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Review on the Air Temperature and Humidity Produce by Solar Dryer and Potential to be Reused

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ABSTRACT

This article presents a comprehensive review of recent advancements in the reuse of waste heat from solar food dryers, a strategy that holds significant potential to improve system efficiency and sustainability. Solar drying systems typically discharge air at temperatures between 40°C and 70°C, resulting in a substantial loss of free solar thermal energy up to 50% of total energy. This review introduces novel approaches to capturing and reusing this low-quality heat, including the integration of desiccant materials that can boost drying efficiency by up to 64%, and innovative designs like rotating dryer wheels, which increase effective heat gains by an average of 153%. Unlike previous studies, this article not only aggregates and analyzes field test data such as outlet temperatures, humidity levels, and heat recovery efficiencies but also identifies practical and scalable solutions for heat reuse, such as water heating, space heating, and heating nearby cold rooms. By providing quantitative results and exploring the potential for continuous 24-hour operation through advanced heat management techniques, this review offers new insights and practical guidelines for engineers and researchers aiming to make solar drying processes more energy-efficient and commercially viable. This work is particularly relevant for those interested in developing sustainable agricultural practices, as it highlights the most promising methods for reducing energy waste and enhancing the overall performance of solar dryers. The novel synthesis of existing technologies and the identification of key areas for future research make this article a valuable resource for advancing the field of solar drying.

Keywords:
Solar drying; temperature; humidity; desiccant material

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1. Introduction

In underdeveloped nations, solar drying technology has become a viable substitute for mechanical dryers that run on fuel for food and agricultural commodities. Over time, solar dryers have proven to be more cost-effective and environmentally friendly, utilizing an endless and free supply of solar radiation as a heating source rather than fossil fuels or biomass [1]. Targeting smallholder farmers without access to large-scale post-harvest drying facilities, thousands of small-scale solar dryers have been constructed and tested globally [2]. However, the lack of temperature control in most passive designs, low thermal efficiency, and sporadic solar radiation are the main obstacles to sun drying. In certain applications, this reduces quality, efficiency, and flexibility in comparison to sophisticated mechanical dryers [3-5]. The temperature of the air exiting the drying chamber is a crucial factor in assessing and contrasting solar dryer designs, as it significantly impacts the product's rate of moisture evaporation and drying duration [6]. According to Lingayat *et al.,* [7], the system's airflow rate, solar radiation intensity, thermal heat loss, solar collector efficiency, and overall design are some of the parameters that affect the output temperature. Experiments conducted over the years using various passive solar dryer setups for drying different crops have recorded outlet temperatures ranging from 40°C to 70°C under real-world conditions [8]. This necessitates matching the temperature supplied to the temperature needed for the commodity being dried, as well as precise solar dryer construction [9-11]. The optimal temperature for the solar dryer outlet has been the subject of much research to increase drying speed and efficiency. However, far less has been studied regarding the possible use of this low-grade thermal heat before its release into the atmosphere. Reusing the waste heat from on-site drying for different thermal purposes, such as heating nearby buildings or heating water for cleaning or processing, can increase overall system efficiency and assist solar-powered farmers and food processors. Theoretically and conceptually, there are several options for recycling the heat from solar dryers: multi-stage cascade drying, combining with solar pasteurizers or burners, integrating into nearby microgrids, and heating livestock facilities or agricultural greenhouses [12-14]. However, very little field study data on actual implementation has been reported [15,16]. A recent systematic assessment of 60 experimental investigations published in the last ten years documented the exit air temperatures from field-tested passive solar dryers under actual conditions. The meta-analysis, conducted by Chanda *et al.,* [13], found an average global temperature of 56°C (+/-8°C), suggesting that most commodity types have residual thermal energy after drying that may be useful [17-19]. It is safe to dry chopped tomatoes, peppers, bananas, mangoes, and papayas at higher temperatures without sacrificing their quality [20,21]. According to the analysis, 40–50% of the entire solar thermal energy input is discharged through the exhaust in a typical passive direct solar dryer [22]. This represents a significant energy loss that could be diverted before the heat is released into the environment [23-25]. The viability of recycling this low-quality heat for various beneficial thermal uses has been assessed based on several factors, including minimum temperature requirements, heat transfer logistics, economic recovery, and implementation challenges [26,27]. The review concluded that heating nearby uninsulated drying rooms, buildings, or night shelters without heating systems, as well as heating water to a temperature between 40°C and 60°C, are the most practical and attractive opportunities to reuse solar dryer heat for sanitizing goods or machinery at the processing location [28]. Solar dryer designs need to include heat exchangers and thermal storage devices to enable these reuse applications [29]. Reusing solar waste heat from food dryers has great potential to improve energy efficiency, but several adoption and technical barriers remain [12,30,31]. In underdeveloped nations, heat exchanger systems and controls may be too expensive and difficult for small farms to implement. Other issues include meeting appropriate sanitary standards for food reuse applications and thermal storage for batch drying systems [32]. There are currently very few commercial solar dryer manufacturers who include heat recycling capabilities in their designs, and little information has been released on actual performance in the field [29,30,33]. There is an immediate need for further demonstration projects and quantifiable field data. Government incentives and industry standards could also help implement this potential concept to reduce energy waste and carbon emissions associated with agricultural drying operations. Since food production accounts for approximately 30% of the world's energy consumption, increasing processing efficiency could have a significant overall impact [34]. This study reviews the most recent research on potential strategies to recover low-quality thermal energy from solar dryers rather than wasting this free heating resource [35,36].

The main objective of this work is to systematically review and evaluate recent advancements in the reuse of waste heat from solar food dryers, with the aim of identifying effective strategies and technologies that can significantly improve the overall efficiency and sustainability of these systems. The review seeks to consolidate existing knowledge, quantify key findings, and provide practical insights into the potential for integrating heat recovery solutions into solar drying processes, ultimately guiding future research and development in this field.

2. Analysis of Air Temperatures and Humidity of Solar Dryer

In 2020, César *et al.,* [37] conducted a comparative study to evaluate the drying performance of tomato slices using an indirect solar dryer (ISD) versus a mixed solar dryer (MSD). They found that the drying time for the MSD was significantly shorter—17 hours compared to 26 hours for the ISD mode. Temperature probes inserted into the drying chambers revealed that the MSD system outperformed the ISD in terms of temperature performance, reaching 65–72.1°C, as opposed to 55–70°C. Significant variations in humidity were also noted; the transparent polycarbonate cover's ability to retain heat allowed the relative humidity within the MSD to vary between 12.7% and 61.7%.

To improve hot air food drying, Cheevitsopon and Jongyingcharoen [38] evaluated a desiccant wheel dehumidification device. Their technology lowered relative humidity from 70% to 44% over a temperature range of 80–120°C. Higher temperatures caused the desiccant to lose more moisture, and dehumidified hot air at 100–120°C dried carrots more quickly than standard hot air at the same temperature. The set points and exhaust drying air temperatures were nearly identical.

When drying food processing wastes, Mutlu *et al.,* [39] investigated the effects of inlet air temperature and flow rate on the output moisture content. They showed that increasing the airflow at the intake quickened the drying kinetics and heat transfer, thereby reducing the moisture content at the outlet. The report also covered control techniques, such as using a backup biomass boiler to maintain a steady drying intake temperature regardless of weather variations. This enables the control of outlet conditions at the appropriate levels. Furthermore, the impact of different heat source capacities, such as the boiler and solar wall, was evaluated. It was suggested that increasing boiler capacity and extending operating hours could enhance process efficiency and outlet parameters, such as temperature and humidity, in a financially feasible way. The combined use of solar and biomass energy was proposed as a sustainable and cost-effective method for low-temperature drying of food processing residues on an industrial scale. Specific temperature and humidity values for the drying process were not mentioned in the available sources.

Sarsavadia [40] developed a solar dryer system with integrated sensors to measure relative humidity (15–20%) and outlet air temperatures (45–60°C) during pilot testing with varying drying conditions (temperature, airflow rate, and recirculated air portion). The temperature varied slightly, ranging from 3 to 4 degrees Celsius, due to the minimal solar radiation penetrating beneath the clouds. However, significant moisture reduction validated the efficacy of the drying process. Heat recovery configurations were estimated to save more than 70% of energy by assessing the potential for reusing the registered warm exhaust air.

According to Figure 1, a recent study by Safri *et al.,* [41] assessed the effectiveness of a portable solar greenhouse dryer utilizing several solar collector designs, such as flat-plate, V-groove, and combinations thereof, with and without insulator materials. The efficacies and outlet temperatures were compared at different mass flow rates and solar radiation intensities. The study reported that at a 0.011 kg/s flow rate and 988 W/m² radiation, the flat-plate with insulator and V-groove with insulator collector designs produced the highest collector output temperatures, at 49.65°C and 56.44°C, respectively. Moreover, Mhd Safri's team found that the combination flat-plate and V-groove collector with an insulator had a higher efficiency of 66.56% under the same conditions compared to 66.34% without an insulator.

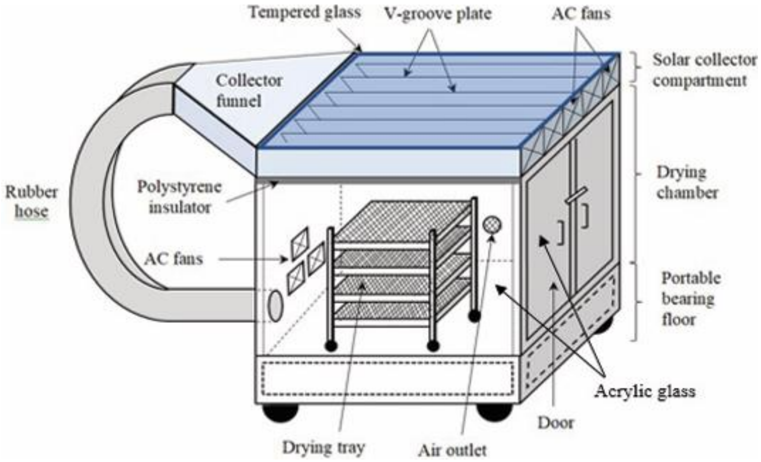


Fig. 1. Schematic of the portable solar greenhouse dryer [41]

In a recent study, Misha *et al.,* [42] investigated a solar-assisted solids dewatering drying system that enhances drying air temperature after moisture removal by regenerating the drying wheel using solar-heated water. The average outlet temperature in the drying chamber ranged from 42°C to 49°C, depending on the position within the chamber. Similarly, the average absolute humidity in the drying chamber varied between 11.9 g/kg and 24.1 g/kg, depending on the location within the chamber. Temperature and humidity measurements were taken at different positions in the drying chamber, including the inlet, outlet, and various levels of the tray. The drying efficiency of the solar-assisted solids absorption dryer was assessed in terms of the overall thermal performance of the system, encompassing the efficiency of both the collector and the dryer. The integration of the dryer with the solar-assisted system enhanced air drying conditions and performance, achieving a full capacity drying rate of 8.37 kg/h. The drying wheel contributed to improved drying air quality, with a sensible efficiency of 74% and a latent efficiency of 67%.

In a separate study, Yassen and Al-Kayiem [43] examined a hybrid solar/thermal dryer system that incorporated a recovery dryer. According to Yassen's findings, the steady-state inlet flue gas temperatures to the rectangular duct ranged from 146.5°C to 158.9°C, while the output temperatures varied from 84°C to 103.5°C. Although the study included experimental measurements of the primary drying chamber and recovery dryer's performance, it did not provide detailed information regarding the outlet temperatures and humidity levels. The hybrid solar/thermal dryer test apparatus depicted in Figure 2 lacked sufficient data to quantify drying chamber temperature, humidity, and related metrics.

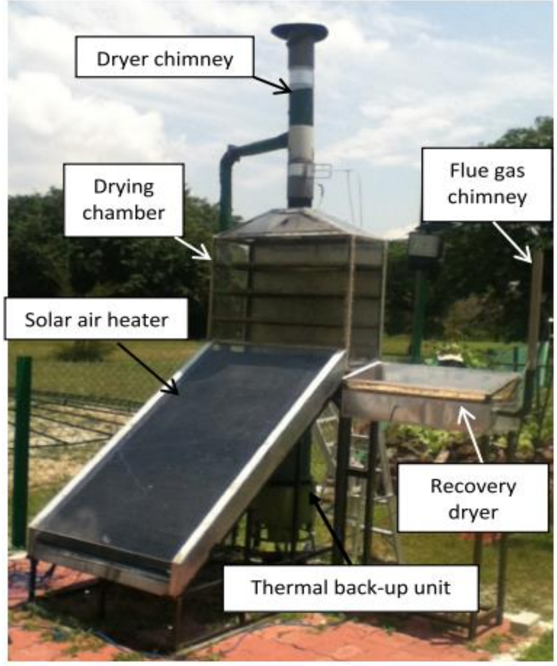


Fig. 2. Experimental hybrid dryer test rig [43]

Al-Kayiem *et al.,* [44] investigated a hybrid solar thermal drying system for drying Tilapia fish, combining direct solar drying with a solar air heater and a biomass-fueled thermal backup unit to ensure continuous operation, even at night or during cloudy conditions. The schematic diagram of the setup as shown in Figure 3. The system achieved a peak temperature of 63°C inside the dryer, compared to ambient temperatures of 36.4°C, with maximum solar irradiance of 1045 W/m². Humidity levels varied significantly, ranging from 43-50% during the day to 91-93% at night, highlighting the importance of maintaining stable drying conditions. The hybrid system reduced the drying time by 70%, drying fish with an initial moisture content of 246.6% (dry basis) to 17.0% (dry basis) within 17.5 hours, compared to 48-72 hours for traditional open sun drying. This efficiency was attributed to the system's ability to maintain consistent drying conditions, independent of weather fluctuations, while eliminating the need for electrical power, making it ideal for rural areas. Moreover, the hybrid dryer provided a more controlled, hygienic, and efficient drying process compared to traditional sun drying. Table 1 summarizes various studies on drying systems, highlighting differences in dryer types, operating conditions, and target products. These studies showcase the diversity of drying systems tailored to specific products and conditions.

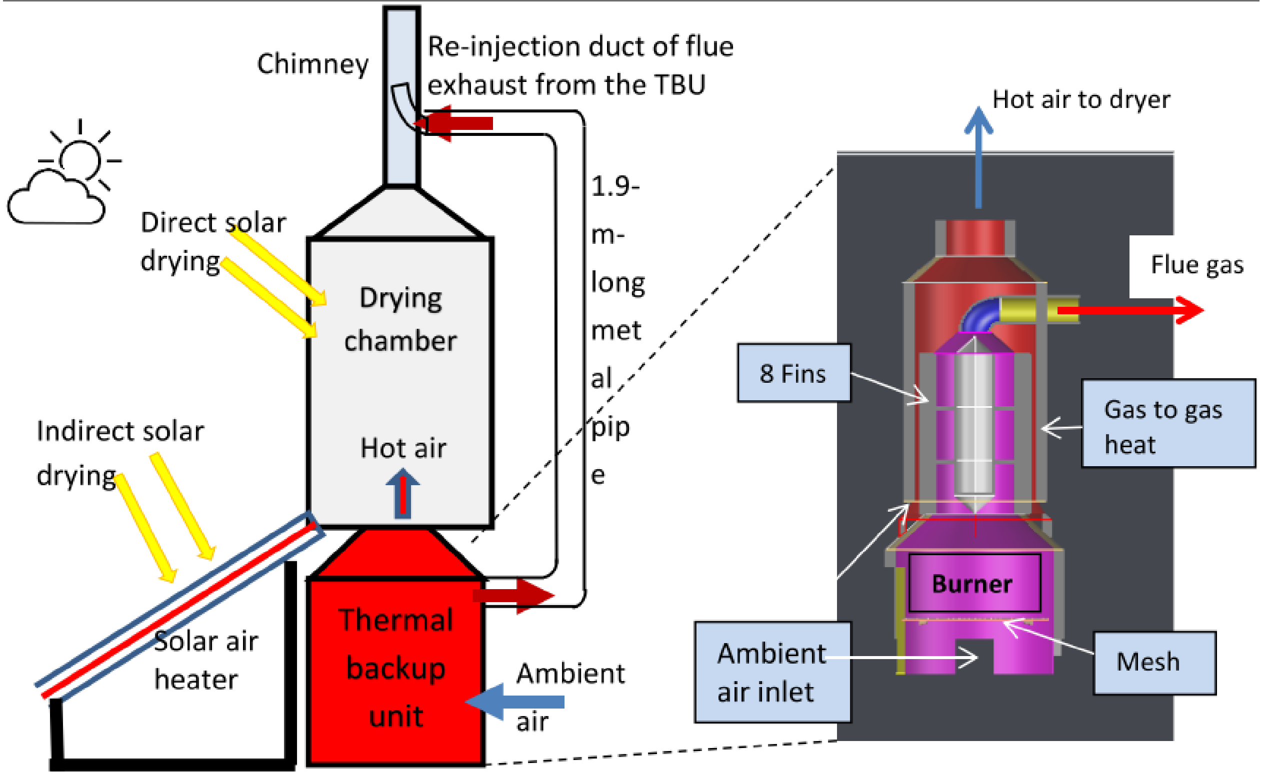


Fig. 3. Schematic diagram of the setup exploring the idea of the flue Re-injection unit [44]

Table 1
Comparison between different drying temperature and humidity

References	Year	Type of dryer	Temperature	Humidity	Product
César *et al.,* [37]	2020	Mixed-type solar dryer	65 ℃ -70 ℃	19.76 ± 9.76	Tomato
Cheevitsopon and Jongyingcharoen [38]	2019	Hot air dryer	80 to120℃.	70 to 44%	Not mentioned
Mutlu *et al.,* [39]	2021	Backup biomass boile	75 ℃	75%	Not mentioned
Sarsavadia [40]	2007	Indirect	45–60 °C	15–20%	Onion slices
Safri *et al.,* [41]	2020	Direct	58.44 °C	65.37%	Not mentioned
Misha *et al.,* [42]	2016	Direct	42°C to 49°C	74%	kenaf core fiber
Yassen and Al-Kayiem [43]	2016	Mixed-type solar dryer	146.5 to 158.9°C	Not mentioned	Red chili
Al-Kayiem *et al.,* [44]	2022	Mixed-type solar dryer	63°C	43-50%	Tilapia Fish

3. Solar Assisted Dryer

Yu *et al.,* [45] conducted an experimental analysis to compare the drying characteristics of a solar-aided ejector-enhanced heat pump dryer system (SE-HPD) with those of a conventional heat pump dryer system (CHPD) under various test conditions. The schematic diagram of the SE-HPD heat pump experimental system is presented in Figure 4. The authors' analysis demonstrated significant improvements in the moisture extraction rate (MER) and exergy efficiency of the SE-HPD compared to the CHPD, with increases of 28.7% and 54.3%, respectively. The enhanced solar radiation intensity notably improved the pressure lift ratio of the ejector, thereby enhancing the heating performance of the SE-HPD. To achieve the optimal MER in the SE-HPD system, an optimal valve opening (OP) of

50% and a bypass return air ratio (BR) of 70% were identified, confirming the performance benefits observed during the experimental investigation.

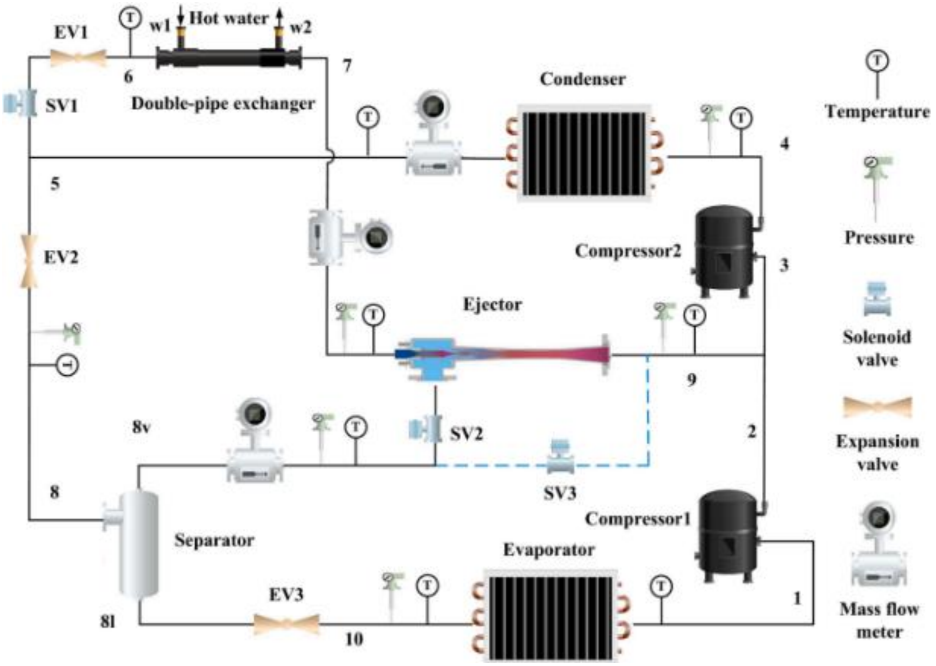


Fig. 4. Schematic diagram of heat pump experimental system of SE-HPD [45]

Misha *et al.,* [46] conducted tests to assess the impact of different drying techniques on temperature uniformity within the chamber of both single-sided and combination solar dryers, with and without top and bottom fans. The study utilized a hybrid solar dryer with varying configurations. Temperature measurements were taken at multiple locations within the dryer, including solar collectors, the surface of each tray, and the exit from the drying chamber. The recorded temperature values during the experiments ranged from 48.75°C to 68.93°C, depending on the location and timing of the experiment, while ambient temperatures varied between 34°C and 37°C. The experiments aimed to evaluate the effect of an additional solar collector on the heat supplied to the chamber, with a reflecting mirror incorporated to enhance the dryer’s performance. However, the study did not specifically address heat reuse, nor did it provide detailed information on humidity measurements.

Ekka and Kumar [47] explored the use of heat storage devices in conjunction with solar drying to maintain a consistent temperature of approximately 50°C, which is considered ideal for preserving food quality. The authors argued that solar thermal storage could meet the 50–400°C heat requirements necessary for food processing. They emphasized the importance of carefully selecting phase change materials (PCMs) for storage, citing the need for high specific heat capacity, non-flammability, non-corrosiveness, and chemical stability, with a melting point below 80°C, aligning with the operating temperature of the dryer. LHS (Latent Heat Storage) materials, which can store 5–14 times more heat than sensible heat storage solutions, were highlighted as superior for solar drying applications due to their efficiency in reducing the required space for storage.

Joan *et al.,* [48] aimed to design and develop a solar evacuated tube heating system to generate heat for drying agricultural products. The study conducted tests to determine the required airflow, the configuration of the solar evacuated tube housing, and the thermal energy needs for effective drying. The effectiveness of the dryer was assessed by measuring changes in temperature and relative humidity, with relative humidity decreasing from 52.4% to 36.5% and air temperature rising from 27.1°C to 56.7°C due to the solar collector. These results indicate sufficient heat generation and dehumidification for drying, positioning the solar dryer as an efficient and reliable alternative to traditional sun drying methods for agricultural products.

Donchi *et al.,* [49] utilized numerical modeling and thermal network analysis to predict heat transfer in a hybrid solar drying system. The study examined spatial and temporal temperature variations influenced by factors such as mass flow, spatial resolution, and solar radiation input. The simulations revealed non-uniform and spatially varying temperatures within the system components, with the radiative heat transfer coefficient between glass covers and the heat loss coefficients of the collector insulation analyzed in detail. The model provided a 2D prediction of temperature profiles within the collector and dryer, based on sinusoidal approximations of solar radiation and air temperature inputs. The temperature was observed to gradually increase from the entrance to the exit of the drying flow, with the study discussing the effects of various factors on heat transfer. The research highlighted the utility of technologies such as infrared imaging, heat flux sensors, and thermocouples in providing valuable data on heat transfer in solar thermal applications.

Gunawan *et al.,* [50] estimated and evaluated the critical energy requirements for designing an optimal solar drying system using a theoretical framework based on basic thermodynamics and mass/thermal energy balances. The study employed Molière diagram analysis to plot relevant variables, such as temperature, humidity, enthalpy, and water content (X), to determine the appropriate energy requirements for heating, cooling, humidification, dehumidification, and air circulation at different points in the system. The research aimed to create an efficient, affordable, and self-sufficient smart energy system for agriculture in Indonesia, specifically for storage or drying purposes. The study recommended the use of additional heating systems to maintain constant temperature and humidity levels throughout the night in solar dryers. Based on observations from PT Impack Pratama Industri Tbk, which monitors over 2,000 solar dryer facilities in remote areas of Indonesia, the study identified challenges such as the need for trained personnel for maintenance and sufficient daytime sunlight for operation. The materials used for the solar dryer were noted to be relatively inexpensive, easy to obtain, and sealed and insulated to protect against external factors like dust, insects, and rain.

Hao *et al.,* [51] developed and explored a novel agricultural drying system that integrates heat pump expansion technology directly with solar thermal collectors. The schematic diagram of the Direct Heat Pump Assisted Solar Drying (DEHPASD) system is presented in Figure 5. The experiments conducted provided three different adaptive functional modes, with the heat pump capable of increasing the air temperature by 9.8°C and maintaining the drying chamber temperature above 40°C, allowing for efficient drying of Lentinus edodes. The average coefficient of performance (COP) of continuous direct expansion heat pump drying was 2.56, indicating energy efficiency, while the solar-assisted intermittent direct expansion heat pump drying achieved a maximum COP of 6.01, further enhancing energy efficiency. The moisture content of Lentinus edodes in the DEHPASD system was lower than in open solar drying, indicating better drying properties. The Page model was identified as the best model for describing the drying kinetics of Lentinus edodes in the DEHPASD system. The research provided valuable benchmarks on the performance and efficiency of an integrated heat pump and solar system under real-world conditions, identifying key factors that influence efficiency, including solar energy density and heat pump compressor frequency.

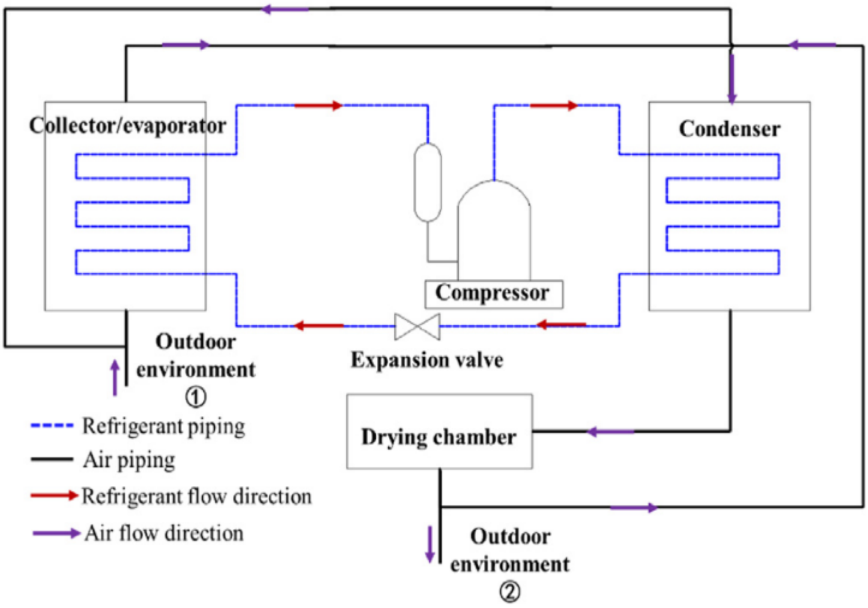


Fig. 5. The schematic diagram of a DEHPASD system [51]

Jha and Tripathy [52] aimed to optimize process parameters and develop a multilayer 3D finite element model to predict moisture and temperature profiles during simulated solar drying of rice. The study utilized specialized design software and ANOVA to optimize drying parameters and assess their effects on quality. The optimized parameters included a power of 700 W, an air velocity of 3.5 m/s, and a moisture content of 12%, resulting in a temperature of 46°C, a grinding efficiency of 71.48%, and a drying time of 90 minutes. The model accounted for the various layers of rice (husk, bran, endosperm) and monitored the hybrid solar drying process. The diffusion coefficients were 2.95×10^{-11}, 8.66×10^{-12}, and 6.00×10^{-12} m^2/s for the endosperm, bran, and husk, respectively. The study also reviewed methods for measuring heat reuse and energy efficiency analysis techniques, providing visual representations, such as Figure 6, to illustrate the equipment needed to capture and use waste heat. However, the study did not include calculations or case studies to substantiate the concepts and connections discussed.

Wagiman *et al.,* [53] presented important demonstrations and performance data of a hybrid air collection system that combines solar and thermal energy. The experimental tests conducted by the authors observed a high thermal efficiency of 27.7%, an electrical efficiency of 13%, and an air heating capacity of 7.8°C. The system produced 448 kWh of usable thermal energy daily between 3 a.m. and 8 p.m. using an integrated rooftop straw drying facility to enhance photovoltaic convection and radiative cooling. These field tests highlighted viable avenues for reusing heat from the PV system. Although the study provided valuable experimental evidence and constructs for efficiently utilizing waste heat from solar PV, the findings were not fully quantified.

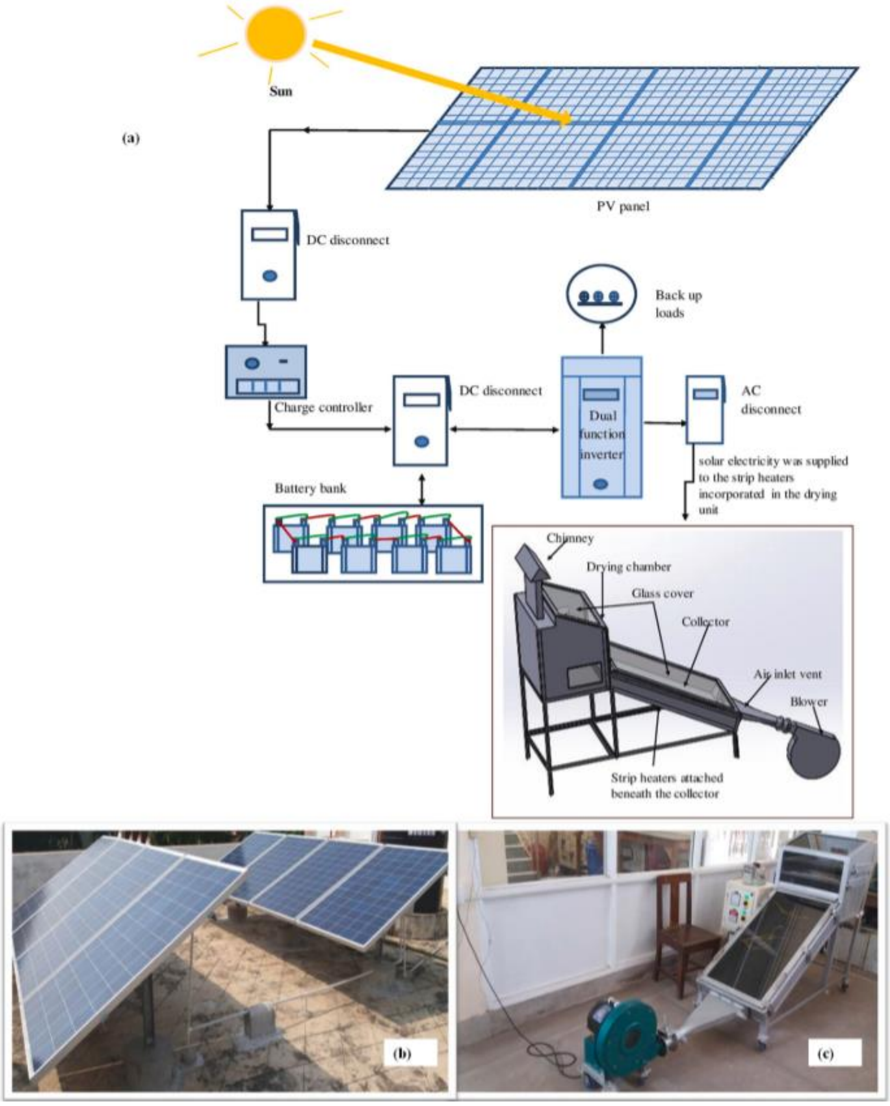


Fig. 6. Pictorial view of (a) schematic representation of the PV integrated hybrid system, (b) photovoltaic panels and (c) drying unit [52]

A study by Assoa *et al.,* [54] examined the effectiveness of a hybrid photovoltaic-thermal solar dehydrator (HSD), revealing notable improvements in temperature regulation and drying efficiency. The HSD prototype is shown in Figure 7. The device achieved a maximum temperature of 44.1°C at 3:00 PM, surpassing both the ambient temperature and the 35.5°C reached by conventional sun drying techniques, highlighting the solar collector's efficacy in enhancing the drying process. Despite a slightly reduced drying rate compared to traditional methods, both approaches achieved a minimum 50% moisture reduction in food items over a six-hour span. The slower drying speed is attributed to the dehydrator's enclosed design, which restricts direct wind and sun exposure but offers substantial advantages in terms of hygiene and food quality preservation. The sealed environment safeguards food from insect and airborne particle contamination, common issues in traditional sun drying. Additionally, the controlled drying conditions help maintain the food's color, texture, and nutritional content, minimizing photodegradation caused by ultraviolet (UV) radiation. These findings suggest that while conventional drying may offer quicker results, the hybrid solar dehydrator provides a more reliable and sanitary method, particularly in high-humidity regions, making it a practical option for improving food preservation practices. Table 2 summarizes studies on various drying systems, highlighting differences in dryer types, operating conditions, and applications. These studies demonstrate a wide range of innovative drying technologies optimized for various applications.

Fig. 7. HSD prototype [54]

Table 2
Comparison between different solar assisted dryer

References	Year	Type of dryer	Temperature	Applications & system	Product
Yu *et al.,* [45]	2023	Indirect	from 50.1 ˚C to 71.2 ˚C	Heat pump dryer system	Not mentioned
Misha *et al.,* [46]	2018	Mixed mode	between 48.75 ˚C 68.93 ˚C	Hybrid solar dryer	Not mentioned
Ekka and Kumar [47]	2023	Mixed mode	50 ˚C	Heat storage systems	Red chili
Joan *et al.,* [48]	2022	Indirect	27.1 °C to 56.7 ˚C	Solar evacuated tubes	Not mentioned
Donchi *et al.,* [49]	2021	Mixed mode	45-135 °C	Thermal Node Model	Not mentioned
Gunawan *et al.,* [50]	2022	Direct	40 °C	hybrid solar drying dome	Not mentioned
Hao *et al.,* [51]	2022	Indirect	63.8%	heat pump	Lentinus edodes
Jha and Tripathy [52]	2021	Indirect	46 °C	3-dimensional, multi-layered finite element	paddy
Wagiman *et al.,* [53]	2017	Indirect	56.9 °C	photovoltaic/thermal hybrid	fodder
Assoa *et al.,* [54]	2022	Mixed mode	44.1 °C	Hybrid Photovoltaic Thermal	carrot, ginger, and banana

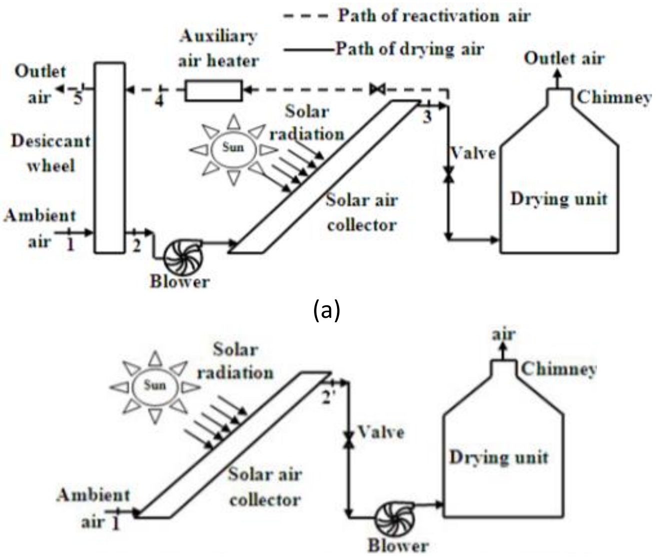
4. The Use of Descant Material in Solar Drying

The review article by Dake *et al.,* [55] explores recent advances in the use of absorbent materials to enhance the performance of solar drying systems. The research focuses on two main strategies: integrating dehumidification processes at air inlets and introducing absorbent thermal storage layers within drying chambers. These approaches have demonstrated significant improvements in drying times and energy efficiency. Specifically, drying times have been reduced by 15% to 30%, with some configurations achieving reductions of up to 50% to 64%. Additionally, the introduction of specialized storage layers has accelerated drying times by 30% to 45%, reducing the risk of product damage. Compared to traditional designs, these absorption-enhanced solar dryers significantly improve energy efficiency and production rates. While further research is needed to evaluate the feasibility of large-scale applications, the evidence presented by Dake *et al.,* [55] provides a strong case for the potential of this technology. Their work offers valuable insights for researchers and engineers focused on renewable energy drying technologies.

Misha *et al.,* [56] conducted a study examining the increasing use of desiccant materials in solar drying systems. The research highlights the advantages of these adsorbents, including low-energy dehumidification and the potential for continuous drying using stored thermal energy outside sunlight hours. The production of hot, dry air enhances the drying process, leading to increased yield, uniformity, and quality control, particularly for heat-sensitive foods. Although desiccants offer benefits over conventional solar drying methods, their integration poses challenges related to pressure drops and adsorption capacities. The literature also suggests that solar regeneration is an efficient and cost-effective method for refreshing moisture-laden desiccants for repeated use. While further development is necessary, the consistent results make a compelling case for combining solar energy with desiccant materials to improve drying processes.

Thoruwa *et al.,* [57] reviewed emerging desiccant materials designed to extend solar drying operations beyond daylight hours. They investigated the use of low-cost clays and calcium chloride ($CaCl_2$)-based compounds for solar thermal regeneration. These solid absorbents enable continuous drying by removing moisture and providing overnight drying capabilities. Tests showed that these materials exhibit high moisture absorption and low-temperature requirements for regeneration, making them suitable for food preservation and air conditioning in tropical regions. The research by Thoruwa et al. underscores the potential of combining custom-designed, solar-renewable sorbents with drying processes, although further confirmation of their long-term performance is necessary.

Kabeel and Abdelgaied [58] analyzed the impact of integrating rotating dryer wheels into solar drying systems, demonstrating significant performance improvements by generating warm, moisture-free air. Compared to conventional designs without dryer wheels, rotary adsorption heat exchangers enhanced system drying temperatures and reduced humidity levels by effectively removing water vapor. Tests revealed that incorporating dryer wheels increased effective heat gains by an average of 153%, significantly boosting the energy efficiency of solar dryers. This integration also addressed the intermittent challenges of solar drying, enabling 24-hour continuous operation. While long-term feasibility studies are needed, the research provides a valuable benchmark for scaling up regenerative drying systems. Figure 8 presents the schematic of the drying units.



(a)

(b)

Fig. 8. Schematic of the drying units; (a) solar dryer unit integrated with rotary desiccant wheel, (b) solar dryer unit without rotary desiccant wheel [58]

Hassan and Hassen [59] explored the use of solar air collectors to regenerate spent silica gel for repetitive drying applications. Silica gel effectively absorbs moisture from air currents, necessitating periodic regeneration to restore its drying capacity. Experiments focused on the impact of dryer column thickness on solar thermal regeneration time. The research found that a 5 cm layer of silica gel could be fully regenerated in 21 minutes, while a 15 cm layer required 42 minutes. The study highlights the feasibility of using solar power for cost-effective regeneration, offering valuable insights into the parameters necessary for large-scale design. While further research is needed to confirm long-term performance, the findings emphasize the potential for 24-hour solar drying operations.

Pramuang and Exell [60] reviewed the solar regeneration of waste silica gel desiccants, which are commonly used for air drying. The study focused on measuring moisture loading and circulation to assess the reuse potential of sorbents in air conditioning and drying processes. The analysis included formulas for determining moisture content based on differences in weight and relative humidity at the outlet. The research tested various generator configurations and identified ideal conditions for solar air collection in tropical regions. The findings highlight the potential of solar-recovered silica gels for efficient and continuous moisture removal, offering valuable reference points for researchers pursuing greener drying approaches.

Hussain [61] examined the use of silica gel as an affordable alternative for drying air through refrigeration. By absorbing moisture, silica gel provides an economical means of dehumidification, suitable for repeated cycles of drying and regeneration. Tests indicated that thermal reactivation using hot air effectively dries moisture-laden gels, making them reusable for drying applications. While additional research is needed to confirm the long-term viability of this approach, Hussein's work contributes to the growing body of knowledge on sustainable desiccant materials. The study suggests that low-grade thermal renewables could provide a flexible and sustainable solution for drying applications.

Manyumbu *et al.,* [62] reviewed the use of diffusion desiccant materials, particularly silica gel, for sustainable humidity control in passive air conditioning applications. Desiccants like silica gel offer high moisture storage capacity and effectively remove water vapor, helping to maintain indoor air quality and comfort. Compared to traditional cooling-based dehumidification, integrating these materials into building envelopes allows for passive humidity regulation without additional energy input. While further research is needed to confirm the long-term feasibility and costs, the study provides important evidence for the potential of moisture storage via dehydration as a low-energy alternative to conventional methods.

Kumar and Yadav *et al.,* [63] conducted experimental research on a solar-powered desiccant air conditioning system using a silica gel-coated heat exchanger. Their study highlights the innovative use of desiccant materials for drying applications, emphasizing the effectiveness of silica gel in enhancing dehumidification performance. The integration of silica gel not only improves the overall performance of the air conditioning system but also reduces energy consumption, making it a sustainable solution with potential applications in residential, commercial, and industrial air drying. Table 3 highlights studies on the integration and impact of desiccants in drying systems, focusing on their types, properties, and contributions to performance. These studies collectively underscore the critical role of desiccant type, design, and properties in optimizing drying system efficiency.

Table 3
Comparison between different of descant material in solar drying

References	Year	Integration	Types of desiccants	Properties and characteristics	Impact of desiccants
Dake *et al.,* [55]	2021	Placement and configuration	Silica gel and others	Adsorption capacity	Humidity control
Misha *et al.,* [56]	2012	Desiccant bed designs	Silica gel and others	Regeneration temperature requirements	Product quality enhancements
Thoruwa *et al.,* [57]	1999	Desiccant bed designs	$CaCl_2$	Adsorption capacity	Drying rate improvements
Kabeel and Abdelgaied [58]	2016	Not mentioned	Not mentioned	Regeneration temperature requirements	Drying rate improvements
Hassan and Hassen [59]	2022	Desiccant bed designs	Silica gel	Adsorption capacity and Regeneration temperature requirements	Humidity control
Pramuang and Exell [60]	2007	Desiccant bed designs	Silica gel	Durability and lifespan	Drying rate improvements
Hussain [61]	2009	Desiccant bed designs	Silica gel	Durability and lifespan	Drying rate improvements
Manyumbu *et al.,* [62]	2014	Desiccant bed designs	Silica gel	Adsorption capacity	Humidity control
Kumar and Yadav [63]	2016	Desiccant bed designs	Silica gel	Adsorption capacity	Humidity control

5. Conclusion

The outlet temperature from the drying chamber remains high, but the moisture content in the air is still significant. Therefore, the use of desiccant materials to remove moisture is essential before the air can be recycled or channelled into a new drying chamber. Integrating desiccant materials, such as silica gel, has proven to be an effective method for enhancing solar drying systems by improving energy efficiency, reducing drying times, and enabling continuous operation.

Future research should focus on optimizing the integration of desiccant materials, particularly in addressing challenges such as pressure drops, transfer, and adsorption capacities. There is also a need for further studies on the large-scale feasibility of these technologies, particularly in tropical regions where low-cost and energy-efficient drying solutions are critical. The quantification of key process parameters, such as dryer column thickness and regeneration times, will be crucial in informing the design of scalable systems. Additionally, exploring innovative configurations, such as rotating dryer wheels and solar regeneration methods, offers promising avenues for improving the performance and sustainability of solar drying systems. The collective findings of the reviewed studies underscore the potential of combining solar energy with desiccant materials to create more efficient and sustainable drying processes, paving the way for future advancements in renewable energy applications.

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