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REVIEW

Recent trends on energy-efficient solar dryers for food and agricultural products drying: a review

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Abstract

The energy efficiency enhancement of solar dryers has attracted the attention of researchers worldwide because of the need for energy storage in solar drying applications, which arises primarily from the irregular nature of solar energy that leads to improper drying which will reduce the quality of the products being dried. This work comprehensively reviews the state-of-the-art research carried out on solar dryers for energy efficiency enhancement using various alternative strategies, including hybrid solar dryers that use auxiliary heating sources, such as electric heaters or biomass heaters, solar-assisted heat pump dryer, use of desiccant materials, and heat storage systems that use both sensible and latent heat storage. The advent of phase change materials (PCM), such as thermally and chemically stable PCMs, for long-term storage, bio-degradable and bio-compatible PCM materials to alleviate the negative environmental impact of conventional PCMs is also presented. The performance parameters considered for evaluating dryers include the maximum temperature attained inside the drying chamber, drying time and efficiency, specific moisture extraction rate (SMER), energy and exergy efficiency and CO_2 mitigation effect. The factors considered to analyze the PCMs application in solar dryers include cost and sustainability of PCMs, and both energy and exergy analyses of dryers using PCMs. The gaps in current knowledge and future scope for further improvement of solar dryers are also elucidated.

Keywords Agricultural and food products · Desiccant materials · Hybrid dryers · Phase change material · Solar-assisted heat pump dryers · Thermal energy storage

Introduction

Throughout the past few decades, new technologies have been created in response to the requirement for using systems with improved energy efficiency. This is mainly due to the rising population and associated living comfort, which have led to the faster depletion of fossil fuel reserves. Agricultural sector and food production, like other sectors, such as transport, industries and buildings, are also heavily dependent on fossil fuels and hence are responsible for greenhouse gas emissions [1]. To meet the world's food demand, it has been estimated that the energy need will rise by 40%–50% by 2030 [2]. Given the projected increase in world population to around 9 billion by the year 2050, the demand for food will continue to rise, aggravating the issue of "food security" playing a crucial role in sustainability [3]. The United Nation’s 2030 Agenda for Sustainable Development states that the objectives of food security and sustainable agriculture can be met using clean energy-based agriculture and sustainable farming methods [4].

Drying is an old-style method of food preservation used to preserve a variety of agricultural and food goods. The process of drying decreases the moisture in agricultural produce and gives a better shelf life. By inhibiting development of germs, yeasts, and mold, it avoids the deterioration of harvested goods [5, 6]. Moreover, drying substantially reduces the objects' weight and volume, which lowers the cost of packaging and shipping [7]. Due to faulty product storage and preservation methods, harvested commodities have been lost. According to reports, ineffective preservation methods cause a significant quantity of grains (10%–30%) and fruits (50%–70%) to

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be wasted [8]. Traditional natural drying methods have some flaws, including their slowness and unstable product quality. The quality of herbs, in particular, can be significantly diminished by direct sun exposure. Moreover, most other drying techniques require excessive energy, which is a major cause of concern from the perspective of the global energy landscape. Solar dryers are more promising than natural drying methods because, despite having a higher initial investment, their operating costs are quite low. Moreover, solar energy is renewable and pollution free, which will aid in lowering the food processing's carbon footprint [9, 10]. The operating temperature typically required to dry fruits and vegetables ranges from of 40–60 °C [11]. The operating temperatures and humidity levels are used to control the moisture and the quality of the product (such as nutritional features). However, these methods differ slightly from product to product [12]. According to a case study conducted in Asia, solar drying has several advantages, including improvements in product quality, drying efficiency, and specific energy use. Also, the amount of dry goods produced per cycle ranged from 1 t to 2 t, with a production loss of less than 10%. A case study also demonstrated that the solar drying method reduced the drying time compared with the open-air sun drying requirement of 5–7 days [13]. Despite the benefits of solar dryers, including their accessibility and low cost (compared to other dryers), their thermal efficiency is lower. For this reason, there is a need to develop energy-efficient solar dryers.

The uniqueness of this review is that it highlights different options for enhancing the energy efficiency of solar dryers, such as hybrid solar dryers that use auxiliary heating sources, solar-assisted heat pump dryer (SAHPD), use of desiccant materials and heat storage systems that use both sensible and latent heat storage. It then proceeds to highlight the advances in the synthesis routes and thermo-physical properties enhancement techniques of phase change materials (PCMs), including novel bio-based PCMs. This work is divided into three parts, first part considers the classification and relative performance of solar dryers; the second part focuses on PCM classification, novel synthesis methods and thermo-physical properties enhancement; and the third part discusses the energy efficiency improvement of solar dryers with different options and an exhaustive review of the literature for each of the cases considered. Finally, conclusions about different options for improving the energy efficiency of solar dryers and the scope for future research are presented.

Classification of solar dryers

Active, passive, and hybrid solar-powered dryers with direct or indirect heat transfer techniques, as well as forced or natural air circulation, are shown in Fig. 1. It is acknowledged that the most crucial variable of the process is the air used for drying, which is hot and contains little moisture. Moreover, the drying rate rises as the drying air temperature and air velocity rise [14].

Natural convection dryers (NCDs)

NCDs allow ambient air to flow through bottom-mounted adjustable vents. The air is heated inside the solar collector before rising into the chamber to dry the food. It then leaves through the chimney. Therefore, it is also known as a passive solar system. It does not use any mechanical equipment to regulate how much air enters the dryer and does not use any additional energy while it is in use [15, 16]. Figure 2 depicts the flow diagrams of natural convection solar dryers of both direct passive and direct active types.

Forced convection dryers (FCDs)

The greater air temperature is maintained in a FCD using a blower or fan to boost the pace at which moisture is removed. In this type of solar dryer, by adjusting the airflow at the vents, it could be possible to control both the temperature and humidity inside the chamber. Using this technique, food items with a high moisture content, including mushrooms and grapes, can be dried. Many variables, including ambient temperature, humidity, radiation intensity, internal temperature, airflow, and food density, affect how well this type of dryer performs [17]. Figure 3 shows a schematic of the forced convection solar dryer.

Mixed-mode type dryers

Utilizing both direct and indirect drying methods, this design sets itself apart as a mixed mode sun drier [20]. The combined effect of solar radiation on the material that needs to be dried and the heated air in the accompanying solar collector/absorber, as shown in Fig. 4, provides the heat required for the drying process of this type.

Hybrid solar dryers

While sun is utilized in this type for drying items, the air movement is produced by numerous techniques. These dryers, for instance, can use fans that are driven by methane combustion and solar photo voltaic (PV). The hybrid solar dryer's schematic, shown in Fig. 5, includes a solar collector, a thermal energy storage unit, a heat exchanger and a drying cabinet.

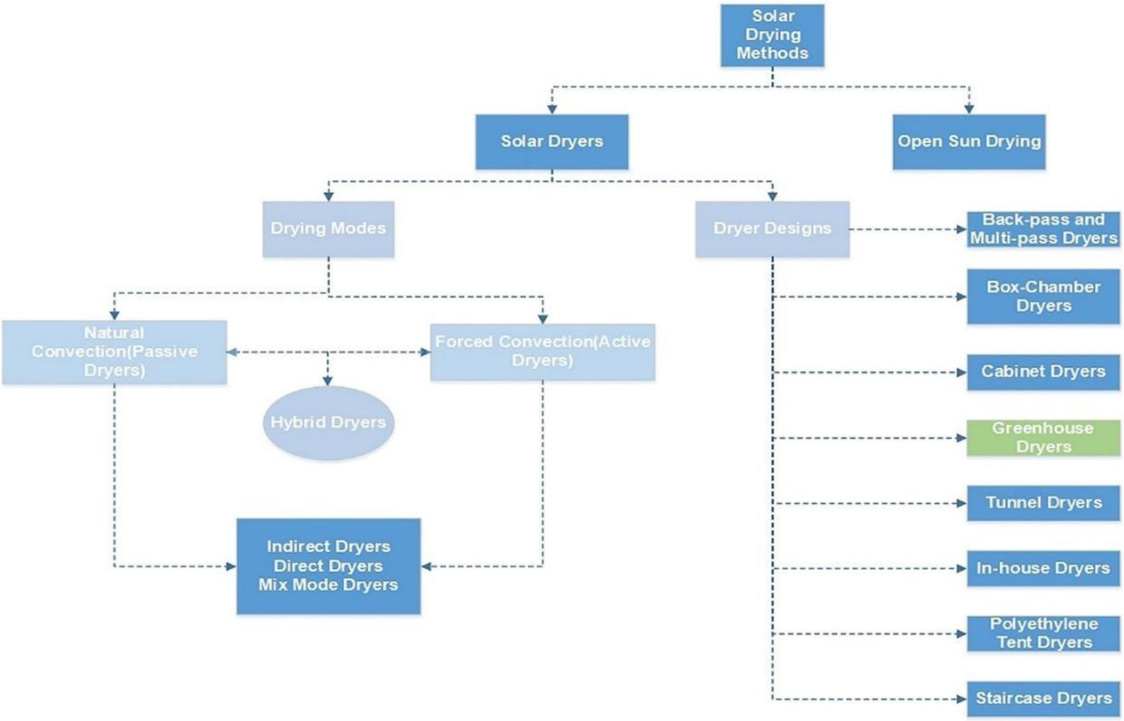

Fig. 1 Classification of solar dryers

Comparison of different solar dryers

Solar dryers with natural convection have certain benefits in terms of the low cost of the ventilation system. Despite this, the drying pace is highly dependent on the weather, and it performs poorly during periods of low sunlight because of its weak buoyancy force. In terms of average collector efficiency—defined as the ratio between the useful heat gained by the solar collector and the energy incident on the plane of the collector—dryer's thermal efficiency—defined as the ratio between the energy utilized for evaporation of moisture and the energy provided as input to the drying system—specific moisture extraction rate (SMER)—defined as the amount of water evaporated to the total energy supplied and effective moisture diffusion for a specific application—forced convection solar drying performs better than natural convection, according to research findings [22]. Moreover, in comparison to solar dryers that use natural circulation, forced convection (active) dryers are much more efficient and adjustable and the heat collection efficiency of FCDs is higher making them more effective and controllable [23].

Table 1 shows the comparison of the NCD, FCD, and heat pump integrated dryer (HPD) based on average drying parameters. Therefore, that the average efficiency of HPD is nearly 30% and 14% greater than that of NCD and FCD, respectively.

PCMs for thermal energy storage

Energy storage can help increase energy efficiency and reduce energy consumption. A family of useful materials called PCMs gain from having a good density of stored energy over a constrained temperature range. When the temperature drops, this energy can be released into the environment as needed by transforming its phase from liquid to solid. This approach is mostly used in several applications, such as solar energy storage, air-conditioning applications, and building energy savings.

PCM classification

There are three different categories of commercially available PCMs. They are organic, inorganic, and eutectic PCMs. Paraffin wax is the most prominent organic PCM, and is a by-product from oil refineries, fatty acids and their esters. Salt hydrates fall under the group of inorganic PCMs, while eutectic salts and solutions belong to the eutectic PCMs [25]. Another classification of PCMs is based on the phase transition state. They are solid–solid, solid–liquid, and solid–gas [26]. Compared to the other two types, solid–liquid PCMs possess high latent heat, are most cost-effective and hence are widely used [27]. On the other hand, solid–solid PCMs eliminate the need for recipients to cover

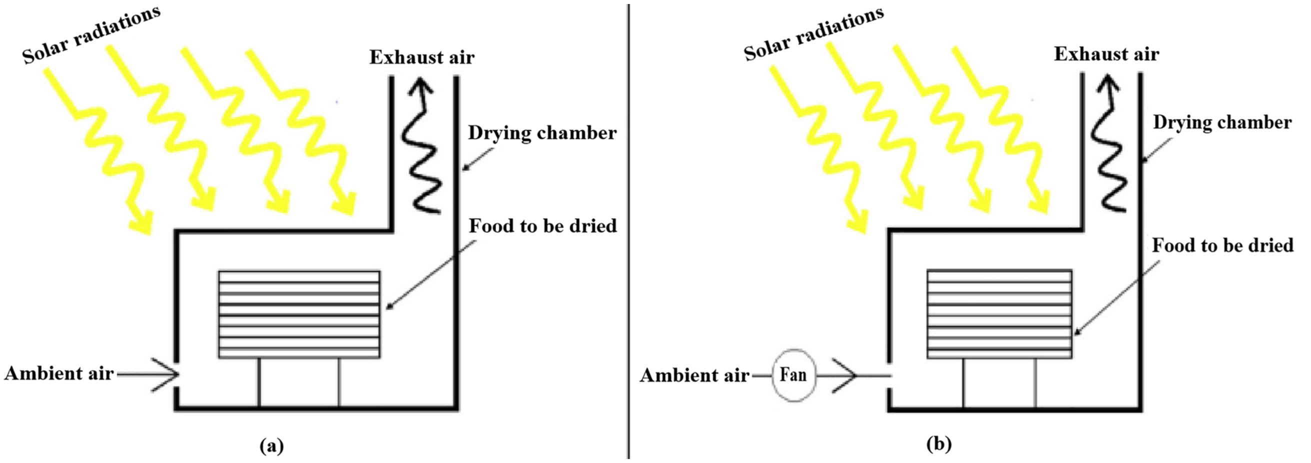

Fig. 2 Natural convection solar dryer **a** direct passive and **b** direct active

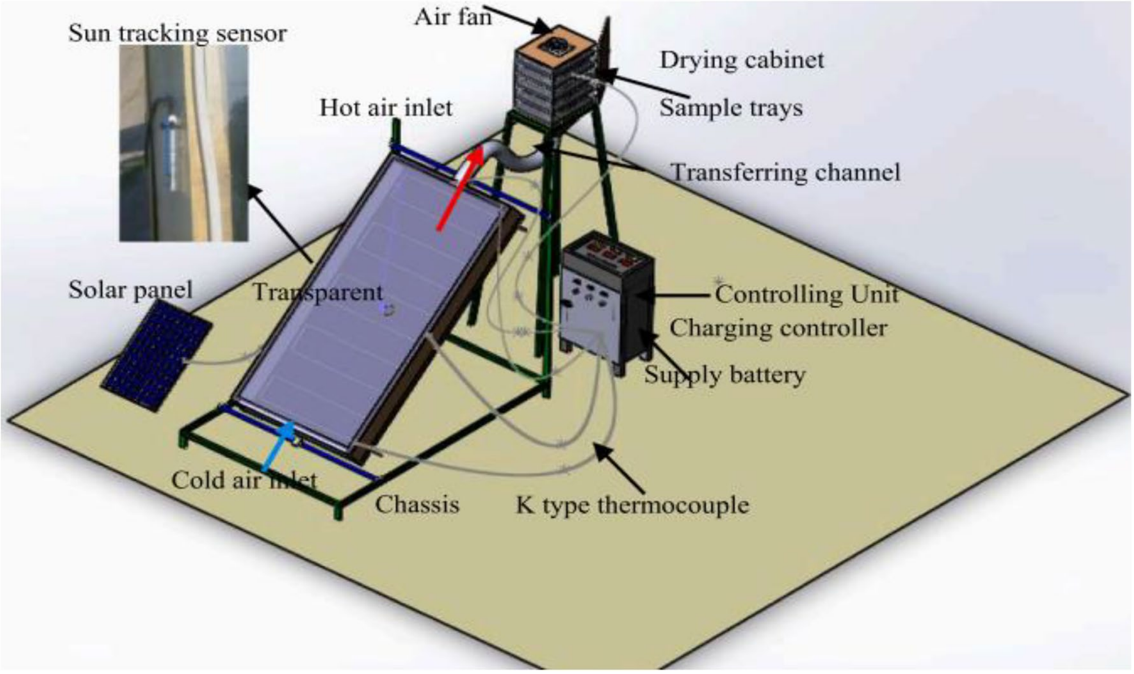

Fig. 3 Schematic diagram of forced convection solar dryer [18]

the PCM at the time of phase change, as no liquid or gas is generated. However, limitations such as lower latent heat and supercooling limit their use for thermal energy storage applications [28]. It has been reported that conventional PCMs are not eco-friendly and can impact the environment negatively. In view of this, researchers have developed PCMs from renewable and sustainable sources. These include fruit oils from tropical trees, such as shea butter, allanblackia, and oils of palm kernel [29].

Paraffin wax PCMs were employed in a variety of temperatures. They have a relatively high heat of fusion. It can also freeze without becoming extremely chilled. The most economical, practical, and extensively utilized PCM is hence technical grade paraffin wax. In contrast to paraffin wax, fatty acids exhibit greater heat of fusion due to their chemical composition, $CH_3(CH_2)_{2n}COOH$. With minimal to no supercooling, fatty acids can mimic melting and freezing. One factor preventing the use of fatty acids is their price,

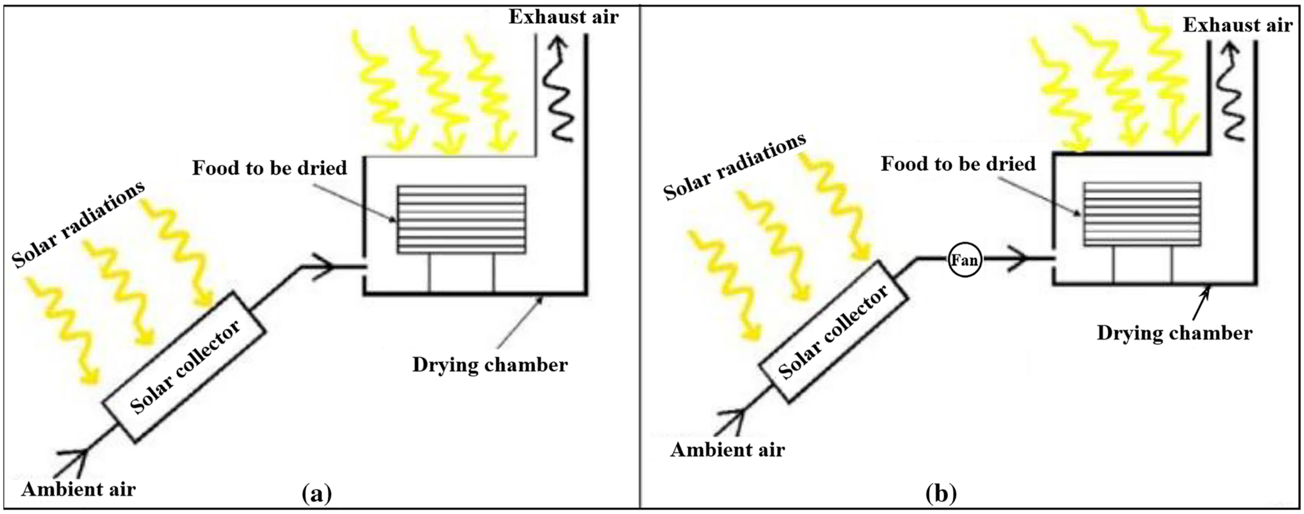

Fig. 4 Schematic diagram of mixed-mode solar dryer **a** natural convection and **b** forced convection

Table 1 Solar dryers' comparison with respect to average drying parameters (reprinted from [24] with permission)

Parameter	NCD	FCD	HPD
Average drying air speed (m/s)	1.01	1.16	1.07
Average mass flow rate (kg/s)	0.30	0.30	0.30
Average volumetric flow rate (m^3/s)	0.24	0.28	0.24
Average efficiency (%)	59.74	67.66	77.45

FCD, Forced convection dryer; HPD, heat pump integrated dryer; NCD, natural convection dryers

which can be 2–2.5 times greater than the price of paraffin wax [30]. Salt hydrates can be considered alloys of inorganic salts (AB) and water (H_2O) and the typical formula for salt hydrates is $AB{\cdot}nH_2O$, where n is the amount of water molecules. This inorganic compound is important for storage of heat because of its high volumetric latent heat storage density [31]. Metals are not strong candidates for use as PCMs due to their weight. PCM systems, however, need a lengthy lifespan to compensate for their high installation costs. The effect of supercooling decreases the PCM efficiency. It results in inadequate heat recovery, and if the PCM system needs to be repaired, heat recovery cannot be achieved without causing harm to the system [32].

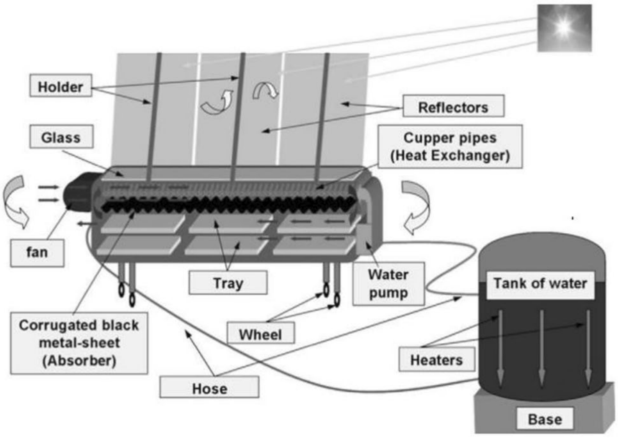

Fig. 5 Schematic diagram of hybrid solar dryer [21]

New routes for synthesis of PCMs

Despite the advantages of PCMs for various applications of thermal energy storage, including solar drying, the preparation of thermally and chemically stable PCMs without compromising the desired properties remains as a challenge. In order to create PCMs with long-term storage capacities, researchers have recently developed some innovative synthesis approaches. These include PCM slurries, composite PCMs of dual phase transition temperatures, shape-stabilized PCMs with microencapsulation, nano-confinement of organic PCMs, PCMs based on metal organic frameworks (MOFs), and novel approaches like handling PCMs using photo-switching dopants [33].

Shape-stabilized PCMs are prepared by a microencapsulation technique in which PCM particles are dispersed in a traditional fluid so that the PCM is encapsulated in a tiny hermetically sealed container, which prevents leakage of the liquid PCM. It can impart more thermal cycling dispersion, a comparatively fixed volume, and an enhanced area of heat transfer for thermal energy storage [34]. Different shell materials used for microencapsulation of different PCMs [35]. These materials include organic, inorganic, and organic–inorganic hybrid. Some kinds of resins, such as acrylic resin, silica, and zinc oxide, are inorganic shell materials, while polymethyl methacrylate (PMMA)-SiO_2 and PMMA-TiO_2 are the organic–inorganic hybrid materials.

However, the traditional process of microencapsulation by thermal processes involves high temperatures, which could damage heat-sensitive PCMs. Moreover, in case of large-scale production, the reaction time required is high. To overcome the above issues, a novel technique, ultraviolet (UV) irradiation-initiated suspension polymerization, can potentially reduce the polymerization time and energy consumption [36]. Materials that are utilized in reversible solid–liquid transitions include azobenzene, spiropyran, and diarylethene because they are photo-switchable [37]. Doping PCMs with these photo-switchable materials has a number of advantages, including the ability to prevent crystallization when PCMs are cooled below their initial phase change temperature and the ability to store thermal energy for extended periods of time well below their crystallization temperature without sacrificing their storage capacity. Additionally, by merging solar energy spectral splitting technology, such PCMs can be used as unique solar thermal fuels. They can be used as high-efficacy solar energy collection and carbon-free heat delivery sources [38]. Despite these benefits, limitations include the use of UV radiation in photo-switching, which can reduce the life time of organic PCMs and cause damage to biological components. Since this technology is newly applied to PCMs, further research is essentially needed to address the issues, such as tuning thermodynamic properties, enhancing quantum yields, reducing the photo-thermal effect to increase energy conversion efficiency, and developing simple synthesis techniques which are cost-effective to make photo-switch/PCMs usable in a wide range of applications.

Natural polymer materials, owing to the features, such as non-toxicity, easy degradation and low cost, can also be considered as organic shell materials [39]. MOFs are formed when organic ligands act as linkers and metal ions act as nodes, forming chemical bonds that result in periodic network crystalline structures with high porosities and expansive surface areas, promoting their potential use in a variety of scientific and technological fields incorporating heterogeneous catalysis, gas storage, medication delivery, and chemical separations [40]. The meticulously crafted structural arrangements of MOFs provide them an edge over conventional materials. By altering the organic linkers and metal species, they can be engineered to have extremely variable porosities and surface areas at the molecular level [41].

The synthesis of MOF-derived porous carbons using direct carbonization at high temperatures results in high surface area, large pore volume, and retained initial morphology. Due to these features, MOF-derived porous carbons play a vital role in variety of fields, such as electro-catalysis, supercapacitators, Li-ion batteries, Li-O_2 batteries, and Li-S batteries [42]. However, it is difficult to carry out large-scale synthesis using this method due to the low yield of MOFs as carbon precursors. Molten salt synthesis is a new route, which stands out as a distinct method for creating size- and shape-tunable nanomaterials, and it can help with future research into the characterization and investigation of potential applications of these materials [43]. Also, it is an efficient and cost-effective method for achieving high yields of carbon-based materials [44, 45]. It is a widely used method for the synthesis of metal MOF-based PCMs. These MOFs can be produced in the lab utilizing a variety of techniques, such as hydrothermal bombs, and the heating of materials at extremely high temperatures. Moreover, by changing the organic and metal ion ratios, the shape of MOFs can be changed to make them functional in extensive fields of applications [46].

Hu et al. [47] created novel shape-stabilized metal–organic framework-based PCMs (MOFPCMs). Iron (Fe) and ellagic acid were used as the metal ion and organic ligand, respectively. They have impregnated sodium acetate trihydrate into MOF aerogel. The produced MOFPCM demonstrated outstanding light-to-thermal performance, which is up to 94.5%. It also exhibited an effective rate of heat transmission, and an excellent heat storage density of 245.6 J/g. This work provides a pathway for MOFs application in solar thermal utilization. However, further research is needed to address these issues, such as stability and scaling up of MOFs. The doping of nitrogen (N), oxygen (O), and phosphorous (P) can improve MOF performance, which can be a useful strategy.

Thermo-physical properties enhancement of PCMs

The thermo-physical properties, which include thermal conductivity, latent heat, heat capacity, phase segregation, and level of supercooling, are crucial in determining the behavior of a particular PCM. For example, if thermal conductivity is low, it takes more time to store and release thermal energy. Similarly, when the specific and latent heats are low, the storage volume requirement will be very high. Material breakdown could eventually happen from phase segregation although thermal energy release could be delayed by supercooling. The majority of PCMs have their own drawbacks, with regard to the aforementioned properties, despite the fact that they have many advantages. Hence, enhancing PCMs' thermo-physical characteristics is essentially required for effective thermal energy storage [48].

Thermal conductivity enhancement

PCMs exhibit poor thermal behavior, which causes an undesirable effect, i.e., a slow heat transfer rate, and limits their use in numerous applications. Numerous researchers have made contributions to improving the heat transfer characteristics of PCMs. The incorporation of highly thermally conductive materials, such as carbon fibers, graphite, metal foams, metal-based nanoparticles (aluminum powder), and carbon nanotubes, can be the viable options which will improve the thermal conductivity of PCMs [49]. The use of fins or extended surfaces and microencapsulation are the other techniques for heat transfer enhancement [50]. Li and Zhai [51] studied the effect of adding 3% (in weight) of expanded graphite (EG) to erythritol PCM in a solar collector storage application. They reported that the storage efficiency could be increased by nearly 40% by the addition of EG to PCM. Lin et al. [52] showed that adding carbon-based additives is a better approach for enhancing the thermal conductivity of PCMs than metal-based additives. Choi et al. [53] added graphite to the stearic acid PCM. They reported that adding 5% by volume of graphite could enhance the heat transfer rate by 3.5 times. Li et al. [54] experimentally explored the effect of adding 10% by volume of nanographite (NG) to the PCM and showed that there was an increase of 7.5 times in thermal conductivity with NG addition compared to that with pure PCM.

Energy efficiency improvement of solar dryers-different options

There have been continual efforts from researchers globally to enhance the performance of solar dryers. These methods include use of hybrid solar dryers, SAHPD, use of desiccant materials and heat storage systems using sensible and latent heat storage. The solar dryer's drying efficiency is determined by dividing the energy gained that may be put to use by the energy required to remove moisture from the product. It is affected by the air's relative humidity, the moisture content of the items that need to be dried, as well as their quantity and thickness. The drying effectiveness is indicated by

$$\eta_{de} = \frac{wL}{Q_u} \tag{1}$$

where Q_u represents the spent total usable energy, and L represents the latent heat of vaporization and w the expelled moisture mass(kg).

SMER is another key factor that governs the energy efficiency of the drying system. This value represents the energy needed to remove one kg of moisture from the product given as

$$\mathrm{SMER} = \frac{w}{Q_u} \tag{2}$$

Hybrid solar dryers

To dry agricultural produce, a hybrid solar dryer typically uses a backup energy or stored heat whenever the amount of solar radiation is insufficient. It uses an auxiliary energy source such as that generated by liquefied petroleum gas (LPG), biomass and diesel combustion, solar PV module, biomass heater and electricity. It can operate both on single and combined modes (direct and indirect types) of drying. In 1985, Bassey [55] became the first person to build a hybrid solar dryer. This dryer had a heat exchanger installed, and the steam produced by the sawdust burner circulated through it. The drying cabinet temperature can vary between 40 °C and 70 °C depending on the source of heat used. However, the main drawback of this design was the heat loss from the burner. Amer et al. [21] recycled around 65% of the drying air in a solar dryer meant for drying ripe banana slices. They installed an electric heater in a water tank that stores heat energy to carry out drying operations at night. This system is capable of drying banana from 82% to 18% moisture level in 8 h. A solar PV powered solar tunnel dryer of mixed type was created by Eltawil et al. [56] to dry potato chips. To keep the drying chamber at the desired high temperature, the equipment was fitted with a flat-plate solar air collector and for effective heat transfer, an axial direct current fan was used. The maximum drying efficiency achieved was 34.29% when air flow rate was 0.786 kg/s. They showed that a lower air flow rate (0.0572 kg/s) resulted in a higher air temperature in the dryer and the collector outlet, while the opposite was true with higher mass flow rates.

A hybrid dryer was created by Lopez-Vidana et al. [57] and included a drying chamber, auxiliary LPG combustion heater, and solar collector. Three different heating systems were employed: a hybrid solar gas heating system (HHS), an LPG gas heating system (GHS) and a solar heating system (SHS). The reported drying efficiencies for GHS, HHS, and SHS were 86%, 71%, and 24%, respectively. The dynamic contributions of the LPG hob and solar collector in three different modes of operation are presented in Table 2. Even though the SHS mode provided the system with more energy than did the LPG or hybrid modes, only 16% of that energy was actually utilized. The rate of LPG use in hybrid mode was 19.74 kW/h, whereas that in LPG mode was 24.59 kW/h. Hence, the hybrid mode is more appealing from an economic standpoint.

Many researchers have assessed the energy, exergy, and economic impacts of hybrid solar dryers, as well as their ability to reduce CO_2 emissions. To provide hot water to the dryer heat exchanger, Singh and Gaur [58] created a hybrid greenhouse dryer with the incorporation of an evacuated tube solar collector. The tomato slices can be dried in this dryer for 10 h, from 94.6% initial moisture content to 10% (wet basis, w.b). When only 16.62 t of CO_2 are emitted at this time, the dryer will reduce 169.10 t of CO_2 over its lifetime. Also, the dryer's payback period, which is 1.73 a for a 30-year lifespan, is quite short. However, the developed hybrid dryer has a high capital cost of 1180 USD, which makes it unsuitable for use on a local scale or in rural locations.

Ayyappan [59] investigated a greenhouse hybrid solar dryer with a back-up heater for the purpose of coconut drying. The developed dryer could dry the coconuts from moisture of 53%–7% in 54 h and 153 h, respectively in the summer and winter periods. The thermal efficiency was 24% in the summer and 21% in the winter. The embodied energy of the dryer was 18,302 kWh and its annual CO_2 emissions were 1518 kg. The total amount of carbon credits gained is 18645 USD, with 678 t of net CO_2 mitigation. The dryer's payback period was assessed to be 3.3 a. The large-scale dryer developed by Atalay and Cankurtaran [60] for drying strawberry could alleviate 99.6 t of CO_2 emissions during the lifetime. Shrivastava and Kumar [61] used indirect sun dryer to dry fenugreek leaves, and it was found that while it only releases 85.46 kg of CO_2 per year, it may offset 391.52 kg of CO_2 per year. A study by Boonyasri et al. [62] showed that the drying time decreased by about 18.8% during the testing of pork drying. This system lowered moisture level of pork to 70% (dry basis, d.b) from 210% (d.b) in 260 min as opposed to 320 min in open sun-drying. The greenhouse dryer's daily and the maximum drying efficiencies were 55.7% and 42.8%, respectively. The dryer’s payback time (PBT) is 1.15 a. According to economic study of hybrid dryer integrated with biomass by Hamdani et al. [63], the dryer's break-even point was reached in 2.6 a, with an net present value of 21.091 USD. Dhanushkodi et al. [64] investigated the viability of replacing traditional steam drying of cashews with biomass, solar, and hybrid dryers. They used four economic indicators for assessing the feasibility of three types of renewable energy-based technologies. The PBTs for solar power, biomass, and hybrid drying were 1.56, 1.32, and 1.99 , respectively, whereas the cost–benefit ratios for solar power, biomass energy, and the hybrid system were 5.23, 4.15, and 3.32, respectively. Another important conclusion of this study is that developing a solar biomass hybrid dryer is crucial for small-scale processing enterprises. Prakash et al. [65] compared both passive and active modes of solar-powered hybrid dryers and found that passive mode offered advantages when compared to active mode counterpart in terms of PBT, CO_2 emissions and embodied energy, which were 1.11 a and 1.89 a, 13.45 kg/a and 17.6 kg/a and 480.28 kWh and 628.73 kWh, respectively. Table 3 compares different solar dryers for their PBT (determined by dividing preliminary investment by annual cash flow).

The fundamental issue with the hybrid dryers is that they are slightly more expensive since they use additional equipment, but the additional money spent on them can be offset by faster drying and shorter drying times for batches. As a result, more crops can be dried each year, increasing the dryer's annual savings. In addition to the cost, environmental effect is another important factor that determines a produced product's acceptability from a sustainable perspective. Renewable energy use can be a workable solution to make the hybrid dryer an environmentally friendly device.

SAHPDs

The most popular method for improving dryer efficiency is the SAHPD. There are three types of SAHPDs: closed loop, opened loop, and semi-opened loop. Each of these systems has benefits and drawbacks. Both long start-up times and environmental pollution are associated with open loops. Closed loops are capable of recovering waste heat from exhaust gases, but they are limited by heat and moisture imbalances, necessitating the use of an auxiliary heat exchanger. On the other hand, a semi-opened loop can solve the heat imbalance issue. An issue with this is the environmental degradation that exhaust emissions produce. In SAHPD, the dryer is supplemented with an air-to-air heat pump unit that serves as a dehumidifier to remove moisture from the air. The moisture in air is continuously condensed with the use of an evaporator serving as a cooling element and a fan to draw outside air through it. The condenser,

Table 2 Energetic contributions of the solar collector and LPG burner to the drying process in the hybrid dryer. (Source: Lopez-Vidana et al. [57]. Reprinted with permission).

Mode of Operation	Solar collector (kWh)	Proportion of solar energy consumed (%)	LPG combustion (kWh)	Proportion of LPG combustion energy (%)	Total amount of consumed energy (kWh)	Avg. drying time (h)	Avg. drying efficiency (%)
LPG	–	–	24.59	45.72	11.24	15	45
Solar	48.51	16.22	–	–	7.86	28	25
Hybrid	14.55	16.33	19.74	49.7	12.18	18	33

LPG, liquefied petroleum gas; η, Average drying efficiency; kWh, Kilowatt-hour which acts as a heating element, is used to reheat the cool dry air, and hot dry air is then delivered into the collector to serve as the drying medium. The drying efficiency of SAHPD is 2–3 times greater than that of conventional dryers [68]. Figure 6 shows the heat pump assisted solar dryer.

Heat is transferred from a low temperature medium to a high temperature medium in SAHPD in order to conserve energy and improve the output quality. It typically uses refrigerants, such as R-134a, R410, R717 or R744. The refrigerant evaporates into gas in the evaporator and absorbs huge amounts of heat energy from air. The gaseous refrigerant is then compressed to higher pressures and temperatures. This high pressure gas is routed to the condenser where it releases heat energy to the air (drying medium) and the cycle repeats [70]. Several researchers have studied SAHPD using different designs and approaches for enhancement of solar drying systems.

Singh et al. [71–74] extensively studied the SAHPDs. Singh et al. [71] compared different dryers SAHPD, infra-red heat pump dryer, solar infra-red heat pump dryer (SIHPD), and simple HPD system. The authors reported that SIHPD exhibited a maximum average moisture extraction rate of 1.1618 kg/h. Overall, SAHPD performed better with η_{energy} and η_{energy} as 58.5% and 24%, respectively. The average drying rates and SMER of both the HPD and the SAHPD were compared by Singh et al. [72]. The average drying rates are 0.205 kg/(kg·min) and 0.342 kg/(kg·min), respectively, and that SMER are 0.886 kg/kWh and 1.417 kg/kWh, respectively. It is observed that SAHPDs have better energy and exergy efficiencies, higher SMER when compared to conventional HPDs. However, their exergy destruction cost is higher than that of the HPD. Singh et al. [73] developed an SAHPD using R1234yf as refrigerant for drying of radish chips and investigated the effect of different intermittency ratios. They concluded that the intermittent drying is better than continuous drying. The improvements in SMER and energy efficiency were 60.6% and 56.4%, respectively, while drying cost was reduced by 37.9%. For various intermittency ratios of 1, 0.66, 0.33, and 0.2, the estimated PBTs are 1.617, 1.459, 1.384, and 1.347 a, respectively. Intermittency (α) is defined as “the ratio of the drying period to the total time spent on drying and heating” [74]. It is given as

$$\alpha = \frac{t_D}{t_T} \tag{3}$$

In the above equation, t_D is extent of drying time and t_T is extent of tempering time of each cycle. Singh et al.

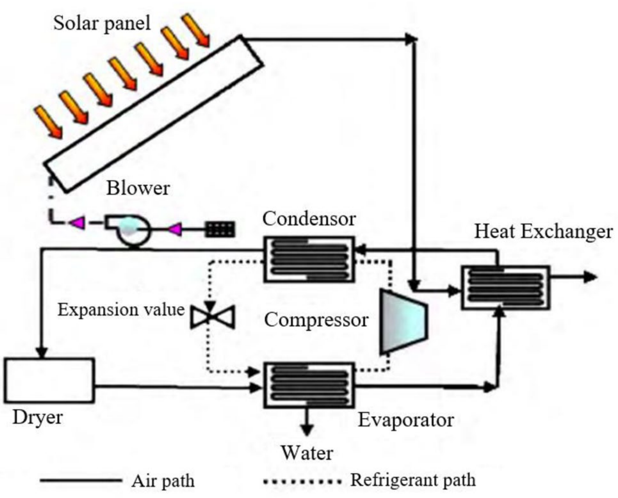

Fig. 6 Solar-assisted heat pump dryer (SAHPD). (Reprinted from Fudholi et al. [69] with permission)

Table 3 Comparison of different solar dryers based on PBT

Type of dryer	Dried item	PBT (a)	Ref.
Forced-mode greenhouse hybrid solar dryer	Pork	1.15	Boonyasri et al. [62]
Hybrid greenhouse dryer with an evacuated tube solar collector	Tomato slices	1.73	Singh and Gaur [58]
Biomass integrated hybrid dryer	Fish	2.60	Hamdani and Muhammad [63]
Renewable energy-based hybrid dryer	Cashew nuts	1.99	Dhanushkodi et al. [64]
Solar-powered hybrid dryer passive-mode	Potato chips	1.11	Prakash et al. [65]
Solar-powered hybrid dryer active-mode		1.89	
Natural convection solar greenhouse dryer with biomass back-up heater	Coconuts	3.30	Ayyappan et al. [59]
Semi-cylindrical greenhouse dryer with solar PV	Chilli	2.00	Prakash et al. [65]
Large-scale greenhouse dryer with solar PV		2.00	Kaewkiew et al. [66]
Natural convection solar greenhouse dryer	Groundnut	1.66	Kumar et al. [67]
Forced convection solar greenhouse dryer		1.72	
SAHPD integrated with biomass furnace	Rice	1.60	Yahya [79]
Natural convection solar dryer	Herbs	1.57	Jain and Tewari [99]

PBT, payback time; SAHPD, solar-assisted heat pump dryer

[75] differentiated the solar-assisted heat pump drier from the traditional heat pump dryer and looked at its energy, exergy, economic, and exergo-economic analyses. The calculated total costs of exergy destruction in the cases of both SAHPD and conventional HPD were 0.1185 USD/h and 0.1386 USD/h, respectively. Hu et al. [76] developed a closed loop heat pump dryer with double evaporator for drying kelp knots. The dehumidifying capacity of this system is 3500 g/h with a condensation temperature is 60 °C . This system is capable of lowering both initial start-up time and initial investment by 20.8% and 6.5%, respectively. Hu et al. [77] investigated the thermal effectiveness of Chinese wolfberry at 40–70 °C in an HPD equipped with solar collector of indirect type. They observed that SHPD consumed less energy than HPD. However, the need for additional dehumidifier of SAHPD is a drawback since it involves excess relative humidity. High relative humidity during kelp drying has negative effects on closed loop methods, resulting in longer drying times and more energy use. Moreover, the instrument's lifespan is also decreased. To address these issues, Kang et al. [78] proposed a novel greenhouse double-evaporator SAHPD to reduce both the drying time and energy consumption and improve the drying efficiency and quality of dried kelp. For the purpose of drying red chilies, Yahya [79] investigated the effectiveness of an SAHPD coupled with a biomass boiler. The average coefficient of performance of a heat pump, solar collector, and a biomass boiler were calculated to be roughly 35.1%, 3.84%, and 30.7%, respectively. From his findings, the red chillies required 11 h to dry from 22 kg with a moisture content of 4.26 dry basis (db) to 0.08 db, when compared to open sun drying which required 62 h. This dryer produced an 82% reduction in drying time when compared to open sun drying. For drying mint leaves, a unique photo-voltaic/thermal (PV/T)-assisted heat pump drying (PVTAHPD) technique was created by Kosan et al. [80].

According to their reports, the effective diffusion coefficient had an average value of 4.69×10^{-11} m^2/s. By comparing the percentages of energy generated by the PV system and PV/T panels used by the compressor, condenser, and fan, it is clear that solar-derived electrical energy from the first trial was stored in the accumulator at a rate of 26%, whereas it was 44% in the second trial. The main issue with these systems is that the exhaust air from the drying cabinet includes a lot of heat energy after the conclusion of drying. However, if this waste heat could be collected to warm the fresh air, the system performance can be further improved. Moreover, the frost deposition and the accumulation on the surface of the coil would be prevented by heating the evaporator and raising the heat pump's surface temperature by the recovered heat.

Desiccant solar dryers

Due to their high water activity, food components with a high moisture content are extremely susceptible to spoiling. The water activity in typical foods is necessary for the growth of microorganisms like bacteria and yeast, and these microbes are currently the main source of food loss [81]. Water activity is defined as the ratio of vapor pressure of water in a product to pure water at the same temperature. The water content of a material that is available for chemical reactions or for attaching to other materials is known as its water activity. Materials with high water activity typically promote more microorganisms. For bacteria, the required water activity is at least 0.91, whereas it is as low as 0.6 for fungi [82]. Sorption materials are primarily employed in sun dryers for dehumidification and heat storage. Before the drying air enters the drying chamber, sorption materials are used as dehumidifiers to reduce the relative humidity of the air [83]. The sorption materials used in solar dryers are exposed to a wide range of circumstances. Since the products are based on agriculture and food, non-toxicity is the primary need for a sorption material. Good handling characteristics and materials with regeneration temperatures consistent with the maximum temperatures that the integrated solar collector(s) in the solar dryer can achieve are additional crucial requirements [84]. In reality, the drying air is blocked by a bed of sorption material, usually at the solar collector's entrance. Air is circulated through the dehumidification bed and into solar collector. Depending on the type of material used, the sorption material may remove or adsorb water molecules and hence lower the relative humidity. The drying air will be heated as a result of the exothermic adsorption/absorption process, increasing its overall drying capacity.

Dake et al. [85] examined the effect of sorption materials for dehumidification and as well as storage materials in solar dryers. They claimed that sorption materials used as thermal energy storage might reduce the drying time by 30%–45% and that solar dryers linked with sorption dehumidifiers could shorten the drying time by 15%–30%. The most popular solid sorption material is silica gel, while other promising materials include composites made of bentonite, vermiculite, and cement. The other solid desiccant materials are molecular sieves, zeolites, and activated alumina. Tri-ethylene glycol, LiCl, $CaCl_2$, and LiBr are examples of liquid desiccants that can be employed as dehumidifiers [86]. Compared with solid desiccant-based systems (90–95 °C), liquid desiccant-based systems are better in terms of regeneration temperature, which is in the range of 60–90 °C. This high regeneration temperature in solid-desiccant systems necessitates sensible cooling of the process air before dehumidification is undertaken in order to increase the cycle efficiency. The pre-cooling, however, is constrained by the process air stream's dew point temperature. Moreover, lowering the temperature of the inlet air lengthens the cycle time [87]. Another important advantage of liquid desiccant-based systems is that the pressure drop is less than that of solid desiccant-based ones.

In some designs, the sorption bed is located before the drying chamber whereas in other designs, it is placed at the outlet of solar collector. For the purpose of drying paper trays, Rane et al. [88] proposed a novel liquid desiccant-based dryer with a two-stage regenerator. The primary benefit of this design is that the latent heat of condensation from the steam generated in the first stage of the two-stage regeneration process is transferred to the liquid desiccant in the second stage. Consequently, with the same heat input in the first stage, the total amount of water evaporated is doubled compared to that in the single-stage regeneration process. Compared to a traditional hot-air-based dryer, they demonstrated that the dryer's average SMER is 1.5 kg/kWh and that the savings in energy with the resultant reduction in CO_2 emissions are nearly 56%. Chramsa-ard et al. [89] studied a solar dryer with a silica desiccant bed with a mass flow rate of 0.08 kg/s and a drying temperature of 60 °C and reported that the moisture content of chilli was reduced from 82% to 13% (w.b). Drying time reduced by 20.83% with dehumidification system compared to that without it.

Thermal energy storage for energy efficiency improvement of solar dryers

Because there is increased heat loss from the collectors when dryers are used in conjunction with solar collectors, this combination has ultra-low thermal efficiency. A significant amount of solar energy is lost from the receiving tube or storage tank and reflected to the focal line as a result of the working fluid's incorrect characteristics [90]. Several researchers combined solar dryers with thermal energy storage that uses both sensible heat and latent heat storages in order to address the aforementioned problems. Thermal energy storage is a technique for physically storing heat for later use. These innovations could reduce waste and improve energy effectiveness. They offer the advantages of greenhouse gas reduction and lowering the energy costs. In terms of energy storage methods, thermal energy storage is generally environmentally favorable. The three techniques for thermal energy storage include latent heat, sensible heat and thermochemical heat storage [91].

Solar dryers using sensible heat storage

Sensible heat storage using pebble stones in a forced convection solar dryer of direct and indirect type was studied by Chaouch et al. [92]. Compared to a drying chamber without a storage medium, the drying chamber's thermal efficiency can be raised by 11.8% with the use of PCM. By putting a porous pebble bed sensible heat storage chamber below the corrugated absorber plate in the passage of air, Vijayan et al. [93] investigated an indirect forced convection solar dryer with PCM for drying bitter gourd slices. They claimed that compared to open drying, the suggested approach could reduce the moisture content of bitter gourds from 92% to 9% (w.b) in 7 h as opposed to 10 h. Additionally, at a mass flow rate of 0.0636 kg/s, the highest specific moisture extraction rate was discovered to be 0.215 kg/kWh. The specific energy use was 4.44 kg/kWh, and the dryer and collector had efficiencies of 22% and 19%, respectively. Another study by Vijayan et al. [94] discovered that the exergy efficiency varied from 28.74% to 40.67% for air mass flow rates between 0.0141 kg/s and 0.0872 kg/s. The solar dryer's energy PBT is only 2.21 a. The energy PBT is defined as the amount of time needed to recover the energy used to produce the raw materials needed to install the system or use it in its production. The CO_2 mitigation and the earned carbon credit values are 33.52 t and 10894 USD to 43576 USD, respectively, for the expected 35-year lifespan of the planned system. Atalay [95] examined the solar dryer with packed bed of pebble stones to assess energy and exergy efficiencies. It was reported that the moisture content of orange slices decreased from 93.50% to 10.28% (w.b). The energy efficiency of the system ranged from 50.18% to 66.58% while the exergy efficiency ranged from 54.71% to 68.37%. Although sensible heat storage has several advantages, it faces major challenges, such as low energy density and heat loss.

PCMs for thermal energy storage in solar drying

This problem may be a potential remedy for the use of a suitable working fluid with PCM [96]. At higher levels of solar radiation intensity, it is even more visible. The primary advantage of PCMs in solar dryers is that they can lessen the mismatch between the collector and dryer, which enhances the reliability and performance of energy systems [97]. The use of PCMs for thermal energy storage in solar dryers has been extensively studied in the literature. In this study's analysis of research articles on PCM use in solar dryers, it was shown that paraffin wax is the most frequently used PCM, with additional PCMs being lauric acid, zinc nitrate hexahydrate, magnesium nitrate hexahydrate ($Mg(NO_3)_2.6H_2O$), and glycerol. Paraffin wax-based composite PCMs using kerosene and Al_2O_3 nanoparticles are also considered as PCMs in some solar drying applications. Some researchers have focused on the SMER, energy, exergy and environmental aspects of the system, while others have considered the maximum temperature attained inside the dryer, moisture content removed and drying time. Based on literature, it is well known that some researchers place PCM bed below the drying chamber, while in other designs, it is placed inside the collector, while in large-scale greenhouse dryers, it is located centrally between the rows of drying trays inside the dryer. Some researchers used two air collectors (one filled with PCM). Also a shell and tube latent heat storage system is located between the air heater and the drying chamber according to some researchers. For good insulation purposes, isoboard materials play a vital role in the preparation of outer materials for both solar dryers and thermal storage media.

For drying mushrooms, Reyes et al. [98] created a hybrid solar drier that is powered by solar energy and incorporates paraffin wax as a PCM. It was demonstrated that the system can recycle between 70% and 80% of the air to reach an air outlet temperature of 60 °C, while the solar panel temperature was raised by 30 °C above the temperature of the surrounding air. Additionally, they demonstrated that the system's thermal efficiency ranged from 22% to 62%. With six trays (with an effective area of $0.5 \times 0.75\ m^2$) and a collector area of $1.5\ m^2$, the natural convection sun dryer with paraffin wax as PCM created by Jain and Tewari [99] can accommodate 12 kg of herbs. This dryer was capable of extending the drying time by 506 h after sunshine hours, with 6 °C higher temperature being maintained inside the dryer after sunshine. Both the thermal efficiency and the PBT of the dryer are 28.2% and 1.57 a, respectively. They h also performed an economic analysis of the dryer, which showed that a net present value of approximately 4725 USD with an annual profit of approximately 780 USD was obtained with this system. Bahari et al. [100] explored the drying of agricultural items in a flat-plate collector-based solar dryer incorporating nanocomposites of Al_2O_3 in combination with paraffin wax as PCM. An increase in proportion of Al_2O_3 in nanocomposite decreased the amount of time needed to dry the agricultural products. A comparison of different dryers developed by researchers is presented in the following sections considering the output parameters, such as higher temperature attained inside dryer, removed moisture level, energy, and exergy analyses.

Maximum temperature attained inside the dryer

The temperature inside the dryer is an important factor, that plays a crucial role by affecting the drying time and drying rate and thus the overall drying process. Table 4 compares the maximum temperature attained inside the dryers of different designs and PCMs. Rakshamuthu et al. [101] studied a small size greenhouse solar dryer in natural convection mode with zinc nitrate hexahydrate for drying gooseberry with the maximum temperature of 51 °C. Purusothaman et al. [102] explored the forced convection parabolic roof greenhouse solar dryer with paraffin wax as PCM for hibiscus leaf drying. The dryer's inside reached a maximum temperature of 48 °C. The maximum temperature reached by Srivastava et al. [103] in their study of a flat-plate collector-based solar dryer in forced convection mode with lauric acid as the PCM for drying potato and carrot was 50 °C, and the maximum temperature reached by Azizia et al. [104] in their study of a mixed-mode greenhouse solar dryer with paraffin wax as the PCM for drying red pepper was 55 °C. A hybrid solar dryer with paraffin wax as the PCM was utilized in a study by Mandal et al. [105] to dry mint and coriander, which achieved a maximum temperature of 52 °C. Missana et al. [106] reported that the maximum temperature reached with the effect of nitrate salt as PCM in a natural circulation sun dryer for drying red pepper was 62.4 °C.

Moisture content removed

Missana et al. [106] also compared the moisture content removed from gooseberry in three different processes, namely, open drying, solar drying without PCM and solar drying with PCM. They showed that within a span of 7 h, the maximum moisture content removed was 25%, 34% and 54%, respectively, in the three different cases mentioned above. Thus, it is known that open drying requires almost double the time to remove the same moisture content as solar drying with PCM. Table 5 compares the moisture content removed by the dryers of different designs and PCMs. It can be seen that the maximum amount of moisture removed can be as high as 75%.

Energy and exergy analyses

The energy utilization ratio (EUR) compares the energy input to the drying section with the energy needed to turn water existing in the product into steam [107]. Energy efficiency is defined as the ratio of the energy sent to the drying cabin during the discharge phase to the energy held in the energy storage system during the charging phase, which is expressed as

$$\eta_{PCM} = \frac{Q_{transferred}}{Q_{stored}} \tag{4}$$

The exergy efficiency during the charging period is defined as the ratio of input exergy to stored exergy while exergy efficiency during the discharge period is defined as the ratio of the amount of stored exergy to the exergy production [108]. Finding the overall exergy efficiency involves:

$$\psi_{\text{overall}} = \psi_{\text{charging}} \psi_{\text{discharging}} \tag{5}$$

The solar drying system's full potential can be assessed with the use of exergy analysis, that relies primarily on the drying time and drying air temperature. It was reported that when the temperature differential between the solar tunnel dryer's input and output reduced, the dryer's exergetic efficiency increased [109]. Chowdhury et al. [110] showed that the dryer's exergy efficiency varies randomly with drying time, with a mean value of 41.42%. They studied jackfruit leather drying in a solar tunnel dryer. While open sun drying lowered to a moisture level of 13.8% (w.b.) from initial value of 76% (w.b) in two days, solar dryer with PCM reduced it to 11.88%. Energy efficiencies of both collector and dryer were in the range of 27.45%–42.5% and 32.34%–65.30%, respectively, when the solar intensity of radiation varied in the range of 100–600 W/m^2. The exergetic efficiency increases with increase in radiation as given in the equation below.

$$\begin{aligned} \eta_{\text{collector}} &= 0.0559\ \text{SR} + 28 \\ 861\ \text{R}^2 &= 0:59 \end{aligned} \tag{6}$$

where ‘SR’ represents sun radiation in W/m^2, and R^2 represents determination coefficient.

However, dryer’s exergetic efficiency was unaffected by the sun's radiation, however, some researchers have shown that this efficiency increases with increasing solar radiation. To dry local agricultural products, Karthikeyan et al. [111] created a simple, affordable solar tunnel dryer. The solar tunnel dryer's total EUR ranged from 9.75% to 33.98% and was higher around 13:00 h, with an average EUR of roughly 19.46%. The average energy efficiency of the dryer is 49.12%, which indicates that the system could use 50.88% of the available energy.

Ebrahimi et al. [112] used a sun tracking mechanism by adjusting the placement of the PCM in the solar collector in four different cases: (a) aligning PCM tube with equal distances, (b) with dissimilar distances, (c), with equal through 2/3 of the plate, and (d) with equal spacing through either half of the plate and without PCM. They found that the highest thermal and overall efficiencies of 40.20% and 25.72%, respectively, were obtained with position (d) of the collector. Specific energy use with PCM for drying of tomato slices reduced by 7.29% to 18.90% when compared to that without PCM. A large-scale greenhouse dryer integrated with PCM (paraffin wax) created by Pankaew et al. [113] is capable of lowering the moisture content of chilli from 74.7% to 10.0% (w.b) in 2.5 d, as opposed to that dryer without PCM and open sun drying, which took 3.5 d and 11 d, respectively. However, the system's energy efficiency is 13.1%, which is somewhat greater than that of a dryer without a PCM (11.4%). The drying cabin's output air is 2–11.2 °C warmer at dusk than the surrounding air [114]. Also, the maximum drying efficiency that could be achieved was determined, and it was discovered that a mass flow rate of 0.008 kg/s produced a maximum of 30.84%. The thermal efficiencies of the dryer with PCM were 30.15%, 30.84% and 30.78% at mass flow rates of 0.006, 0.008 and 0.01, respectively, when compared to 28.76%, 28.30% and 28.76% when PCM was not used. Rabha et al. [115] investigated a forced convection solar tunnel dryer integrated with heat storage using a shell and tube heat exchanger. This system also comprises a parallel flow tunnel dryer and a blower. With this system, sliced ginger and ghost pepper were dried for 42 h and 33 h, respectively, under drying air temperatures of 42–61 °C and 37–57 °C. The thermal efficiencies of the first and second solar air heaters were estimated to be 22.10%–40.24% and

Table 4 Comparison of maximum temperature attained inside of different dryers

Type of dryer	Temperature (°C)	Reference
Greenhouse solar dryer in natural convection mode	51	[101]
Parabolic roof greenhouse solar dryer with forced convection	48	[102]
Flat-plate collector-based solar dryer in forced convection mode	50	[103]
Mixed-mode greenhouse solar dryer	55	[104]
Hybrid solar dryer	52	[105]
Sun dryer in natural circulation mode	62.4	[106]

PCM, phase change material

Table 5 Comparison of moisture content removed by different dryers

Type of dryer	Temperature (°C)	Reference
Greenhouse solar dryer in natural convection mode	53.5	[101]
Parabolic roof greenhouse solar dryer with forced convection	72	[102]
Flat-plate collector-based solar dryer in forced convection mode	75	[103]
Mixed-mode greenhouse solar dryer	75	[104]
Sun dryer in natural circulation mode	76	[106]

PCM, phase change material

9.64%–19.57%, respectively. The drying chamber's energy efficiency ranged from 21% to 98%, with a mean value of 63%. Similar results were reported for the drying of ginger, where the average energy efficiency varied from 4% to 96%. Lakshmi et al. [116] studied the effect of PCM in a forced convection mixed mode dryer for drying sliced black turmeric. This system is capable of drying the items from 73.4% moisture level to 8.5% moisture level in 18.5 h when compared to that 46.5 h in open sun drying. The overall thermal efficiency is 25.6% while efficiency of dryer is 12%. Abubakar et al. [117] tested the use of PCM in mixed-mode forced convection under climatic conditions in Nigeria. They reported that the average drying rates, and collector and dryer efficiencies with and without PCM were 2.7×10^{-5} kg/s and 2.35×10^{-5} kg/s, 67.25% and 40.10%, and 28.75% and 24.20%, respectively. The test results showed that using thermal storage boosted the dryer's effectiveness when drying the storage materials by about 13%. In Table 6, several sensible and latent heat energy storage media are compared for their energy and exergetic efficacy in solar drying applications. Exergetic research on solar dryers show that when the temperature of the air entering the dryer rises, exergetic efficiency decreases. This can be due to the energy loss that is taking place. Most of the researchers reported that exergy input, exergy outflow and exergy loss follow similar trends. Other researchers have reported that fans consume the most energy with the highest exergy loss and minimum exergy efficiency, while others have shown that drying chambers result in highest exergy loss.

Conclusion and recommendations for future research

Conclusion

This work comprehensively reviews the state-of-the-art research carried out on solar dryers with their classification, novel synthesis routes for preparing PCMs, and energy efficiency enhancement using various alternative strategies including hybrid solar dryers resorting to auxiliary heating sources, SAHPD, use of desiccant materials, and heat storage systems using sensible heat and latent heat storage. The conclusions are as follows:

1. Hybrid solar dryers equipped with biomass heaters could be a better option than other auxiliary sources, such as solar PV and electricity.
2. The drying efficiency of SAHPDs is nearly 2–3 times higher than that of connectional dryers. However, there is more scope for further enhancement of thermal energy savings. For cost reduction in solar driven heat pump dryers, intermittent drying can be advantageous.
3. The liquid desiccant-based systems are better in terms of their regeneration temperature (single-stage) which is in the range of 60–90 °C when compared to that of 90–95 °C of solid desiccant-based ones.
4. Solar dryer that is integrated with PCM can shorten the time required for drying. The moisture removed by solar drying with PCM is more than 100% and 55% greater than that removed by open sun drying and sun drying without PCM respectively. With the use of PCM, the dryer temperature can be maintained in excess of 50 °C with its relative humidity lower than the ambient relative humidity for more efficient drying.
5. The collector's exergetic efficiency rises with solar radiation, whereas solar radiation has no effect on dryer's exergetic efficiency. However, there is only a slight increase in the drying process' energetic efficiency when using PCM as opposed to that without PCM. PCM use can extend the drying period past 5–7 h of sunlight.
6. SAHPDs have better energy and exergy efficiencies and greater SMERs than conventional HPDs.

Recommendations for future research

The CO_2 mitigation potential and the life cycle assessment of solar drying systems can be considered:

1. The novel energy storage options using next-generation storage materials can be researched using 2-D transition metal carbides, carbonitrides, and nitrides known as MXenes, which exhibit remarkable electrical, mechanical, and optical properties.
2. Future research should also focus on MOF-based PCMs because they exhibit higher light-to-thermal conversion efficiency (nearly 95%) for energy storage in solar drying applications.
3. To avoid the problems of desiccant materials, such as low thermal conductivity, high regeneration temperature, and limited sorption capacity at low relative humidity, novel desiccant materials with considerable adsorption capacities, and quick kinetics must be introduced and synthesized.
4. Focus should also be on nanoparticle enhanced PCMs, PCMs integrated with copper foam fins for enhanced storage capacity, V-shaped fins and corrugated rod inserts for effective heat transfer enhancement.
5. Dried items quality assessment considering the factors, such as drying temperature, moisture content, drying time and cover materials, used for greenhouse dryers should also be considered.

Table 6 Comparison of solar dryers' energy and exergetic efficiencies with different energy storage media

Type of dryer	PCM material	Energy efficiency (%)	Exergetic efficiency (%)	Refs
Sensible storage-based indirect solar dryer	Pebble stones	–	28.74 to 40.67	Vijayan et al. [94]
Flat plate collector-based dryer	Paraffin wax	40.20	–	Ebrahimi et al. [112]
Large-scale solar dryer with PCM	Paraffin wax	76.00	69.59	Atalay and Cankurtaran [60]
Indirect forced convection solar dryer with PCM	Paraffin wax	30.84	–	Salve et al. [114]
Mixed mode forced convection solar tunnel dryer	Pebble stone	–	49.12	Karthikeyan et al. [111]
Solar dryer integrated with the pebble bed storage	Pebble stone	–	54.71 to 68.37	Atalay [95]
Indirect through pass natural convective solar crop dryer with PCM	Paraffin wax	28.20		Jain and Tewari [99]
Forced convection solar tunnel integrated with a shell and tube-based latent heat storage module	–	SAH1: 22.10 and 40.20 SAH2: 8.50 and 19.50	Ghost chilli: 63.00 Sliced ginger: 47.00	Rabha et al. [115]
Mixed mode forced convection solar dryer integrated with PCM	Paraffin wax	25.60	–	Lakshmi et al. [116]
Mixed-mode solar crop dryer with PCM	Rock	67.25	–	Abubakar et al. [117]

PCM, phase change material

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Declarations

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