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A Review Of Solar Dryer With Phase Change Material As Sensible Heat Storage Mediums

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ABSTRACT

The quality of agricultural products will have deteriorated as the preserved technology is inadequate and the storage process is not guaranteed. Utilizing the sun's energy for drying is an ancient technique, however, inefficiency due to the natural intermittency of solar energy is its challenge. Besides sensible heat storage materials (SHSM), the use of latent heat storage materials (LTSM) well-known as phase change materials (PCM) is mentioned as the most efficient approach to address such problem of solar thermal devices. In comparison with SHSM, phase change materials have advantages of higher storage density, supplying almost constant temperature even after sunset which is important to sufficient drying system for the majority of agricultural products, and simultaneously have small difference heat transfer between charging and discharging heat process. This work reviews the prior studies associated with solar dryers integrated with the latent heat storage system. The different temperature between drying air and surrounding air was obtained at 19°C by application of PCM. Compared to OSD, The drying time was saved by 180% with the support of PCM. It is revealed that the heat losses of the solar dryer can be reduced by the employment of PCM, simultaneously, the efficiency of the system also is improved.

KEYWORDS

solar dryer; energy storage; phase change materials; heat storage materials

INTRODUCTION

One of the historical and potential applications that utilize solar energy is to dry agricultural products. The categories of solar dryer systems consist of open solar drying (OSD), direct type solar dryers (DSD), indirect type solar dryers, mixed-mode type solar dryers, and hybrid solar dryers [1][2]. In another way, solar dryers are also divided into natural convection groups and forced convection groups [3]. In OSD, the products normally are arranged on the ground, trays or canvas, and exposed to nature [4]. OSD is the cheapest method, independent of other energies, however, the products can be lost and spoiled by animals and micro-organisms, their quality also is degraded by rain, humidity, dew, direct solar exposure, dust, and dirt. Moreover, it is difficult to control influencing parameters in the OSD method such as fluid temperature, humidity, and air velocity [5][6]. To enhance the quality of the drying process by managing parameters, controlled solar dryers (direct and indirect solar dryers) have been studied, which frequently are taken place in enclosure systems. As shown in figure 1a, a direct solar dryer (DSD) system normally has a glass on the top to transmit solar energy to dry products kept on a tray, and the air was supplied into the dryer naturally [7]. Meanwhile, the indirect solar dryer (ISD) is constructed from two main components are the drying cabinet along the solar air heater (SAH) which are connected together [8].

The former consists of trays to keep materials while the latter normally is a solar flat plate air heater. A simple SAH comprises a flat plate absorber and a glass or plastic cover, its incline angle usually is designed to similar to the latitude of the drying place [9]. Design configurations, improvement methods, and applications of solar air collectors were reviewed by Kabeel et al. [10] and Eswaramoorthy [11] conducted an experiment to compare some type of solar air heater for drying. The temperature of the absorber increases due to absorbing solar irradiation and transfers convection heat to the air [12][13]. The high-temperature air dries the food and removes the moisture content of products. Additionally, the mixed-mode was presented to utilize the advantages of DSD and ISD [14]. The products are absorbed heat energy by direct solar irradiation as well as the hot air after flowing through the SAH [15][16]. Different from mix-mode type solar dryers, hybrid solar dryers generally operate with the support of electric heaters. Hence, minimizing the power consumption is the study aims to improve this system's economic efficiency [16].

It is apparent that there is an increasing development of utilizing alternative energies such as wind, wave especially the sun in an effort of reaching net-zero emissions through manage energy rationally and effectively [17]. The promising of solar energy is undeniable. Moreover, solar energy is applied for a variety of purposes such as electrical generation (solar photovoltaic cell) [18][19], maritime transportation [20][21], the distillation of water [22][23], air and water heating [24], and ventilation [25], biodiesel production [26], water disinfection [27]. However, the intermittent characteristic is its disadvantage for commercial scale [26]. This issue can be addressed with the support of energy storage materials that possibly store excess heat as solar irradiation reached a peak (normally at midday) in order to utilize after sunset or in inadequate energy time. Additionally, the performance and reliability of solar applications can be enhanced by heat storage mediums. Thermal energy storage can be categorized into thermal and thermos-chemical types. Thermal storage materials can be classified as sensible heat storage and latent heat storage materials (or PCM)[28]. Sensible heat storage materials (SHSM) can be either liquid or solid [29]. Water is well known as the best SHS liquid due to its low cost and high specific heat. However for temperature is more than 100^{o}C, molten salts, mineral oils, and liquid metals are used.

The use of water as a storage material was studied by Nabnean [30]. Indeed, in their experiment, water was heated up by a solar water heater and then transfer heat to drying air through a heat exchanger tank. 100 kg of dehydrated cherry tomatoes were dried in 4 days to reduce the moisture content from 62% to 15%. Meanwhile, thermic oil was employed in the work of Potdukhe et al. [31] to dry chilies and fenugreek leaves. They concluded that although the cost of such dryer raised by 10% due to thermic oil, drying time reduced by 40%. Shanmugam and Natarajan [32] proposed a desiccant medium comprised of bentonite (60%), vermiculite (20%), calcium chloride 10%, and cement for drying green peas and pineapple slices. The desiccant usage reduced drying time by 2 hours and by 4 hours for green peas and pineapple slices respectively as compared to a forced convection solar dryer. Whereas, the popular solid phase for heat storage is sand, concrete, rock bed, limestone, gravel, fire bricks, or a mix of them. solar greenhouse drier applied three sensible heat storage materials: concrete, sand, and rock bed were investigated by Ayyappan et al. [33]. Their conclusion showed that rock bed has the best performance compared to sand and concrete. In addition, an investigation of gravel, limestone, and iron scrapes was conducted by El-Sebaii et al. [34] in a double pass solar air collector. Their findings revealed the best performance belonging to gravel with 22–27% of efficiency higher than dryer without storage materials. The common advantage of using sensible heat storage is to extend daily drying time especially at off sun-shine hours and good performance for high moisture content products; however, there is the reductant of efficiency in the storage system due to the air temperature is not constant in the discharging process.

Because of the imbalance between supply and demand in thermal solar devices, employing the energy storage system to achieve the most effective when harnessing alternative energy sources is critical. As a result, the reductant of time between energy supply and demand can be done by the latent heat storage materials (LHSM) usage approach which plays an important key in conserving energy as well as enhancing the reliability of solar devices. The principle of LHSM or phase change materials (PCM) is to use the converting in materials' state to provide a high energy storage density and absorb more heat under a constant temperature [35]. For instance, considering a specific mass of water and ice, the energy for melting ice is 80 times higher than energy spends on the increasing temperature of water by 1 ^{o}C. Therefore, an important factor to determine whether PCM is suitable is its thermophysical properties at the change phase temperature. Recently, phase change materials have emerged as a potential and suitable support material for not only solar applications but thermal devices also such as photovoltaic thermal systems [36], passive cooling in the building [37], solar still [38], solar water heater [39], heat exchanger [40][29], solar cooker [41], automotive applications [42]. Specific heat, the heat of fusion; density, thermal conductivity are essential when designing the

PCM in a solar dryer system. Nevertheless, several factors such as a novel technique, small space availability, high initial investment, and intermittency of the sun's energy are limitations of the PCM usage. In spite of certain literature on the solar dryer, no specific studies have contributed to references of solar dryers with latent heat storage methods. This study fulfills the above gaps and extensively reviews the researches on the solar dryer to draw considerable contributions. Reviews solar dryers with LHSM based on various designs, influence parameters, and heat storage techniques.

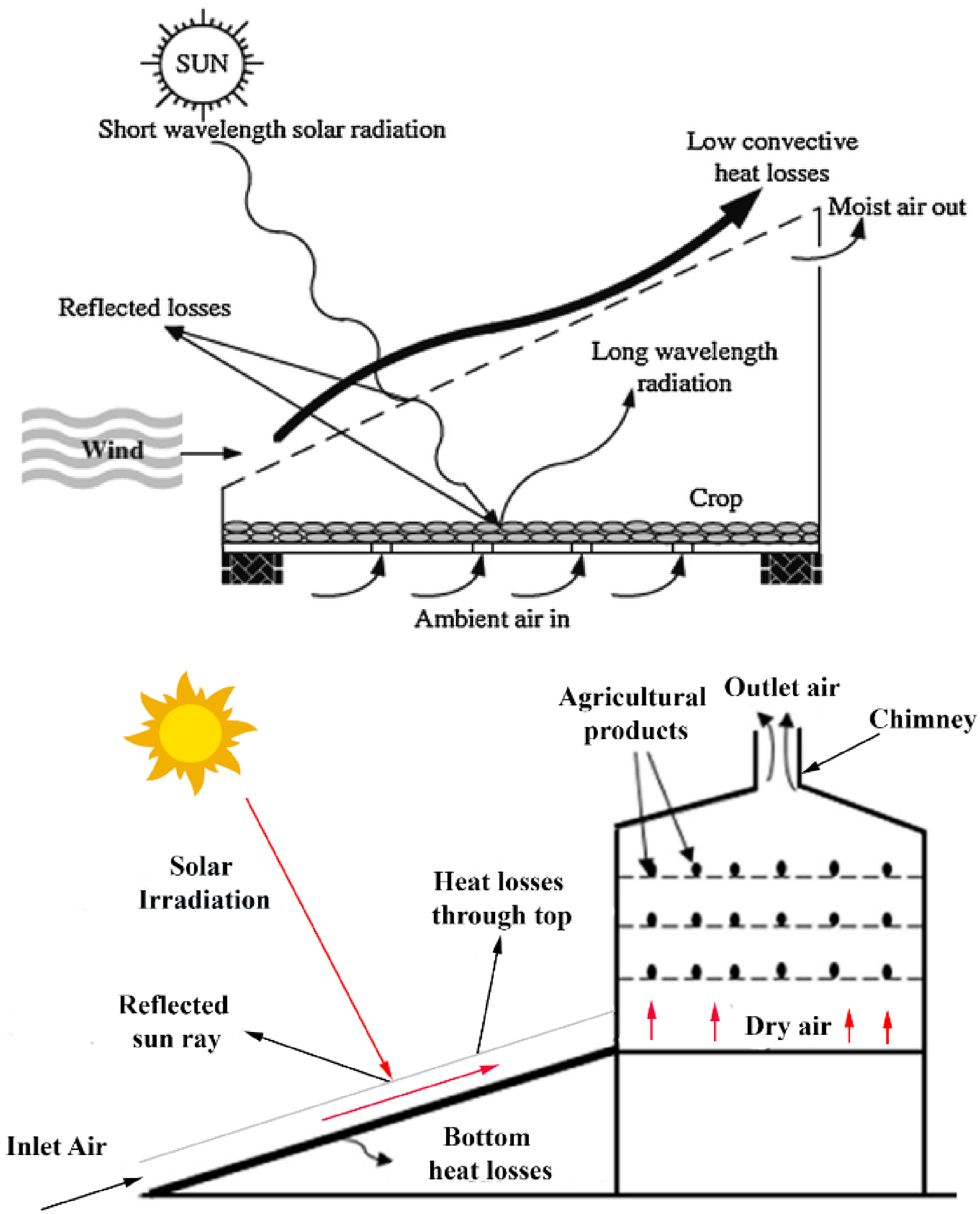

Figure 1. Schematic view of the direct and indirect type solar dryer (ISD)

LATENT HEAT STORAGE

Latent heat storage (LHS) refers to two processes namely energy absorption and energy release by a material changing state at a constant temperature. Transferring heat is performed since the chemical bonds in the material were broken up and changes from the solid-state to the liquid state, or vice versa [43]. Firstly, in the solid-liquid change, their temperature increases by absorbed heat. when materials reach melting temperature, large amounts of heat was absorbed without hotter. The temperature remains unchanged till completing the melting process [44]. The majority of PCMs are melted with a specific fusion heat at any requested range [45]. Nevertheless, in order to utilize for storing heat, the certain desires for these phase change materials have to include thermal, kinetic, physical as well as chemical properties. Additional importantly properties need to be considered consisting of economical effective and large-scale availability. Table 1 provides desirable thermophysical, kinetics, and chemical properties of LHS should possess in the thermal-storage systems.

Table 1. Desirable properties for selecting phase change materials for energy storage system [46][47][48]

Parameters	Properties of PCM
Thermal properties	➢ Depending on the specific application, selecting reasonable temperature of changing material's phase.
	➢ Appropriate melting temperature to prevent segregation
	➢ Density is recommended to be high leading to small volume for material's quantity.
	➢ High specific heat allows additional considerable SHS (sensible heat storage)
	➢ High thermal conductivity of both liquid and solid phases to charge and discharge the energy.
	➢ Phase change enthalpy should be high due to its effect on the storage unit ability.
	➢ The thermal expansion coefficient should low
Kinetic properties	➢ The rate of crystallization should be adequate
	➢ In the freezing process, lesser or no undercooling
Chemical properties	➢ Chemical stability in a long time
	➢ Compatibility with structural material of the system
	➢ No risk of ignition
	➢ Non-toxic, non-poisonous, non-flammable, non-explosive, non-dangerous
Physical properties	➢ Long-term chemical stability
	➢ No chemical decomposition to facilitate the LTES system life higher
	➢ Non-corrosiveness to construction material
	➢ Safety, non-poisonous, inflammable, non-explosive
Economic properties	➢ High availability and quantity
	➢ Effective cost
	➢ Recycling capability

The advantage of LHS compared to sensible heat storage:

- Due to the transformation of the phase, the temperature of the material is unchanged.
- PCMs have better energy densities for unit area
- Charging and discharging energy at a constant temperature.
- The heat per unit volume stored by PCM is 5 to14 times higher than that of SHSMs
- High volumetric/specific heat capacity for small differences between the temperature of fluid and storage medium.
- Heat transfers as absorbed and emitted heat are not much different.
- charging and discharging processes can be taken place Simultaneously if the heat exchanger is selected well.

Indirect solar drier (ISD) with latent heat storage materials (LHSM)

The usage of a thermal storage system help ITSD operate possibly in off sunshine hours. The devices that can store solar energy in terms of sensible and latent heat are described in Figure 2 (a) to (c). TES medium can be fabricated under the absorber plate which directly transfers conductive heat to them which is described in Figure 2a (Type A). In Figure 2b (Type B), TES material is set up at the lowest tray in the chamber. In the daytime, hot air dry agricultural products, and a part of the heat is stored by TES material which will be utilized in the evening time. Different from the above designs, a model in Figure 2(c) (Type C) uses the heat exchanger or storage tank. Water is used and heated up by a solar water heater. This high-temperature water transfers heat to TES medium in the storage tank which then increases the temperature of the drying air.

Designing a solar dryer with an SH storage system is not complicated to fabricate and unexpensive but their storage capacity per one unit of volume is low and their characteristics when exchange heat is not isothermal. Such a problem of sensible heat storage materials can be compensated by LH storage that can maintain high heat storage capacity and isothermal characteristics in melting and solidifying processes with small volume. Specific heat, density, thermal conductivity, and heat of fusion are requested to be high for PCMs. Moreover, selected PCMs should be economical, not toxic, be an inert chemical material, along with have stable composition [49]. The performance of the indirect solar dryers using PCMs is reviewed in this section. Normally, in the indirect solar dryer, PCMs are designed under the solar air heater which supplies hot air to the cabinet dryer.

Cakmak and Yildiz [50] experimented to evaluate the drying kinetics of a solar dryer for grapes. Their system includes a chamber connecting to two solar air collectors and PCM was fabricated in a collector. They endeavor to create swirl airflow in the drying chamber by using swirl components at the entrance and the special parts in the chamber. In addition, because drying time for the grapes requests to be certain, they used calcium chloride hexahydrate as latent heat storage material at the lower position of a collector to help the drying process to be able to take place at off sunshine hours. A mirror was installed on the collector applying PCM in order to maximize solå irradiation absorbed by the collector surface. The effect of air velocities also was investigated in their experiment and they found that the air velocity was inversely proportional with the drying time. Moreover, Their system with PCM and swirl effect spent 56 hours on reducing initial moisture content (MC) of 75% to 8.26%, which saved by 24 hours, 48 hours, and 144 hours compared to cases of only swirl (no PCM), no PCM and swirl effect, and OSD, respectively.

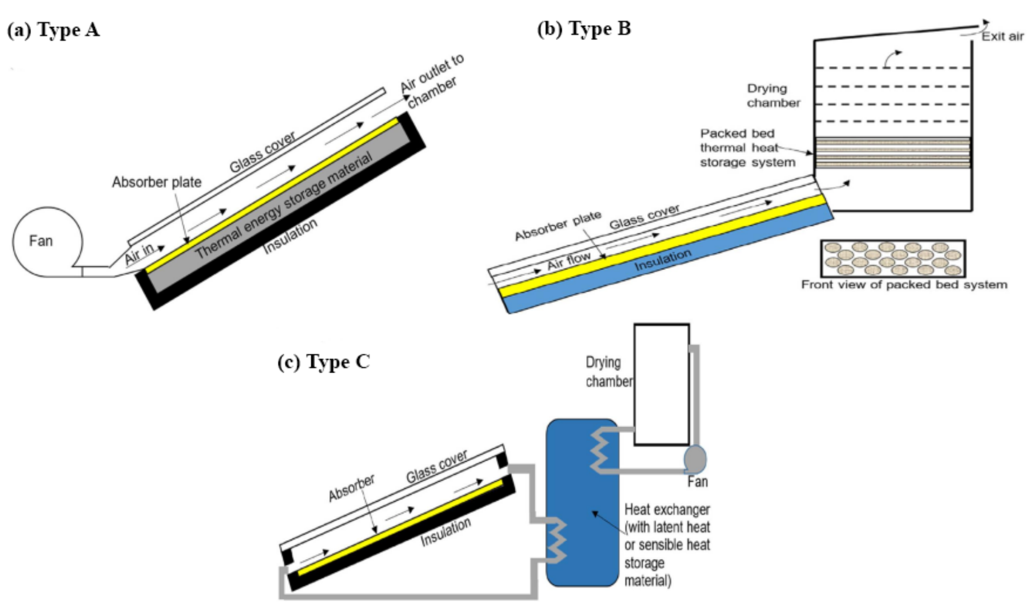

Figure 2. Different designs of indirect solar dryers for the use of latent heat storage medium.

A novel indirect solar dryer was proposed by Shalaby and Bek [51]. They also used paraffin wax arrange at the bottom of the drying compartment to store heat from hot air. The medical plants, O. basilicum and T. neriifolia which contain volatile oil experimented in their study. Their system was concluded to be reasonable for volatile oil medicinal plants. After sunset, The temperature of drying air was improved by 7.5 °C compared to ambient air temperature. It took 12 hours to achieve the required MC while 18 hours in the case without PCM. An ISD with a thermal storage tank was presented by Esakkimuthu et al. [52]. HS58 is an inorganic salt used as latent heat storage material in their study which was filled in polyethylene spherical balls and placed in the storage tank. The air was blown with a mass flow rate of 200 kg/h through a double pass SAH with V corrugated absorber, before flowing in a packed bed thermal storage tank and finally a drying cabinet. It is observed that due to PCM balls, such a dryer system can provide an approximately uniform rate of heat exchange with minimizing consumption of additional energy. According to their conclusions, the increment of the collector efficiency is due to the growth of the flow rate of drying air, which may lead heat losses to decline. As a consequence, the average temperature of the solar air collector decreased.

Additionally, the higher heat transfer coefficient as rising the mass flow rate was another explanation for this result. It is especially important to choose a phase change material has with an appropriate phase change point to prevent the food products are damaged. A uniform rate of heat exchange with minimum consumption of additional energy was obtained with their system which avoids the pressure drop during absorbed and emitted energy. Additionally, the storage system work with a low flow rate of drying air can maximize PCM‘s capacity and supply heat in uniform. Forty-eight kilograms of Parafin wax was employed as storage material in the study of Jain and Tewari [53] for solar dryers. Their system consisted of a solar air heater (SAH), two thermal storage parts, and a chamber to dry 12 kg of leafy herbs. The thermal storage systems were designed at the bottom and top of the drying chamber. The bottom part included 48 tubes filled PCMs and placed zigzag orientation while the top part or natural draft system comprised of absorber with PCM layer under and glass cover. The heat stored by PCM could be used possibly more than 5 to 6 hours after sunset and the different temperature between the air of system and ambient air was 6°C till 0 o’clock. Their estimation showed 28.2% of thermal efficiency for such a system with PCM and 1.5 years for the payback period. The design of a forced convection solar dryer with PCM was presented and constructed by El-Khadraoui et al. [54].

Their system employed a solar air collector and a solar energy accumulator that was set up paraffin wax under the absorber, and both of them supplied hot air into a drying cabinet. Their work endeavor to estimate paraffin wax behavior as charging and discharging energy. The SAH with paraffin wax had a thermal efficiency of 33.9% and an exergy efficiency of 8.5%. The findings showed 4–16 °C of a temperature gradience in the cabinet during the night with the PCM usage. The effect of paraffin wax on drying kinetics was studied by Devahastin and Pitaksuriyarat [55]. Their solar dryer for sweet potatoes included an air compressor, a heater, a cylindrical acrylic tank with latent heat storage material (LTSM), and a drying chamber. In the LTSM vessel, a U-turn copper tube with a diameter of 1.27 cm attached with 18 copper fins which have a diameter of 8 cm, spacing between two is 1 cm while paraffin wax was fulfilled. The air was supplied from the compressor to the heater which was controlled temperature ranges from 70 to 90ºC. The hot air continued to flow into copper tubes in the LTSM vessel before going to the drying chamber. Their results showed that energy during drying of sweet potato was saved up to 40% by the use of LHS with 1 m/s of air velocity.

An indirect solar drier for 6 kilograms of Thyme leaves (Thymus Vulgaris) was fabricated and investigated by El-Sebaii and Shalaby [56]. Four cases were studied in their work including using PCM and without PCM for drying whole leaves and cut leaves. They cut leaves for purpose of drying time reductant. As drying whole leaves from 95% (wb) of moisture content to 12% (wb), it took 126 hours without PCM and 84 hours with PCM. Whereas, for cut leaves, ISD without PCM spend 56 h on declining to 12% of moisture content, while ISD with PCM took 28 hours for reductant of moisture content to 11.77%. As a result, the drying time of cut leaves was 70 hours lower than that of whole leaves and the use of PCM saved time for drying by 28 hours and 42 hours for cut leaves and whole leaves respectively. Bhardwaj et al. [57] constructed various types of sensible heat storage material in SAH and Paraffin RT-42 at the bottom of the drying cabinet to improve the performance of an ISD for Tagar herbs (Valeriana Jatamansi). Sand, gravel, a combination of sand and iron scrap, a combination of gravel and iron scrap, and gravel with iron scrap and the copper tube filled engine oil was tested with a solar air collector and their result showed that a mixture of gravel and iron scrap along with engine oil carried in the copper tube showed better thermal performance with 43.11% compared to without sensible heat storage material.

Additionally, the remark analysis showed that the drying time of their system with PCM was 37.5% and 64.29% lower than that of heat pump drying and shade drying respectively. 89% of rhizomes's initial MC was declined by 80% (wb) in 5 days. Indirect and isothermal drying under the optimized temperature of Valeriana (40ºC) retained volatile substances without any loss which helped the quality of rhizomes to be superior. In 2019, Bhardwaj et al. [58] investigated experimentally an ISD that applied sensible heat storage material and/or latent heat storage material in the Himalayas. A solar collector in which gravel mixed iron scraps were placed and copper tubes with engine oil inside play a role as sensible storage materials. Valeriana rhizomes are drying products to dry in their study. They experimented till the moisture content of rhizomes reach 9 %, which was taken completely in 150 hours with the support of sensible heat storage material and in 120 hours in case of including phase change material. The energy efficiency with SHSM was 26.1% while the exergy efficiency was 0.81%. A mix mode type solar dryer for apricot and plum was tested with granulated paraffin fulfilled in the copper coil by Baniasadi et al. [59]. the solar drier consists of a solar collector consist of three parallel, drying chambers and a photovoltaic panel, and a fan.

The photovoltaic panel supplied power for the fan and connected to battery storage which was used as no sunshine. They concluded that the TES system decreased the drying time up to 50% and help the dryer possibly work after sunset. overall efficiencies of such system were 10.7% and its pick-up efficiency was 11%. The shell and tube type containing paraffin wax was design for solar dryer was proposed by Agarwal and Sarviya [60]. They evaluated the thermal and heat transfer characteristics of the latent heat storage system when it charged and discharged heat. In addition, the effectiveness of paraffin wax for drying potato slices and their drying kinetics was determined. Their finding obtained that The air gained 5 to 19°C for 10 h during LH storage system released heat. As a result, it was approved the benefit of LH storage medium at off-sunshine hours. It is noted that the low thermal conductivity of PCMs affects the heat transfer rate during the discharging process. Iranmanesh et al. [61] developed computer fluid dynamic CFD modeling for apple solar dryer augmented with an evacuated tube solar collector and paraffin in the thermal storage system to compare experimental results. The overall efficiency of the system with PCM was calculated to be 40%. The use of paraffin reduced drying time by 10% with an airflow rate of 0.09 kg/s. Reyes et al. [62] built and investigated a solar dryer system for kiwifruit.

Their system consisted of a fin solar panel, solar accumulator (contain 59.5 kg of paraffin wax and 4.8 kg aluminum strips), and a dryer. Such a system can remain temperature of drying air 12ºC over the ambient temperature in 9 hours of the experiment. Similar studies are obtained by Vásquez et al. [63]. Thermodynamic analysis on solar dryers during drying of garlic cloves was carried out by Shringi et al. [64] where the MC of garlic cloves was reduced from 55.5% to 6.5% (wb) in 8 h. The energy efficiency was in the range of 43.06–83.73%. Properties of some LH storage material used by different studies are reported in Table 2. Singh and Mall developed and experimented with an ISD with Paraffin wax as PCM for 0.4 kg of banana slices [65]. Their dryer comprised a natural convection solar air heater and a drying chamber with a chimney. PCM was placed in the gap between absorber and casing. The PCM extends the operation time of the system more than 5 hours after sunset. The moisture content of bananas decreased from 73.2% to 20% in 18 hours. The average efficiency of this system was 9.88%. It appears that the charging process of the latent heat storage system occurs under natural convection heat from high-temperature drying air to latent heat storage materials. It is noted that the temperature of air for the dryer has remained almost unchanged with the help of PCM, which is difficult to get in the sensible heat storage system. It is remarked that It is reliable and appropriate to dry medicinal plants with LHS medium especially plants that have volatile oil [66][51][52], [54].

Additionally, the drying cabinet was supplied continuously heat by LHSM even if sunset come or solar radiation is not high. The PCMs minimize the drying time and are considered as a potential key to save energy and optimize the performance of the drying system. The LHSM should be suitable with the operating temperature of the system, generally, the melting point of PCM has to be lower than drying air temperature. According to review related literature, the most popular use in the latent heat storage system is paraffin wax [67][66][50][52][56], due to its suitable melting point (50°C), cheap and availability. Several different inorganic salts like HS-58 [52], and calcium chloride [50] also was employed. The different temperature between drying air and surrounding air was obtained at 19°C by application of PCM [59]. In comparison with the system without PCM, the time for the drying process with PCM was reduced by 43% for seedless grapes [50]. Drying time for Thevetia Neriifolia, Ocimum Basilicum [51], and Thyme leaves [56] declined by 50% while that for Valeriana Jatamansi (Tagar) saved 80% thank PCM. Compared to OSD, The drying time was saved by 180% with the support of PCM [58]. Forced convection system integrated with latent heat storage system improve the drying rate [55]. the dryer for apple slices with PCM observed the highest drying efficiency of 40% [61]. Similar drying efficiency was obtained in the CFD modeling of Iranmanesh et al. [61].

Table 2. Properties of several selected phase change materials for solar dryers

Ref	**LTHM**	**T_M**	**H_L (kJ/kg)**	**C_p (kJ/kg K)**		**k (W/m K)**	**ρ (kg/m^3)**	
				Liquid	**Solid**		**Liquid**	**Solid**
[60]	Pw	41-55	176	2.8	n. a.	0.21	835	n. a.
[51]	Pw 5.2 kg	49	173	n. a.	n. a.	0.167	790	n. a.
[55]	Pw 60 kg	35-54	196.1	2.44	2.35	n. a.	786.1	833.6
[58]	Pw RT-42	42	165	2	n. a.	0.2	880	760
[62]	Pw 59.5 kg	55	220	2.38	1.85	0.15	778	861
[50] [68]	$H_{12}CaCl_2O_6$	30	140	2.1	1.4	1	1400	n. a.
[52]	HS-58	57-58	250	n. a.	n. a.	n. a.	1290	1400
[64]	n.a	87	180	2.65	n. a.	0.5	1540	1630

CONCLUSIONS

Indirect type solar dryers with latent heat storage were reviewed in this work through various designs and performance estimation of the different models for a variety of agricultural products. Designing an efficient solar dryer needs be considered solar radiation, the temperature of the surrounding air, the mass flow rate of drying air, relative humidity, moisture content, kind and mass of drying products, etc. Different types of products require different periods for drying to reach standard moisture content. The drying quality of the product is affected by temperature and velocity drying fluid. The recent research is interested in using PCMs for storing energy more than sensible heat storage materials due to the higher possible amount of energy to storage. High latent heat and a large area of heat transfer surface are requested for the higher thermal efficiency in a solar dryer system. The solar dryers with the help of PCMs may minimize the heat loss and reduce the time between supply and demand of energy, along with enhancing considerably the overall efficiency. However, the drawback of almost PCM is thermal conductivity which normally is low. Therefore, there is an interest in analyzing heat transfer between drying air and PCM to improve the performance of PCM. It is approved that phase change material is suitable for the drying process of herbs as well as medicinal plants that require unchanged temperature. Furthermore, the use of PCM for seafood and meat also needs to be investigated in future works. The use of numerical methods and computational fluid dynamic software should be encouraged to improve the design of the dryer with the latent heat storage system.

REFERENCES

[1] A.A. Fernandez, A. Rakhmatsyah, and A.A. Wardana, “Monitoring Floating Solar Tracker Based on Axis Coordinates using LoRa Network,” Int. J. Renew. Energy Dev., vol. 9, no. 2, pp. 141–149, 2020.

[2] P. Singh and M. K. Gaur, “Review on development, recent advancement and applications of various types of solar dryers,” Energy Sources, Part A Recover. Util. Environ. Eff., vol. 00, no. 00, pp. 1–21, 2020, doi: 10.1080/15567036.2020.1806951.

[3] Jinpu Liu, Rui Song, Saima Nasreen, and Anh Tuan Hoang, “Analysis of the Complementary Property of Solar Energy and Thermal Power Based on Coupling Model,” Nat. Environ. Pollut. Technol., vol. 18, no. 5, pp. 1675–1681, 2019.

[4] A. B. Lingayat, V. P. Chandramohan, V. R. K. Raju, and V. Meda, “A review on indirect type solar dryers for agricultural crops – Dryer setup, its performance, energy storage and important highlights,” Appl. Energy, vol. 258, no. May 2019, p. 114005, 2020, doi: 10.1016/j.apenergy.2019.114005.

[5] O. K. Ahmed, R. W. Daoud, S. M. Bawa, and A. H. Ahmed, “Optimization of PV/T Solar Water Collector based on Fuzzy Logic Control.,” Int. J. Renew. Energy Dev., vol. 9, no. 2, 2020.

[6] J. Gulomov et al., “Studying the Effect of Light Incidence Angle on Photoelectric Parameters of Solar Cells by Simulation,” Int. J. Renew. Energy Dev., vol. 10, no. 4, pp. 731–736, 2021.

[7] C. S. Guno, C. B. Agaton, R. O. Villanueva, and R. O. Villanueva, “Optimal Investment Strategy for Solar PV Integration in Residential Buildings: A Case Study in The Philippines,” Int. J. Renew. Energy Dev, vol. 10, pp. 79–89, 2021.

[8] F. Chabane, N. Moummi, and A. Brima, “An experimental study and mathematical modeling of solar drying of moisture content of the mint, apricot, and green pepper,” Energy Sources, Part A Recover. Util. Environ. Eff., vol. 00, no. 00, pp. 1–15, 2019, doi: 10.1080/15567036.2019.1670755.

[9] A. Agarwal, O. M. Seretse, M. T. Letsatsi, L. T. Maele, and D. Koketso, “Performance Evolution Of An Improved Solar Thermal Hot Air Heating System For Drying Ground-Nut,” J. Mech. Eng. Res. Dev., vol. 42, no. 3, pp. 1–5, 2019.

[10] A. E. Kabeel, M. H. Hamed, Z. M. Omara, and A. W. Kandeal, “Solar air heaters: Design configurations, improvement methods and applications – A detailed review,” Renew. Sustain. Energy Rev., vol. 70, no. November 2015, pp. 1189–1206, 2017, doi: 10.1016/j.rser.2016.12.021.

[11] M. Eswaramoorthy, “A comparative experimental study on flat and v groove receiver plates of a solar air heater for drying applications,” Energy Sources, Part A Recover. Util. Environ. Eff., vol. 37, no. 1, pp. 68–75, 2015, doi: 10.1080/15567036.2011.580322.

[12] S. J. Zwalnan, G. A. Duvuna, Y. A. Abakr, and T. Banda, “Design and Performance Evaluation of a Multi-Temperature Flat Plate Solar Collector.,” Int. J. Renew. Energy Dev., vol. 10, no. 3, 2021.

[13] O. El Alani et al., “A Visual Support of Standard Procedures for Solar Radiation Quality Control.,” Int. J. Renew. Energy Dev., vol. 10, no. 3, 2021.

[14] D. Aydin, S. E. Ezenwali, M. Y. Alibar, and X. Chen, “Novel modular mixed-mode dryer for enhanced solar energy utilization in agricultural crop drying applications,” Energy Sources, Part A Recover. Util. Environ. Eff., vol. 43, no. 16, pp. 1958–1974, 2021, doi: 10.1080/15567036.2019.1663306.

[15] E. Ayua, V. Mugalavai, J. Simon, S. Weller, P. Obura, and N. Nyabinda, “Comparison of a mixed modes solar dryer to a direct mode solar dryer for African indigenous vegetable and chili processing,” J. Food Process. Preserv., vol. 41, no. 6, pp. 1–7, 2017, doi: 10.1111/jfpp.13216.

[16] N. Nwakuba, V. C. Okafor, and O. O. Okorafor, “Techno-economic analysis of a hybrid solar-electric dryer,” Energy Sources, Part A Recover. Util. Environ. Eff., vol. 00, no. 00, pp. 1–25, 2020, doi: 10.1080/15567036.2020.1782537.

[17] A. T. Hoang, V. V. Pham, and X. P. Nguyen, “Integrating renewable sources into energy system for smart city as a sagacious strategy towards clean and sustainable process,” J. Clean. Prod., vol. 305, p. 127161, 2021, doi: 10.1016/j.jclepro.2021.127161.

[18] J. Ajayan, D. Nirmal, P. Mohankumar, M. Saravanan, M. Jagadesh, and L. Arivazhagan, "A review of photovoltaic performance of organic/inorganic solar cells for future renewable and sustainable energy technologies," Superlattices Microstruct., vol. 143, p. 106549, 2020, doi: https://doi.org/10.1016/j.spmi.2020.106549.

[19] A. T. Hoang et al., "Impacts of COVID-19 pandemic on the global energy system and the shift progress to renewable energy: Opportunities, challenges, and policy implications," Energy Policy, vol. 154, p. 112322, 2021.

[20] A. A. Salem and I. S. Seddiek, "Techno-Economic Approach to Solar Energy Systems Onboard Marine Vehicles," Polish Maritime Research. 2016, doi: 10.1515/pomr-2016-0033.

[21] Y. Shi and W. Luo, "Application of solar photovoltaic power generation system in maritime vessels and development of maritime tourism," Polish Marit. Res., vol. 25, pp. 176–181, 2018, doi: 10.2478/pomr-2018-0090.

[22] H. Tri Le, T. Chitsomboon, and A. Koonsrisuk, "Development of a Solar Water Distiller with a Receiver and Condenser," IOP Conf. Ser. Mater. Sci. Eng., vol. 886, no. 1, 2020, doi: 10.1088/1757-899X/886/1/012042.

[23] T. H. Le, M. T. Pham, H. Hadiyanto, V. V. Pham, and A. T. Hoang, "Influence of Various Basin Types on Performance of Passive Solar Still : A Review," vol. 10, no. 4, pp. 789–802, 2021, doi: 10.14710/ijred.2021.38394.

[24] S. Faisal Ahmed et al., "Recent progress in solar water heaters and solar collectors: A comprehensive review," Therm. Sci. Eng. Prog., p. 100981, 2021, doi: https://doi.org/10.1016/j.tsep.2021.100981.

[25] Z. Ma, H. Ren, and W. Lin, "A review of heating, ventilation and air conditioning technologies and innovations used in solar-powered net zero energy Solar Decathlon houses," J. Clean. Prod., vol. 240, p. 118158, 2019, doi: https://doi.org/10.1016/j.jclepro.2019.118158.

[26] S. E. Hosseini, "Development of solar energy towards solar city Utopia," Energy Sources, Part A Recover. Util. Environ. Eff., vol. 41, no. 23, pp. 2868–2881, 2019, doi: 10.1080/15567036.2019.1576803.

[27] A. Aboushi, M. Hamdan, E. Abdelhafez, E. Turk, J. Ibbini, and N. Abu Shaban, "Water disinfection by solar energy," Energy Sources, Part A Recover. Util. Environ. Eff., vol. 43, no. 17, pp. 2088–2098, 2021, doi: 10.1080/15567036.2019.1666182.

[28] M. Jurčević, S. Nižetić, D. Čoko, A. T. Hoang, and A. M. Papadopoulos, "Experimental investigation of novel hybrid phase change materials," Clean Technol. Environ. Policy, pp. 1–12, 2021.

[29] T. S. Le, T. H. Le, and M. T. Pham, "A review of the indirect solar dryer with sensible heat storage mediums," vol. 44, no. 7, pp. 131–140, 2021.

[30] S. Nabnean, S. Janjai, S. Thepa, K. Sudaprasert, R. Songprakorp, and B. K. Bala, "Experimental performance of a new design of solar dryer for drying osmotically dehydrated cherry tomatoes," Renew. Energy, vol. 94, pp. 147–156, 2016, doi: 10.1016/j.renene.2016.03.013.

[31] P. A. Potdukhe and S. B. Yhombre, "Development of a new type of solar dryer: Its mathematical modelling and experimental evaluation," Int. J. Energy Res., vol. 32, no. 4, pp. 765–782, 2008, doi: 10.1002/er.1387.

[32] V. Shanmugam and E. Natarajan, "Experimental study of regenerative desiccant integrated solar dryer with and without reflective mirror," Appl. Therm. Eng., vol. 27, no. 8–9, pp. 1543–1551, 2007, doi: 10.1016/j.applthermaleng.2006.09.018.

[33] S. Ayyappan, K. Mayilsamy, and V. V. Sreenarayanan, "Performance improvement studies in a solar greenhouse drier using sensible heat storage materials," Heat Mass Transf. und Stoffuebertragung, vol. 52, no. 3, pp. 459–467, 2016, doi: 10.1007/s00231-015-1568-5.

[34] A. A. El-Sebaii, S. Aboul-Enein, M. R. I. Ramadan, and E. El-Bialy, “Year round performance of double pass solar air heater with packed bed,” Energy Convers. Manag., vol. 48, no. 3, pp. 990–1003, 2007, doi: 10.1016/j.enconman.2006.08.010.

[35] R. Pichandi, K. Murugavel Kulandaivelu, K. Alagar, H. K. Dhevaguru, and S. Ganesamoorthy, “Performance enhancement of photovoltaic module by integrating eutectic inorganic phase change material,” Energy Sources, Part A Recover. Util. Environ. Eff., vol. 00, no. 00, pp. 1–18, 2020, doi: 10.1080/15567036.2020.1817185.

[36] S. Nižetić, M. Jurčević, D. Čoko, M. Arıcı, and A. T. Hoang, “Implementation of phase change materials for thermal regulation of photovoltaic thermal systems: Comprehensive analysis of design approaches,” Energy, vol. 228, p. 120546, 2021, doi: 10.1016/j.energy.2021.120546.

[37] S. R. T, G. N.B., and S. Rajkumar, “Parametric analysis of thermal behavior of the building with phase change materials for passive cooling,” Energy Sources, Part A Recover. Util. Environ. Eff., pp. 1–13, Apr. 2021, doi: 10.1080/15567036.2021.1910752.

[38] V. P. Katekar and S. S. Deshmukh, “A review of the use of phase change materials on performance of solar stills,” J. Energy Storage, vol. 30, no. March, p. 101398, 2020, doi: 10.1016/j.est.2020.101398.

[39] E. Douvi et al., “Phase change materials in solar domestic hot water systems: A review,” Int. J. Thermofluids, vol. 10, p. 100075, 2021, doi: https://doi.org/10.1016/j.ijft.2021.100075.

[40] I. Jmal and M. Baccar, “Numerical Investigation of PCM Melting in a Finned Tube Thermal Storage,” Adv. Heat Exch., 2019, doi: 10.5772/intechopen.76890.

[41] D. Tarwidi, D. T. Murdiansyah, and N. Ginanjar, “Performance evaluation of various phase change materials for thermal energy storage of a solar cooker via numerical simulation,” Int. J. Renew. Energy Dev., vol. 5, no. 3, pp. 199–210, 2016, doi: 10.14710/ijred.5.3.199-210.

[42] J. Jaguemont, N. Omar, P. Van den Bossche, and J. Mierlo, “Phase-change materials (PCM) for automotive applications: A review,” Appl. Therm. Eng., vol. 132, pp. 308–320, Mar. 2018, doi: 10.1016/j.applthermaleng.2017.12.097.

[43] M. A. Theeb, M. H. Alhamdo, and R. S. Fahad, “Thermal effects of using various metal disks inside liquid-PCM thermal storage system,” J. Mech. Eng. Res. Dev., vol. 43, no. 5, pp. 218–230, 2020.

[44] A. N. Olimat, A. S. Awad, F. M. Al-Gathain, and N. A. Shaban, “Performance of loaded thermal storage unit with a commercial phase change materials based on energy and exergy analysis,” Int. J. Renew. Energy Dev., vol. 6, no. 3, pp. 283–290, 2017, doi: 10.14710/ijred.6.3.283-290.

[45] Z. Zhang, Z. Wang, and X. He, “Analytical solution of the melting process of phase-change materials in thermal energy storage system,” Energy Sources, Part A Recover. Util. Environ. Eff., vol. 00, no. 00, pp. 1–16, 2020, doi: 10.1080/15567036.2020.1779413.

[46] L. Yang, X. Jin, Y. Zhang, and K. Du, “Recent development on heat transfer and various applications of phase-change materials,” J. Clean. Prod., vol. 287, p. 124432, 2021, doi: 10.1016/j.jclepro.2020.124432.

[47] Y. Zhou et al., “Dynamic thermal stress analysis of PCM-glazed unit under intermittent solar irradiation,” Energy Sources, Part A Recover. Util. Environ. Eff., pp. 1–19, May 2021, doi: 10.1080/15567036.2021.1923871.

[48] A. K. Pandey, M. S. Hossain, V. V. Tyagi, N. Abd Rahim, J. A. /L. Selvaraj, and A. Sari, “Novel approaches and recent developments on potential applications of phase change materials in solar energy,” Renew. Sustain. Energy Rev., vol. 82, pp. 281–323, Feb. 2018, doi: 10.1016/j.rser.2017.09.043.

[49] P. Devaux and M. M. Farid, “Benefits of PCM underfloor heating with PCM wallboards for space heating in winter,” Appl. Energy, vol. 191, pp. 593–602, 2017, doi: 10.1016/j.apenergy.2017.01.060.

[50] G. Akmak and C. Yildiz, "The drying kinetics of seeded grape in solar dryer with PCM-based solar integrated collector," Food Bioprod. Process., vol. 89, no. 2, pp. 103–108, 2011, doi: 10.1016/j.fbp.2010.04.001.

[51] S. M. Shalaby and M. A. Bek, "Experimental investigation of a novel indirect solar dryer implementing PCM as energy storage medium," Energy Convers. Manag., vol. 83, pp. 1–8, 2014, doi: 10.1016/j.enconman.2014.03.043.

[52] S. Esakkimuthu, A. H. Hassabou, C. Palaniappan, M. Spinnler, J. Blumenberg, and R. Velraj, "Experimental investigation on phase change material based thermal storage system for solar air heating applications," Sol. Energy, vol. 88, pp. 144–153, 2013, doi: 10.1016/j.solener.2012.11.006.

[53] D. Jain and P. Tewari, "Performance of indirect through pass natural convective solar crop dryer with phase change thermal energy storage," Renew. Energy, vol. 80, pp. 244–250, 2015, doi: 10.1016/j.renene.2015.02.012.

[54] A. El Khadraoui, S. Bouadila, S. Kooli, A. Farhat, and A. Guizani, "Thermal behavior of indirect solar dryer: Nocturnal usage of solar air collector with PCM," J. Clean. Prod., vol. 148, pp. 37–48, 2017, doi: 10.1016/j.jclepro.2017.01.149.

[55] S. Devahastin and S. Pitaksuriyarat, "Use of latent heat storage to conserve energy during drying and its effect on drying kinetics of a food product," Appl. Therm. Eng., vol. 26, no. 14–15, pp. 1705–1713, 2006, doi: 10.1016/j.applthermaleng.2005.11.007.

[56] A. A. El-Sebaii and S. M. Shalaby, "Experimental Investigation of Drying Thymus Cut Leaves in Indirect Solar Dryer with Phase Change Material," J. Sol. Energy Eng. Trans. ASME, vol. 139, no. 6, pp. 1–8, 2017, doi: 10.1115/1.4037816.

[57] A. K. Bhardwaj, R. Chauhan, R. Kumar, M. Sethi, and A. Rana, "Experimental investigation of an indirect solar dryer integrated with phase change material for drying valeriana jatamansi (medicinal herb)," Case Stud. Therm. Eng., vol. 10, pp. 302–314, 2017, doi: 10.1016/j.csite.2017.07.009.

[58] A. K. Bhardwaj, R. Kumar, and R. Chauhan, "Experimental investigation of the performance of a novel solar dryer for drying medicinal plants in Western Himalayan region," Sol. Energy, vol. 177, no. October 2018, pp. 395–407, 2019, doi: 10.1016/j.solener.2018.11.007.

[59] E. Baniasadi, S. Ranjbar, and O. Boostanipour, "Experimental investigation of the performance of a mixed-mode solar dryer with thermal energy storage," Renew. Energy, vol. 112, pp. 143–150, 2017, doi: 10.1016/j.renene.2017.05.043.

[60] A. Agarwal and R. M. Sarviya, "An experimental investigation of shell and tube latent heat storage for solar dryer using paraffin wax as heat storage material," Eng. Sci. Technol. an Int. J., vol. 19, no. 1, pp. 619–631, 2016, doi: 10.1016/j.jestch.2015.09.014.

[61] M. Iranmanesh, H. Samimi Akhijahani, and M. S. Barghi Jahromi, "CFD modeling and evaluation the performance of a solar cabinet dryer equipped with evacuated tube solar collector and thermal storage system," Renew. Energy, vol. 145, pp. 1192–1213, 2020, doi: 10.1016/j.renene.2019.06.038.

[62] A. Reyes, J. Vásquez, N. Pailahueque, and A. Mahn, "Effect of drying using solar energy and phase change material on kiwifruit properties," Dry. Technol., vol. 37, no. 2, pp. 232–244, 2019, doi: 10.1080/07373937.2018.1450268.

[63] 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, doi: 10.1016/j.renene.2019.02.085.

[64] V. Shringi, S. Kothari, and N. L. Panwar, "Experimental investigation of drying of garlic clove in solar dryer using phase change material as energy storage," J. Therm. Anal. Calorim., vol. 118, no. 1, pp. 533–539, 2014, doi: 10.1007/s10973-014-3991-0.

[65] D. Singh and P. Mall, "Experimental investigation of thermal performance of indirect mode solar dryer with phase change material for banana slices," Energy Sources, Part A Recover. Util. Environ. Eff., 2020, doi: 10.1080/15567036.2020.1810825.

[66] H. Atalay, "Performance analysis of a solar dryer integrated with the packed bed thermal energy storage (TES) system," Energy, vol. 172, pp. 1037–1052, 2019, doi: 10.1016/j.energy.2019.02.023.

[67] Y. Chan, N. Dyah, and K. Abdullah, "Performance of a recirculation type integrated collector drying chamber (ICDC) solar dryer," Energy Procedia, vol. 68, pp. 53–59, 2015, doi: 10.1016/j.egypro.2015.03.232.

[68] P. Charvat, L. Klimes, J. Stetina, and M. Ostry, "Thermal storage as a way to attenuate fluid-temperature fluctuations: Sensible-heat versus latent-heat storage materials," Mater. Tehnol., vol. 48, no. 3, pp. 423–427, 2014.