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Solar hybrid drying technologies: A comprehensive review of recent trends and developments

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Abstract
Solar drying technologies have become well-established and popular technologies throughout the world. In present scenario, dried food plays a crucial role in the domestic as well as commercial area. To achieve this, may researchers have been studied and much more are to be expected in the near future to overcome the current limitations in the solar drying industry. Solar dryers have enormous potential in agriculture, where they are used to dry vegetables, fruits, cereal grains, spices, and medicinal plants, other crops. As a result, the dependency on non-conventional resources has been reduced by solar dryer hence, saving vast amounts of fossil resources. Solar dryers are ineffective during rainy season or cloudy days and could be used during daytime which leads less control over drying process. In response to these challenges, solar dryers are amalgamated with supplementary energy sources, which is commonly known as a ' Solar Hybrid Dryer.' This innovative solar hybrid drying technology for agricultural products stands out as an eco-friendly and economically viable substitute for the highly energy-intensive thermal dryers commonly employed in agri-food processing supply chains. In this paper, we mainly reviewed on use of metal matrix, metal fibre (finned tubes) or sand which can enhance the thermal conductivity effectiveness of the phase changing materials (PCMs), thermal storage materials and ultimately influencing the efficiency of heat transfer within the broader system. Recent trends and developments of solar hybrid drying technologies are mainly reviewed in this paper.

Keywords: Hybrid solar dryers, phase changing materials (PCMs), solar dryer and thermal storage medium

Introduction

Countries in the process of development, such as India, are situated in tropical and subtropical regions, with geographical coordinates ranging from approximately 8°04′ to 37°06′ north latitude and 68°07′ to 97°25′ east longitude. This geographical positioning endows these countries with the advantage of receiving abundant sunlight almost continuously throughout the year. Specifically, India, with the majority of its regions experiencing approximately 250–300 sunny days annually, benefits from its favorable geographical location. And in the year 2018, the country received an average solar radiation ranging from 2.5 to 7 kWh/m²/day (Masoom *et al.* 2020) [16]. Solar dryers have enormous potential in agriculture, where they are used to dry vegetables, fruits, cereal grains, spices, and medicinal plants, other crops. As a result, the sun drying, reduced the use of non-conventional resources for drying of products, which saves vast amounts of fossil resources (Agrawal and Sarviya, 2016) [1]. The utilization of solar dryers serves as an optimal alternative to mitigate the drawbacks associated with conventional drying methods (Sontakke and Salve, 2015) [19]. Traditionally, solar energy alone was employed for drying various agricultural products, necessitating extensive drying space and consistent sunlight availability throughout the day. The open sun drying method posed challenges such as potential contamination (dust, birds, fungi, and insects), uneven drying and more time consuming. To address drawbacks, solar drying technologies have been developed, with numerous models emerging over the past two decades to efficiently harness solar energy for drying purposes (Leon *et al.*, 2002) [13]. Agricultural commodities, specifically fruits and vegetables, necessitate the use of heated air falling within the temperature spectrum of 40–60 °C to ensure a secure and efficient drying process. Controlled drying conditions, maintaining specific humidity and temperature, have been recognized for producing rapidly superior-quality dried products (Gutti *et al.*, 2012; Sontakke and Salve, 2015) [9, 19].

Classification of Solar Drying Technologies

Solar dryers can be methodically categorized according to their heating mechanism, the utilization of solar heat, and the external energy source incorporated into the drying process. The key classifications encompass natural (passive) convection dryers, forced (active) convection dryers, and hybrid dryers. Figure 1 provides a detailed breakdown of these solar dryers. Within the pasive or forced solar drying systems, three distinct sub-classes emerge: direct types, indirect types, and mixed-mode types solar dryers. Hybrid solar drying systems, which involve the integration of additional energy resources, are further categorized into two types: i) renewable-non-renewable dryers and ii) renewable-renewable dryers. Furthermore, with consideration to the mechanism of operation, hybrid solar drying technologies are subcategorized into i) solar dryers assisted by auxiliary energy sources and ii) solar-assisted conventional dryers (Jha and Tripathy., 2020) [23].

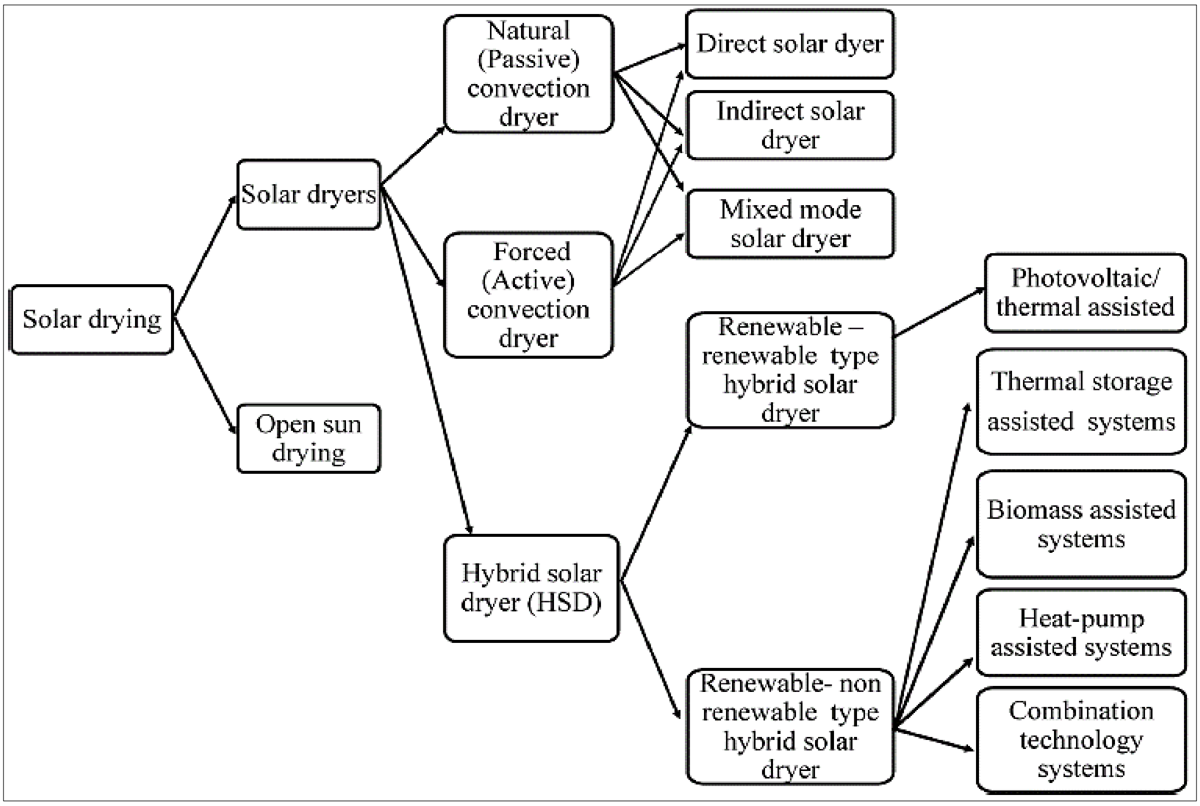

Fig 1: Classification of solar dryer technologies (Jha and Tripathy., 2020) [23]

Solar dryers encounter challenges, particularly during the rainy season characterized by cloudy weather, where their effectiveness is limited. Additionally, these dryers often exhibit constraints in controlling the drying process. In response to these issues, solar dryers are enhanced by the integration of other energy sources, leading to the development of 'Hybrid solar dryers.' This paper aims to establish a knowledge base by analyzing and summarizing recent studies and development efforts in hybrid drying technologies.

Hybrid drying Technologies

In today food market, dried foods play a crucial role in the food supply chain, presenting a significant challenge for the drying industry. Hybrid dryers address this challenge by combining solar energy with conventional or auxiliary sources for air heating (Fudholi *et al.*, 2010) [8]. Within the framework of these dryers, solar energy is complemented by various alternative energy sources such as biomass energy, heat pumps, electricity and more. This augmentation ensures the continued functionality of the system even in scenarios where solar radiation is absent. Embracing hybrid solar drying technology for food products emerges as an environmentally sustainable and economically viable alternative to the prevalent energy-intensive thermal dryers extensively employed in agri-food processing chains (Jha and Tripathy., 2020) [23].

Recent developments in the area of solar hybrid drying technology are reviewed in this paper; some solar hybrid drying technologies are listed and the relevant references are mentioned.

Different Advancements in Hybrid Drying Technologies

Aktas *et al.* (2016) [2] constructed a solar dryer infrared. The components are i.) solar based air collector and ii). heat recovery unit (air-to-air) as shown in Fig. 2. Experimental trials were conducted with melon surfaces maintained at temperatures of 50.1 °C and 60.1 °C, along with 0.5 ms^{-1} an air velocity. The designed system aimed to achieve a reduction in specific energy consumption, resulting in a noteworthy decrease in the moisture content of melon slices from 9 g of water/g of dry matter to a significantly lower value of 0.0441 g of water/g of dry matter. The system's performance metrics further indicated variations in effective moisture diffusivity and average mass transfer coefficient, ranging from 8.24×10^{-10} to 1.25×10^{-9} m^2s^{-1} at 50 °C, with an increase to 1.47×10^{-7} ms^{-1} at 60 °C. Notably, the heat recovery unit contributed 23.1–28.01% of the total input energy, while the solar collector achieved an efficiency of 50.61%.

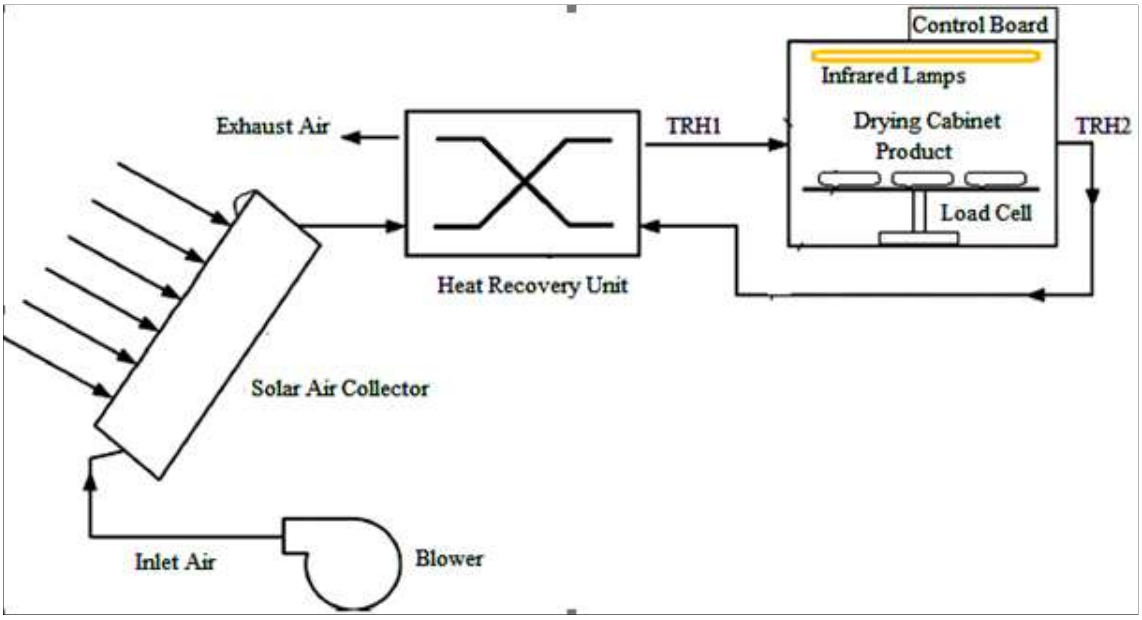

Fig 2: Infrared solar dryer (Aktas *et al.*, 2016) [2]

Yassen *et al.* (2016) [22] studied a solar-thermal drying type hybrid system integrated with a heat energy recovery system. Through experimental analysis, the integrated drying unit's performance was evaluated under both hybrid and thermal modes for drying of red chili. The outcomes of the study revealed a substantial improvement in the overall efficiency of the dryer, demonstrating an impressive escalation from 9.91% to 12.89% with the incorporation of the recovery dryer in heat mode. The study reported that, the overall drying efficiency reached 25.85% in day and night hybrid drying and 29.72% in thermal energy drying mode due to the inclusion of the recovery heat dryer.

Vijayan *et al.* (2016) [21] investigated the indirect type of active (forced) convection solar dryer using heat storing medium for drying of the bitter gourd. Pebbles served as the thermal storaging medium, positioned beneath the absorber plate of corrugated type. In this system, 92.1% (wb) initial moisture content in bitter gourd was reduced to 9.0% (wb) within 7 h of drying, compared to 10 h in traditional drying conditions. The system exhibited a maximum specific moisture extraction rate which was found as 0.214 kg/kWh at 0.0634 kgs^{-1} mass flow rate of air. The specific energy consumption was measured at 4.5 kWh/kg, with the collector efficiency of solar was 22.1% and drying efficiency of the system was found as 19.0%.

Prakash *et al.* (2016) [18] studied a greenhouse type dryer that operates in two distinct mechanisms: natural (passive) and forced (active) mechanism incorporating thermal energy storing medium. In the modified greenhouse dryer, exergy efficiency varied within the range of 29.1% to 86.0% under natural mode and 30.0% to 78.1% in forced (active) mode. The HUF (heat utilization factor) for the modified type greenhouse dryer was measured at 0.121–0.381 in passive mode and 0.26–0.53 in active mode. Furthermore, the coefficient of performance for the greenhouse dryer was reported as 0.55–0.87 in natural mechanism and 0.59–0.72 in forced mechanism.

Tiwari *et al.* (2016) [20] studied experiments on a hybrid photovoltaic-thermal (PVT) integrated greenhouse solar dryer of single-slope roof. The tests were carried out under passive and active modes, with load test and without load test conditions. As the increased packing factor of the photovoltaic (PV) module, there was a notable decrease in thermal energy by 76.39% and a simultaneous increase in electrical energy by 88.73%. The study also observed a respective increase of 89.44% and 65.70% in thermal energy for natural and forced modes with an elevation in the mass flow rates.

Dhanushkodi *et al.* (2017) [6] conducted an analysis on the solar-biomass hybrid dryer for drying of cashew nuts and studied the drying characteristics. The study involved a mathematical model incorporating components such as a solar air collector, biomass backup heater, drying cabin, and a blower (variable speed control unit). During the experimental study, a quantity of 80 kilograms of boiled cashew nut shells was meticulously processed to extract raw cashew kernels, initially possessing a moisture content of 10.0%. The researchers successfully developed and applied a fitting drying model that effectively elucidated the intricate drying characteristics exhibited by the cashew kernels.

Karunaraja *et al.* (2017) [12] studied a solar tunnel dryer by utilizing heat storing material like aluminum filings, sand, and rock bed. The results unveiled a noteworthy decrease in both the drying duration and moisture removal rate when contrasting the solar tunnel dryer, with or without heat storage materials, to the conventional sun drying approach. The solar tunnel dryer integrated with heat storage materials demonstrated a consistently higher average thermal efficiency, surpassing conventional methods by 2.0 to 3.0%. Notably, among the heat storage materials investigated, the sand bed exhibited superior effectiveness, achieving an average thermal efficiency of 19.61% and 15.50%.

Khadraoui *et al.* (2017) [7] studied on forced solar dryer (an indirect type) employing phase changing materials (PCMs). This system comprised a solar energy powered panel and accumulator, which is essentially a air collector with a phase changing materials cavity. The central aim of the experiment was to thoroughly investigate and assess the viability of employing a solar air heater integrated with a phase-changing material for the purpose of storing solar energy during daylight hours and subsequently utilizing this stored energy during the nighttime period. Experiments were conducted to assess the characteristics of the phase changing material and the charging/discharging. The accumulator using sun energy demonstrated exergy efficiency and energy efficiency of 8.50% and 33.91%, respectively. The outcomes revealed a rise in the dryer temperature, ranging from 4.0 to 16.2 °C, when employing the solar energy accumulator during nighttime. Furthermore, the relative humidity (RH) within the dryer was observed to be in the range of 17.01% to 34.5%, aligning with the ambient relative humidity characteristic of the solar dryer integrated with the phase-changing material (PCM).

Atalay *et al.* (2017) [3] designed and constructed a solar dryer outfitted with a thermal storage medium in the form of a packed bed. For waste heat energy recovery, a recuperator unit was used, aiming to assess the drying rates of apples. A notable advantage of developed unit is its minimal energy consumption, registering at 76.80% lower than that of other drying systems.

Deeto *et al.* (2018) [5] studied the a thin-layer dehumidification process for drying coffee beans and incorporating hot water as a thermal storage system within a solar greenhouse dryer. The thermal storage system employed recycled hot water during periods of no sunlight. The outcomes revealed a noteworthy decrease in the initial moisture content of coffee beans, dropping from 54.98% to 12.1% (wb) below within a 12 hours drying period. Additionally, the effective moisture diffusivity coefficient of the dryer was determined to be 9.755 x 10^{-11} m^2s^{-1}.

Baniasadi *et al.* (2017) [4] conducted an analysis on active (forced) convection mixed-mechanism solar dryer, incorporating a phase changing materials (PCM). The system was designed with components including a solar collector, PV panel, drying chamber, fan for draft, absorber, and battery for storing electrical energy. The experimental outcomes demonstrated that the moisture pick-up efficiency of the system was approximately 10.01%, and the overall thermal efficiency of the dryer was found to be around 11.0%.

Ndukwu *et al.* (2017) [15] conducted an analysis of a natural (passive)-convective solar dryer coupled with a thermal storing medium, utilizing sodium sulfate decahydrate and sodium chloride. The drying procedure encompassed red chili, witnessing a substantial decrease in moisture content from 72.28% to 7.60%, 10.11%, and 10.30%, respectively. Remarkably, there was a noteworthy surge in exergy efficiency for the drying system during sunlight hours, escalating from 66.80% to 96.08%. Throughout the night period, the exergy efficiency achieved using sodium sulfate decahydrate reached 81.21%, with an overall exergy efficiency for the entire drying process recorded at 66.84%.

Natarajan *et al.* (2017) [14] constructed a solar tunnel dryer and conducted experimental analyses on drying of grape (*Vitis vinifera*) and bitter gourd (*Momordica charantia*) samples. Thermal storing materials, including sand bed, rock bed, and other aluminum filings, were employed to enhance heat accumulation inside the dryer. Effective reductions in drying period and moisture removal rate were found, in solar tunnel dryer outperforming traditional sun drying (85.0%-10.01% in 27 h and 88.1%-6% in 6 h). The average thermal efficiency of the solar tunnel dryer with thermal storage materials exceeded that without by 2-3%. Among the thermal storage materials, sand exhibited higher effectiveness, achieving average thermal efficiencies of *Vitis vinifera* was found to be 19.61% and 15.50% for *Momordica charantia* while drying.

Kabeel *et al.* (2018) [11] assessed the performance of a two-stage indirect solar energy-based desalination unit cum dryer (reheating and coupled with a humidification-dehumidification water) as shown in Fig. 3. The system was proposed by considering the shortage of energy resources and distilled water in remote areas, the proposed system emerges as a viable option for such regions. The drying unit comprises a humidification-dehumidification water desalination unit and two-stage indirect solar dryer with reheating. Experimental results demonstrate that an increase in airflow from 49.98 to 74.98 m^3h^{-1} leads to a rise in water (distillate) productivity from 28.97 to 41.29 liters per day, accompanied by an increase in moisture removal from the product from 8.34 to 12.36 kg day^{-1} during the period from 8:00 am to 7:00 pm.

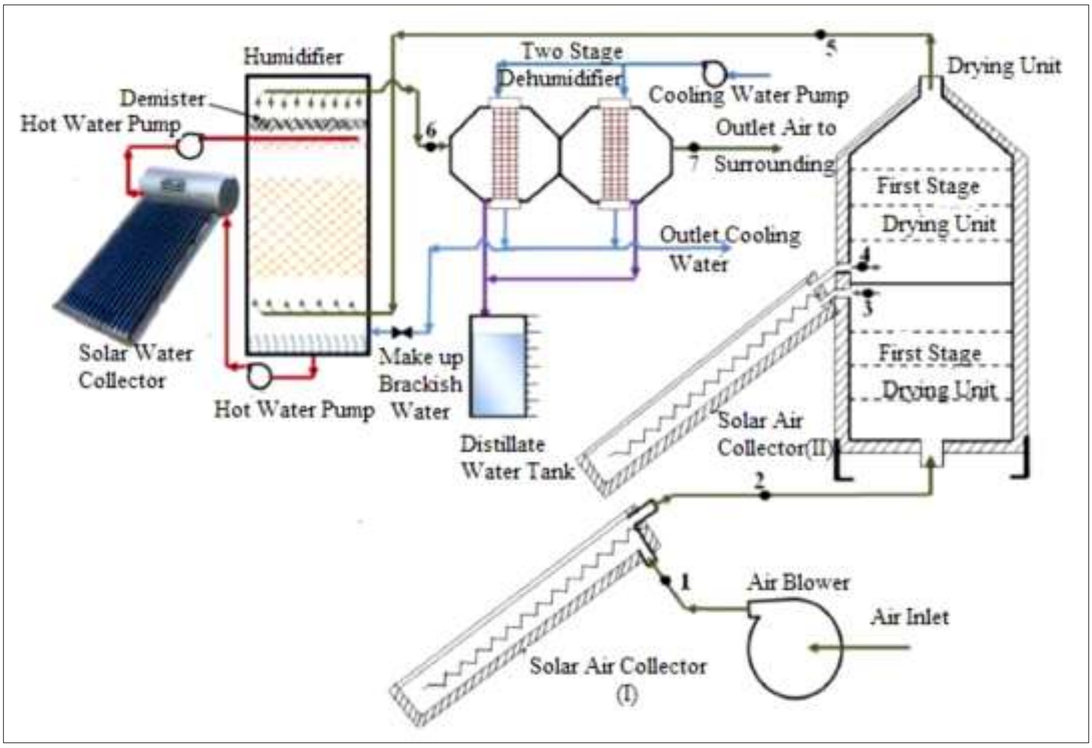

Fig 3: Integrated type of Solar energy-based dryer (Two-stage indirect) and desalination unit (Kabeel *et al.*, 2018) [11]

Pavane *et al.* (2018) [17] conducted an experiment on a pyramid-shaped solar-biomass dryer, assisted with biomass for the batch drying of nutmeg (Fig. 4). Their findings indicated that during a without load test of the pyramid-shaped solar-biomass hybrid dryer, the solar radiation was observed as 239.22 W/m², average temperature inside was recorded at 55.86 °C, with a corresponding ambient temperature of 27.16 °C, and relative humidity of 87.59% in the winter season (December 2017). Over a 19-hour period, the average moisture content of the nutmeg sample decreased from 614 to 7.9% (dry basis). The average drying rate ranged from 0.2565 to 0.0004 g/100g bdm per minute, respectively. The maximum efficiency of the biomass combustor was determined to be 74.85% and the pyramid-shaped solar-biomass hybrid dryer was found to be 29.12%.

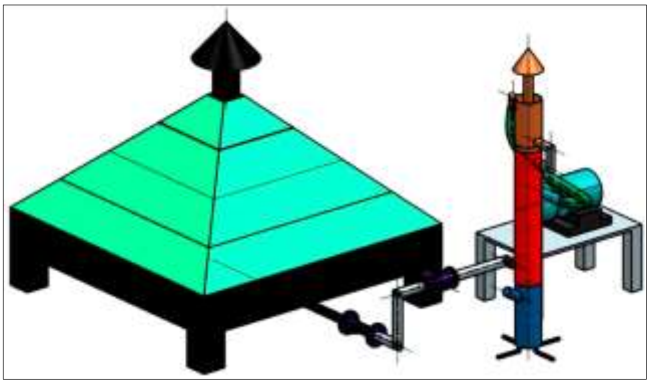

Fig 4: Pyramid shape solar-biomass hybrid dryer (Pavane *et al.*, 2018) [17]

Conclusions

Recent trends in solar drying highlight the superiority of solar hybrid drying technologies in achieving rapid and high-quality solar drying. With an elevated average collector efficiency, a hybrid solar dryer has the potential to enhance drying efficiency by up to 35%. Although paraffin wax is commonly employed as the primary heat storage materials (latent heat), it exhibits low thermal conductivity. To tackle this concern, it is suggested to enhance the surface area of heat transfer between the phase-changing material and the heat transfer fluid. This can be achieved through the use of metal fibered finned tubes, metal matrix, thereby enhancing the thermal conductivity of the phase-changing material and, consequently, improving heat transfer rates. Exploring various phase change materials available in the market holds promise for further investigation. Moreover, enhancing drying efficiency is achievable by minimizing thermal losses and employing specialized techniques such as recirculating hot air and incorporating reflectors into the system. Overall, hybrid dryers have a promising future; however, various issue s such as heat transfer rate, phase change material characteristics, storage, and operat ional parameters such as velocity and temperatures must be ad dressed.

Hybrid solar dryers provide a cleaner and more sustainable alternative to energy-intensive thermal dryers. By combining solar power with other eco-friendly energy sources, these systems contribute to reduced carbon emissions and a greener drying process. The solar hybrid drying technologies will be used compare to conventional dyers in upcoming years.

References

1. Agrawal A, Sarviya RM. A review of research and development work on solar dryers with heat storage. International Journal of Sustainable Energy. 2016;35(6):583-605.
2. Aktaş M, Şevik S, Amini A, Khanlari A. Analysis of drying of melon in a solar-heat recovery assisted infrared dryer. Solar Energy. 2016;137:500-515.
3. Atalay H, Çoban MT, Kıncay O. Modeling of the drying process of apple slices: Application with a solar dryer and the thermal energy storage system. Energy. 2017;134:382-391.
4. Baniasadi E, Ranjbar S, Boostanipour O. Experimental investigation of the performance of a mixed-mode solar dryer with thermal energy storage. Renewable energy. 2017;112:143-150.
5. Deeto S, Thepa S, Monyakul V, Songprakorp R. The experimental new hybrid solar dryer and hot water storage system of thin layer coffee bean dehumidification. Renewable Energy. 2018;115:954-968.
6. Dhanushkodi S, Wilson VH, Sudhakar K. Mathematical modeling of drying behavior of cashew in a solar biomass hybrid dryer. Resource-Efficient Technologies. 2017;3(4):359-364.
7. El Khadraoui A, Bouadila S, Kooli S, Farhat A, Guizani A. Thermal behavior of indirect solar dryer: Nocturnal usage of solar air collector with PCM. Journal of cleaner production. 2017;148:37-48.
8. Fudholi A, Sopian K, Ruslan MH, Alghoul MA, Sulaiman MY. Review of solar dryers for agricultural and marine products. Renewable and sustainable energy reviews. 2010;14(1):1-30
9. Gutti B, Kiman S, Murtala AM. Solar dryer-an effective tool for agricultural products preservation. Journal of Applied Technology in Environmental Sanitation, 2012, 2(1).
10. Jha A, Tripathy PP. Recent advancements in design, application, and simulation studies of hybrid solar drying technology. Food Engineering Reviews. 2021;13:375-410.
11. Kabeel AE, Abdelgaied M. Experimental evaluation of a two-stage indirect solar dryer with reheating coupled with HDH desalination system for remote areas. Desalination. 2018;425:22-29.
12. Karunaraja N, Thokchom SS, Verma TN, Prerana N. Convective solar drying of *Vitis vinifera* & *Momordica charantia* using thermal storage materials. Renewable Energy. 2017;113:1193-1200.
13. Leon MA, Kumar S, Bhattacharya SC. A comprehensive procedure for performance evaluation of solar food dryers. Renewable and Sustainable Energy Reviews. 2002;6(4):367-393.
14. Natarajan K, Thokchom SS, Verma TN, Nashine P. Convective solar drying of *Vitis vinifera* & *Momordica charantia* using thermal storage materials. Renewable energy. 2017;113:1193-1200.
15. Ndukwu MC, Bennamoun L, Abam FI, Eke AB, Ukoha D. Energy and exergy analysis of a solar dryer integrated with sodium sulfate decahydrate and sodium chloride as thermal storage medium. Renewable Energy. 2017;113:1182-1192.
16. Masoom A, Kosmopoulos P, Bansal A, Kazadzis S. Solar energy estimations in India using remote sensing technologies and validation with sun photometers in urban areas. Remote Sensing. 2020;12(2):254.
17. Pavane DR, Khandetod YP, Mohod AG. Techno-

economics of pyramid shape solar-biomass hybrid drying of nutmeg. Int J Curr Microbiol App Sci. 2018;7(10):1984-1993.

18. Prakash O, Kumar A, Laguri V. Performance of modified greenhouse dryer with thermal energy storage. Energy reports. 2016;2:155-162.
19. Sontakke MS, Salve SP. Solar drying technologies: A review. International Journal of Engineering Science. 2015;4(4):29-35.
20. Tiwari S, Tiwari GN. Thermal analysis of photovoltaic-thermal (PVT) single slope roof integrated greenhouse solar dryer. Solar Energy/. 2016;138:128-136.
21. Vijayan S, Arjunan TV, Kumar A. Mathematical modeling and performance analysis of thin layer drying of bitter gourd in sensible storage based indirect solar dryer. Innovative food science & emerging technologies. 2016;36:59-67.
22. Yassen TA, Al-Kayiem HH. Experimental investigation and evaluation of hybrid solar/thermal dryer combined with supplementary recovery dryer. Solar Energy. 2016;134:284-293.
23. Kumar K, Gambhir G, Dass A, Tripathi AK, Singh A, Jha AK, *et al*. Genetically modified crops: current status and future prospects. Planta. 2020 Apr;251:1-27.