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A review of solar drying technology for agricultural produce

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ABSTRACT

Agriculture contributes to large export earnings for many countries and provides food all over the world. However, most agricultural products need some post-harvest processing, such as drying, to extend their shelf life while still maintaining their respective nutrient quality. One popular post-harvest processing method is drying using solar energy. It is a type of renewable energy that is abundant and free. Conventional dryers use grid electricity and can be expensive to operate. Consequently, there is a growing need for cost-effective solar-powered agricultural dryers that is reasonable for smaller-scale farmers. Although current solar dryers are still not on par with modern electricity-powered dryers, solar dryers have lower running costs and are sustainable and able to generate electricity. They can also be used practically anywhere with abundant solar energy. As numerous solar drying technologies have been proposed over the past decade, it is necessary to assess the current state of solar drying technology in the agricultural sector to identify current advancements and potential research gaps. In this paper, a review of existing solar dryers mechanism and the state of the art of solar drying technology research for agricultural products is presented.

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1. INTRODUCTION

Agricultural harvested products contain water or moisture content that is usually in a condition that stimulates the growth of unwanted microorganisms. The drying process of these agricultural products is one of the stages in post-harvest production [1], [2]. The drying process aims to remove enough moisture content from the product so that it can be stored and preserved for a longer period without spoilage [3]. Traditionally, the standard method for drying agricultural produce was the open-sun method, where the agricultural produce is distributed thinly over a large area in direct sun. This drying method is labor-intensive and time-consuming [4], [5]. The agricultural dryer machine currently available on the market is largely intended for commercial-scale farming purposes. Most of this industrial machinery operates on burning fossil fuel and coal, which would be detrimental to the environment in the long run. Moreover, the conventional agricultural dryer is expected to be far more expensive; thus, it would require a large amount of capital for most small-scale farmers.

In the past decade, one of the efforts in bridging this gap has been developing dryer machines powered naturally by renewable solar energy. Solar energy is a type of non-conventional energy that is unlimited, renewable, and free, reducing environmental pollution and reducing the cost of drying agricultural produce [4],

[6]. The solar dryer works in a way similar to the traditional technique, where products are dried using readily available sun rays to dry products in a safe and confined space. Researchers continue to focus their attention on the solar-powered dryer machine to find more solutions to the problems currently faced by solar dryers in the agriculture industry and bring them on par with machines that use more traditional technology.

The solar dryer's drying process of each agricultural product, for example, black peppers, has various dependencies. These dependencies, such as temperature and humidity level, play a significant factor in the rate at which it reduces the moisture content of products [7], [8]. However, as the market for dried products becomes a competitive field for commercial industrial dryers, it is necessary to further increase the performance capacity of solar dryers to be on par with modern conventional dryers to produce higher-quality dried products [1]. As the drying process of agricultural products causes modification in the quality constituent of a product, these drying parameters must be controlled so that a suitable drying environment is provided to dry each product optimally. These physio-chemical constituents that hold the product's benefit are important since they describe the product's taste, color, and so on. The drying temperature for common commodities such as black pepper, wheat, and rice is between 45 °C to 60 °C [9]. Different commodities dry at different rates; thus, they each have a particular set range of temperatures they can withstand. It is argued that at any temperature below 45 °C, microbes that cause spoilage are still active inside drying products. In comparison, a temperature above 75 °C can damage products' important biochemical compound and physical structure [3], [9].

The uncertainties of solar dryer operations that are heavily dependent on solar energy availability led to many advances, including backup thermal storage, hybrid dryer system, solar panel integration, drying chamber reconstruction, and improvements or changes to solar air collector [8], [10], [11]. Hybrid dryers that utilize a combination of solar energy and non-renewable energy sources, such as grid power, have been developed to mitigate any limitations of the dryer [8], [12]. Nowadays, the solar dryer is often equipped with a control system where monitoring and controlling the drying parameters is readily available. This controller-based dryer enhances convenience in operating and further improves the drying process, as the drying temperature can be automatically regulated. This improvement can be further expanded by integrating many possible functions, including the internet of things (IoT) integration feature and machine learning tools.

The solar drying technology have received a lot of attention in the food production research field to continue provide novel contribution in improve existing drawbacks of solar dryer system in drying agriculture products. With increasing study in analyzing and developing new ways to further enhance performance of solar dryer to compete with conventional-energy powered dryer system towards a better sustainable, clean, and cost-effective dryer, many review papers of related work to sum up the solar drying technology field. Table 1 provides a rundown of the review work mentioned earlier.

Table 1. Overview of published research on solar dryer technology and its applications

Authors	Topic Discussed	Similarity
Tiwari [1], Bala and Debnath [13], Fudholi *et al*. [14], Bervile *et al*. [15]	Advancements and applications of solar drying technology in various regions and industries	Overview of solar energy, advancement in solar drying technology, and organizations and local policy in encouraging the work in advancement for solar dryers in agriculture.
Wakjira [7], Zhang *et al*. [9], Mustayen *et al.* [16], Sopian *et al.* [17], Jha and Tripathy [18]	Various solar dryer types, designs, and performance, as well as the influence of solar drying on the quality of fruits and the potential of solar dryers in agriculture production	Drying methods, solar drying technology, problems and opportunities of food production, solar dryer classification, types, design considerations, and research applications with agricultural products.
Srinivasan and Muthukumar [19], Lingayat *et al*. [20], Mehta *et al*. [21], Khallaf and El-Sebaii [22], Srinivasan *et al.* [23], Nukulwar and Tungikar [24], Natarajan *et al*. [25], Hani *et al*. [26]	Specific techniques and technologies used in solar dryers, such as thermal energy storage, indirect solar dryers, mixed-mode solar dryers, and the application of solar energy in drying medicinal plants and fish products.	Solar dryer types, design, performance, application of different solar dryer types, thermal energy storage, indirect solar dryers, mixed-mode solar dryers, and the application of solar energy in drying medicinal plants and fish products.
Ndukwu *et al.* [27]	Solar greenhouse dryers in various aspects for drying agricultural products	Not available
Jangde *et al.* [28]	Solar dryer types and highlights work of different solar dryer study in the African region, research gap in the solar drying application of agricultural products in Africa.	Not available
Fudholi *et al*. [14]	Advancements in SDT and its impact on environment analysis.	Not available

Table 1 presents an overview of published research on solar dryer technology and its applications. It includes studies on the classification, types, design considerations, and applications of solar drying technology in agriculture, as well as its potential for sustainability in different countries such as India, Ethiopia, China, Indonesia, and Malaysia. The table also covers advancements in solar drying technology, including the use of phase changing materials, desiccant thermal storage, and hybrid solar dryers. The studies discuss the performance and efficiency of different solar dryer types, as well as their impact on the environment and economic aspects. The paper also presents a review of existing solar dryers mechanism and the state of the art of solar drying technology research for agricultural products, highlighting current advancements and potential research gaps in the agricultural sector. The key contributions of this paper are listed in: i) To provide a clear and concise insights into the drying process of post-harvest agricultural produce and its importance in the agricultural field; ii) To provide a compact overview of solar dryer's classification; and iii) To identify and summarize state-of-the-art clean-energy solar dryer technologies and the application of solar technology in the agricultural industry.

The paper has six sections, the first of which is an introduction that covers background study and motivation. Section 2 discusses the method used to obtain research data. The findings of the drying process in the agricultural post-harvest process are presented in section 3. Section 4 describes solar dryer classification and techniques. Section 5 presents a summary of the frequent solar dryers' development studies for agricultural harvest. Subsequently, the final section of the paper (section 6) wraps everything up.

2. METHOD

The data sources in this review were compiled from multiple research articles obtained from IEEE XPlore and Google Scholar. The main keywords of this review are solar dryer, solar drying technology, and solar dryer for agriculture. Many sources cited in this paper have been published within the last five years in this review article. Previous and recent developments related to solar drying for the agriculture sector are analyzed. Several literature review in similar field are available as summarized. However, this present article aims to provide compact review for the state-of-the-art of recent solar dryer machines as well as outlining the drying process of agricultural crops and understanding the latest trend and difficulties in solar drying technology in the past years.

3. RESULTS AND DISCUSSION

3.1. Principle of drying of agricultural produce

In agricultural context, a drying process is the removal of moisture or water content to obtain a solid product in a controlled manner, with the aim of preserving the product for safe and longer storage while ensuring a good quality dried product. This process is part of the post-production of agricultural harvest. Drying operation involves simultaneous heat and mass transfer operations. The three critical parameters that govern drying behavior are the environment relative humidity, air velocity, and temperature. The quality of the resulting dried product is also affected by the initial quality of the drying product, the nature of the raw product, the pre-drying process treatment, the drying process methods used, and the density or amount of load per drying batch [1]-[3], [29].

Removing the excessive water content of a product prevents the growth and reproduction of harmful microorganisms that stimulate decay and the risk of deterioration. The process reduces product weight and volume, allowing lighter packaging and reducing storage weight and transportation costs [7]. Moisture removal is commonly through evaporation or sublimation, where a phase change occurs from liquid (water) to gas (vapor) or from solid (ice) to gas (vapor) during sublimation drying. The product uses the heat that circulates between the products during this phase change. The high temperature provides more heat to the environment; therefore, the moisture removal rate is higher at higher temperatures [3].

Generally, the drying environment of food products or other commodities occurs in heated air or a mixture of air and flue gas. This environmental condition allows the moisture content of the products to be dried and then diffuse into the surrounding environment. The drying mechanism works when there is a difference in water vapor pressure between the surrounding air and the product, water vapor flows from higher pressure to lower pressure of moisture content. The drying process continues until the commodities reach an equilibrium of moisture content or humidity level. This equilibrium state is reached when the water vapor pressure equals the drying environment pressure. The water content of a product is generally defined on a dry or wet basis, the wet basis is the comparison between the weight of water in the matter and the wet weight, the dry basis is the difference between the dry condition (weight after drying) and the wet condition (weight before drying) [3], [30]. Using black pepper berries as an example, the drying of fresh pepper berries occurs in two stages. The first stage of drying is usually faster than its later stage [31]. In the early stage, the moisture readily sitting on the product's surface vaporizes at a constant rate and faster than the product's internal moisture. The second stage typically occurs at a lower drying rate since its moisture must be diffused to the surface before transferring to the air.

3.2. Pre-treatment before drying of agricultural produce

As the drying process is time-extensive, pre-treatment practices can shorten the drying process. These treatments are known as blanching and sweating. Blanching treatments are soaking or immersing products in a hot water bath for about a minute. The sweating treatment is where the products are stored in a controlled climatic chamber before the actual drying process. Weil *et al*. [32] studied the effects of these treatments and the drying process on the quality of black pepper. The author found that blanching black pepper before drying can significantly reduce the drying duration compared to the drying process alone. Furthermore, all three processes change the color of the black pepper, primarily through the drying process. Overall, the quality of black pepper was preserved in both the pre-treatment and drying processes. Similar topics have been studied in the past by [32]-[34]. Weil *et al*. [32] and Cmi *et al*. [33] generally share the same views but differ slightly from [34]. In the report by Nisha *et al*. [34], the black pepper piperine content was reduced by 28% after 20 minutes at 100 degrees celsius (°C). In comparison, both Weil *et al*. [32] and Cmi *et al*. [33] reported only a 2.2% and 2.5% reduction, respectively. Their disagreement may be due to the treatment condition applied to severely different products [32]. It is vital to strengthen the knowledge with more research in this area using controlled conditions.

3.3. Drying temperature

Agricultural products that go through the drying process have their drying conditions that must be obeyed to provide a safe drying environment without affecting the quality of the dried products [2], [9]. Although the drying method influences quality, other factors, such as the drying temperature, also affect the process [7]. Suresh *et al*. [35] evaluated the effect of temperatures between 45 °C and 75 °C on the quality of various commodities. It is argued that at any temperature below 45 °C, microbes that cause spoilage are still active [3]. For black pepper specifically, the highest temperature for drying is 65 °C, where a temperature higher than that may degrade the color and quality of the product. Generally, an agricultural harvest is usually dried its moisture content is down to about 10-12%. These guidelines should be met for better preservation of taste [8]. Rizalman *et al*. [2] pointed out that drying agricultural products at high air velocities may lead to volatile compound losses. Table 2 shows some works conducted on solar drying for different commodities.

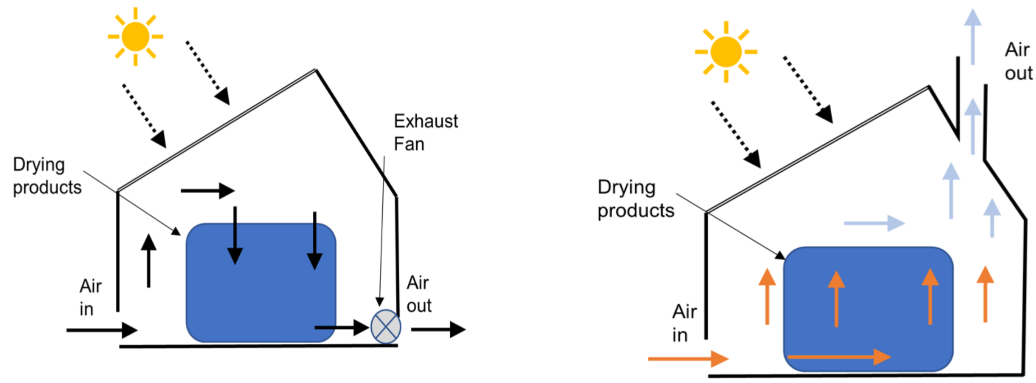
Table 2. The solar dryer works for different commodities

Product	Highest drying temperature (°C)	Authors
Apricot Waste	65	Zhang and Wang [36]
Banana	70	Lan [8]
Bilimbi	57	Harun *et al*. [30]
Bitter Melon	75	Lan [8]
Black Pepper	75	Amarasinghe *et al*. [29], Shreelavaniya *et al*. [31], Metidji [37], Manukaji [38], Akinoso *et al*. [39]
Coffee Bean	75	Larasati *et al*. [40]
Grapes	70	Jiskani *et al*. [4], Hafeezgayasudin *et al*. [41]
Green Chilli	60	Rabha and Muthukumar [42], Mursalin *et al*. [43]
Jack Fruit	80	Lan [8]
Mango	44	Iskandar and Ya'acob [3]
Orange Peels	65	Bukke *et al*. [10]
Palm Oil	67	Fudholi *et al*. [44]
Potato (Slice)	42	Ndukwu *et al*. [45]
Red Chilli	70	Jiskani *et al*. [4], Mustayen *et al*. [16], Nhut *et al*. [46]
Tomatoes	65	Oueslati *et al*. [47]

3.4. Classification of agricultural produce solar dyers

Referencing to recent studies and development of solar dryer technology, these systems are commonly divided into two main categories of hot air circulation mechanism, namely [1]: i) Active mode dryers or forced air convection, and ii) Passive mode dryers or natural air convection. Active mode dryers is a solar dryer system that adopts the active mode operation and uses an additional component, such as a mechanical fan, to promote streamlined air flow circulation and allow air to distribute much faster. This mechanical fan is either operated by electricity or a solar module. Passive mode dryer is a solar dryer system with natural air convection means that the dryer allows air to move naturally and circulate freely in the drying system. When hot air enters the drying cell inside a passive mode dryer, the temperature differences inside cause air buoyancy forces, which force the air to circulate [13].

Figure 1 depicts the difference between an i) active mode dryer as illustrated in Figure 1(a) and a ii) passive mode dryer as illustrated in Figure 1(b). In active mode, as shown in Figure 1(a), the air flow within the drying enclosed space is circulated by the forced convection provided by the exhaust fan installed in the system. The orange-colored arrows going into the chamber in Figure 1(b) represent hot air entering the drying space. The light blue colour depicts hot air rising naturally due to density differences and exiting through the chimney.



(a) (b)

Figure 1. Depicts the difference between an (a) active mode dryer and (b) passive mode dryer

Each mode of air movement shown in Figure 1 has its own merits and weakness. Compared to the passive mode, the active mode dryer system has a more complex structure and relatively higher equipment cost but performs better with higher efficiency [9]. Therefore, the natural convection mode dryer is easier and much more economical to reduce the cost required for active mode dryers [10], [13].

There are two main solar energy applications; one application uses this energy to convert it to electricity using photovoltaic (PV) panel, and the second application is converted it to thermal energy used for drying through a device called solar air collector [46]. Figure 2 illustrates the different types of solar dryer systems, including direct type, indirect type, and mixed mode, and their variations.

As can be seen from Figure 2, solar energy is used to dry foods in three different types of drying methods [14], [19]: i) direct type, ii) indirect type, and iii) mixed mode. Hence, there is six basic types of solar dryer techniques which are (a) direct active dryer, (b) direct passive dryer, (c) indirect active dryer, (d) indirect passive dryer, (e) mixed-mode active dryer, and (f) mixed-mode passive dryer.

In the direct-type solar dryer system, the products are placed inside the drying unit or room where the heating or drying occurs. The products are dried by exposing them directly to solar radiation through a transparent material such as glass [19]. Lakshmi *et al*. [48] defined that the direct solar dryer's purpose is to reduce heat loss during operation. Interestingly, [5] reported that "alteration of vitamin 'A' and 'C' with direct exposure to sunlight cannot be avoided," which is an indirect implication that a direct type of dryer may be a hindrance in the effort to improve product quality.

The indirect type commonly comprises of two components: a drying chamber made of opaque material and the solar air collector, which provides hot air for drying. The products sit inside the chamber unexposed to sunlight, where the heated air from the solar air collector enters and dries the product load [19]. In this method, the product may be protected from direct sun rays to prevent any possible discoloration and better humidity release [8], [20]. In a review article on solar drying technology by [13], it was reported that the indirect forced mode is more popular due to its higher efficiency than the indirect natural mode [13]. Some of the existing developed solar dryers that adopted this operation mode uses various kind of product enclosure box, including solar tunnel dryers, semi-penetrable greenhouse-type solar dryers, roof-integrated solar dryers, and solar-assisted dryers.

The third solar dryer type, which is the mixed-mode type, mixes both drying methods from the direct and indirect types into a single dryer. Like an indirect dryer, a mixed-mode type dryer has a solar air collector that traps thermal energy from the sun radiation to heat the ambient air that enters it. The drying chamber is roofed with transparent material, similar to direct dryer mechanism so that sunlight can directly reach the products inside it through this material [19]. Furthermore, the combined features of direct exposure to solar radiation and a heated environment by solar collector result in a faster drying rate of the products in this mixed-mode type of solar drying [36], [49].

To further sustain a good quality of products, it is essential to follow acceptable practices and necessary procedures when handling and operating solar dryer. These steps include [7]: i) Procurement of good quality produce, ii) Carefully handle and store products before loading, iii) Preparation of products to be dried before loading (pre-treating, cutting, and slicing), iv) Ensuring good hygiene of the drying environment and correct loading of products to the dryer, v) Correctly operate the dryer at an optimum condition for the particular product, and vi) Immediately unload, pack, and store the product in a safe place.

In addition, the operation personnel need to be knowledgeable in identifying good quality products and characteristics of well-dried products. They also must be skilled in handling the dryer machines to prevent hiccups during operation [7].

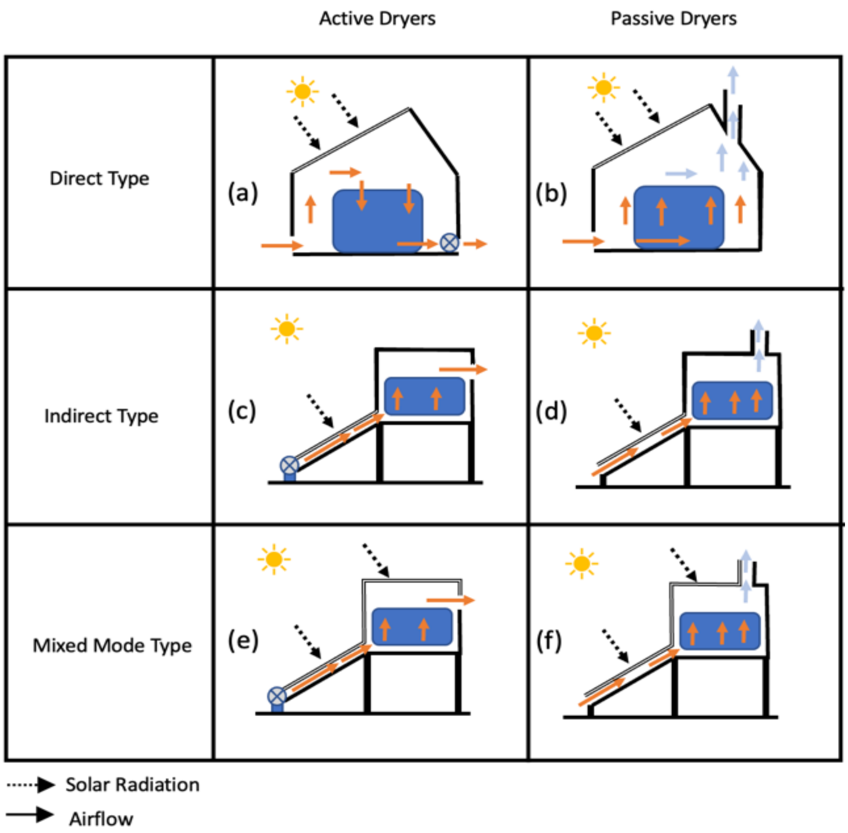


Figure 2. Types of solar dryer systems

3.5. Review discussion

In the last decade, the solar dryer's advancement has shown substantial improvement from what we have seen over the last few years. The solar dryer system has been derived from the old open sun drying practice and combined with the latest technology to produce an efficient, much more reliable system and able to compete with modern conventional drying technologies. Application of different drying techniques was used in many studies to provide further understanding of its performance in different aspect. Additionally, we have seen many of the existing articles in solar dryers capable of drying high-quality products within a shorter duration compared to open sun drying.

For the most part, solar dryers can be constructed locally and can be used anywhere with a sufficient supply of solar radiation such as Malaysia, Indonesia, and Africa. The application of solar dryers in agricultural communities can contribute heavily to developing countries to increase food production, further prevent food wastage and improve the general socio-economy without the burden of high capital prices and operational costs. The continuous research on the solar dryer will provide a steppingstone in developing an enhanced and more efficient dryer in the future so that the practice of sustainable machines can be delivered and used more widely. The real application and experience of utilizing solar dryers will also lead more personnel to handle these types of machinery and be more knowledgeable in handling these systems even better. The existing study of solar dryer systems for mixed mode is summarized in Table 3 and the indirect mode in Table 4.

The main parts of a solar dryer are the dryer loading space area and a solar air collector. Referring to Table 3 and Table 4, solar dryers may be coupled with emergency or backup heating system when solar heat energy is not reliable for drying products due to a rainy, cloudy, or overnight period. Additionally, some solar dryers are of a hybrid system that incorporates a conventional electric system to supply continuously the required temperature levels for drying. Most solar dryers that have a conventional electric system only use it as an emergency or backup heating mechanism to boost the drying performance. The dryer that has the 'backup heating system' column ticked means that it either uses natural heat resources or a heating component that only uses solar generated electricity through photovoltaic (PV) panel. Solar dryers also use sensor components to monitor and control important drying parameters such as drying temperature and humidity level within the dryer chamber. This integration of internet-of-things (IoT) technology is in line with the implementation of the fourth industrial revolution (IR4) to introduce smart farming system in the agricultural sector. This is an important aspect of the implementation since it plays a role in increasing precision and accuracy of farming.

It was also discovered that different drying space designs exist. These variation of drying space designs are typically proposed for multiple research goals in understanding the effect of drying space design on drying rate and heat behavior in each geometric shape. Nevertheless, the commonly chosen design choices are the chamber, tunnel, or greenhouse design. The interest in further enhancing drying performance of solar dryers, works in manipulating design of drying chamber, air inlet of solar collector is also available. Types of solar air collector used in solar dryers also varies in their mechanics to collect heat energy and this includes single-bypass solar collector, double bypass air collector and evacuated heat tube collector to heat up water storage tank.

Another important point to note from Table 3 is that the dryers in [10], [45], and [48] have a backup heating system that uses thermal storage material (such as glycerol, pebbles, and paraffin wax) to store thermal energy to be released when solar energy heating is ineffective. Similarly, biomass and electrical heaters are also used as the emergency heating systems in [12] and [43] to raise the drying temperature during the sun intermission. The dryer system reported in [12] utilized thermal fluid heating to dry the agricultural commodities inside its chamber. Lastly, one of the extra features mentioned in [45] is that in addition the use of solar as heat to provide thermal energy, the dryer also utilizes readily available wind energy to generate power for the axial fan.

Referring to Table 4, the dryer in [49] uses solar energy to heat up a thermal fluid for the distributing hot air throughout the drying chamber through a mechanism called evacuated tube collector. The dryer [5] and [47] use an external burner to provide additional heat to dry agricultural products inside the chamber. At the same time, dryer [31] and [49] burns biomass materials to release heat energy to the dryer. Additionally, dryer [40] and [50], [42], and [51] uses a solar-generated electric heater, paraffin wax, and water tank storage, respectively, to increase the drying temperature inside its' drying space. The dryer Cetina-Quiñones *et al.* [52] introduces limestone and beach sand as another thermal storage material that was able to provide the additional heat during the downtime of solar availability. Dryer [6], [8] and [46] depends on grid electricity to power up the heater module to provide additional heat to increase the temperature inside the drying space.

Table 3. Summary of mixed mode solar dryers for agricultural produce

Authors	Employs forced convection	Has a backup heating system	Employs conventional electric heating system	Dryer with photovoltaic panel	Has a monitoring and control system	Drying space style		
						Chamber style	Tunnel style	Greenhouse
Jiskani *et al*. [4]						✓		
Bukke *et al*. [10]	✓	✓					✓	
Ostia *et al*. [12]	✓	✓	✓	✓	✓	✓		
Metdji *et al*. [37]	✓						✓	
Zhang and Wang [36]	✓			✓				✓
Hafeezgayasudin *et al*. [41]					✓	✓		✓
Mursalin *et al*. [43]	✓	✓				✓		
Ndukwu *et al*. [45]	✓	✓				✓		
Lakshmi *et al*. [48]	✓	✓					✓	
Coriolano *et al*. [49]						✓		
Cetina-Quiñones *et al*. [53]	✓							✓
Arifianti *et al*. [54]	✓							✓
Nair *et al*. [55]	✓			✓	✓	✓		

Table 4. Summary of indirect mode solar dryers for agricultural produce

Authors	Employs forced convection	Has a backup heating system	Employs conventional electric heating system	Dryer with photovoltaic panel	Has a monitoring and control system	Drying space style	
						Chamber style	Tunnel style
Iskandar and Ya'acob [3]		✓		✓	✓	✓	
Zoukit *et al*. [5]	✓	✓			✓	✓	
Xiao *et al*. [6]	✓	✓	✓		✓	✓	
Lan [8]	✓		✓		✓	✓	
Tarigan [11]	✓			✓		✓	
Harun *et al*. [30]						✓	
Shreelavinya *et al*. [31]	✓	✓				✓	
Manukaji [38]						✓	
Larasati *et al*. [40]	✓	✓		✓	✓	✓	
Rakbha and Muthukumar [42]	✓	✓					✓
Fudholi *et al*. [44]	✓					✓	
Minh Nhut *et al*. [46]	✓		✓		✓		✓
Oueslati *et al*. [47]	✓	✓					✓
Lakshmi *et al*. [48]	✓	✓					✓
Coricolano *et al*. [49]		✓			✓	✓	
Etim *et al*. [56]	✓			✓		✓	
Veeramanipriya *et al*. [57]	✓			✓		✓	
Tarigan *et al*. [58]	✓			✓		✓	
Mehran *et al*. [51]	✓	✓		✓	✓	✓	
Grecia *et al*. [59]	✓	✓				✓	
Sharma *et al*. [60]	✓			✓	✓	✓	
Singh *et al*. [61]	✓			✓		✓	
Kokate *et al*. [62]				✓	✓	✓	
Krabch *et al*. [63]						✓	
Murali *et al*. [64]	✓			✓	✓		✓
Cetina-Quiñones *et al*. [52]		✓				✓	
Abdenouri *et al*. [50]	✓	✓	✓		✓	✓	

Finally, comparing the number of authors from both types of solar dryers presented in Table 3 and Table 4 implies that the indirect type of solar dryer receives more attention than the mixed type of solar dryers. This conclusion is largely since the indirect drying mode may dries the food sample at a relatively faster rate, and the quality of the dried sample may be found to be much better than the mixed mode drying [26]. Most of the solar dryer design incorporated the box-chamber style to load the drying sample. Although there are no strong comparative study to prove this however, it may provide the resources needed for further research in the design of air dynamics in a similar structure. IoT-based solar dryers are slowly gaining momentum in recent years to simplify the monitoring of drying process inside the solar dryers and to regulate drying condition in the loading space as can be seen in dryers studied in [60]-[62]. It can also be observed that studies in the application of real-time monitoring and control of the drying process in a solar-powered dryer are still not common. We have seen previously that the advancement in the control system of the agricultural drying process for a solar-based system with machine learning capabilities does not have many attentions in recent articles.

Sharma *et al.* [60] to implement deep learning techniques to learn types of crops inside dryer to predict drying characteristic was presented. This topic is essential to advancing the technology of solar dryer systems in the agricultural industry to keep up with the fourth industrial revolution, which then can immensely simplify and drastically improve the farmer's work process, quality and accuracy in the post-production of agricultural harvest.

One of the highlights in 12th Malaysia Plan 2021-2025 was to grow and boost several strategic and high-impact industries including smart agriculture. This can be seen as an opportunity to further provide a e competitive clean and cost-effective solar dryer [65]. Governments, non-profit organization, and professional group in the industry should build greater awareness and interest towards clean energy and the importance of sustainability in agriculture. It is also a good idea to provide a platform for people in agriculture industry and also young inspiring leader in agriculture to train and be well inform about modern technologies applicable to farming [66]. Implementing smart farming system bears high financial investment that may be difficult for companies to adopt. The government needs to offer incentives to companies that are ready to carry out plans in the research and development of renewable technology system in the agricultural business [7]. The execution of smart farming system into real practice cannot be achieve if the internet infrastructure with regards to coverage and speed is not facilitate and improve upon especially in rural areas. Additionally, government policies to promote the usage of renewable energy such as solar can contribute in the creating investment from private sector, interest and attract not only the larger community but also professional groups. These regulatory policies and frameworks such as national green technology and green technology financing scheme, are able to further motivate develop into green technology system using renewable energy for example, solar dryers [67], [68]. The self-consumption (SELCO) scheme was introduced to benefit users of solar PV panel for self-consumption. This scheme expedites the installation process for immediate self-use which does not require to go through power system study [69]. In most studies and development of solar-based dryer systems, little of which runs the environmental impact assessment of their dryer model. Most research only considers the performance, efficiency, and energy consumption of the system during the operating period without considering the energy required for the full life cycle of the system itself [13].

4. CONCLUSION

This paper discusses state-of-the-art technology in the agriculture sector to promote benefits of renewable energy. Countries located in the tropics can utilize readily available solar energy all year long. To combat weather uncertainties like rain and cloudy days, research incorporates backup thermal system, such as a burner and conventional heater. These techniques are viable and have been shown to assist the process when solar is not reliable. Using solar energy in machinery of post-production agricultural harvest is economically beneficial, especially for small-scale farmers. However, not all studies have analyzed quality and performance of the dried product. Most of the solar dryers presented in the paper have not shown how rate distribution of the produce occurred during testing from their respective developed. This is an important issue to address to manage quality of dried products and analyze performance capability of a particular comparison to a conventional industrial. For future advancement, it is recommended to analyze actual sustainability factor and economic viability of the system. Additionally, a comparison analysis between dried product and minimum benchmark quality standard can also be included in future works when examining performance. To further optimize process, data information of any particular agricultural harvest during its process needs to be recorded all year long. This data will also be beneficial in developing real-time smart monitoring system for in the agricultural field later on.

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