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A Comprehensive Review of Advanced Solar Drying Technologies: Concentrators, Optical Enhancements, and Thermal Energy Storage Systems

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ABSTRACT

The conventional open sun drying is not efficient, it is slow and contaminated and there is a necessity to develop highly advanced technologies in solar drying. The review looks critically at solar dryers that are improved with concentrator, optical, thermal energy storage (TES) or phase-change materials (PCM). The incorporation of parabolic trough or compound parabolic concentrators leads to a high temperature of over 100-115 °C and a thermal efficiency of up to 88%. Reflective walls are also made to enhance optical capturing by up to 37.6%, and shorten drying time by 15-20 %. TES/PCM systems increase the operation of TES systems beyond the sunset, nano-enhanced PCMs reduce drying time by 40% and enhance thermal efficiency by more than 48%. These systems demonstrate short payback periods (0.43-5.14 years) with regard to economics. They minimise the emission of CO_2 by 2-44 tons/ lifetime of systems. These combined technologies have addressed intermittency and low efficiency and enabled solar drying to be a reliable and cost-effective and sustainable solution, as the UN Sustainable Development Goals of clean energy and climate action suggest.

1. Introduction

The technology of solar drying has an alternative economic and viable solution in use of traditional drying methods as it has enormous costs in the reduction of energy waste and environmental pollution. One of these developments is the application of photovoltaic-thermal (PV-T) systems, that convert energy into electrical energy and thermal energy to dry, a paradigm shift in the use of renewable energy. These hybridized systems are highly performing with multi-criteria analysis systems such as the 4E analysis (energy, economic, embodied energy, environmental) [1].

Mathematic modeling and computation techniques have gone further to ensure that prediction of the behavior of the system under different conditions is precise [2]. Predictive capabilities and system design are further improved by the integration of artificial intelligence, e.g., artificial neural networks [3]. Energy and exergy breakdowns are critical to the study and optimization of thermodynamic efficacies of PV-T dryers [4], whereas optical refinements such as parabolic concentrators are found to enhance the thermal gathering and drying speeds considerably [5].

Many of these cutting-edge technologies and techniques, such as; the thermal behavior of working fluids, such as reference data on air conductivity [6]; the advanced heat transfer enhancement techniques, such as fins and turbulators [7], are essential towards optimising collector performance. One of the key advances is the introduction of TES and phase change materials (PCMs) to give operations prolonged periods outside the sunshine and iron out thermal fluctuations and enhance reliability [8, 9]. Advanced thermal control practices such as hybrid cooling using PCMs and nanoparticles are necessary in the process of controlling the temperature of the PV cells and system durability [10, 11].

Studies on drying kinetics respond to the changing environmental conditions giving models on the transport of moisture in products such as date palm fruits [12]. Predictive electrical efficiency analytical tools can be used in system design [13]. Moreover, PCM incorporation boosts the performance of PV panels [14], and semitransparent PV modules allow producing electricity and drying it at the same time [15].

The innovative hybrid system designs are geared towards optimum use of energy in all applications [16, 17], such as solar stills with evacuated tubes [18] and PV-T greenhouse systems during agricultural processes such as biogas slurry heating [19]. The controlled experimental studies set the performance targets and confirm glazed hybrid PV-T system models [20], whereas exergo-economic studies bring thermodynamic performance and cost into alignment [21].

PV-T dryers are designed with sensitive products, such as green tea [22], and whole 4E analyses are conducted on hybrid infrared-convective dryers [23]. Now artificial intelligence can predict and make changes in real time [24], and more advanced concepts integrate concentrated solar with PCM storage to produce energy efficiently [25]. The kinetics of drying and the energy requirements of hybrid systems are dynamic, thus modeling has a crucial impact on capturing their performance [26]. The effect of climatic and geographical conditions on drying kinetics and the energy requirement has been noted to be significant [27, 28].

Comparative analysis of natural and forced mode of convection is informative to sustainable and economical operation [29]. The modeling and experimentation are used to validate the integration of TES and enhance stability and increase the drying hours [30]. Large scale processing arrangements, including multi-tray systems with built-in storage [31] and mixed mode greenhouse dryers [32], are more efficient and environmentally manageable.

The simulations using a computer enrich the knowledge on TES dynamics such as nano-enhanced PCMs [33]. The comparative studies highlight the importance of optimization of systems based on climate peculiarities [34]. The effect of PCM thermal properties on storage performance is systematically defined by research [35], surface modifications such as ribbed geometries are researched to enhance the heat transfer [36]. Novel strategies involve the integration of multi-layer nano-modified PCM structure in enhancing thermal management [37].

Techno-economic studies also consider new designs of dryers, including screw conveyor-based systems [38], and the characterization of portable dryers gives insights on small-scale use [39]. Recent review articles summarize the progress and determine the further trends in solar dryers with energy storage [40]. Additionally, the classification systems can be used to organize the emerging body of knowledge, evaluating the use of PCMs in the fruit dryers [41] as well as examining the design principles in greenhouse solar dryers [42]. Natural convection dryers are also reviewed in systematic reviews considering design techniques and issues of implementation [43]. This comprehensive literature provides a solid base on which the solar drying technology should be developed by including concentrators, optical enhancement and TES systems with the aim of achieving sustainable and efficient preservation of agriculture.

The novelty of the present paper is that it is the first systematic review to bring together and critically examine two crucial, synergistic technological pathways to the future of solar drying: the synthesis of solar concentrators and optical improvements, and the use of TES and PCM. It is also more thorough in describing a wide range of concentrator types, such as parabolic troughs and dishes as well as CPCs and Fresnel-lenses, and directly compares their performance gains to that of different TES/PCM systems. Comprising an enormous amount of current studies (2014-2025), it gives a distinct, comparative view of how these technologies correct the intrinsic limitations of solar drying, i.e. intermittency and low thermal efficiency, by creating a concise roadmap of established solutions to reach higher temperatures, higher drying speeds, longer duration of operation, and better economic and environmental results in a wide range of diverse applications.

2. Review Method

The present review has used a systematic literature review methodology, where literature (peer-reviewed journals, conference papers, and books on the topic) published between the years 2014 and 2025 have been used to ensure that the latest developments in the solar drying technology are captured. The review is made of high-impact articles in the most prominent international publishers, and Elsevier journals (Solar Energy, Energy Nexus, Journal of Cleaner Production, and Renewable Energy) are used heavily, and other authoritative sources (International Solar Energy Society and IEEE) make a significant contribution. The gathered literature is then critically classified and analysed under three primary themes namely solar dryers with concentrators and optical enhancers, solar dryers with TES and PCMs, and the fundamental performance analysis and modeling of solar dryers, in an attempt to present a comprehensive and up-to-date coverage of the area.

2.1. Solar Dryers with Concentrators and Optical Enhancements

Liu et al. (2014) [44] developed a new novel parabolic trough concentrating solar heating device to dry cut tobacco using V-type metal cavity absorber (Figure 1). The researchers tested how the opening width of the absorber influences the heating rate, factor of acquisition, and efficiency of collector system and discovered that the wider the opening was the better the absorber prevented deformation. A mathematical model of the cut tobacco drying process that was solved through the fourth-order Runge-Kutta method was found to be in good agreement with data obtained through experimental methods with relative errors that were less than 8. Optimal drying conditions were established through orthogonal testing using an inlet airflow velocity of 15 m/s, an initial cut tobacco moisture content of 26% and an inlet airflow temperature of 200 °C, which yielded a final moisture content of 14.15 and a dryer thermal efficiency of 66.32%. The experiment revealed the possible potential of the solar heating system as a workable heat source to dry cut tobacco in industries as temperature of air flow reduces with the increment of drying pipe height as shown in Figure 2. The cut tobacco temperature is high at the accelerating part, and gradually rises as the drying pipe height rises.

Figure 1. An illustration of a cut tobacco drying system using a parabolic trough concentrating solar heating [44]

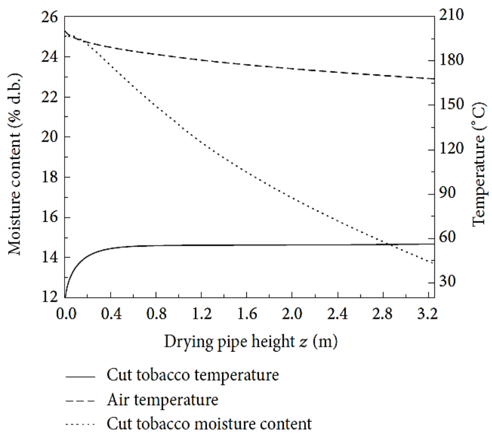

Figure 2. Airflow and cut tobacco parameters are distributed through simulation [44]

Sulaiman an Taha (2014) [45] examined the application of concentration solar thermal power in drying oil palm fronds (Figure 3), which is a biomass resource in Malaysia with great moisture content leading to its low suitability in combustion or gasification. The prototype solar dryer was designed based on Fresnel lens, which focuses solar heat on a black-painted aluminum receiver tray inside an insulated drying chamber and the temperature inside the drying chamber should not exceed 110 °C as it may destroy organic material. It was observed through experimentation that the solar dryer was able to fully dry oil palm fronds samples in 6.5 hours with an average of 4.75 g/hr, which was much faster than an electric oven with a corresponding 10.5 hours and an average of 2.83 g/hr. The solar system had an efficiency of 55.4%, which was due to a good heat retention and the natural airflow. The results indicated the promise of concentrated solar drying as an efficient and affordable way of pretreating biomass. Figure 4 depicts an accumulation of the amount of moisture eliminated per second of time.

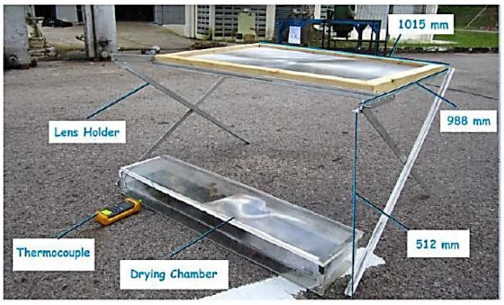

Figure 3. An image of the experimental apparatus [45]

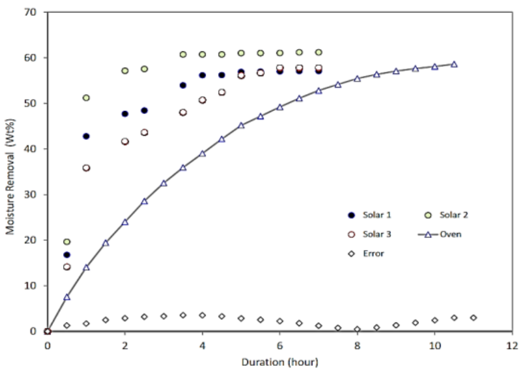

Figure 4. Changes in the OPF's ability to remove accumulated moisture over time as a result of oven and solar drying [45]

Ky et al. (2018) [46] proposed a new indirect solar dryer, which uses fixed hemispherical concentrators using the hot-spot theory, and does not need solar tracking or absorbers. The system was experimented in Burkina Faso under various seasons with a maximum temperature of 103.4 °C in the collector outlets and an effective temperature of 40-82 °C in the drying chamber. The findings indicated that tomato slices could be dried with an 83% weight loss taking place in 12.5 hours. The suitability of the dryer was tested on various types of agricultural products, and it was noticed that the theory of the hot-spot was indeed viable, and it could be extended to more mathematical modeling and thermodynamics optimisation.

Lamrani et al. (2019) [47] created a numerical model with TRNSYS software to explore energy and environmental performance of indirect hybrid solar dryer of wood with a CPC. This model was tested against the experimental data and it was found to be consistent with a Mean Relative Error of 3.9% and a root mean squared error of 0.024 kg/kg. Dynamic simulations at Moroccan climatic condition revealed that this system could effectively dry wood with an initial moisture level of 0.7 kg/kg to 0.1 kg/kg in about 84 hours. The experiment established that drying time was greatly reduced with increases in drying air velocity and reduction in thickness of wood boards. The energetic analysis indicated that the solar collector is potentially able to provide a significant share of the necessary thermal energy and cut the consumption of the auxiliary heater. On the environmental front, it was demonstrated that the integration of the solar collector helped to eliminate about 34% of CO_2 emissions per year during the work of the auxiliary heater, which is why this system could contribute to the increase in energy efficiency and the decrease in greenhouse gases emissions in the wood industry. The collector slope of 35.7 is appropriate throughout the year and contributes to meet approximately 47% of dryer system energy requirements in summer and approximately 30% in winter, as illustrated in Figure 5.

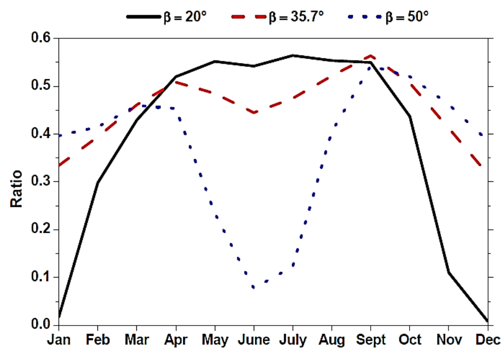

Figure 5. The ratio of the energy flows at the solar collector to the dryer system's overall energy requirements varies every month [47]

Hosseinzadeh et al. (2019) [48] introduced the simulation and analysis of an optical solar parabolic dish collector with replaceable cavity receivers, which will be used in the solar dryer under the climatic conditions of Iran. This collector (1.5 m in diameter) was designed in SolidWorks and simulated in TracePro (receiver models) and the receiver was tested with two different cavity types: cylindrical and semi-spherical. Monte Carlo ray-tracing was used and 120,000 rays were used to evaluate optical performance. The simulation findings showed that the semi-spherical cavity receiver achieved a higher absorbed flux of 1262.72 W and superior irradiance distribution compared to the cylindrical receiver, which absorbed 990.23 W. The researchers found that the semi-spherical receiver exhibited better optical properties and can be highly recommended to enhance the efficiency of different solar drying systems, including direct (solar box) and indirect (solar cabinet) dryers.

Referring to Spall and Sethi (2020) [49], Figure 6 shows the design, modeling, and analysis of an efficient multi-rack tray (MRT) solar cabinet dryer with an added reflective north wall (RNW) to increase the solar radiation absorption especially in the winter season with a higher latitude (>30° N). An advanced solar radiation capture model and thermal model were designed and tested experimentally, during ludhiana, India (30.56° N) under natural and forced convection conditions. It was found that the RNW enhanced radiation uptake up to 37.58, 31.57 and 23.24% at 30 0, 40 0 and 50 0N latitudes, respectively, in winter. RNW also achieved increased daily average dryer efficiency by 5% (natural convection) and 4.35% (forced convection), high chamber air temperatures by 4-7 °C, and shorter time to dry carrots by 20% and 15% under natural and forced convection regimes, respectively. Prediction of chamber and crop surface temperature using models were close to experimental values, with root mean square errors ranging between 2.12 to 2.36. The researchers concluded that the RNW does remarkably improve the performance of dryers in a low solar-radiation environment. Figure 7 shows the impact of NWR when the mode is natural and forced convection. It has been made clear that NC mode with NWR had the largest drying rate then FC mode with NWR.

Figure 6. An illustration of the MRT solar cabinet dryer with the reflector sheet on the north wall [49]

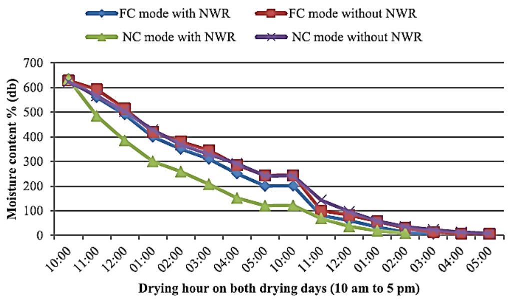

Figure 7. Differences in the percentage decrease in moisture content during two consecutive drying days in Ludhiana, India (30°N latitude), using forced convection (FC) and natural convection (NC) modes with and without a north wall reflector (NWR) [49]

Seeuwanga et al. (2020) [50] provided the performance analysis of a developed Hybrid Indirect Passive (HIP) solar dryer, that is, it has incorporated the use of multiple metallic solar concentrators in the collector plate and a special greenhouse plastic covering on the cabinet to minimize postharvest losses of fruits. Pineapples and mangoes were used to test the drying performance of the HIP dryer and compared to a conventional active-mode Solar Photovoltaic and Electric (SPE) dryer and the traditional Open Sun Drying (OSD) process. It was found that the SPE dryer took the shortest time, 10 hours, then HIP dryer (18 hours), and OSD method (30 hours) to produce the dried product. The HIP dryer had a comparable drying efficiency with the SPE dryer and was 18% more efficient than the OSD method. The researchers concluded that the adapted HIP dryer has a major impact on drying performance, thus it is a recommendable alternative to OSD to be instigated at large scale, especially in rural and off-grid locations. The dryer efficiency was more with the conventional SPE dryer than the better

HIP dryer and lowest with the traditional OSD method (Figure 8).

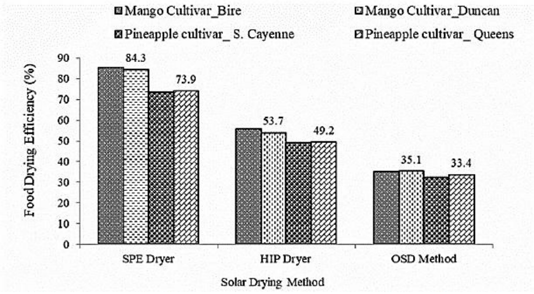

Figure 8. Efficiency of food drying for SPE, HIP, and OSD dryers [50]

Teklu et al. (2020) [51] intended to refine the operation of a natural convection indirect solar dryer with a combination of side and bottom reflectors. The dryer was developed, built and tested experimentally with reflectors and without reflectors under no-load and load conditions using tomato slices. Tests with no-load revealed that the maximum absorber plate temperature rose considerably by 98-154 oC perfectly with reflectors compared to no-reflectors. Drying tests on 5 kg and 10 kg loads showed that using reflectors together increased the rate of drying by 14% and 8%, respectively, enabling the final desired moisture content to be easily obtained. These findings provided strong evidence that the reflectors would significantly enhance the thermal performance and drying performance of the solar dryer.

Ajunwa et al. (2020) [52] studied the performance of an indirect solar dryer that was equipped with a single-axis manual sun-tracking system on the flat plate collector (FPC) and optimisation of its east and west reflectors angular positions. The software, TRNSYS 16 and Engineering Equation Solver (EES) were used to model the best reflector angles at the first quarter months of Zaria, Nigeria. The best angles that were identified to be used during the experimental month of March are 40° and 80°, respectively, on the east and west reflector. Its performance on the dryer was assessed and compared under fixed and manual tracking. The outcomes proved that, with the use of the manual tracking system, the performance of the dryer was significantly enhanced as the total percentage moisture loss grew by 5.11%, the total rate of drying grew by 2.10x10-5 kg/s, the mean collector efficiency grew by 3.92%, and the total drying efficiency grew by 2.0% points versus the fixed mode. The researchers concluded that a FPC, which is tracked manually and equipped with optimally positioned reflectors, is an affordable way of enhancing efficiency of indirect solar dryers.

Castellano et al. (2021) [53] experimentally examined the practice of using concentrated solar energy to dry the aggregates of asphalt plants as an environmental-friendly substitute to traditional rotary kilns. A low-concentration ratio (4 suns) CPC system was used to concentrate solar irradiation on a silica-sand receiver. The findings showed that temperatures of up to 70 oC were obtainable and in 150 minutes, a 5 mm thick silica sand layer was dried. The researchers ascertained the promise of solar thermal projects to lower the carbon footprint of hot mix asphalt manufacturing and recommends that more concentrated technologies would further enhance performance and achieve greater temperatures.

Hosseini and Zhang (2021) [54] examined the technical and economic viability of the Concentrated Solar Power (CSP) implementation into the low-rank coal (Victorian brown coal) drying and pyrolysis process (Figure 9). The researchers compared four integration cases based on the parabolic trough collectors (PTC) and solar tower (ST) systems to deliver thermal energy. In theory, adding a solar tower to provide heat to the coal-drying process and pyrolysis could conserve a mean of 12.8% of the yearly thermal energy consumption. Nonetheless, the economic consideration showed that this overriding situation was economically unfeasible because the CSP component was expensive. Contrastingly, the scenario, which used PTC to provide heat, specifically to coal dryer, was the most economically favorable with a superior performance compared to the traditional pyrolysis process with a net present value (NPV) of $81.1 million and a payback period of 4.9 years. The analysis noted that the economic feasibility of solar thermal assistance in high-temperature processes such as pyrolysis is not currently possible with a design point DNI of 950 to 750 W/ m2, but at lower temperatures, such as drying, the overall solar field thermal energy output rises as design point DNI reduces between 79.4 and 99.7 GWh as demonstrated in Figure 10.

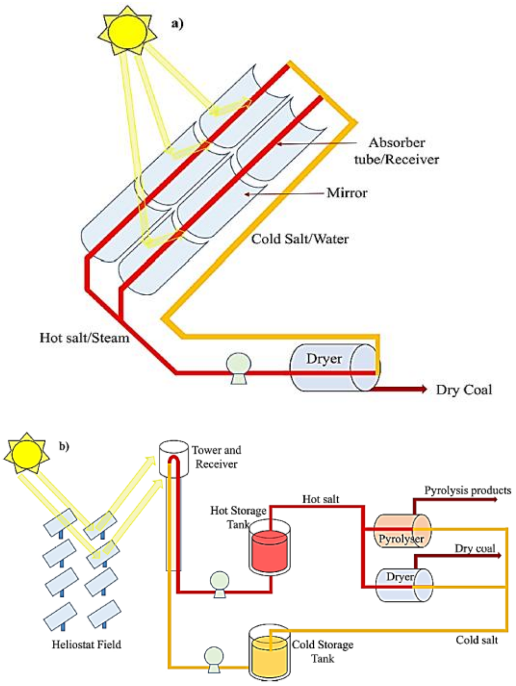

Figure 9. a) For situations 1 and 2, the PTC system was used and b) Scenarios 3 and 4 were designed using a solar tower system [54]

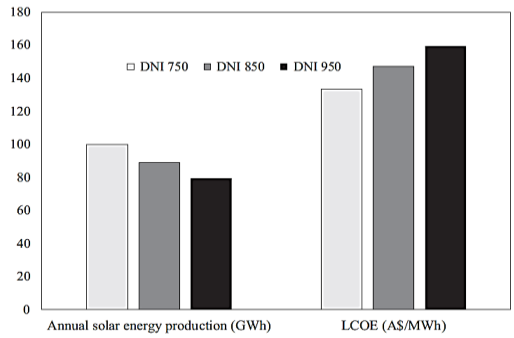

Figure 10. The impact on the yearly solar thermal energy output and LCOE for scenario 4 of altering the design point DNI [54]

Shoebi et al. (2021) [55] experimentally examined the improvement of the performance of a solar air dryer that is photovoltaic/thermal (PV/T) by incorporating a CPC and V-shaped fins underneath the PV panel. It was tested using 0, 8, 16 and 24 fins. The findings showed that the application of fins was extremely effective in improving electrical and thermal performance in cooling the PV panel and increasing the transfer of heat to the air. The 24-fin configuration gave the most significant improvement, as it improved electrical and thermal efficiencies by 28.7% and 30.6% respectively, relative to the non-fin system. The 24-fin system was economically costing 0.206/kWh per power generation. This arrangement also produced the greatest CO_2 reduction of 44.19 tons during its lifetime which was environmental. The researchers found that the finned PV/T solar air dryer is a feasible system technically and environmentally that can be used to produce electricity and heat air at the same time. The exergy efficiency of SAD-FPV has a similar trend to the solar intensity. In addition, SAD-FPV with 24 fins has the greatest exergy efficiency of 5.21% at 13:00, which is nearly 45% greater than the other fins as illustrated in Figure 11.

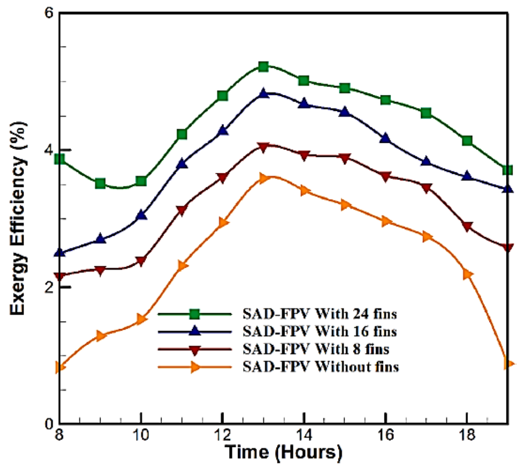

Figure 11. The SAD-FPV's energy efficiency at different fin values [55]

Ebadi et al. (2021) [56] created a hybrid solar drying method based on the use of a CPC solar collector and an electric auxiliary heater that dries tomato slices. Tests were run to determine the impact of the thickness of the sample (4, 6, 8 mm), airflow rate (0.01, 0.025, 0.04 m^3/s) and the temperature of the drying process (55, 65, 75 oC) on drying performance and product quality. It was found that the optimum drying time was 83 minutes under optimal conditions (4 mm thickness, airflow 0.04 m^3/s, 75 °C). Image processing and HPLC quality analysis results showed that the thickness of the sample was the dominant factor of shrinkage, and the color was largely affected by drying temperature. It was able to cut down vitamin C degradation at 55 °C, 4 mm thickness and at 0.04 m3/s of airflow (8.3). CPC collector had a maximum energy and exergy efficiency of 25% and 6%, respectively. The hybrid system showed to be reliable and up to 50% of the energy was supplied by the solar during the medium load conditions thus showing that it is sustainable in drying agricultural products.

Othman et al. (2022) [57] researched the drying of the olive mill sludge with an indirect solar dryer powered by a PTC. The system made use of a heat exchanger to move thermal energy contained in solar-heated oil to air to be utilised in drying the sludge. Experimental and simulation modeling showed that the system was capable of reaching an air temperature of over 100 °C over a period of up to 10 hours when favorable solar irradiance (DNI high at 800 W/m²) was available. This high temperature drying decreased the drying time needed to reach the desired moisture target in sludge valorization as biomass by 30%. The highest thermal efficiency of the system was 88%, and it was estimated to produce 23,909 kWh of thermal energy each year, offsetting about 15,900 kg of CO_2 emissions. Figure 12 indicates how temperature of the drying air affects the various positions of the sludge samples in a single tray. By determining the estimated sludge temperature at various points (x) with an inlet air temperature of 120 °C and with a velocity of 2.5 m/s, it is demonstrated that, at a distance much further than the hot air entry, the sludge temperature is lower (a decrease in ΔT is less than 4°C).

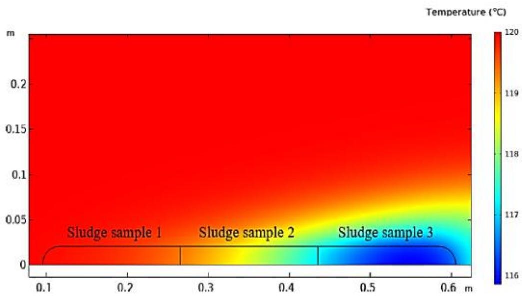

Figure 12. Changes in the drying chamber's sludge temperature for a particular position [57]

A study conducted by Fadhel et al. (2023) [58] examined an original and greener phosphate drying technology by means of the prototype Linear Fresnel Solar Collector (LFSC). A combination of numerical optical modeling and experimental validation by the study shows that the designed LFSC is highly efficient optically with a peak of over 0.7 in the summer months (May-July). Drying experiments revealed that the LFSC process lowers phosphate residual moisture to 0.016-0.021 kg water/kg dry matter in 4 hours and 40 minutes compared to the open-air drying, which had only reached 0.063-0.072 kg water/kg dry matter and could not satisfy international marketing standards. The researchers provided an approximation of how it might be scaled to a 100 m^2 aperture size, stating that it would supply 59,766 kWh of thermal energy every year and eliminate about 38,255 kg of CO_2 emissions, which demonstrated that the software has a potential to save a significant amount of energy and benefit the environment. When high radiation of the sun and low relative air humidity and low air velocity, the drying of phosphate in the tube receiver (LFSC) requires less time than drying in the open air (Figure 13).

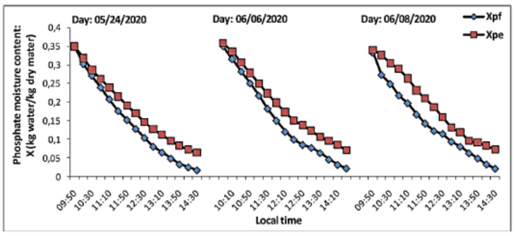

Figure 13. Changes in the water content of phosphate over time in the LFSC tube (X pf) and in the open air (X pe) [58]

Jain et al. (2023) [59] interested in the creation and performance of a Solar Conduction Dryer (SCD) to dry agricultural products. The SCD applied a conduction form of heat transfer by using trays with black-coated metal surfaces as opposed to a traditional solar dryer that mostly operates on a convection method, resulting in higher thermal efficiency. The system was also enhanced by the reflectors on both sides to enhance the amount of solar radiation getting captured. Experiments were carried out on drying beetroot slices at no-load and full-load conditions and in the presence and absence of reflectors. It was found that the reflectors contributed a significant amount in the highest temperatures recorded in the dryer and drying efficiency was enhanced to 50.09% at 59.4 °C. The reflectors shortened the drying period of the beetroot to 17 hours instead of the 20 hours. Economic analysis showed that the initial capital investment of the SCD is recoverable after a period of around 1.02 years, showing economic viability in the application of the SCD in agricultural drying.

Hussain and Lee (2023) [60] designed and tested an agricultural products-based multi-conical solar dryer on an industrial scale using copper oxide/water Nanofluid as the medium of heat transfer. The researchers involved thorough energy, exergo-economic and exergo-environmental analyses. The outcomes proved that the Nanofluid-based solution outperforms thermal performance by a factor of 40% than traditional dryers and has the capability of remaining at the desired drying temperature over the course of 10 hours. The mean efficiency was 38.08% and the energy loss is 0.61 kW. The Nanofluid system got shorter length of energy payback period (4.38 years compared to 7.65 years of water) and reduced greater CO_2 than the water over 20 years of life span (13.41 tons compared to 10.39 tons). The researchers concluded that Nanofluid-driven multi-conical solar dryer is a very efficient, economically viable and environmentally friendly technology in industrial level agricultural drying.

Khawale et al. (2023) [61] made an experimental experiment to compare the performance of a solar crop dryer (SCD) equipped with a reversed absorber and reflector and without them. The purpose of the research was to develop a dryer that will be able to harvest as much solar radiation as possible. Two types of dryers were experimented: one with no reversed absorber and reflector and another (SD6) with these two characteristics. The performance metrics such as collector efficiency, drying efficiency and pick-up efficiency were measured. The findings showed that the SD6 configuration had better average efficiencies of 34%, 49% and 64%, respectively. The drying properties of red chilli were determined by using the thin-layer drying models, where the model that fitted the experimental data best, based on the highest coefficient of determination (R^2), the lowest mean bias error (MBE), and root mean square error (RMSE).

Bori et al. (2024) [59] carried out a heat transfer study of a concentrated-type dryer by using PTC to dry ginger. The experiment compared the coefficients of convective heat transfer in the receiver tube and drying chamber yielding the results 1372.48 W/m^2 K and 17.60 W/m2 K, respectively. The thermal efficiency of the dryer was 30%, and the average temperature gradient between the drying chamber and ambient was about +11 °C. This left the ginger samples with a final moisture content of 11.1%, which was far much less than the 23.74% that was obtained through open-air drying using the sun. The researchers established that the solar PTC dryer is effective in improving the performance and dryness of drying.

Salah et al. (2024) [63] proposed the design, construction, and experimental performance analysis of an innovative indirect solar dryer aided by a PTC with a dual-axis solar tracker. The system was created out of locally sourced materials and tested in the Saharan climate of El Oued, Algeria. The experimental findings revealed that the dryer could reach high temperatures of up to 115 °C at the receiver and 70 °C in the drying chamber and thus managed to lower the moisture content of apricots of 69% of the apricots to 8%. Mean thermal efficiency of the system was 25.93% with a maximum of 45.25%. A financial analysis showed that the system has a low cost of capital of around 521 and an exceptionally short payback period of 0.43 years, which significantly supports the economic viability of the system as an agricultural dry system and its ability to save the use of traditional energy sources. Figure 14 demonstrated how annual savings would grow throughout the life of our solar dryer aided by PTC to a maximum annual savings of 2,485.76$.

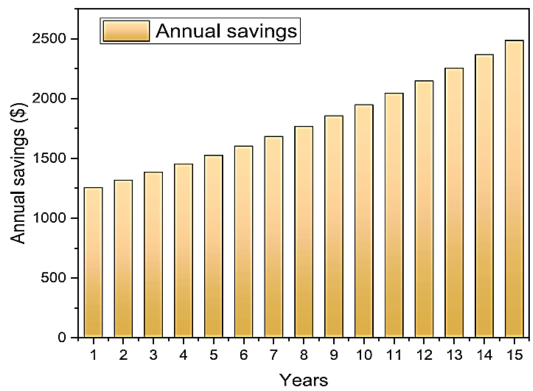

Fig. 14. The solar dryer's yearly savings with PTC assistance [63]

A comparative study, designed by Chtioui and Khouya (2024) [64], was an efficacy evaluation of an indirect solar dryer furnished with a CPC with drying Pine wood during Continental (Berlin) and Mediterranean (Nice) climatic conditions. The researchers used simulations in TRNSYS and MATLAB to achieve drying times of 129 hours with a Continental climate and 168 hours with a Mediterranean climate by reducing wood moisture content to 50% to 10% moisture content. The CPC greatly shortened the drying time by about 34% in the Continental area and drove out 43.5 kg of water vapor off the stack of wood. Mediterranean climate used more energy, with the drying efficiency of 57-82% and Continental of 23-45%. Also, the annual carbon dioxide emission was cut 17.764 tons in Continental and 1.45 tons in Mediterranean climates. Optimisation methods in Mediterranean climate to improve the drying performance were also suggested in this research, which included the expansion of CPC area and the decrease of wood thickness. The results showed a significant reduction in the drying time of the fan, as the time would have been 168 h without the fan, but the time is now 100 h with the fan as illustrated in Figure 15.

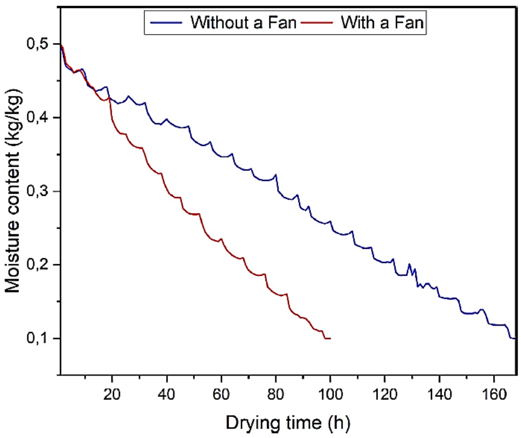

Figure 15. Impact of Fan Usage on Drying Time Optimisation [64]

Kumar et al. (2024) [65] experimentally evaluated the behavior of a new passive mixed-mode solar dryer (MMSD) with a north wall reflector in the drying of tomato slices. The performance of the MMSD was measured and compared with three set-ups including the presence of the north wall reflector, no reflector, and conventional OSD. The findings revealed that the reflector MMSD was the most successful one, recovering the moisture content of tomatoes by 94.5% to 1% in 24 hours. This was much quicker than the MMSD that had no reflector (32 hours to 2.4% moisture) and OSD (32 hours to 2.7% moisture). The MMSD also had the highest drying efficiency and total drying efficiency of 22.07% and 20.29%, respectively, without the reflector at 15.38% and 12.39% respectively. It was also concluded that addition of a north wall reflector in a mixed-mode solar dryer significantly enhances the drying parameters, such as drying rate and efficiency, which makes it a more effective solution in preservation of agricultural products than configurations without a north wall reflector and open sun drying.

In a study by Muthuvairavan and Natarajan (2025) [66], the effectiveness of a new surface-modified (SM) natural air-circulation mode (NACM) single-slope direct solar dryer with a flat-plate reflector, CPC, and TES was experimentally studied using sodium acetate trihydrate to dry Kohlrabi. The system was contrasted to the OSD and unmodified NACM dryers. It was found that the combined system obtained the greatest average drying rate of 108.91 g/h, moisture content was reduced 82.61 times quicker than OSD and 39.13 times quicker than traditional NACM. The checkered aluminum wall distributed the temperature evenly and served as a sensible heat storage, and the TES prolonged the drying time by 2 hours after the sunset, raising the air temperature by 0.85 to 12.2 °C. The system had a payback period of 3.34 months, reduced 25.99 tons of CO2 during its life, and earned carbon credits of 379.91, which is an efficient and sustainable drying system.

Chouchane et.al. (2025) [67] quantitatively examined the output of a new Ribbed Photovoltaic Thermal Phase Change Material Solar Dryer (R-PVTPCM-SD) with tropical weather conditions in Kuala Lumpur, Malaysia. The hybrid system proposed combines L-shaped ribs and PCM into a photovoltaic-thermal (PVT) air collector to achieve better thermal control, greater electrical performance, and higher drying efficiency. The findings showed that the R-PVTPCM-SD design reaches the highest electrical efficiency of 15.23%, which is higher than the traditional PVT systems by up to 0.56 and increases the total energy output by 4.77. The combination of PCM and ribs also played a clear role in reducing moisture content of Deglet Nour dates by 26.6% in the drying process. The optimal configuration was found to be RT44HC PCM with 0.01 m thickness, solar concentration of 4 and mass flow rate of 0.07 kg/s. The researchers found that the R-PVTPCM-SD system is an effective and powerful all-in-one method of producing electricity and drying agricultural products. Table 1 shows a summary of the studies that are related to solar dryers with concentrators and optical enhancements.

Table 1. A summary of the studies that are related to solar dryers with concentrators and optical enhancements

Authors and year [reference]	Configuration	Application	Results and remarks
Liu et al. (2014) [44]	Parabolic trough concentrating solar heating system with V-type metal cavity absorber	Cut tobacco drying	Achieved dryer thermal efficiency of 66.32%. Optimal conditions: 15 m/s airflow, 26% initial moisture, 200 °C inlet temperature. Reduced final moisture to 14.15%. Mathematical model agreed with experiments (<8% error).
Sulaiman an Taha (2014) [45]	Fresnel lens concentrator with aluminum receiver tray	Oil palm fronds drying	Solar dryer completed drying in 6.5 hrs (4.75 g/hr) vs. electric oven's 10.5 hrs (2.83 g/hr). Efficiency of 55.4% due to good heat retention and natural airflow.
Ky et al. (2018) [46]	Indirect solar dryer with fixed hemispherical concentrators (no tracking)	Tomato drying	Achieved collector outlet temps up to 103.4 °C, drying chamber 40–82 °C. 83% weight reduction in 12.5 hrs. Validated hot-spot theory for solar drying.
Lamrani et al. (2019) [47]	Indirect hybrid solar dryer with CPC (TRNSYS model)	Wood drying	Dried wood from 0.7 kg/kg to 0.1 kg/kg in ~84 hrs. Solar collector provided significant energy, reducing auxiliary heater use and 34% annual CO_2 emissions. Collector slope 35.7° optimal.
Hosseinzadeh et al. (2019) [48]	Solar parabolic dish collector with cylindrical/semi-spherical cavity receivers	Optical simulation for solar dryers	Semi-spherical receiver outperformed cylindrical (1262.72 W vs 990.23 W absorbed flux). Recommended for enhanced efficiency in solar box and cabinet dryers.
Spall and Sethi (2020) [49]	Multi-rack tray solar cabinet dryer with reflective north wall (RNW)	Carrot drying	RNW increased radiation capture up to 37.58% in winter. Improved efficiency by 5% (NC) and 4.35% (FC). Reduced drying time by 20% (NC) and 15% (FC).
Seemwanga et al. (2020) [50]	Hybrid Indirect Passive (HIP) solar dryer with metallic concentrators	Pineapple and mango drying	HIP dryer took 18 h vs. SPE dryer (10 h) and OSD (30 h). HIP efficiency comparable to SPE and 18% higher than OSD. Suitable for off-grid areas.
Teklu et al. (2020) [51]	Natural convection indirect solar dryer with side and bottom reflectors	Tomato drying	Reflectors increased max absorber plate temp from 98°C to 154 °C (no-load). Improved drying rate by 14% (5kg load) and 8% (10kg load).
Ajunwa et al. (2020) [52]	Indirect solar dryer with single-axis manual sun-tracking and optimised reflectors	General drying	Manual tracking increased moisture loss by 5.11%, drying rate by 2.10×10^{-5} kg/s, collector efficiency by 3.92%, and overall efficiency by 2.0% against fixed mode.
Castellano et al. (2021) [53]	CPC with low concentration ratio (~4 suns)	Asphalt plant aggregate (silica sand) drying	Achieved temps up to 70 °C. Dried 5 mm sand layer in ~150 mins. Potential to reduce emissions in asphalt production.
Hosseini and Zhang (2021) [54]	CSP integration (Parabolic Trough and Solar Tower) for thermal energy	Low-rank coal drying and pyrolysis	Solar Tower integration saved 12.8% annual thermal energy, but was not economically viable. PTC for coal drying only was most favorable (NPV $81.1M, payback 4.9 yrs).
Shoebi et al. (2021) [55]	PV/T solar air dryer with CPC and V-shaped fins	Air heating and Electricity generation	24 fins increased electrical and thermal efficiencies by 28.7% and 30.6% respectively. Cost $0.206/kWh. Highest CO_2 mitigation (44.19 tons lifetime). Max exergy efficiency 5.21% (24 fins).
Ebadi et al. (2021) [56]	Hybrid solar dryer with CPC and auxiliary heater	Tomato slice drying	Min drying time 83 mins (4mm, 0.04 m³/s, 75 °C). Vitamin C degradation minimized to 8.3% at 55 °C. Max CPC energy/exergy efficiencies

			25% and 6%. Solar contributed up to 50% energy.
Othman et al. (2022) [57]	Indirect solar dryer with PTC and heat exchanger	Olive mill sludge drying	Achieved air temps >100°C for up to 10 h (DNI>800 W/m²). Reduced drying time by 30%. Max thermal efficiency 88%. Annual energy 23,909 kWh, mitigating ~15,900 kg CO_2.
Fadhel et al. (2023) [58]	Linear Fresnel Solar Collector (LFSC) prototype	Phosphate drying	High optical efficiency (>0.7 summer). Dried phosphate to 0.016–0.021 kg water/kg dry matter in 4 h 40 m against OSD (0.063–0.072). Scaling to 100 m² could save 59,766 kWh/yr and avoid 38,255 kg CO_2.
Jain et al. (2023) [59]	Solar Conduction Dryer (SCD) with reflectors	Beetroot drying	Reflectors increased max temps and improved efficiency from 50.09% to 59.4%. Reduced drying time from 20 to 17 hrs. Payback period ~1.02 years.
Hussain and Lee (2023) [60]	Industrial multi-conical solar dryer with CuO/water nanofluid	Agricultural product drying	Nanofluid reduced heating time by 40%, maintained temp for 10 hrs. Average energy efficiency 38.08%. Shorter energy payback (4.38 yrs vs 7.65 yrs for water). CO_2 mitigation 13.41 tons (20 yrs).
Khawale et al. (2023) [61]	Integrated solar crop dryer (SCD) with/without reversed absorber and reflector	Red chilli drying	SD6 (with absorber/reflector) had best average efficiencies: collector 34%, drying 49%, pick-up 64%. Page's model best fit drying data.
Bori et al. (2024) [62]	Concentrated solar dryer with PTC	Ginger drying	Receiver tube HTC 1372.48 W/m² K, chamber HTC 17.60 W/m² K. Thermal efficiency 30%. Final moisture 11.1% vs. 23.74% for OSD.
Salah et al. (2024) [63]	Indirect solar dryer with PTC and dual-axis tracker	Apricot drying	Achieved 115 °C at receiver, 70 °C in chamber. Moisture reduced 69% to 8%. Average thermal eff. 25.93% (max 45.25%). Low cost (~$521), short payback (0.43 yr). Annual savings $2,485.76.
Chtioui and Khouya (2024) [64]	Indirect solar dryer with CPC	Pine wood drying	Drying time 129 h (Continental) vs 168 h (Mediterranean). CPC reduced time ~34% (Continental). Fan usage reduced time from 168h to 100h. Drying eff. 57–82% (Continental), 23–45% (Mediterranean). Reduced CO_2 emissions.
Kumar et al. (2024) [65]	Passive mixed-mode solar dryer (MMSD) with north wall reflector	Tomato slice drying	MMSD with reflector reduced moisture 94.5% to 1% in 24 h, faster than without reflector (32 h to 2.4%) and OSD (32 h to 2.7%). Drying eff. 22.07% (with reflector) vs 15.38% (without).
Muthuvairavan and Natarajan (2025) [66]	Surface-modified direct solar dryer with reflector, CPC, and TES (Sodium Acetate)	Kohlrabi drying	Integrated system had highest drying rate (108.91 g/h), 82.61% faster than OSD, 39.13% faster than conventional NACM. TES extended drying by 2 h post-sunset. Payback 3.34 months, CO_2 mitigation 25.99 tons, carbon credits $379.91.
Chouchane et al. (2025) [67]	Ribbed PVT-PCM Solar Dryer (R-PVTPCM-SD) with L-shaped ribs and PCM	Date drying and Electricity generation	Max electrical eff. 15.23% (0.56% higher than conventional PVT). Increased overall energy output by 4.77%. Reduced date moisture by 26.6%. Optimal: RT44HC PCM, 0.01m thickness, concentration 4, flow rate 0.07 kg/s.

The revised studies of Table 1 introduce a combination of solar concentrators and image improvement can significantly maximise the performance of drying, but the best system will depend on operational needs and limitations. Parabolic trough concentrators (PTCs) and Linear Fresnel systems are always the highest operating temperatures (>100 °C), thus being used in large-scale drying of industries, where thermal input is important. Fixed concentrators, such as hemispherical and Compound Parabolic Concentrators (CPCs) however have large temperature increments and do not require complicated tracking, which makes them a viable solution to moderate-temperature agricultural drying. Critical comparison showed that optical upgrades, especially reflective north walls and side/bottom reflectors are providing high efficiency (typically 4-5%) and shorter drying times (nearly all types of dryers), which is an extremely cost-effective upgrade. The economic feasibility of system combining active tracking and high-performance concentrators is however very dependent on the scale and local solar irradiance with payback periods of few months to years. The combined facts make it clear that although concentrators stretch the limits on temperature, speed, less complex optical additions are often the most effective in terms of performance, durability, and availability to many applications.

2.2. Solar Dryers with Thermal Energy Storage and Phase Change Materials

Abuelnuor et al. (2020) [68] performed an experimental research on solar drying of tomatoes in a forced convection solar dryer combined with reflectors and PCM under Khartoum weather in Sudan. The researchers intended to address the weaknesses of intermittent solar radiation and low drying rates of an intermittent solar dryer. Four configurations were used in the experiments, which included indirect solar dryer (Mode 1), mixed solar dryer (Mode 2), mixed solar dryer with PCM (Mode 3), and mixed solar dryer with PCM and reflectors (Mode 4). The findings showed that mode 4 had the shortest drying time of 6 hours as compared to mode 1, 2, and 3 which had 10, 9, and 7 hours, respectively. Mode 4, therefore, enhanced the drying rates of Mode 1, Mode 2 and Mode 3 by 39.4%, 32% and 8.2%, respectively. The researchers deduced that PCM integration with reflectors substantially increases the efficiency and the performance of the solar drying systems.

Rashidi et al. (2021) [69] experimentally studied how a reflective canopy and a desiccant wheel (WRD) improve a solar drying system to dry oleaster fruit (Elaeagnus angustifolia L.). This configuration was compared to systems that had reflectors alone (WR) and those that had neither at three air flow rates (0.025, 0.05 and 0.09 kg/s). The findings showed that using reflectors in conjunction with the desiccant system was found to dramatically ($P < 0.05$) quicken the drying process and shorten the drying period by at least 44% than WORD system. The highest performance was also observed with this configuration, a maximum exergy efficiency of 56.7% was reached, specific energy consumption (SEC) was between 1.73 to 1.80 MJ/kg (excluding solar thermal energy) and overall drying efficiency had increased by 16.15% to 22.14%. The optimised system saved about 15% on the payback period economically. WR, WRD and WORD have exergy efficiency of 20.3% to 38.8%, 31.2% to 56.7% and 15.6% to 32.1%, respectively. As the rate of air flow increases (as working fluid) the exergy efficiency of drying process and cabinet increases as demonstrated in Figure 16.

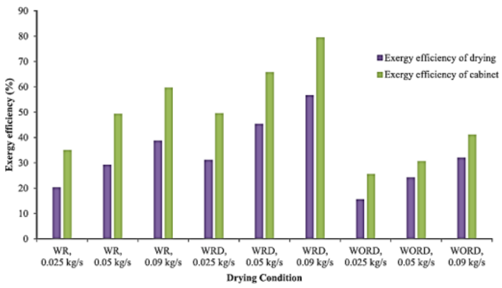

Figure 16. Exergy efficiency differences across cabinets and drying processes using various sun dryers at varying air flow rates [69]

The study by Karaağac et al. (2021) [70] was an experimental study of a focused photovoltaic-thermal solar dryer (CPV/TSD) that incorporates Nano-enhanced PCM, and used paraffin wax and Al2O3 Nanoparticles as a mixture. An extensive thermodynamic study using the first and second law of thermodynamics was carried out. It was found that the system has reached a total thermal energy efficiency of 20% and an exergy efficiency of 8%. It was discovered that the Nano-enhanced

PCM could hold the greenhouse temperature up to the 100 minutes in the presence of reduced solar radiation. Mushrooms were dried using a starting moisture content of 17.450 g water/g dry matter to a final moisture content of 0.05150 g water/g dry matter with the drying rate of 0.4360 g water/g dry matter/min. Also, Artificial Neural Network (ANN) and Support Vector Machines (SVM) algorithms were used to predict the drying parameters (moisture content and moisture ratio). Although the two machine learning models both achieved satisfactory results, ANN algorithm showed a better predictive performance on all evaluation measures (R2, rRMSE, MBE, and rMAE).

Kabeel et al. (2021) [71] experimentally studied the efficiency of a natural convection solar dryer that has an external reflector to dry anchovy fish and compared it with the traditional open solar drying. The findings showed that under the solar dryer, modified the solar dryer is much more efficient in drying, moisture content is lessened more quickly and quality of products is maintained as low as possible by reducing the loss of colour and eliminating dust and insect contamination. The lower tray (16.73) and upper tray (19.34) were determined to have a thermal efficiency of 16.73% and 19.34% respectively, and was better than open drying techniques. External reflectors also decreased total drying time to 56 hours (compared to 96 hours with open drying), which proved the possibility of such a design to be efficient and hygienic in food preservation. The mass of fish when the method of drying used is the open solar drying is greater than that of fish mass in tray 1 and tray 2 (Figure 17).

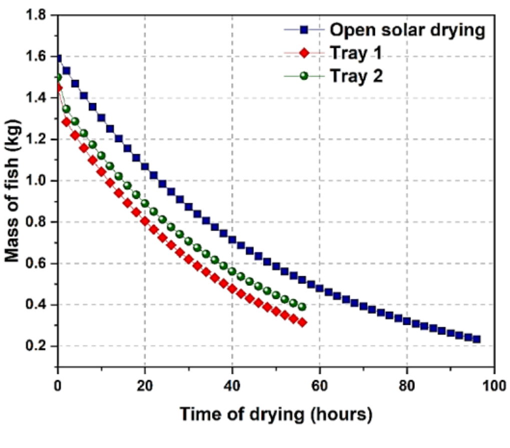

Figure 17. Fish mass variation during the drying process utilizing a customised solar dryer and traditional open solar drying [71]

Dubey et al. (2022) [72] designed and built a domestic solar-based dryer and tested it on grapes to turn them into raisins and compared the performance of the solar-based dryer with traditional open sun drying. Solar dryer dried quicker with an initial moisture content of 78.10% dropping down to 9.05% in a span of 7 hours whereas, open sun drying took 6 days to dry. Nutritional evaluation showed that solar dried raisins had higher levels of ash (2.71 against 1.95), monounsaturated fatty acids (10.95 vs. 7.12) and some vital mineral ions including iron, zinc and molybdenum. Further, the bacterial growth in the solar dried raisins was insignificant than open sun dried raisins, and the hygienic benefits of solar drying were demonstrated. It is reasonable to conclude that solar drying does not harm nutritional value, rather improves the food safety, and provides a usable alternative to food preservation on a household and small scale.

Dharmadurai et al. (2022) [73] conveyed the outcomes of an experimental study on the efficiency of a solar dryer with a separate reflector to dry grapes, and its effectiveness was compared with the open solar dryer. It was established that the addition of an external reflector could enhance the incident solar energy on the dryer by up to 1520% and this resulted in elevated internal temperature, approximately 20% greater than when using open basket drying, and a more importantly reduced relative humidity in the drying chamber. These improved conditions led to a lower drying duration of 5 days of the modified solar dryer in comparison to 8 days that is taken by open solar drying. The rate of drying and thermal efficiency was also greater in the dryer with a reflector proving that it was superior in removing moisture efficiently and safeguarding the produce against dust and insects. The researchers concluded that an external reflector combined with a closed-chamber solar dryer is a useful approach to enhancing the performance of a drying process and saving the time of the product processing of agricultural goods such as grapes. The mean temperature within the drying room is comparatively higher to approximately 15.45 °C and the relative humidity within the room is minimized to approximately 45%, as demonstrated in Figures 18, and 19.

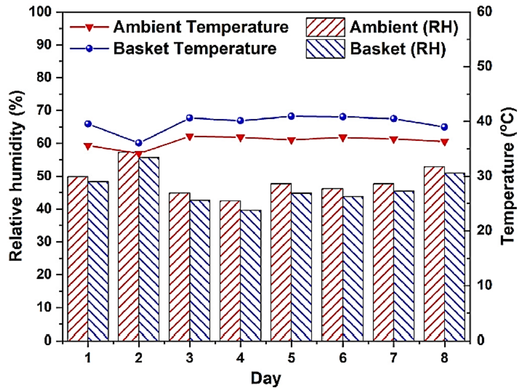

Figure 18. Day-to-day variations in the open basket solar dryer's RH, tray temperature, and ambient temperature [73]

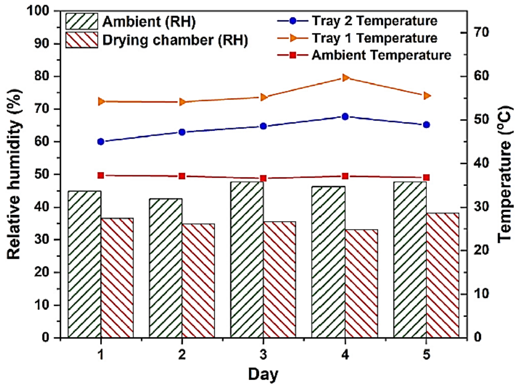

Figure 19. Variability in the temperature, relative humidity, and tray temperature of the modified dryer on several days [73]

The design and performance analysis of a new Indirectly Forced Convection Desiccant Integrated Solar Dryer (IFCDISD) to dry tomatoes in Pakistan were described by Zeeshan et al. (2024) [71]. This system used solar energy when the sun is shining, and, unlike all others, uses a calcium chloride (CaCl) bed of desiccant to sustain the drying at the times other systems are not in the sunshine. A DC fan was driven by a solar charged battery and forced across the desiccant bed at night. The results of the experiment showed that the dryer had an overall efficiency of 58.07%, capable of eliminating 56% of the water volume in the tomatoes in two days. Economic and environmental analyses showed payback period to be 5.14 years, CO_2 mitigation was 2.0335 tons. The researchers concluded that the IFCDISD is an efficient, cost effective, and environmentally sustainable solution owing to preservation of agricultural products.

Yematawu et al. (2024) [75] experimentally studied the performance of an indirect solar dryer with an evacuated tube collector (ETC), a separate rock bed TES unit and reflectors used to dry potato slices. The apparatus was set to dry 7.5 kg of sliced potato with the starting moisture content of 80.1% to a final content of 7-13. The units were tested at several rates of air flow (0.008, 0.016 and 0.024 m3/s) and compared to open-sun drying. The findings showed that an air flow rate of 0.016 m3/s produced the best performance with a collector efficiency of 62.02%, a dryer efficiency of 23.87%, a moisture content of 9.3 after eight hours and a heat recovery of 4837.8 kJ by the rock bed. The reflectors enhanced the net heat gain of the collector by 5.1% and shortened the time spent drying the system by 12.5% compared to the non-reflective system, and shortened drying time compared to drying in the open sun, by 30%. This combination of the independent rock bed was successful in providing heat when the sun was not shining and made the system more reliable and faster at drying. The heat energy obtained in the experiment with the air flow rate of 0.016 m^3/s was somewhat higher than the estimated thermal load used in designing the developed solar dryer as depicted in Figure 20.

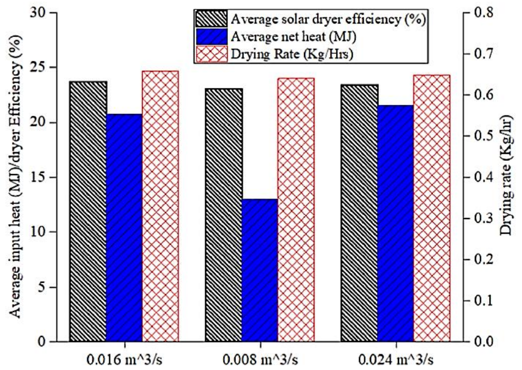

Figure 20. Evaluation of the dryer's performance at various air flow rates [75]

Nakum et al. (2024) [76] made a comparative life-cycle evaluation (LCA) between two types of solar drying systems, a phase-change material-based solar dryer (PCMBSD) and a cylindrical solar-assisted dryer (CSAD). The researchers assessed cradle-to-gate environmental impacts with the help of ReCiPe 2016 endpoint method and SimaPro 9.5.0.1 software. The findings showed that the PCMBSD has, on average, 40% higher environmental effects than the CSAD, with much greater effects on such categories as human non-carcinogenic toxicity, which is largely attributed to the production of PCM. Nevertheless, the CSAD had a higher effect on human carcinogenic toxicity and scarcity of fossil resources. The PCMBSD also added 13.7% more to the global warming. With a greater environmental footprint, the PCMBSD dried within 10 hours -3 hours quicker than the CSAD.

Kebede et al. (2025) [77] introduced the design and performance analysis of a small solar dryer to dry green coffee beans in the Ethiopian highlands. The new design of the dryer also consists of a reflector to maximise the absorption of sun energy and a solar-powered blower to provide forced convection, avoiding the alteration of the taste of the beans. Experimental evidence showed that the dryer was capable of drying a 20 kg lot of coffee beans on the dry side down to 10% (wet basis) in two days (12 effective sunshine hours), much faster than the 5-7 days of traditional natural drying. The highest temperature recorded in the drying chamber was 70 °C. The analytical analysis revealed that the system had a thermal efficiency of 35.2%. According to the findings, this small-scale solar dryer is an effective, long-term, and low-cost solution to small-scale coffee farmers, as it provides a valid alternative to traditional drying techniques to minimize post-harvest losses and enhance the quality of the products.

An indirect solar drying system for tomatoes was experimentally studied by Joseph et al. (2025) [78] with evacuated tube solar air heater (ETSAH) (Figure 21). Three configurations were tested in this research; a traditional ETSAH system, ETSAH reflector, and a system with a reflector and a latent thermal storage (paraffin wax). They showed that the incorporation of the reflector and thermal storage played a great role in the performance of the systems. The maximum temperature of the heater outlet of 65.2 oC was attained using the integrated system. The efficiency of drying rose to 48.63% in the improved system compared to the 41.31% in the traditional system and the maximum drying rate rose to 0.253 kg/h as compared to 0.203 kg/h in the traditional system. In the combined system, the final moisture ratio was also lowest (0.183). The research concluded that reflectors and latent thermal storage integration with ETSAH can improve significantly the drying efficiency, rate, and consistency and provide a more sustainable and efficient solution to drying in agriculture. Figure 22 provides a comparative overview of achievements of the system in the three configurations. As observed in the findings, Case 3 which incorporates a reflector and latent thermal storage has done better in all the parameters measured than the other setups. Table 2 shows a summary of the studies that are related to solar dryers with TES and PCM.

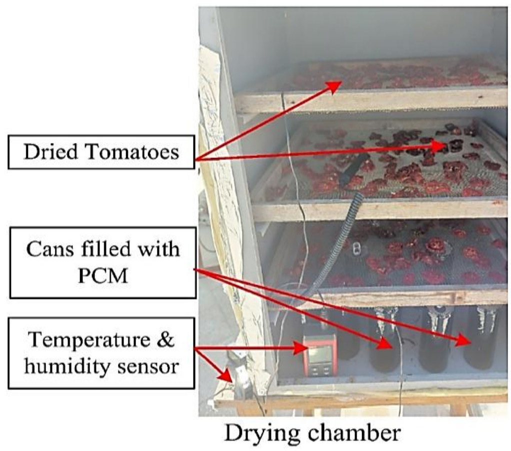

Figure 21. The components of the drying chamber [78]

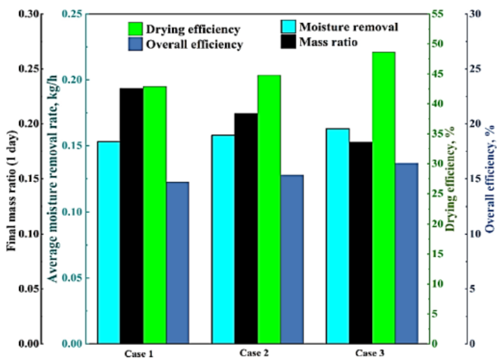

Figure 22. An analysis of every instance [78]

Table 2. A summary of the studies that are related to solar dryers with TES and PCMs

Authors and year [reference]	Configuration	Application	Results and remarks
Abuelnuor et al. (2020) [68]	Forced convection solar dryer with reflectors and PCM	Tomato drying	Mode 4 (PCM + reflectors) had shortest drying time (6 h), improving rates by 39.4%, 32%, and 8.2% over Modes 1, 2, and 3, respectively.
Rashidi et al. (2021) [69]	Solar dryer with reflectors and desiccant wheel (WRD)	Oleaster fruit drying	WRD reduced drying time by ≥44% vs. basic system (WORD). Max exergy efficiency 56.7%. Reduced SEC to 1.73–1.80 MJ/kg. Increased overall efficiency by 16.15–22.14%. Reduced payback by ~15%.
Karaağaç et al. (2021) [70]	Concentrated PV/T solar dryer (CPV/TSD) with nano-enhanced PCM (AlO_3+paraffin)	Mushroom drying	Overall thermal efficiency 20%, exergy efficiency 8%. PCM maintained temp for 100 mins post-radiation drop. ANN and SVM predicted parameters well, ANN superior. Drying rate 0.436 g water/g dry matter min.
Kabeel et al. (2021) [71]	Natural convection solar dryer with external reflector	Anchovy fish drying	Thermal efficiency 16.73% (lower tray) and 19.34% (upper tray). Reduced drying time from 96 hrs (open) to 56 hrs. Better product quality (color, hygiene).
Dubey et al. (2022) [72]	Domestic solar dryer	Grape drying (raisins)	Reduced moisture 78.10% to 9.05% in 7 hrs against 6 days for OSD. Higher nutritional retention (ash, fatty acids, minerals) and negligible bacterial growth against OSD.
Dharmadurai et al. (2022) [73]	Solar dryer with external reflector	Grape drying	Reflector increased radiation by 15–20%, internal temp by ~20%, reduced RH. Drying time 5 days against 8 days for OSD. Higher drying rate and thermal efficiency.
Zeeshan et al. (2024) [74]	Indirectly Forced Convection Desiccant Integrated Solar Dryer (IFCDISD) with $CaCl_2$	Tomato drying	Overall efficiency 58.07%, removed 56% moisture over 2 days. Payback 5.14 yrs, carbon mitigation 2.0335 tons, carbon credits 11,559.6. Desiccant enabled off-sunshine drying.
Yematawu et al. (2024) [75]	Indirect solar dryer with ETC, rock bed TES, reflectors	Potato slice drying	Optimal airflow 0.016 m^3/s: collector eff. 62.02%, dryer eff. 23.87%, moisture to 9.3% in 8 hrs. Reflectors increased heat gain 5.1%, reduced time 12.5%. TES supplied heat post-sunset.
Nakum and (2024) [76]	Comparative LCA of PCM-based solar dryer (PCMBSD) vs. Cylindrical (CSAD)	General drying (LCA focus)	PCMBSD had ~40% higher environmental impact than CSAD (mainly due to PCM production), but dried 3 hrs faster (10 hrs vs 13 hrs). CSAD had higher impact in some toxicity categories.
Kebede et al. (2025) [77]	Diminutive solar dryer with reflector and solar-powered blower	Green coffee bean drying	Reduced moisture 60% to 10% in 2 days (12 sunshine hrs) against 5–7 days traditional. Max chamber temp 70 °C. Thermal efficiency 35.2%. Efficient for small-scale growers.
Joseph et al. (2025) [78]	Indirect solar dryer with ETSAH, reflector, and latent storage (PCM)	Tomato drying	Combined system (reflector+PCM) achieved highest outlet temp (65.2°C), drying efficiency of 48.63%, max rate 0.253 kg/h, lowest final moisture ratio (0.183). Outperformed conventional ETSAH.

The revised studies of Table 2 reveal that the combination of TES and PCMs is a key requirement in combating the problem of solar intermittency and improving the reliability of the systems. Critical comparison demonstrated that in spite of the fact that simple reflector additions may be used to enhance daily efficiency, their combination with TES/PCM systems has deeper effects since it allows long-term activity after the sunset, which decreases the overall time of drying up to 44% relative to simple makeup. Nevertheless, a significant change in terms of environmental and performance trade-offs can be seen: those systems with nano-enhanced or advanced PCMs (e.g., Karaağac et al., 2021 [70]) have better thermal regulation and drying, however, the evaluation of their impact on the environment (e.g., life-cycle assessments, e.g., Nakum et al., 2024 [76]) reveals that the manufacturing of such materials cancels part of the advantage, which brings us to a conclusion that sustainable PCM development is necessary. The payback times of these improved systems are economical (0.43-5.14 years), and desiccant-combined systems have special off-sunshine features. The general point is that the best integration of TES/PCM should be unique to each situation, between the required improvement in the drying rate and operating duration and the financial limitation and the entire environmental impact of the storage materials.

2.3. Fundamental Analysis of Solar Dryer Performance and Modeling

The drying behavior of ginger rhizomes was experimentally studied using a natural convection indirect solar dryer (Sansaniwal and Kumar 2015) [79]. In the experiment, the convective heat transfer coefficient and the rate at which moisture was removed was measured in relation to various sample masses. The findings revealed that the coefficient of convective heat transfer was less as ginger mass increased and across the drying days and ranged between 0.59 and 5.42 W/m^2 °C. The rate of moisture removal corresponded to mass of sample but decreased with extension of drying. Collector efficiency was average at 14.97% to 16.14% depending on the trends in solar radiation. The drying kinetics were best explained by the Modified Page model amongst the thin-layer drying models that were tested. The range of experimental error was between 29.19% and 46.25%.

Dhande et al. (2020) [80] developed and tested a low-cost mixed-mode solar dryer to improve postharvesting of food grains. The dryer was made of locally available and environmentally friendly materials and consisted of a solar collector, drying chamber, helical screw assembly, and air heater chamber. The dryer had a loading capacity of 10 kg of wheat grains with an average temperature increase of 27.7 °C above ambient temperature with a peak temperature of 68 °C in the drying chamber. The experimental findings revealed that the dryer was useful in drying wheat grains after one hour to reduce the moisture level of grains by 22% to 14.5%, thus assuring a rapid and consistent drying process in addition to guarding the grains against contamination and other environmental risks. The researchers concluded that the mixed-mode solar dryer is an effective and affordable technology to small-scale farmers especially where alternative energy sources are limited and mostly in rural regions.

Nukulwar (2020) [81] compared the kinetic study on the use of an indirect natural convection solar dryer to study the study of the thin-layer drying kinetics of turmeric with a Scheffler dish. The aim of this study was to find the most appropriate mathematical model to predict the behavior associated with drying. The findings indicated that the moisture content of turmeric decreased by 63.33% compared to dry drying in open sun and the solar dryer dried the turmeric in 22 hours by reducing the moisture content of the product to 11.93%. The drying efficiency was determined as 29.85% with a degree of uncertainty 0.67. Out of the seven thin-layer models tested, the Page model gave the closest fit to both the open sun drying and the solar drying, and thus it proved effective in predicting both the moisture ratio and kinetics of drying.

The prototype system of the study of Chaanaoui et al. (2021) [82] is an experimental analysis of a phosphate sludge drying system with the energy source being a PTC solar loop. The system combines a PTC loop, an oil-air heat exchanger (HX) and a rotary dryer. The experiments were performed under semi-arid conditions in Morocco, where each subsystem was tested individually and the entire system was tested at different conditions of solar irradiance.

The findings showed that a drying air of between 105 oC to 123 °C is needed to obtain the desired moisture content of 7 or lower, based on the air flow rate. The system achieved 32 kg sludge drying on sunny days with consistent temperatures, and the performance was much lower on cloudy days owing to the intermittence of the sun as it dried the sludge, leading to an uneven product with a higher water content than the target value in three-quarters of the measurement sites as depicted in Figure 23. Table 3 shows a summary of the studies that are related to fundamental analysis of solar dryer performance and modelling.

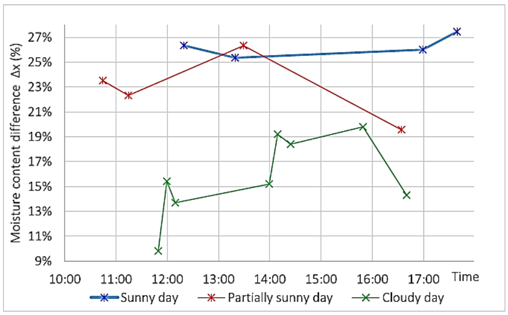

Figure 23. Variation in water content on average days [82]

Table 3. A summary of the studies that are related to fundamental analysis of solar dryer performance and modeling

Authors and year [reference]	Configuration	Application	Results and remarks
Sansaniwal and Kumar (2015) [79]	Natural convection indirect solar dryer	Ginger rhizomes drying	Convective heat transfer coefficient ranged 0.59–5.42 W/m² °C. Collector efficiency 14.97–16.14%. Modified Page model best described drying kinetics. Experimental uncertainty 29.19–46.25%.
Dhande et al. (2020) [80]	Low-cost mixed-mode solar dryer	Wheat grain drying	Reduced moisture from 22% to 14.5% in 1 hr. Average temperature rise of 27.7 °C above ambient, peak 68 °C. Cost-effective for small-scale farmers.
Nukulwar (2020) [81]	Indirect natural convection solar dryer powered by Scheffler dish	Turmeric drying	Reduced moisture from 77% to 11.93% in 22 hrs (63.33% faster than OSD). Drying efficiency 29.85%. Page model best fit.
Chaanaoui et al. (2021) [82]	PTC solar loop with oil-air HX and rotary dryer	Phosphate sludge drying	Drying air temps of 105–123°C needed for ≤7% moisture. Performance stable on sunny days (dried 32 kg), declined on cloudy days. Moisture removal variable, product often above target moisture.

Altogether, the papers in Table 3 highlighted the significance of the basic modeling and performance analysis in the optimisation of the design and functioning of solar dryers despite the variety in the configurations of different dryers and their use in agriculture. One point that can be made critically is that empirical modeling (including the Modified Page and Page models) has consistently been effective in predicting the drying characteristics of a variety of products, including ginger rhizomes and turmeric, and is suggestive of a general method of thin-layer drying characterization. Nevertheless, a large discrepancy begins to be observed in performance results based on the complexity and integration: when simple, low-cost mixed-mode dryers are used, with their strong demonstrated ability to operate effectively in small-scale applications with high moisture-reduction rates, more complex systems incorporating parabolic trough collectors together with heat exchangers are observed to be highly sensitive to climatic intermittency, as the end result is variable product quality and instability in operations under less-than-ideal solar conditions. This trade-off highlights a major trade-off between reliability, cost, and scalability with the point that high-temperature drying with advanced solar thermal loops is possible where there is a steady supply of solar irradiance, but their usefulness is strongly dependent on variability in practice in the field with the consideration of the hybrid or storage-assisted designs to provide consistent operating conditions.

3. Critical analysis of advanced solar drying technologies

This section intends to critically analyse the associated advantages and disadvantages of the advanced solar dryer technologies that incorporated solar concentrators, optical enhancements, and TES systems, including PCMs. The most advantages of integrated solar dryers and solar concentrators such as parabolic troughs and Fresnel lenses were demonstrated by enhancing the overall thermal efficiency. For instance, Liu et al. (2014) [44] ascertained an efficient energy utilisation by integrating a parabolic trough system with a 66.32% thermal efficiency. Also, the incorporation of PCMs has maintained elevated temperatures that improved the drying rate of solar dryer as confirmed by Karaağaç et al. (2021) [67]. Several studies were highlighted reduced drying time for the advanced solar drying technologies in a comparison to conventional drying processes. Sulaiman and Taha (2014) [45] reported a reduced drying time of 4 hours for oil palm fronds in a comparison to electric ovens. Undoubtedly, this reduction would enhance the productivity, particularly for agricultural applications where timely processing is vital. Sustainable and environmental advantages have been realised due to the implication of advanced solar dryer technologies. This was notified by reducing the reliance of fossil fuels. In this aspect, Othman et al. (2022) [57] assigned the possibility of lowering greenhouse gas emissions approximately 15,900 kg annually due to the employment of TES and PCMs that further reduced the overall energy consumption. the versatility of advanced solar dryer technologies has permitted their implications in different sectors such as food processing and industrial applications. On top of this, the economic viability is one of the best merits of advanced solar dryer technologies. These systems can provide long-term savings on energy cost despite their high-initial investments. In this regard, Salah et al. (2024) [63] showed a payback period of just 0.43 years for the solar drying system equipped with tracking mechanisms and concentrators.

Although, there are a number of advantages of advanced solar drying technologies, the associated disadvantages should be addressed to be resolved later. First of all, these technologies require a considerable upfront investment for installation and setup. Also, they are characterised by a high-level of design complexity, which may hinder widespread adoption, particularly in remote regions. The inherently reliance on weather conditions is another disadvantage of solar drying technologies. Indeed, variable drying rate would be the consequence of intermittency in solar radiation and thus these systems require auxiliary heating methods. Specifically, this issue was ascertained by a number of studies such as Hosseini and Zhang (2021) [54] who noted the economic challenge of solar tower integration. The complexity of multiple technologies including the concentrators, TES, and PCMs would arise a key complexity concern, which require specialized person for operation and maintenance. The issue of variable efficiencies of advanced solar drying technologies should also be realised as the performance strictly depends on seasonal variation and geographical location. In turn, this would result in different drying times.

4. Conclusions

This review showed that combination of solar concentrators, optical enhancements, and TES or PCMs is a basic step forward in solar drying technology. The integration of modern studies confirmed that all these integrations directly target these fundamental limitations of the traditional solar drying process, that is, intermittency and low thermal efficiency, and is converted into a powerful, sustained, and high-performance process. The main results determined that concentrators and optical components, including parabolic troughs and reflective walls, make it possible to achieve much more operating temperatures and radiation uptake, which allows significantly shortening the drying periods. At the same time, TES/PCM systems will play a central role in maintaining operational continuity even during times of absence of sunshine, thermal conditions and also reducing the periods of processing. More importantly, these technological advancements are providing strong economic sustainability, as seen by the short payback periods, as well as large scale benefits to the environment in terms of significant reductions in energy usage and greenhouse gas emission. Specifically, these trends highlight how far the advanced solar drying has been developed into a very efficient profitable and sustainable solution across various agricultural and industrial uses, which fits the objectives of the global clean energy and climate action in close accordance.

5. Further enhancements and accompanying challenges

This section focuses on suggesting a number of recommendations to assure a continuous improvement of solar drying systems to an even greater level. These suggestions are as follows;

1. Developing intelligent hybrid systems is essential. This would include the design of more advanced systems, which smartly alternate between various energy sources (solar, biomass, geothermal, grid) depending on availability and price controlled by a smart controller. Also, installing of multi-stage PCM (advanced thermal storage) with electrical batteries in PV/T systems is viable to assure the availability of temperature and electricity.

2. Integrating of new nanomaterials, e.g., high-conductivity nanoparticles in PCMs and selective surfaces of Nano-coated absorbents is beneficial to enhance the heat transfer and absorption efficiency by a significant margin. Furthermore, the consideration of bio-based and biodegradable PCMs is a feasible option to improve the environment lifecycle of TES-built dryers.

3. Integration of smart control and IoT sensors into advanced solar dryers can be a primitive suggestion of improvement. Indeed, the use of machine learning algorithms to do real-time, closed-loop control of drying parameters (airflow, temperature, humidity) depending on the moisture content of the product and weather predictions could be plausible trend of future research. The remote monitoring and controlling through mobile application can present the solar dryers technology to be more user friendly and easy to manage.

4. The optimal solar dryer process design can be attained by using the multi-objective optimisation techniques. This would implicitly afford optimal parameters such as thermal efficiency, drying time, product quality, and economic cost.

However, the road to the mass use of these improved solar dryers has technical, economic, and practical challenges that need to be addressed in a systematic manner. The important restrictions are as follows;

1. The introduction of concentrators, PCMs and complicated controls make upfront and startup costs very high. Thus, a major discouraging factor to small-scale farmers and entrepreneurs is essential even with encouraging payback periods.

2. Advanced solar dryer systems are designed with tracking and heat exchangers and PCMs. These systems need a level of technical expertise to operate, maintain, and repair, which may also not be readily accessible in off-grid or rural areas.

3. Advanced solar dryer technologies are associated with material and durability concerns. Indeed, phase segregation and degradation of PCMs in repeated thermal cycles may be encountered and this may decrease their effectiveness as time goes on. Also, the durability of solar concentrator surfaces, reflector finishes and seals under severe conditions (UV radiation, dust, wind) is an issue of great concern.

4. Despite TES can alleviate intermittency, prolonged cloudy conditions can nonetheless bring the solar-dependent systems to their knees, particularly in areas with low Direct Normal Irradiance and reduce their efficiency as an exclusive source of energy.

Abbreviations

Symbol	Definition
A	Area (m²)
ANN	Artificial Neural Network
CPC	Compound Parabolic Concentrator
CSP	Concentrated Solar Power
CO_2	Carbon Dioxide
DNI	Direct Normal Irradiance (W/m²)
EES	Engineering Equation Solver
ETSAH	Evacuated Tube Solar Air Heater
FC	Forced Convection
FPC	Flat Plate Collector
g	Gram
H	Hour
HIP	Hybrid Indirect Passive
HTC	Heat Transfer Coefficient (W/m²·K)
HX	Heat Exchanger
IFCDISD	Indirectly Forced Convection Desiccant
kWh	Kilowatt-hour
LCA	Life-Cycle Assessment
LCOE	Levelized Cost of Energy
LFSC	Linear Fresnel Solar Collector
m	Meter, Mass
MBE	Mean Bias Error
min	Minute
MMSD	Mixed-Mode Solar Dryer
MRE	Mean Relative Error
MRT	Multi-Rack Tray
NACM	Natural Air-Circulation Mode
NC	Natural Convection
NPV	Net Present Value
NWR/RNW	North Wall Reflector / Reflective North
OSD	Open Sun Drying
PCMs	Phase Change Materials
PTC	Parabolic Trough Collector or
PV/T	Photovoltaic/Thermal
R^2	Coefficient of Determination
RH	Relative Humidity
RMSE	Root Mean Square Error
s	Second
SAD-	Solar Air Dryer - Finned
SCD	Solar Conduction Dryer / Solar Crop
SEC	Specific Energy Consumption
SM	Surface-Modified
SPE	Solar Photovoltaic and Electric
SVM	Support Vector Machine
TES	Thermal Energy Storage
TRNSYS	Transient System Simulation Tool
V	Volt
W	Watt
X	Moisture Content (kg water/kg dry

Greek Letters	
η	Efficiency (%)
ηc	Collector Efficiency (%)
ηd	Drying Efficiency (%)
ηp	Pick-up Efficiency (%)
ΔT	Temperature Difference (°C or K)

Conflict of interest

The authors declare no conflicts of interest concerning this research.

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Author Contribution

Mudhar A. Al-Obaidi 1 conceptualization, writing—original draft, writing—review and editing, visualisation, formal analysis, supervision, project administration.

Deyaa M. N. Mahmood 2 visualisation, formal analysis, resources.

Farhan Lafta Rashid 3 conceptualization, writing—original draft.

All authors participated in the discussion of the results and contributed to writing the manuscript.

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References

[1] L. A. Valencia Ceballos, E. C. López-Vidaña, C. K. Romero-Perez, J. Escobedo-Bretado, O. García-Valladares, and I. R. Martín Domínguez, "Techno-economic and environmental assessment of a photovoltaic-thermal (PV-T) solar dryer for habanero chili (Capsicum chinense): 4E (Energy, Economic, Embodied and Environmental) analysis," *Renew. Energy*, vol. 122, p. 122758, 2025, https://doi.org/10.1016/J.RENENE.2025.122758

[2] S. Chtioui and A. Khouya, "Mathematical modeling and performance evaluations of a wood drying process using photovoltaic thermal and double-pass solar air collectors," *Appl. Therm. Eng.,* vol. 255, p. 123901, 2024, https://doi.org/10.1016/J.APPLTHERMALENG.2024.123901

[3] A. Gupta, B. Das, E. Arslan, M. Das, M. Kosan, and O. F. Can, "Artificial neural networks based computational and experimental evaluation of thermal and drying performance of partially covered PVT solar dryer," *Process Saf. Environ. Prot.,* vol. 183, pp. 1170–1185, 2024, https://doi.org/10.1016/J.PSEP.2024.01.068

[4] E. Çiftçi, A. Khanlari, A. Sözen, I. Aytaç, and A. D. Tuncer, "Energy and exergy analysis of a photovoltaic thermal (PVT) system used in solar dryer: a numerical and experimental investigation," *Renew. Energy*, vol. 180, p. 180, 2021, https://doi.org/10.1016/j.renene.2021.08.081

[5] S. Shoeibi, H. Kargarsharifabad, S. A. A. Mirjalily, and M. Zargarazad, "Performance analysis of finned photovoltaic/thermal solar air dryer with using a compound parabolic concentrator," *Appl. Energy*, vol. 304, p. 117778, Dec. 2021, https://doi.org/10.1016/J.APENERGY.2021.117778

[6] K. Stephan and A. Laesecke, "The thermal conductivity of fluid air," *J. Phys. Chem. Ref. Data,* vol. 14, no. 1, pp. 227–234, 1985, https://doi.org/10.1063/1.555749

[7] S. B. Kim and H. U. Choi, "Numerical analysis of photovoltaic-thermal air collector with fins and rectangular turbulators," *Thermal Sci. Eng. Progress,* vol. 59, p. 103393, 2025, https://doi.org/10.1016/J.TSEP.2025.103393

[8] E. Y. Gürbüz, I. Şahinkesen, A. D. Tuncer, and A. Keçebaş, "Design and experimental analysis of a parallel-flow photovoltaic-thermal air collector with finned latent heat thermal energy storage unit," *Renew. Energy,* vol. 217, p. 119154, 2023, https://doi.org/10.1016/J.RENENE.2023.119154

[9] Z. Zhao, L. Zhu, Y. Wang, Q. Huang, and Y. Sun, "Experimental investigation of the performance of an air type photovoltaic thermal collector system with fixed cooling fins," *Energy Rep.,* vol. 9, pp. 93–100, 2023, https://doi.org/10.1016/J.EGYR.2023.02.059

[10] R. Gad, H. Mahmoud, S. Ookawara, and H. Hassan, "Evaluation of thermal management of photovoltaic solar cell via hybrid cooling system of phase change material inclusion hybrid nanoparticles coupled with flat heat pipe," *J. Energy Storage*, vol. 57, p. 106185, Jan. 2023, doi: https://doi.org/10.1016/J.EST.2022.106185

[11] D. Su, Y. Jia, G. Alva, L. Liu, and G. Fang, "Comparative analyses on dynamic performances of photovoltaic–thermal solar collectors integrated with phase change materials," *Energy Convers. Manag.,* vol. 131, pp. 79–89, 2017, https://doi.org/10.1016/J.ENCONMAN.2016.11.002

[12] A. Boubekri, H. Benmoussa, and D. Mennouche, "Solar drying kinetics of date palm fruits assuming a step-wise air

temperature change," *J. Eng. Sci. Technol.*, vol. 4, no. 3, pp. 292–304, 2009

[13] S. Dubey, G. S. Sandhu, and G. N. Tiwari, "Analytical expression for electrical efficiency of PV/T hybrid air collector," *Appl. Energy*, vol. 86, no. 5, pp. 697–705, 2009, https://doi.org/10.1016/J.APENERGY.2008.09.003

[14] R. Stropnik and U. Stritih, "Increasing the efficiency of PV panel with the use of PCM," *Renew. Energy*, vol. 97, pp. 671–679, 2016, https://doi.org/10.1016/J.RENENE.2016.06.011

[15] S. Tiwari and G. N. Tiwari, "Grapes (Vitis vinifera) drying by semitransparent photovoltaic module (SPVM) integrated solar dryer: an experimental study," *Heat Mass Transfer,* vol. 54, no. 6, pp. 1637–1651, 2018, https://doi.org/10.1007/S00231-017-2257-3/TABLES/7

[16] J. S. Al-Huwaidi, M. A. Al-Obaidi, A. T. Jarullah, C. Kara-Zaitri, and I. M. Mujtaba, "Modeling and simulation of a hybrid system of trickle bed reactor and multistage reverse osmosis process for the removal of phenol from wastewater," *Comput. Chem. Eng.,* vol. 153, p. 107452, 2021, https://doi.org/10.1016/j.compchemeng.2021.107452

[17] O. M. A. Al-Hotmani, M. A. Al-Obaidi, Y. M. John, R. Patel, F. Manenti, and I. M. Mujtaba, "Minimisation of energy consumption via optimisation of a simple hybrid system of multi effect distillation and permeate reprocessing reverse osmosis processes for seawater desalination," *Comput. Chem. Eng.,* vol. 148, p. 107261, 2021, https://doi.org/10.1016/j.compchemeng.2021.107261

[18] H. Panchal and A. Awasthi, "Theoretical modeling and experimental analysis of solar still integrated with evacuated tubes," *Heat Mass Transfer,* vol. 53, no. 6, pp. 1943–1955, 2017, https://doi.org/10.1007/S002310161953-8/METRICS

[19] S. Tiwari and G. N. Tiwari, "Thermal analysis of photovoltaic thermal integrated greenhouse system (PVTIGS) for heating of slurry in potable biogas plant: an experimental study," *Sol. Energy,* vol. 155, pp. 203–211, 2017, https://doi.org/10.1016/J.SOLENER.2017.06.021

[20] S. Agrawal, G. N. Tiwari, and H. D. Pandey, "Indoor experimental analysis of glazed hybrid photovoltaic thermal tiles air collector connected in series," *Energy Build.,* vol. 53, pp. 145–151, 2012, https://doi.org/10.1016/J.ENBUILD.2012.06.009

[21] S. Agrawal and G. N. Tiwari, "Exergoeconomic analysis of glazed hybrid photovoltaic thermal module air collector," *Sol. Energy*, vol. 86, no. 9, pp. 2826–2838, 2012, https://doi.org/10.1016/J.SOLENER.2012.06.021

[22] A. Gupta, A. Biswas, B. Das, and B. V. Reddy, "Development and testing of novel photovoltaic-thermal collector-based solar dryer for green tea drying application," *Sol. Energy*, vol. 231, pp. 1072–1091, 2022, https://doi.org/10.1016/J.SOLENER.2021.12.030

[23] E. Arslan and M. Aktaş, "4E analysis of infrared-convective dryer powered solar photovoltaic thermal collector," *Sol. Energy*, vol. 208, pp. 46–57, 2020, https://doi.org/10.1016/J.SOLENER.2020.07.071

[24] Y. Chaibi, M. Malvoni, T. El Rhafiki, T. Kousksou, and Y. Zeraouli, "Artificial neural-network based model to forecast the electrical and thermal efficiencies of PVT air collector systems," *Clean Eng Technol,* vol. 4, p. 100132, 2021, https://doi.org/10.1016/J.CLET.2021.100132

[25] M. A. Al-Nimr, A. I. Dawahdeh, and J. A. Al-Omari, "Dual power generation modes for thermally regenerative electrochemical cycle integrated with concentrated thermal photovoltaic and phase change material storage," *J. Energy Storage*, vol. 58, p. 106373, 2023,

https://doi.org/10.1016/J.EST.2022.106373

[26] H. Hasan, S. Alsadaie, M. A. Al-Obaidi, and I. Mujtaba, "Dynamic modelling and simulation of industrial scale multistage flash desalination process," 2023. [Online]. Available: http://creativecommons.org/licenses/by/4.0/

[27] W. Fan, G. Kokogiannakis, Z. Ma, and P. Cooper, "Development of a dynamic model for a hybrid photovoltaic thermal collector – solar air heater with fins," *Renew. Energy*, vol. 101, pp. 816–834, 2017, https://doi.org/10.1016/J.RENENE.2016.09.039

[28] M. Simo-Tagne and L. Bennamoun, "Numerical study of timber solar drying with application to different geographical and climatic conditions in Central Africa," *Sol. Energy*, vol. 170, pp. 454–469, 2018, https://doi.org/10.1016/J.SOLENER.2018.05.070

[29] M. Simo-Tagne, H. D. Tamkam Etala, A. Tagne Tagne, M. C. Ndukwu, and M. El Marouani, "Energy, environmental and economic analyses of an indirect cocoa bean solar dryer: a comparison between natural and forced convections," *Renew. Energy*, vol. 187, pp. 1154–1172, 2022, https://doi.org/10.1016/J.RENENE.2022.02.015

[30] J. Vásquez, A. Reyes, and N. Pailahueque, "Modeling, simulation and experimental validation of a solar dryer for agro-products with thermal energy storage system," *Renew. Energy,* vol. 139, pp. 1375–1390, 2019, https://doi.org/10.1016/J.RENENE.2019.02.085

[31] D. Jain, "Modeling the system performance of multi-tray crop drying using an inclined multi-pass solar air heater with in-built thermal storage," *J. Food Eng.,* vol. 71, no. 1, pp. 44–54, 2005, https://doi.org/10.1016/J.JFOODENG.2004.10.016

[32] S. Tiwari, G. N. Tiwari, and I. M. Al-Helal, "Performance analysis of photovoltaic–thermal (PVT) mixed mode greenhouse solar dryer," *Sol. Energy,* vol. 133, pp. 421–428, 2016, https://doi.org/10.1016/J.SOLENER.2016.04.033

[33] S. Ebadi, S. H. Tasnim, A. A. Aliabadi, and S. Mahmud, "Melting of nano-PCM inside a cylindrical thermal energy storage system: numerical study with experimental verification," *Energy Convers*. Manag., vol. 166, pp. 241–259, 2018, https://doi.org/10.1016/J.ENCONMAN.2018.04.016

[34] Chtioui and A. Khouya, "Improving solar drying efficiency of Pine wood with compound parabolic concentrator: comparative study in Continental and Mediterranean climates," Sol. Energy, vol. 283, p. 112981, 2024, https://doi.org/10.1016/J.SOLENER.2024.112981

[35] F. Román, Z. Munir, and O. Hensel, "Mathematical modelling of a latent heat storage: influence of PCM thermal conductivity and enthalpy-temperature relationship," J. Energy Storage, vol. 94, p. 112424, 2024, https://doi.org/10.1016/J.EST.2024.112424

[36] V. B. Gawande, A. S. Dhoble, D. B. Zodpe, and S. Chamoli, "Experimental and CFD investigation of convection heat transfer in solar air heater with reverse L-shaped ribs," *Sol. Energy*, vol. 131, pp. 275–295, 2016, https://doi.org/10.1016/J.SOLENER.2016.02.040

[37] S. Al Arni et al., "Novel multi-layer nano-modified PCM configuration for efficient thermal management of photovoltaic-thermal systems," *J. Energy Storage*, vol. 103, p. 114352, 2024, https://doi.org/10.1016/J.EST.2024.114352

[38] R. Karthikeyan, P. Saji Raveendran, P. Thangavel, R. Prabakaran, and S. C. Kim, "Techno-economic evaluation of a screw conveyor-based solar dryer for Ivy gourd dehydration," *Case Studies in Thermal Engineering,* vol. 75, p. 107056, 2025, https://doi.org/10.1016/j.csite.2025.107056

[39] P. Tsopbou Ngueagni and A. Mawire, "Experimental drying characteristics of a portable solar dryer for apple slices in consecutive and continuous tests," *Scientific African*, 2025, e03012, https://doi.org/10.1016/j.sciaf.2025.e03012

[40] F. L. Rashid, S. A. Kadhim, A. Bouabidi, M. K. Abdalrahem, M. A. Al-Obaidi, A. M. Ashour, and E. B. Agyekum, "Recent advances of solar dryer with energy storage: A comprehensive review," *J. Stored Prod. Res.,* vol. 115, 2026, https://doi.org/10.1016/j.jspr.2025.102820

[41] P. Salami, M. Safvati, M. S. Barghi Jahromi, V. Kalantar, and H. Samimi-Akhijahani, "Classification of fruit solar dryers and the role of phase change materials in enhancing performance: A review," *Solar Energy,* vol. 297, p. 113570, 2025, https://doi.org/10.1016/j.solener.2025.113570

[42] N. I. Román-Roldán, A. López-Ortiz, J. F. Ituna-Yudonago, P. K. Nair, J. Rodríguez-Ramírez, S. Sandoval-Torres, and A. Martynenko, "A current review: Engineering design of greenhouse solar dryers exploring novel approaches," *Sustainable Energy Technol. Assess.*, vol. 73, p. 104137, 2025, https://doi.org/10.1016/j.seta.2024.104137

[43] R. Prakash, A. Gnanasekaran, M. Rengasamy, and K. Rajaram, "A review on recent developments in natural convective solar dryer for agricultural products: Methods, collector design, influencing factors, performance and challenges," Renew. *Sustain. Energy Rev.,* vol. 215, p. 115613, 2025, https://doi.org/10.1016/j.rser.2025.115613

[44] J. T. Liu, M. Li, Q. F. Yu, and D. L. Ling, "A novel parabolic trough concentrating solar heating for cut tobacco drying system," *Int. J. Photoenergy*, vol. 2014, Article ID 209028, 2014, http://dx.doi.org/10.1155/2014/209028

[45] S. A. Sulaiman and F. F. F. Taha, "Drying of oil palm fronds using concentrated solar thermal power," *Appl. Mechan. Mater.,* vol. 699, pp. 449–454, 2014, http://dx.doi.org/10.4028/www.scientific.net/AMM.699.449

[46] T. S. M. Ky, B. Dianda, E. Ouedraogo, S. Ouedraogo, and D. J. Bathiebo, "Novel natural convection process: Indirect solar dryer built with spherical concentrators. Application to tomato drying," *Elixir Thermal Eng.,* vol. 122, pp. 51615–51620, 2018.

[47] B. Lamrani, A. Khouya, and A. Draoui, "Energy and environmental analysis of an indirect hybrid solar dryer of wood using TRNSYS software," *Solar Energy*, vol. 183, pp. 132–145, 2019, https://doi.org/10.1016/j.solener.2019.03.014

[48] J. Hosseinzadeh, A. Mohhebi, and R. Loni, "Optical simulation of a solar parabolic collector and cavity receivers using ray-tracing software TracePro with native conditions of Iran for solar dryers," *INMATEH - Agric. Eng.,* vol. 59, no. 3, pp. 197-206, 2019, https://doi.org/10.35633/inmateh-59-22

[49] S. Spall and V. P. Sethi, "Design, modeling and analysis of efficient multi-rack tray solar cabinet dryer coupled with north wall reflector," *Solar Energy*, vol. 211, pp. 908–919, 2020, https://doi.org/10.1016/j.solener.2020.10.012

[50] M. Seemwanga, E. Makule, and S. I. Kayondo, "Performance analysis of an improved solar dryer integrated with multiple metallic solar concentrators for drying fruits," *Solar Energy,* vol. 204, pp. 419–428, 2020, https://doi.org/10.1016/j.solener.2020.04.065

[51] H. Teklu, M. Bayray, D. Abay, and M. Kalamegan, "Performance enhancement of natural convection indirect solar dryer by integrating reflectors," *Momona Ethiopian J. Sci.,* vol. 12, no. 2, pp. 212–222, 2020, http://dx.doi.org/10.4314/mejs.v12i2.4

[52] I. Ajunwa, D. S. Yawas, D. M. Kulla, M. B. Abdullahi, I. U. Ibrahim, and M. Jnr Iorpenda, "Performance improvement of an indirect solar dryer with single axis manual

tracking system and angular simulation of the flat plate collector reflectors," *Arid Zone J. Eng. Technol. Environ.*, vol. 16, no. 2, pp. 293–308, 2020.

[53] M. J. Simón Castellano, R. A. López Quiroz, S. Taramona, A. Gallo, P. Contreras-Lallana, and J. Gómez Hernández, "Drying of asphalt plant aggregates using concentrated solar energy," SWC2021 Proceedings, *International Solar Energy Society*, 2021, http://dx.doi.org/10.18086/swc.2021.26.06

[54] T. Hosseini and L. Zhang, "Process modeling and techno-economic analysis of a solar thermal aided low-rank coal drying-pyrolysis process," *Fuel Process. Technol.*, vol. 220, p. 106896, 2021, https://doi.org/10.1016/j.fuproc.2021.106896

[55] S. Shoebi, H. Kargarsharifabad, S. A. A. Mirjalily, and M. Zargarazad, "Performance analysis of finned photovoltaic/thermal solar air dryer with using a compound parabolic concentrator," *Appl. Energy*, vol. 304, p. 117778, 2021, https://doi.org/10.1016/j.apenergy.2021.117778

[56] H. Ebadi, D. Zare, M. Ahmadi, and G. Chen, "Performance of a hybrid compound parabolic concentrator solar dryer for tomato slices drying," *Solar Energy*, vol. 215, pp. 44–63, 2021, https://doi.org/10.1016/j.solener.2020.12.026

[57] F. Ben Othman, F. Eddhibi, A. Bel Hadj Ali, A. Fadhel, Ö. Bayer, İ. Tari, A. Guizani, and M. Balghouthi, "Investigation of olive mill sludge treatment using a parabolic trough solar collector," *Solar Energy*, vol. 232, pp. 344–361, 2022, https://doi.org/10.1016/j.solener.2022.01.008

[58] A. Fadhel, F. Eddhibi, K. Charfi, and M. Balghouthi, "Investigation of a linear Fresnel solar collector (LFSC) prototype for phosphate drying," *Energy Nexus*, vol. 10, p. 100188, 2023, https://doi.org/10.1016/j.nexus.2023.100188

[59] R. Jain, A. S. Paul, D. Sharma, and N. L. Panwar, "Enhancement in thermal performance of solar dryer through conduction mode for drying of agricultural produces," *Energy Nexus,* vol. 9, p. 100182, 2023, https://doi.org/10.1016/j.nexus.2023.100182

[60] M. I. Hussain and G. H. Lee, "Concentrated solar powered agricultural products dryer: Energy, exergoeconomic and exergo-environmental analyses," *J. Cleaner Prod.,* vol. 393, p. 136162, 2023, https://doi.org/10.1016/j.jclepro.2023.136162

[61] V. R. Khawale, B. N. Kale, and V. G. Dhore, "Experimental study and comparison of integrated solar dryer with and without reversed absorber and reflector," *Int. J. Renewable Energy Technol.*, vol. 14, no. 1, pp. 1–15, 2023.

[62] I. Bori, J. Y. Jiya, A. M. Orah, S. Bako, and M. O. Oyebamiji, "Heat transfer analysis of a concentrated-type solar dryer for ginger," *GU J. Sci., Part A,* vol. 11, no. 4, pp. 690–700, 2024, https://doi.org/10.54287/gujsa.1538840

[63] S. E. Bousbia Salah, A. Benseddik, N. Meneceur, A. Zine, and K. Deghoum, "Design and realization of a new solar dryer assisted by a parabolic trough concentrator (PTC) with a dual-axis solar tracker," *Solar Energy*, vol. 283, p. 113001, 2024, https://doi.org/10.1016/j.solener.2024.113001

[64] S. Chtioui and A. Khouya, "Improving solar drying efficiency of Pine wood with compound parabolic concentrator: comparative study in Continental and Mediterranean climates," *Solar Energy,* vol. 283, p. 112981, 2024, https://doi.org/10.1016/j.solener.2024.112981

[65] S. Kumar, H. K. Ghritlahre, S. Agrawal, and S. Shekhar, "Investigation of a novel mixed-mode solar dryer using north wall reflector: An experimental study," *Solar Energy*, vol. 282, p. 112909, 2024, https://doi.org/10.1016/j.solener.2024.112909

[66] G. Muthuvairavan and S. K. Natarajan, "Experimental study on drying Kohlrabi under surface modified direct solar dryer integrated with flat plate reflector, compound parabolic concentrator, and thermal energy storage," *SSRN*, 2025, https://ssrn.com/abstract=5231087

[67] H. Chouchane, S. Hassani, S. Mekhilef, A. Lekbir, M. Mubin, and K. S. Tey, "A novel ribbed photovoltaic thermal solar dryer with phase change materials: Thermal regulation and drying performance," *J. Energy Storage,* vol. 122, p. 116380, 2025, https://doi.org/10.1016/j.est.2025.116380

[68] A. A. A. Abuelnuor, A. A. M. Omara, I. K. Salih, E. K. M. Ahmed, R. M. Babiker, and A. A. M. Mohammedali, "Experimental study on tomato drying using a solar dryer integrated with reflectors and phase change material," in Proceedings of the 2020 International Conference on Computer, Control, Electrical, and Electronics Engineering (ICCCEEE), 2020, pp. 1–5, IEEE.

[69] M. Rashidi, A. Arabhosseini, H. Samimi-Akhijahani, and A. M. Kermani, "Acceleration of the drying process of oleaster (Elaeagnus angustifolia L.) using reflectors and desiccant system in a solar drying system," *Renew. Energy,* vol. 171, pp. 526–541, 2021, https://doi.org/10.1016/j.renene.2021.02.094

[70] M. O. Karaağaç, A. Ergin, Ü. Ağbulut, A. E. Gürel, and İ. Ceylan, "Experimental analysis of CPV/T solar dryer with nano-enhanced PCM and prediction of drying parameters using ANN and SVM algorithms," *Solar Energy*, vol. 218, pp. 57–67, 2021, https://doi.org/10.1016/j.solener.2021.02.028

[71] A. E. Kabeel, P. D. L. Dharmadurai, S. Vasanthaseelan, R. Sathyamurthy, B. Ramani, A. M. Manokar, and A. Chamkha, "Experimental studies on natural convection open and closed solar drying using external reflector," *Environ. Sci. Pollut. Res.,* 2021, https://doi.org/10.21203/rs.3.rs-357329/v1

[72] S. Dubey, K. Bhayani, C. Bhatt, S. Maiti, and S. Mishra, "Design and development of domestic solar dryer with comparative analysis of nutritional aspect of dried raisins," J. *Food Eng. Technol.,* vol. 11, no. 1, pp. 13–21, 2022, https://doi.org/10.32732/jfet.2022.11.1.13

[73] P. L. Dharmadurai, S. Vasanthaseelan, R. Bharathwaaj, V. Dharmaraj, K. Gnanasekaran, D. Balaji, and R. Sathyamurthy, "A comparative study on solar dryer using external reflector for drying grapes," *Mater. Today: Proc.,* vol. 50, pp. 552–559, 2022, https://doi.org/10.1016/j.matpr.2020.11.197

[74] M. Zeeshan, I. Tufail, S. Khan, I. Khan, S. Ayuob, A. Mohamed, and S. T. Chauhdary, "Novel design and performance evaluation of an indirectly forced convection desiccant integrated solar dryer for drying tomatoes in Pakistan," *Heliyon*, vol. 10, e29284, 2024, https://doi.org/10.1016/j.heliyon.2024.e29284

[75] S. Yematawu, B. Tamrat, D. Tarekegn, and H. Mulugeta, "Experimental testing on the performance of solar dryer equipped with evacuated tube collector, rock bed heat storage and reflectors," *Energy Rep.,* vol. 12, pp. 453–471, 2024, https://doi.org/10.1016/j.egyr.2024.06.027

[76] D. Nakum, K. Sharma, N. L. Panwar, and G. Saichandhu, "Sustainability assessment of solar drying systems: A comparative life-cycle analysis of phase-change material-based vs. cylindrical solar dryers," *Clean Energy,* vol. 8, no. 4, pp. 183–196, 2024, https://doi.org/10.1093/ce/zkae049

[77] A. Y. Kebede, M. T. Tigabu, A. T. Admase, and A. J. Bezie, "Performance evaluation of diminutive solar dryer for drying of green coffee beans: In Ethiopian highlands," *Case Stud. Thermal Eng.,* vol. 65, p. 105653, 2025, https://doi.org/10.1016/j.csite.2024.105653

[78] A. Joseph, S. Ataya, M. Ismail, and S. W. Sharshir, "Innovative system for enhancing tomato drying performance using evacuated tube solar collectors, thermal storage materials, and reflectors," *Solar*

Energy, vol. 299, p. 113745, 2025, https://doi.org/10.1016/j.solener.2025.113745

[79] S. K. Sansaniwal and M. Kumar, "Analysis of ginger drying inside a natural convection indirect solar dryer: An experimental study," *J. Mech. Eng. Sci.,* vol. 9, pp. 1671–1685, 2015, http://dx.doi.org/10.15282/jmes.9.2015.13.0161

[80] H. K. Dhande, S. D. Shelare, and P. B. Khope, "Developing a mixed solar drier for improved postharvest handling of food grains," *Agric. Eng. Int.: CIGR J.,* vol. 22, no. 4, pp. 166–173, 2020.

[81] M. R. Nukulwar, "Thin-layer mathematical modeling of turmeric in indirect natural conventional solar dryer," *J. Sol. Energy Eng.,* vol. 142, no. 4, p. 041001, 2020, http://dx.doi.org/10.1115/1.4045828

[82] M. Chaanaoui, S. Abderafi, S. Vaudreuil, and T. Bounahmidi, "Prototype of phosphate sludge rotary dryer coupled to a parabolic trough collector solar loop: Integration and experimental analysis," *Solar Energy*, vol. 216, pp. 365–376, 2021, https://doi.org/10.1016/j.solener.2021.01.040