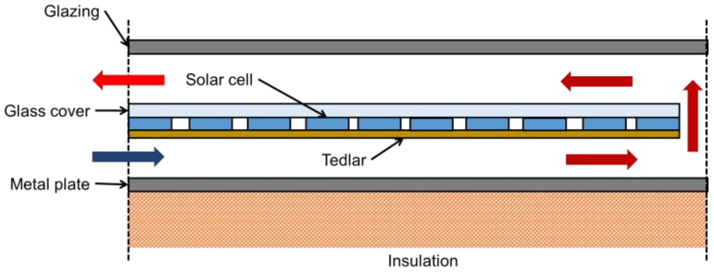

Fig. 9. Cross-sectional view of the PV / T air collector developed by Slimani et al., adapted from [45].

5 Mixed mode solar dryer

Baniasadi et al. [46] experimentally investigated a mixed-mode solar dryer of apricot slices with thermal energy storage. The drying rate was found to be nearly constant throughout the drying chamber. The overall thermal and moisture removal efficiency of the dryer was approximately 11% and 10%, respectively. Fterich et al. [47] used mixed-mode forced convection with a PV/T air collector. The moisture content was found to have reduced from 91.94 to 22.32 % for the first tray and 28.9 % for the second tray, while the reduction from the open sun dryer was only 30.15 %.

Ekka and Palanisamy et al. [48] used red chili dried in a mixed-mode forced convection solar dryer. The results showed that the heat transfer coefficient of the convective ranged from 1.67 to 1.7 W/m^{2}C, while that of the evaporative ranged from 22.77 to 74.06 W/m^{2}C. Moreover, the Midili-Kucuk was found to be the best kinetic model for red chili. César et al. [49] constructed a passive, mixed-type solar dryer for tomato drying and compared it with an indirect solar dryer. The drying chamber temperature of the mixed-mode solar dryer was reported between 65 and 70°C with a drying time of 17 hours, as shown in Fig. 10, a significant improvement compared to the indirect solar dryer which was in the range of 55 - 60°C with a drying time of 26 hours. Furthermore, the drying kinetics was predicted using five mathematical models. For the mixed-mode and indirect solar dryer, the best fit was given by the changed Henderson & Pabis model with R^2 of 0.9888 and 0.9996; and RMSE of 0.0027 and 0.008, respectively.

6 Conclusions

Several open sun drying technology has been reviewed and observed regarding to each design and performance. The review presented three common different types of solar dryer with their performance, such as direct, indirect and mixed solar dryer. Open sun drying is affordable, but it gives inconsistent quality of drying products. Solar drying technology is developed to overcome the drawbacks of the open sun drying method and maximize the benefits of solar energy to the greatest extent. Solar drying technology is valuable in both the domestic and industrial sectors for agro-based products. The preservation process becomes far more straightforward, while at the same time increasing the storage capacity and reducing the cost of transportation.

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