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Review Article

A review of natural energy storage materials used in solar dryers for food drying applications

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ABSTRACT

The application of solar energy in food drying is a well-known technology. Open sun drying has some limitations but these limitations can be overcome in solar dryers. Thermal energy storage (TES) systems for solar dryers receive wide attraction as the TES system enhances the performance of dryers. Among TES materials, the natural energy storage materials are inexpensive and easy to collect in remote areas. This work extensively reviews solar dryers with various natural energy storage materials. It discusses thermo-physical properties of various natural energy storage materials. The performance analyses of direct, indirect, mixed-mode and hybrid mode solar dryers with and without natural energy storage materials are reviewed. natural energy storage materials placed in different locations such as kind 1, kind 2 and kind 3 are discussed. The performance of frequently used natural energy storage materials such as sand, sandstone, gravel, rocks, pebbles, limestone, clay, soil, bricks, quartz, reinforced concrete and water are reviewed. The drying time saving is in the range of 9.52−47.2% using natural energy storage materials compared to conventional solar dryers. The drying efficiency (η_d) and thermal efficiency (η_{th}) of the direct solar dryer with natural energy storage are in the range of 2.85−42% and 9.9 − 58.2%, respectively, for various food materials. The drying air temperatures inside the chamber are 5 to 20 °C higher than the atmospheric temperature even after sunset hours with the natural energy storage system. The progress, benefits, challenges and recommendations of natural energy storage materials for use in solar dryers are also addressed in this paper.

1. Introduction

To maintain harmony between the growing world population and food supply, food wastage must be controlled and minimized at the time of harvesting, processing, marketing and distribution. The quality, taste, color and flavor of food materials degrade because of inadequate storage units (cold storage) and lack of processing techniques. Many developing countries experience significant losses in agricultural food products. It is calculated that the total post-harvesting losses in fruits and vegetables are 30 to 40% of the total production [1] and this is one of the main reasons for the increase in food prices. Solar drying is one of the best food preservation techniques to dry agricultural food products because the energy from the sun is free and abundantly available. Open sun drying (OSD) is a century-old practice but the exposure of food products to direct solar radiation deteriorates the quality and color of end products. It has other limitations such as dust formation, wastage because of rain and disturbance from animals and birds. Solar dryers can overcome the limitations of OSD [2]. The solar dryers are classified into two main types such as natural and forced convection solar dryers (Fig. 1).

- Natural convection solar dryers – airflow is generated by buoyant forces
- Forced convection solar dryers - air is generated by a fan or blower powered by electricity or solar PV panels.

There are four groups of solar dryers in either natural or forced convection: direct, indirect, mixed-mode and hybrid solar dryers [3]

- Direct solar dryer (DSD): It contains a box or greenhouse covered by transparent cover under which the products are placed on a tray. Solar energy is transmitted through a transparent glass and reaches the products directly.
- Indirect solar dryer (ISD): It has a solar air collector (SAC) where the air is heated. SAC is fixed with a drying cabinet where the products are placed on trays. A chimney is on the top for moisture transfer.

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Nomenclature

Abbreviations

db	Dry basis
dc	Drying Chamber
DSD	Direct solar drying
ISD	Indirect solar dryer
MC	Moisture content
OSD	Open sun drying
PCM	Phase change materials
SAC	Solar air collector
SHS	Sensible heat storage
TES	Thermal energy storage

Symbols

m	Mass of the material (kg)
C_p	Specific heat (kJ/kgK)
C_m	Mass specific heat (kJ/kgK)
t	Drying time (h)
T	temperature (°C)

Greek symbols

ρ	Density (kg/m^3)
α	Thermal diffusivity (m^2/s)
k	Thermal conductivity (W/mK)
η	Efficiency (%)

Subscripts

co	Collector outlet
d	Drying
ex	Exergy
f	Final
i	Initial
pu	Pick-up
th	Thermal

- Mixed-mode solar dryer (MSD): It is a combined model of DSD and ISD dryers. It consists of SAC, a drying cabinet with transparent covers and a chimney. The moisture in the food products is made to evaporate due to heated air from SAC and direct solar radiation.
- Hybrid solar dryer (HSD): In HSD dryers, the moisture in the food products is evaporated by not only solar energy but through other auxiliary energy sources such as biomass, electricity, waste heat, etc.

The performance of solar dryers can be enhanced further by integrating thermal energy storage (TES) systems into them. TES materials store excess energy during day time and deliver it at night so that food products can be dried round the clock. Solar dryers with TES systems help to enhance the performance of the dryers, reduce drying time, minimize manpower needed and increase the overall drying efficiency of the system [4–6]. The quantity of energy stored in the TES materials depends upon the heat capacity of the materials, temperature difference and quality of materials used. Factors such as climatic conditions, the volume of the drying chamber and the temperature range of dryers must be evaluated while selecting TES materials.

The choice of TES material plays an important factor in the techno-economic aspect of the drying system as some of the TES materials are expensive. TES materials are broadly classified as sensible and latent heat storage materials. Rock, sand, concrete, gravel, water etc. come under sensible heat storage materials while paraffin wax, glycol, calcium chloride hexahydrate, etc. come under latent heat storage materials. There are some TES materials such as sand, pebble, water, granite and rock that are inexpensive and freely available in nature which is classified under natural energy storage materials. These materials are used for low-temperature drying applications.

Solar dryers are extensively used by farmers with almost zero maintenance cost. Adding expensive TES materials with the solar dryer is not necessary as it burdens the farmers. It is easy for farmers to gather natural energy storage materials from remote areas that can be used in solar dryers to dry different food products to overcome post-harvest losses and get high quality food products. Therefore, these freely available natural energy storage materials need to be reviewed thoroughly, so that some materials can be proposed by considering the performance parameters of dryers. This was exactly what impelled the authors of this paper to carry out a feasibility study in this area. The applications of TES materials in solar drying systems were reviewed by Bal et al. in 2010 [7]. It emphasized the different properties of sensible and latent heat storage materials and classification of phase change materials, but little discussion is done on various solar dryers integrated with TES materials [7]. In addition to the study, a specific review has been carried out on the applications of latent heat storage materials on various solar drying applications [8].

Srinivasan and Muthukumar reviewed the 3E (energy-economic-environment) aspect of DSD dryer systems [9]. The authors reported that the performance of the system could be enhanced with the integration of photovoltaic (PV) panels [9,10]. Also, it was mentioned that continuous drying could be achieved by the use of a TES system with dryers. A combination of paraffin wax and black painted gravel can be used as TES materials for the continuous drying process. In another review, different modes of drying techniques, performance parameter

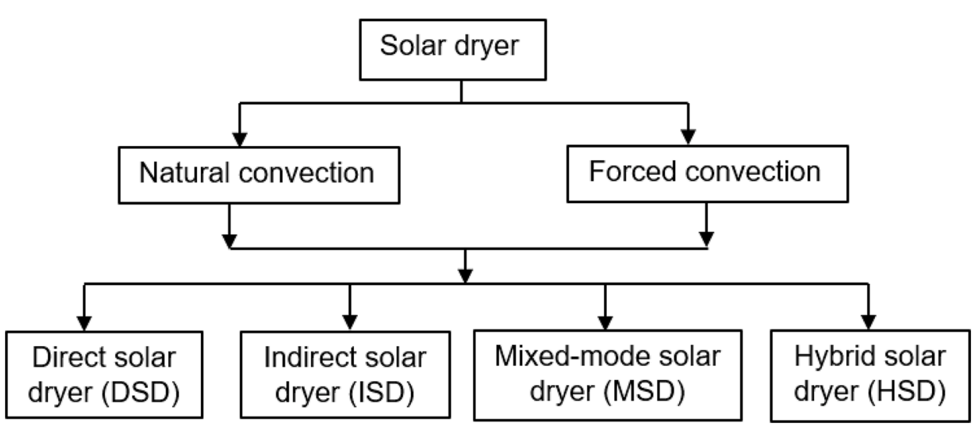

Fig. 1. Classification of solar dryers.

evaluation, energy storage techniques and techno-economic analysis pertained to ISD were reviewed in detail by Lingayat et al. [11]. They discussed only ISDs with sensible and latent storage materials. Also, recommendations were given for the improvement of performance of ISD. The progress and recent advancement in solar drying were reviewed by Mohana et al. [12] and convective drying was reviewed by Chandramohan [13]. The detailed review addressed various aspects such as drying techniques, performance parameters, socioeconomic aspects and challenges for industrial scale implementation of solar drying [12]. Different mathematical models for convective drying were reviewed and recommendations to solve numerical models were presented [13].

Most of the previous review articles were specific to the performance analysis of drying systems. Most of the reviews were limited to either DSD drying [9] or ISD drying systems [11]. They did not address the mixed-mode and hybrid solar dryers which produce higher drying air temperature that results in higher drying rate and minimize drying time. Most of the previous studies discussed the description of the setup, but the comparison of various performance parameters in each type of solar dryer is not presented. The Earlier studies did not discuss up-to-date data on the use of TES materials (specifically natural energy storage materials) in all types of solar dryers and the contents were not comprehensively presented. use of chemical PCMs in solar dryers has some demerits. Appropriate careful design is needed for the boxes, stored food degrades after several freeze/melt cycles, has low thermal diffusivity and even a small leakage of PCM contaminates food material. The use of natural energy storage materials in solar dryers overcomes the limitations of chemical PCMs. The various natural energy storage materials used in solar dryers and their thermo-physical properties need to be addressed to find a suitable material for a specific purpose to dry food products. Considering the rapid development in the area of solar drying, it is essential to do a critically comprehensive review in the field to capture all recent developments in solar drying systems with natural energy storage materials, address its challenges and future prospects. There is no study found in the literature on various natural energy storage materials, their thermo-physical properties, their usage in different types of solar dryers such as DSD, ISD, MSD and HSD dryers, the challenges and future recommendations on various solar dryers. The present review article aims to look for ways to overcome the above limitations.

The objectives of the present review article are: (i) to study the different types of natural energy storage materials used in solar dryers, (ii) to identify and compare the values of thermo-physical properties of various natural energy storage materials, (iii) to analyze the performance of DSD and ISD dryers with and without natural energy storage materials including different locations where the TES systems are placed, (iv) to analyze the performance of MSD and HSD dryers integrated with natural energy storage materials as TES systems, (v) to propose proper natural energy storage material for solar different dryers and (vi) to address the progress, benefits, challenges and future recommendations of natural energy storage materials used in solar dryers.

2. Methodological approach

The present study aims to map the knowledge generated by the researchers in the area of solar drying integrated with thermal energy storage materials (specifically, natural energy storage materials) for various food drying applications. A systematic review method was established for the purpose to define the keywords and research field. There are three major steps identified in the review process such as the collection of peer-reviewed articles, filtration and assessment of selected articles in the specific area. Initially, the data sets are identified using proper keywords in online search tools such as Google Scholar, Science Direct, Springer Link, Taylor and Francis, Wiley Online Library, etc. The broad areas on applications of solar drying using different modes of drying methods such as direct, indirect, mixed-mode and hybrid solar drying are identified. The ranges of keywords used such as natural energy storage, sensible energy storage, solar dryers, performance analysis, drying efficiency, indirect solar dryers, food drying, etc. to collect papers. The peer-review articles were listed with their sources and a clear understanding of the knowledge gap was developed. The search process was done by keeping the fact in mind that the articles from the last two decades include recent advances. The total number of articles collected was close to 200, out of which 88 important articles were shortlisted and presented in this review. 75–80% of cited articles are based on the area of solar drying applications using NES materials belonging to the recent decade.

The methodology used in the present paper can be described below. Step 1 is discussed in Section 3, while steps 2 and 3 are discussed in Sections 4 and 5 respectively. Lastly, step 4 is discussed in Section 6 of the paper.

Step (i): Different types of thermal energy storage materials, their classifications, thermo-physical properties, progress and benefits of NES materials are identified and discussed.

Step (ii): An extensive literature survey on solar dryers integrated with NES materials is carried out and the progress and development in different modes of drying (DSD, ISD, MSD and HSD) are highlighted. The types of NES material used, products dried, moisture content and drying time with and without storage system are also reported. The performance parameters such as drying efficiency, thermal efficiency, drying time saved are also discussed.

Step (iii): The highlights, perspectives and challenges of NES materials for food drying applications are assessed.

Step (iv): The conclusions and recommendations of the presently developed knowledge gap are reported.

3. Overview of various natural energy storage materials used in solar dryers

Heat energy can be stored in solids or fluids because the change in internal energy of a substance can happen due to sensible and latent heat and thermo-chemical or combination of any two or all. Sensible (or) specific heat storage (SHS) materials consistently bring an increase (or) decrease in material temperature. Because of comparatively excellent thermal stability and heat transfer characteristics, SHS materials are widely used as TES materials for high and low temperature applications. Solid state SHS materials are used in many energy storage applications because of their consistency, low investment cost, easy execution and appropriateness in different practical applications. As shown in Fig. 1, SHS materials are mainly categorized into solid state and liquid state heat storage materials, which are further sub-classified into natural energy storage and manufactured energy storage materials (shown in Fig. 2) [14]. Eq. (1)

In this article, only naturally available storage materials are discussed as this is the main aim of this work. The solid state SHS is a better option to store thermal energy for heating (or) cooling applications because of the more heat capacity of solid materials. The natural materials which are used in SHS can store heat energy without changing its phase. The amount of heat energy stored in (or) delivered from solid state energy storage materials is governed by:

$$Q = \int_{T_i}^{T_f} mC_p dT \tag{1}$$

Where, m is the mass of the material (kg), C_p is specific heat (kJ/kgK), dT is a temperature difference, T_i and T_f are initial and final temperatures of the energy storage system (K), respectively [14,15]. The importance of various thermo-physical properties of solid-state energy storage materials used for solar drying applications is mentioned in Table 1.

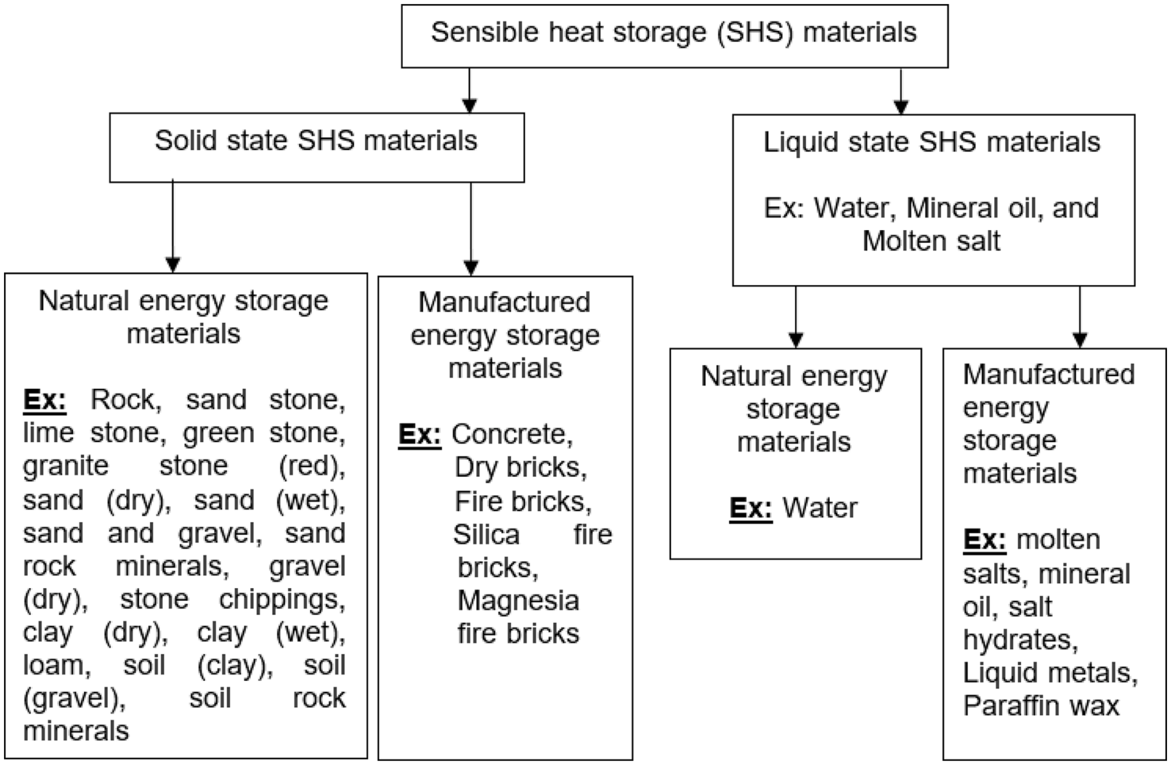

Fig. 2. Classification of sensible heat storage (SHS) materials.

Table 1
Importance of various thermo-physical properties of solid-state energy storage materials.

Property	Requirement	Reason / Description
Density (ρ) (kg/m^3)	High	High density material can enhance its storage capacity for a given volume of TES system. It can reduce the required volume of TES system for producing the same heating effect.
Mass specific heat (C_m) (kJ/kgK)	High	High value of C_m indicates that the storage material can improve its storage density.
Thermal conductivity (k) (W/m-K)	High	High thermal conductivity of the material can increase its charging and discharging rate.
Thermal stability	High	The storage materials should not decay (or) decompose at higher temperature applications. Thermo-physical properties of the materials must be stable even after repeated usage of cooling and heating applications.
Availability	Abundant and easily available	All the energy storage materials should be available abundantly and easily at local market.
Cost	Cheap	Investment must be reduced.

3.1. Types of natural energy storage materials used for solar drying applications

Solid state natural energy storage materials include rocks, sand, gravel, clay, concrete, bricks and soil which have been utilized for both low and high temperature applications because they do not freeze (or) boil. These materials do not face issues such as high vapor pressure of water or drawbacks of other liquids. The efficiency and practicality of the natural energy storage system integrated with solid materials mainly depend on the shape and size of material, packing density, heat transfer medium (air) and flow pattern [16]. The frequently and freely available natural energy storage materials such as sand, sandstone, gravel, rocks, pebbles, limestone, clay, soil, bricks, quartz and reinforced concrete are mentioned in Fig. 3. The next section explains the important characteristics of the frequently used natural energy storage materials used for solar drying applications.

3.1.1. Rock

Generally, rocks are found in the shape of a loosely packed pebble bed (or) rock pile. Efficient heat transfer takes place from the rock material due to the huge wetted surface area with the working fluid [17]. Rocks and pebbles have certain advantages such as being cheap, easily available, nontoxic and non-flammable [18]. In terms of quantity, 300 to 500 kg rocks are required per m^2 surface area of solar collector for solar heating applications. Nearly, 22 kJ of energy is stored in one kg of rock for a temperature difference of 30 °C. Usually, this kind of energy storage is used in combination with solar air heaters (or) solar dryers for a temperature range of up to 100 °C [19]. Rocks exhibit excellent thermal performance for 20 years approximately [20].

Different types of rocks are available in nature such as limestone, Helvetic siliceous limestone, serpentinite, dolerite, granite, gneiss, peridotite and amphibolite, sandstone, quartzite, basalt and greenstone which can be chosen as natural energy storage materials as per their thermo-physical characteristics (shown in Table 2). Limestone and quartzite are best suited for energy storage for low temperature applications (< 100 °C temperature) but they are not used for higher temperature applications (500–600 °C) because of material deformation and fracturing [21,22].

Ferouali et al. [23] examined the influence of natural energy storage materials such as rock salt and pebble bed on the drying efficiency (η_d) of the solar dryer. Experiments were conducted with a sample food material of lemon with and without the storage medium. They reported that there was a reduction in air mass flow rate of 17.6% and 9% during the charging of rock salt and pebble bed, respectively.

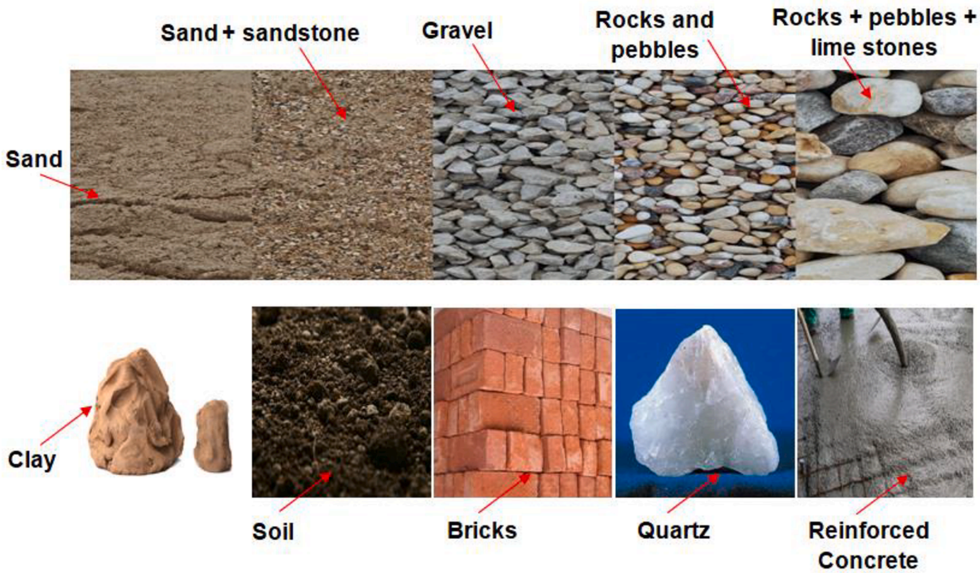

Fig. 3. Solid state natural energy storage materials.

Table 2
Thermo-physical properties of natural energy storage materials [4,11,16-18,20,21,26-28,30].

Natural energy storage material	Mass specific heat (*kJ/kg-K*)	Volumetric specific heat (*MJ/m³-K*)	Density (*kg/m³*)	Thermal conductivity (*W/m-K*)	Temperature range (°C)	Thermal diffusivity (m²/s) 1 × 10⁻⁶
Rocks	1.18	3.30	2800	4 - 10	20 - 700	1.2
Sandstone	0.712	2.80	2200	1.8 – 5.24	20 - 650	1.3
Limestone	1	2.60	2600	1.74 – 5.64	20 - 650	1.19
Greenstone	0.62	2.9	2760	3.3	20 - 650	1.15
Basalt	0.84	2.6	3100	4.0	20 - 700	0.9
Granite stone (red)	0.9	2.39	2650	7.8	20 - 650	1.18
Quartz	0.79	2.1	2650	8.4	20 - 650	3.8
Sand (dry)	0.84	1.35	1602	0.65	20 - 300	0.48
Sand (wet)	1.67	3	1800	1 – 1.9	up to 500	0.5
Sand and gravel	1.18	2.27	1922	2	up to 500	1.4
Gravel (dry)	0.89	1.64	1840	0.3 – 0.5	20 - 600	0.8
Stone chippings	1	2.05	2050	–	20 - 600	–
Clay (moist)	0.92	2.09	1330	1.17	up to 500	0.9
Clay (dry)	0.795	1.00	1260	0.25	up to 500	0.25
Clay (wet)	2.093	2.93	1700	1.6	up to 500	0.45
Waste concrete	0.85	1.87	2200	1.45	20 - 600	0.94
Loam	2.09	3.5	1360	2.4	20 - 600	0.85
Fire bricks	1.05	1.16	1100	0.47	20 - 700	0.4
Silica fire bricks	1	1.82	1820	0.7	20 - 700	0.38
Magnesia fire bricks	1.15	3.45	3000	2.2	20 - 1200	0.64
Dry bricks	0.84	1.51	1800	0.5	20 - 700	0.33
Bricks	0.92	1.56	1698	0.72	20 - 700	0.33
Soil (clay)	0.88	1.28	1450	1.28	up to 500	1
Soil (gravel)	1.84	3.75	2040	0.59	up to 500	0.16
Soil minerals	0.75	1.95	2650	2.9	up to 500	1.46
Sand rock minerals	1.3	2.21	1700	–	20 - 300	–
Soil	0.84	1.54	1842	2.16	up to 500	1.4
Water at 25 °C	4.182	4.182	1000	0.6	25 - 100	0.142

3.1.2. Sand

Rocks are frequently affected by air and water over a long period and become sand particles. These sand particles are buried in the ground and again converted into fine sand particles. Granite is the main source of fine sand particles. These fine particles are bigger than silt but smaller than gravel [24]. Sand is one of the best materials for energy storage in low as well as high temperature applications because of its peculiar thermal inertia [25]. Locally accessible small size grained silica sand material with an average size of 0.2 – 0.5 mm can be used as a storage medium.

3.1.3. Clay

Clay is one more promising natural energy storage material used for low temperature systems due to its ability to absorb approximately 7 to 10 times water of its mass. It is chemically inactive, resistant to deterioration in quality and locally available in huge quantities. It is one of the highly porous materials whose surface area is available in the range of 3×10^5 and 7×10^5 m^2 per kg. It can absorb and store 2038 kJ of thermal energy per kg of dry clay [26].

3.1.4. Soil

Different types of soils exist in nature such as red, black and arid soils. Red soil is generally formed on crystalline rocks in low rainfall areas. Arid soils are sandy in structure and saline in nature. Black soils are clayey, deep and impermeable. It has low absorption, and it retains moisture for a long time to store thermal energy. Arid soils exhibit maximum temperature retaining capacity compared with black and red soils [27]. At a drying temperature of 60 °C, excessive shrinkage and micro-cracks are formed in soils due to internal stresses which cause a decrease in thermal conductivity and also reduce overall system efficiency. The thermal conductivity of soil increases with the decrease of sand particle size [28].

3.1.5. Water

The most extensively used liquid for energy storage application is water because of several advantages such as being abundant, inexpensive, with relatively low thermal diffusivity which causes good thermal stratification, easy flow control, nontoxic, non-combustible, and easy to mix with additives. It has a high specific heat value (4.182 kJ/kgK) compared with solid state natural energy storage materials. At 90 °C, water stores 81.7 kWh of thermal energy [29]. If water is used with dissolved salts such as sodium chloride (NaCl) and Magnesium chloride ($MgCl_2$) as energy storage material, then it can trap and store heat at the bottom layer of the storage medium due to the retarding effect of salts during convection heat transfer process. Water can also be mixed with pebbles or sand to provide large-scale energy storage for solar applications [30,31].

3.2. Thermo-physical properties of natural energy storage materials

Table 2 represents the important thermo-physical properties of natural energy storage materials which include rocks, sand, clay, soil, gravel and so on. These substances have a temperature range of 20 to 1200 °C and have thermal conductivity from 1 to 10 W/m-K for rocks, sandstone, limestone, greenstone, granite, soil and sand. Crystalline silicate rocks (Quartz) exhibit higher thermal conductivity because of their rich silica content. The materials shown in Table 2 are mostly freely and abundantly available and, their prices are very low (maximum of 0.05 $ per kg or Rs. 3.75 per kg) [20].

Table 2 shows the important properties of various solid state and liquid state TES materials. These materials work between the temperature range of 20 to 1200 °C. Materials such as fire bricks, sand-rock minerals and concrete have superior thermal conductivities of 1 to 7 W/m-K. In Table 2, it is observed that quartz exhibits the highest α followed by sand, gravel, soil, soil minerals, rocks, sandstone, limestone, greenstone and granite. Dry clay, dry bricks, water and dry sand exhibit poor k which leads to a lower α. Water can absorb and store a large quantity of thermal energy per unit volume, but it cannot quickly conduct heat due to lower k. As compared with solid state SHS materials, water is a good energy storage material but a bad conductor of heat. During the selection of natural energy storage material, it is very important to balance both the characteristics (energy storage and heat transfer) of the material.

Based on thermo-physical properties of natural energy storage materials, it is concluded that quartz, rocks, soil, sand and gravel are the best TES materials that are available at a lower cost. The prices of granite and quartz are on the higher side among natural energy storage materials, but in the present application of food drying, one can choose used or waste materials. Sand and gravel have better thermo-physical characteristics at a lower cost (0.02 $ per kg or Rs. 1.5 per kg). Therefore, materials such as granite and quartz, rocks, soil, sand and gravel can be chosen as TES materials.

3.3. Progress and benefits of natural energy storage materials

3.3.1. Progress of natural energy storage materials

From the last two decades, various types of natural energy storage materials have been used for different solar applications (solar drying, solar air heating, solar water heating, etc.) by introducing various energy storage techniques. Table 3 presents the progress of solar dryers which are integrated with natural energy storage materials for energy storage [3,32–40].

The research outcomes confirm that the sustainability approach was utilized for different thermal processes [39]. Vijayan et al. [40] estimated an energy payback period by conducting an environmental impact analysis on ISD integrated with porous bed SHS medium and it was found to be 2.21 years. They reported that hygienic copra slices were produced from the forced convection solar dryer (FCSD) [37]. The best possible thickness of the heat storage material was 120 mm which is suitable for drying different agricultural produces [33].

3.3.2. Benefits

Natural energy storage materials can considerably meet society's needs as they provide efficient and environmentally harmless energy during solar heating applications. Compared with thermo-chemical energy storage systems, natural energy storage materials have some important benefits such as a decrease in carbon dioxide emissions, reduction in chlorofluorocarbon (CFC) emissions, decrease in space heating or cooling prices, better ambient temperature, low electrical charge because of the enhanced power load factor, the chance of round-the-clock use, minimized power demand, etc. [41,42].

Other benefits of natural energy storage materials used in solar heating applications are:

- Natural energy storage materials (rock, soil, gravel, clay) are capable of storing thermal energy up to 108 MJ per m^3 vol for heating and cooling applications [42].

Table 3
Progress of natural energy storage materials in various solar dryers.

Studies	natural energy storage materials	Progress of natural energy storage materials used in solar dryers
Chauhan et al. [32]	Rock bed	Moisture content (MC) of coriander was reduced from 73.82% to 53.27% in just 2 days (more than 18 h) with a rock bed. It took 3 days in without rock bed setup
Aboul-Enein et al. [33]	Sand, granite and water	The thermal characteristics of air heaters with SHS materials were reportedly maximum than those without them.
El-Sebaii et al. [34]	Sand	TES system with dryer reduced drying time of 12 h compared to without storage material.
Mohanraj and Chandrasekar [35]	Sand	Copra was dried in a dryer (integrated with sand). MC was reduced from 51.78% to 7.77% and 9.68% at 82 h in the bottom and top trays. The rate of drying was higher compared with a dryer without sand material.
Mohanraj and Chandrasekar [36]	Gravel	The consideration of natural energy storage material enhanced the drying period by 4 h / day.
Mohanraj and Chandrasekar [37]	Sand mixed with aluminum scrap	Specific moisture removal rate (SMRR) was evaluated as 0.81 and 0.94 kg/kWh for SAH with and without energy storage materials, respectively.
Ayyappan et al. [4]	Sand and rock bed	The dryer (concrete as natural energy storage substance) decreased the MC from 52 to 7% in 78 h. The OSD took 174 h.
Chaouch et al. [38]	Pebble bed	Reduced drying time of 10 h.
Atalay [39]	Packed bed	The exergy efficiency of the drying system with TES enhanced from 54.7% to 68.4%.
Vijayan et al. [40]	Pebbles	Maximum drying rate was achieved by 2.8 kg of moisture removal per kg of dry mass.

- They have good thermal reliability (no variation in thermal characteristics) and chemical stability (no alteration in chemical composition and no decay) even after a vast number of working/thermal cycles.
- They have excellent thermal stability because of no weight loss or degradation during higher temperatures (> 100 °C) which causes a long-life span.
- Their use permits efficient solutions through large scale underground thermal energy storage (UTES) systems because stratification is maintained over long periods, the material price is negligible and underground solutions have the advantage of utilizing the ground as insulation.

4. Solar dryers with natural energy storage materials

A solar dryer with an energy storage system is mainly helpful to continue the drying process even after sunset so that drying days can be minimized appreciably [43]. Solar thermal energy can be collected and stored in SHS or/and LHS systems. As of now, three kinds of energy storage systems are designed and developed in solar dryers as mentioned in Fig. 4. In the first design, the natural energy storage material is placed in the SAC but below the absorber plate (kind 1) (Fig. 4a) [35]. It is in direct exposure with the absorber sheet, where the thermal energy absorbed is transferred to the TES system by conduction heat transfer. In the second kind (kind 2), the natural energy storage material is kept in a box type heat exchanger which is placed between SAC and drying chamber (Fig. 4b) [32]. The energy collected and stored in the heat exchanger is used to heat the incoming air for drying products. In the third design (kind 3), the natural energy storage system is placed at the bottom of the drying chamber (Fig. 4c) [23]. The energized air coming from SAC flows through the TES system where energy is absorbed by natural energy storage material and the stored energy is used for drying applications during off sunshine hours [20,43].

4.1. Performance analysis of solar dryer with natural energy storage materials placed under SAC system

Aboul-Enein et al. [33] carried out a mathematical analysis on flat plate SAC by assuming natural energy storage materials (sand, water and granite) to be energy storage materials (kind 1). The impact of various design elements of SAC such as length (l), width (w), air entrance gap (c), the mass flow rate of air (m_a) and natural energy storage material thickness on outlet conditions of SAC was examined. Outcomes of the study revealed that the exit air temperature of SAC was decreased by an increase of c and m_a. The optimum thickness of the TES system was estimated to be 120 mm which is the most appropriate thickness for drying food and agricultural products. At night, the maximum temperature of air left from the dryer (T_o) was 79 °C which provides the highest temperature difference between flowing air and atmospheric air. The efficiency of the air heater integrated with the TES system increased by 4%.

The drying of copra in an ISD dryer with and without TES material was examined by Mohanraj and Chandrasekhar [37]. The TES material was located under the absorber plate of SAC (kind 1). The MC of copra was reduced from 1.083 to 0.087 kg/kg of dry basis (db) in 80 and 104 h in the ISD, with and without TES, respectively. The average thermal efficiency (η_{th}) of the dryer was found to be 23%. The specific moisture extraction rate (SMER) of the solar dryer was observed to be 0.81 and 0.94 kg/kW-h with and without TES material, respectively. The quality of the dried products in the ISD with TES was found to be better compared to without TES due to lower drying time in ISD with TES. Kumar et al. [44] evaluated the thermal performance of double pass SAC where absorber plate was made with various porous assisted materials (pebbles, mild steel, aluminum chips). They reported that maximum thermal efficiency of 84% was observed while using aluminum chips. The same with pebble and mild steel was observed as 65% and 69.5%, respectively. They concluded that the performance of double pass SAC was improved by 33% with porous materials compared to without porous materials.

4.2. Performance analysis of DSD dryer with natural energy storage materials

Direct solar drying (DSD) is a method that is self-sufficient energy-wise and generally used by most small-scale producers for processing various agricultural food products. To enhance the overall system performance, the solar dryer is fitted with a TES system. The TES system carrying natural energy storage materials was installed with DSD either below the absorber plate (kind 1) or a heat exchanger (kind 2) or inside the drying chamber (kind 3). Various natural energy storage materials such as water, sand, pebble and gravel are used largely in DSD dryers [3,38,45–49].

Ahmed and Prakash [45] evaluated the influence of various storage materials such as concrete bed, gravel bed, ground bed black coated gravel bed on the heat gain and overall heat transfer coefficient of air inside the drying chamber (kind 3). It is reported that the black coated

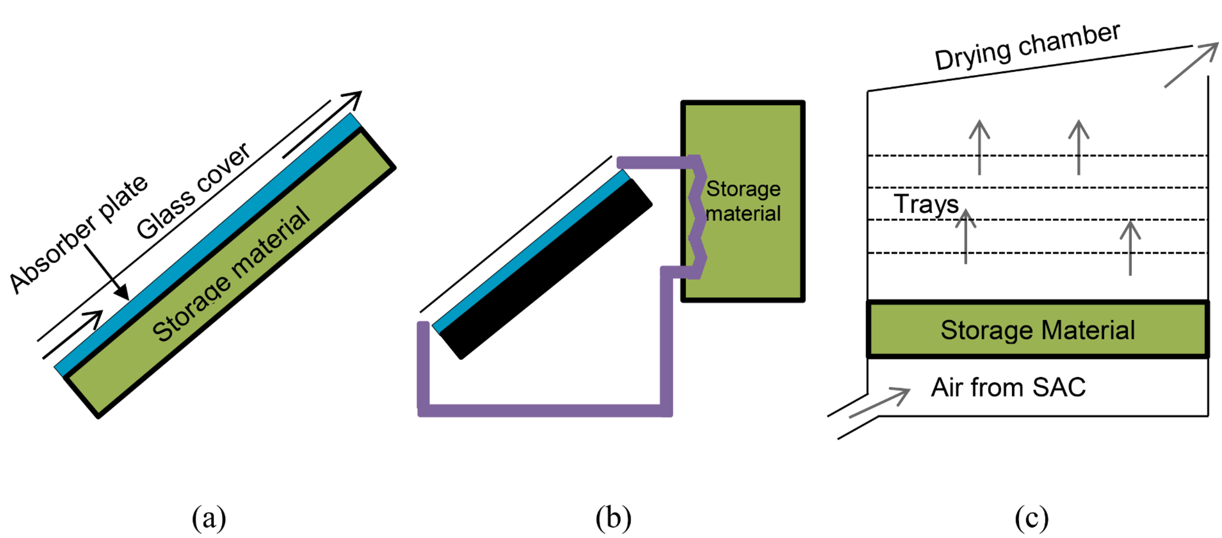

Fig. 4. Natural energy storage material placed (a) below the absorber plate in SAC (kind 1) (b) in the heat exchanger (kind 2) and (c) in the bottom of the drying chamber (kind 3).

gravel bed gains maximum heat of 53% while gravel bed, concrete bed and soil bed gain 49%, 33% and 29%, respectively. A similar analysis was performed by Ayyappan et al. [4] to determine the performance of drying systems for various types of storage beds (concrete, sand and gravel) (kind 3). The study reported that the gravel bed integrated drying setup was the most energy efficient among other selected types of storage beds. Compared to OSD drying, the drying time saved for concrete, sand and gravel bed integrated DSD system was 55.2%, 62% and 69.5%, respectively. The maximum drying efficiency (η_d) of the gravel bed integrated dryer was found to be 11.65%.

The effectiveness of DSD integrated with and without storage system was evaluated by Natarajan et al. [46] (kind 3). The sand bed was observed to be a more energy efficient storage material than rock bed and aluminum fillings. The integration of the sand bed storage system resulted in the saving of drying time by 47.2% and 24.3% for drying grapes and bitter gourd, respectively compared to without a storage system. The maximum thermal efficiency (η_{th}) was noticed for the sand bed integrated DSD system compared to all other storage materials and it was observed to be 19.6% and 15.5%, for grape and bitter gourd, respectively.

Sekhar et al. [50] studied the performance of DSD integrated with pebbles as TES material for ginger drying (kind 3). They reported that the drying cabinet temperature was enhanced by 10 °C compared to ambient temperature. Nimnuan and Nabnean [51] evaluated the performance of DSD for ginger drying. A concrete floor was considered as the storage unit. The drying time saved and increased drying efficiency of the system was estimated as 67% and 38.9% respectively, compared to OSD. The techno-economic analysis of DSD with different storage materials (concrete, concrete with black PVC and black coated concrete) under no-load conditions were evaluated by Prakash et al. [47] (kind 3). Among those studied materials, concrete with black PVC was recommended for drying applications.

The MC of banana was decreased from 4.55 to 0.22 kg/kg of db within 8 h of drying in a DSD dryer with water as natural energy storage material (kind 2). For the same 8 h, MC was reduced to only 1.63 kg/kg of db in the OSD method [48]. Similar studies were carried out by Deeto et al. [49] where coffee beans were dried from 1.22 to 0.136 kg/kg of db in 12 h (kind 2). From the above studies, it is concluded that expensive chemical TES materials are not necessary for solar drying applications and freely available natural energy storage materials are enough to dry foods. The detailed drying performances of the DSD dryer with natural energy storage materials are tabulated in Table 4.

From Table 4, it is observed that most of the studies used sand [3,46], water [48,49] and pebble or rock or gravel [3,38,45] as natural energy storage material. The drying time saved was 55.2–69.5% for coconut drying [3], 51.7% for grapes (Vitis vinifera) [46], 47% for bitter gourd (Momordica charantia) [46] in DSD system integrated with storage (natural energy storage) compared to OSD. The drying time saved was 47.2% and 24.3% for grape and bitter gourd, respectively, with the use of storage material [46].

The η_d of DSD system with natural energy storage material varies in the range of 2.85 – 42% as mentioned in Table 4 for various food materials. The η_{th} of the solar dryer with natural energy storage materials was in the range of 32–58.2% for water followed by 9.9–21.2% for sand and 11.8% for pebble. It proves that water is a potential natural energy storage material for drying processes compared to other materials. The drying chamber temperature (T_{dc}) plays a crucial role in enhancing the drying kinetics of various food products and is observed to be varied in the range of 45 to 67.5 °C. The T_{dc} was higher while the dryer was integrated with the natural energy storage system. T_{dc} range of DSD dryers with natural energy storage system was 62.5 − 67 °C compared to 55 °C without TES [46] system. These advantages prove that natural energy storage materials can be successfully used in DSD dryers for food drying applications.

4.3. Performance analysis of ISD dryers with natural energy storage materials

The major components of ISD are SAC, drying chamber and chimney. SAC consists of an absorber plate and a collector cover. ISD overcomes all the shortcomings of DSD and OSD methods. It is one of the most energy efficient methods and can be used for large scale applications. To enhance the drying performance of the system, the TES system is integrated with it. The performance of ISD can also be increased by providing forced convection provision using solar PV panels, which are renewable and free of cost [52,53]. The availability of various natural energy storage materials gives wider choices for applications. The major natural energy storage materials used in ISD dryers are sand, water and rock or pebble or gravel. In the ISD system, SAC plays a formidable role in airflow to the drying chamber and the performance of the system. The amount of solar intensity that reaches the collector cover is transmitted inside SAC and a part is absorbed by the absorber sheets. The TES system carrying natural energy storage materials was integrated into the ISD either below the absorber plate (kind 1) [34–36,39,40,54–60] or with a heat exchanger (kind 2) [61–66] or inside the drying chamber (kind 3) [67–71]. The various studies carried out in ISD with natural energy storage materials over the last two decades have been included in the following sections.

4.3.1. SACs with natural energy storage below the absorber plate (kind 1)

There are a lot of studies available in the literature where the storage system (specifically having natural energy storage materials) is placed

Table 4
Direct solar dryer with natural energy storage material.

Studies	Load and product	natural energy storage	MC (kg/kg of db)		Drying time (t), h or day			Efficiencies,%		T_{dc} (°C)
			MC$_i$	MC$_f$	OSD	With TES	Without TES	η_{th}	η_d	
Amer et al. [48]	30 kg banana slices	water[£]	4.55	0.22	–	8 h	–	58.23	37.4	–
Ayyappan et al. [4]	coconuts	rock-bed[@]	1.083	0.0753	174 h	53 h	–	–	11.65	49
Ayyappan et al. [4]	coconuts	concrete[@]	1.083	0.0753	174 h	78h	–	–	9.5	50
Ayyappan et al. [4]	coconuts	sand[@]	1.083	0.0753	174 h	66 h	–	–	11	46
Deeto et al. [49]	Coffee beans	water[£]	1.22	0.136	–	–	–	32–38.8	–	45
Natarajan et al. [46]	5 kg Vitis vinifera	sand[@]	5.67	0.11	58 h	28 h	53 h	21.2	5–40	62.5
Natarajan et al. [46]	2 kg Momordica charantia	sand[@]	7.33	0.064	10 h	5.3 h	7 h	9.9	12–42	67.5
Chaouch et al. [38]	4 kg camel meat	pebble[&,@]	–	–	–	–	–	11.8	2.84–10.35	60
Ahmed and Prakash [45]	4 kg Tomato flakes	black painted gravel[@]	24	0.10	–	13 h	–	–	23.49	64.4

[&] kind 1,
[£] kind 2,
[@] kind 3 dryers.

below the absorber plate (kind 1). A total of 40 kg green chili was dried in an ISD with gravel as natural energy storage material [36]. The MC was reduced from 2.676 to 0.1 kg/kg of db in 24 h. The system worked 4 h extra time after sunshine-off time. Bharadwaj et al. [55] developed an ISD for drying chili. Iron scraps mixed with gravel and engine oil poured in copper tubes were employed for absorber plate cum energy storage purposes. The MC of 9 kg chili was reduced from 6.407 to 0.0507 kg/kg of db in 36 h. The drying time was saved by almost 76% with the integration of the TES system. The η_{th} and η_d of the system were 78.02 and 15.62%, respectively. Mohanraj and Chandrasekar [35] evaluated the drying kinetics of copra with an ISD dryer integrated with sand as natural energy storage material. The MC was reduced from 1.075 to 0.085 kg/kg of db in 82 h. The η_{th} of the system was 24%. 51.2% of drying time was saved with natural energy storage material compared to OSD drying.

The MC of bitter gourd was reduced from 11.5 to 0.099 kg/kg of db and 30% drying time was saved in an ISD system integrated with pebbles as natural energy storage material compared to the OSD process [56]. The η_{th} and η_d of the system were 22 and 19%, respectively, whereas the maximum outlet temperature of the collector reached almost 51.2 °C which is 12 °C more than the room temperature. The exergo-environmental analysis of a similar experiment was carried out by Vijayan et al. [40]. They reported that by the integration of the pebble-based storage system, the performance of the ISD system increased and the payback period was achieved within 2.21 years. Atalay [57] determined the drying characters of lemon slices using a pebble integrated dryer and observed that the MC reduced from 18.23 to 0.111 kg/kg of db in the time range of 6.15–6.37 h.

Cetina-Quinones et al. [58] examined the influence of natural energy storage materials (beach sand and limestone) during the drying of tomato slices. Limestone performed better with 1.55% higher η_d than beach sand. The sand was used as natural energy storage material and kept below SAC during the drying performance evaluation of 0.5 kg of fresh mint leaves [59]. The MC was reduced from 4.55 to 0.083 kg/kg of db in 4 h. The maximum η_{th} and drying chamber temperature were 58.5% and 54 °C, respectively. In another study [60], thermo-economic analysis of a multi-pass solar dryer integrated with sand was examined for drying potato slices. The MC_f reached 0.15 kg/kg of db from MC_i of 3.17 kg/kg of db in 4.5 h. The maximum collector outlet temperature was 62 °C which is 26.3 − 30 °C more compared to room temperature and the payback period of the system was estimated as 2.4 years. It can be concluded that this system was most suitable for drying potato slices.

4.3.2. SACs with natural energy storage in the heat exchanger (kind 2)

The storage system can be integrated into the drying system or it can be placed as a single unit based on the space constraints of the unit. A heat exchanger is required to pack the natural energy storage materials in dryers of this kind 2. The heat energy is absorbed by the water when it comes to the water heater and storage tank. The extracted heat is transferred to the air so that the air temperature is increased and used for drying. Most of the studies [62−64] used water as natural energy storage material, which was integrated into a heat exchanger.

Nabneen et al. [62] investigated the drying performance of cherry tomatoes in an ISD system where water was used for heat storage. A heat exchanger was integrated with the system to heat the drying air. The η_{th} of the system was in the range of 21 to 69% and the payback period was 1.37 years. Similar studies were performed by Essalhi et al. [63] for grape drying. The MC was reduced from 3.95 to 0.253 kg/kg of db and 40.3% drying time was saved when the system was integrated with the natural energy storage system compared to the OSD process. The water can store a huge amount of sensible heat which is one of the reasons most of the studies used water as natural energy storage material. Also, for a long drying process, water can be used as natural energy storage material. It was validated in the study of wood drying by Luna et al. [64] where the drying process happened for more than 10 days. The drying time saved was 21.74 to 35.14% in the dryer with the TES system compared to without the TES system.

Poblete and Painemal [65] observed enhanced solar drying potential during sludge drying with the storage system. There was an enhancement of 70.3% in η_{th} while the system was integrated with rock bed as TES material. In this system, the preheated air from the SAC was passed to the drying chamber through the integrated TES system. A similar study for wood drying was carried out by Lamrani and Draoui [66].

4.3.3. SACs with natural energy storage inside the drying chamber (kind 3)

The storage materials are kept inside the drying chamber (kind 3) to enhance the drying performance of the system so that the dryer can be used in the off-sunshine period. Hot air from the SAC is allowed to pass through the storage system which is kept below the trays where the products are kept inside the drying chamber. Some studies were performed with phase change materials (PCM) [69] or desiccants [70,71], but only a limited number of studies are available with natural energy storage materials [67,68]. Vlachos et al. [67] evaluated the performance of a forced convection ISD dryer integrated with water storage under no-load conditions. There were 25 metallic containers of water carrying a capacity of 5 L, each painted black, and used for energy storage purposes. The system works fine at the sunshine-off time as well. In another study, Tiwari et al. [68] analytically carried out a thermodynamic analysis of the ISD system and evaluated the collector outlet temperature and storage temperature. The maximum collector outlet temperature was in the range of 60 to 70 °C. However, there was a lack of detailed analysis on ISD dryers with natural energy storage materials integrated into the drying chamber.

Shanmugam and Natarajan [70] studied the effect of forced convection ISD dryer with desiccant on product quality and drying ability. The desiccant material considered by them is a mix of bentonite (60%), calcium chloride (10%), vermiculite (20%) and cement (10%). The desiccant bed was fabricated at the top of the drying cabinet at a slanted angle for better circulation of airflow. The inclusion of external mirrors as reflectors caused a decrease in drying time (2 − 4 h) and enhancement of the overall temperature gradient (10 °C). In another study, Dina et al. [71] studied the effectiveness of ISD integrated with desiccant storage system (kind 3) for drying of cocoa beans.

The studies available on natural energy storage systems inside the drying chamber show promising results. However, further studies are required to determine the performance of dryers fitted with natural energy storage materials. The detailed drying performance of indirect solar dryer (ISD) with natural energy storage materials is tabulated in Table 5.

From Table 5, it is observed that most of the studies used sand [34,35,58−60], water [62−64], pebble or rock or granite, etc. [38,39,54−57] as energy storage materials for drying agricultural products. By introducing natural energy storage materials, the drying time saved was 51.2% for copra [35], 30% for bitter gourd [56], 40.3% for grapes [63], 10% for potato [60] and 60% for rosella [54] in the ISD system compared to OSD. Similarly, 76% and 9.52% of drying time were saved for green chili [55] and green peas [70] while using ISD dryers with natural energy storage materials compared to without storage [70]. Similarly, the drying time saved for pineapple was 12.5% [70]; for pinewood, it was in the range of 21.7 to 35.1% [64]. The type of natural energy storage material also affects the overall drying time required for the product. The drying time saved for tomato slices was 8% and 12% in the dryer with natural energy storage material of sand and limestone, respectively, compared to without a storage system [58].

The η_d of ISD with natural energy storage varies in the range of 1.6 – 53% for (Table 5) various food materials. The moisture removal rate from the product by drying air is defined using pickup efficiency (η_{pu}). It varies in the range of 2.5 − 66.95%. However, η_{th} of ISD with natural energy storage materials was observed in the range of 22 −78% for gravel followed by 21−69% for water and 12−66% for sand. The collector outlet temperature (T_{co}) plays an important role in enhancing drying kinetics of various food products and it was found that it was in

Table 5
Indirect solar dryer with natural energy storage materials.

Studies	Load and product	natural energy storage	Moisture content (MC) (kg/kg of db)		Drying time (*t*), h or day			Efficiency (*η*)%			T_{co} (°C)
			MC_i	MC_f	OSD	With TES	Without TES	η_{th}	η_d	η_{pu}	
Shanmugam and Natarajan [70]	20 kg of green peas	desiccant type [*,@]	4	0.053	–	19 h	21 h	36	43–48	15–45	40–60
	20 kg of pineapple slices		–	–	–	28 h	32 h	36	49–53	52–62	40–60
Mohanraj and Chandrasekar [35]	Copra, 60 kg from 160 kg nuts	sand[&]	1.075	0.085-0.107	168 h	82 h	–	24	–		43
Vijayan et al. [56]	4 kg bitter gourd	pebble[&]	11.5	0.099	10 h	7 h	–	22	19		51.2
Kareem et al. [54]	75.2–81.3 kg Roselle	granite[&]	5.94	0.101	35 h	14 h	–	64.08	36.22	66.95	40–57
Chaouch et al. [38]	4 kg camel meat	pebble[&,@]	–	–	–	–	–	28	1.6–18.34	–	47
Essalhi et al. [63]	0.384 kg grapes	water[£]	3.95	0.253	201 h	120 h	–	–	–	–	46.8
Kesavan et al. [60]	4 kg potato slices	sand[&]	3.17	0.15	5 h	4.5 h	–	12–66	–	2.5–62.9	62
Kesavan and Arjunan [59]	0.5 kg fresh mint leaves	sand[&]	4.55	0.083–0.111	–	4 h	–	58.48	–	–	54 42[#]
Luna et al. [64]	pine wood	water[£]	3.16–15.67	0.136	–	180–240 h	230–370 h	–	–	–	–
Bhardwaj et al. [55]	9 kg chili	Gravel[$]	6.407	0.0509	150 h	36 h	–	78.02	15.62	–	25.9–63.8
Cetina-Quinones et al. [58]	0.8959 kg tomato slices	limestone[&]	25.95	0.077	–	22 h	25 h	–	12.57	52.19	51.4
	0.9641 kg tomato slices	beach sand[&]	25.95	0.069	–	23 h	25 h	–	11.02	66.79	43.01
Atalay [57]	10 kg lemon slices	pebble[&]	18.23	0.111	–	6.15–6.37 h	–	–	–	–	52.05–52.2
Atalay [39]	10 kg orange slices	pebble bed[&]	14.385	0.115[#] 0.121		7 h	7.2 h		33.4[#] 34.36		55.25[#] 45.25
Nabnean et al. [62]	100 kg Cherry tomatoes	water[£]	1.632	0.176		4 days	–	21–69	–		30–65

[*] 60% bentonite, 20% vermiculite, 10% calcium chloride and 10% cement;.
[#] no TES.
[$] The mixture of iron wastes, gravel and engine oil in a copper enclosure.
[&] kind 1,.
[£] kind 2,.
[@] kind 3 dryers.

the range of 25.9 to 68 °C. It was 12 °C higher [59] when the dryer was integrated with sand as natural energy storage material compared without the TES system. These studies show the importance of natural energy storage materials in ISD dryers.

The discharge time or retention time of the NES materials (such as sand, pebble, water, etc.) depends upon various factors such as working temperature range, the capacity of the storage system, efficiency of the system, storage period, thermo-physical properties of energy storage materials, etc. Higher energy storage density and thermal diffusivity are the desirable properties while charging and discharging energy from NES materials. The estimated discharge time of sand while copra drying is 3.5 h [35], pebbles for meat drying is from 0.83 to 1.17 h [38], granite for Roselle drying is 6 h [54], gravel for green chili drying is 3 h [55], desiccant for green peas and pineapple drying is from 10 to 12 h, respectively [70].

4.4. Performance analysis of mixed-mode solar dryer (MSD) with natural energy storage materials

In the mixed-mode solar dryer (MSD), the air is heated indirectly using a SAC and directly by solar radiation. The increase of air temperature inside the cabinet is more compared to the ISD dryer because of the combination of convection and radiation effects in the MSD dryer [72]. Various studies on MSD dryers using natural energy storage materials are discussed in this section.

Jain [72] developed an MSD dryer where the granite grits were used as storage material under the absorber plate (kind 1) in a multi-pass SAC during drying paddy crop. The crop receives indirect energy from SAC and direct sol ar energy through the glass windows of the drying chamber. It is observed that the use of window glass on walls enables higher temperatures on trays and therefore the drying performance is increased. Ugwu et al. [73] developed an MSD dryer where the pebble bed was used as absorber and storage material in SAC during drying of timber. Subbian et al. [74] used river sand under the absorber plate (kind 1) while drying coconut in MSD. It is observed that the Page model was the most suitable model to describe the drying kinetics of coconut and the maximum η_{th} of MSD was 23.32%.

Abubakar et al. [75] developed a multi chimney MSD dryer where each tray has a chimney and the trays are separated by a wooden plate. Rock was the storage material that was located below the absorber sheets of SAC (kind 1) during the drying of yam slices. The drying rate and drying efficiency (η_d) were increased by 10% and 13%, respectively, due to the storage facility. The drying time was reduced by 2 h when the MC reduced from 4 to 0.2048 kg/kg of db compared to without a storage system in the dryer. Similarly, Andharia et al. [76] evaluated the performance of MSD for gooseberry drying and compared the system performance with a storage system. The authors found that the moisture content of gooseberry reduced from 5.49 to 0.047 kg/kg of db in 11 and 9 h for sensible (black painted pebble) and latent heat storage (paraffin wax) materials, respectively.

Komolafe et al. [77] conducted energy and exergy analysis on MSD dryer with the SHS material of firebrick during drying of cocoa beans. The firebricks were placed below the drying chamber (kind 3). The solar PV panel was placed below the drying trays which was coupled to fans to maintain drying air temperature below 60 ℃. The temperature of the drying chamber was maintained 4.2 to 4.5 ℃ higher than the temperature outside from 6.00 pm to 8.00 am (next day). A total of 10 kg cocoa beans was dried and their MC reduced from 1.5 to 0.063 kg/kg of db in 50 h. Similarly, Sekyere et al. [78] used a concrete absorber integrated with a rock bed below the drying chamber (kind 3) in MSD during drying pineapple slices. The pickup efficiency (η_{pu}) of MSD was found to be 27% and MC of pineapple was reduced from 9.24 to 1.66 kg/kg of db in 19 h.

Different types of MSD dryers used natural energy storage materials such as granite [66], sand [74], rock [75] and firebrick [77] to dry different products. In MSD dryers, higher tray temperatures were achieved in the drying chamber because of a combination of convection and radiation effects. It produces a higher drying rate compared to ISD dryers because, in ISD, the air is heated only in SAC. The natural energy storage materials were placed below the absorber plate (kind 1) [72–76], with a separate storage unit made available via a heat exchanger (kind 2) [79] and inside the drying chamber (kind 3) [77,78] in different MSD dryers. Most of the studies used natural energy storage material below the absorber plate (kind 1) [72–76] because higher temperatures were noticed compared to other positions.

4.5. Performance analysis of hybrid solar dryer (HSD) with natural energy storage materials

In the HSD dryers, the food materials are dried using solar energy with other provisions such as electricity, biowastes, etc. [80–88]. The dryers using solar energy can be effectively used only on clear days, whereas HSD dryers are useful in unfavorable weather conditions also. The various studies on HSD dryers using natural energy storage AGE materials are discussed in this section.

Madhlopa and Ngwalo [80] developed an HSD dryer consisting of a SAC, granite rock bed (360 kg) as storage, a drying chamber including three trays and a biomass burner. The rock bed storage was placed above the biomass burner and below the concrete absorber (kind 1). The rock bed absorbs solar energy through SAC as well as energy from biomass burner. The drying time to reach the final MC of pineapple slices was found to be 96, 72 and 72 h during solar, biomass and solar-biomass modes of operation (at cloudy conditions), respectively. η_d was 20, 15 and 11% and 15, 11 and 13% on the first day and last day, respectively. η_d was found to be higher in solar operation mode compared to biomass and solar-biomass mode due to higher energy losses through flue gasses in biomass burners. Similarly, Tarigan [86] developed an HSD dryer that consisted of SAC, drying chamber and bricks as storage material above the biomass burner and below the drying chamber (kind 3). It is observed that the temperature of the tray was 18 ℃ higher than the atmospheric temperature at midnight due to the supply of heat from bricks.

Mohajer et al. [83] made an HSD dryer that has a dual-purpose SAC for heating the air with an electrical heater. Water was used as natural energy storage material and placed in copper tubes below the absorber plate (kind 1). It was observed that the temperature inside the drying cabinet is 20 to 30 ℃ higher in the dryer with an electric heater compared to without heater. The drying time is reduced with a heater but low-quality products are obtained due to higher drying air temperatures. Similarly, Ndukwu et al. [87] developed an HSD dryer integrated with biomass furnace during drying plantain slices. The granite pebbles were used as storage material under aluminum absorber plate of SAC (kind 1). The drying time was reduced by 10 to 21 h in HSD while MC of plantain slices reduced from 1.94 to 0.18 kg/kg of db compared to OSD method.

Amer et al. [88] designed and fabricated an HSD dryer consisting of SAC with reflectors, a heat exchanger with auxiliary heaters and a drying chamber. Chamomile was dried in the study. The heat exchanger consisted of 70 copper tubes (15 mm diameter) which were placed in the SAC between the glass cover and absorber plate (kind 2). The heated water was stored in the storage tank. The average night temperature in the dryer was found to be 35 ℃ using an auxiliary heater. The drying time was saved by 30–50% compared to the OSD method.

Murali et al. [84] determined the efficiencies of the HSD dryer during the drying of tomatoes. LPG water heater was used to heat the water. The HSD dryer consists of a solar water collector, heat exchanger, water tank, LPG water heater and drying cabinet. Coldwater is supplied to the solar water collector, heated during sunny hours and stored in the storage tank. The hot water transfers the heat through a cross-flow heat exchanger using blowers (kind 2). The heated air is circulated inside the chamber to dry the shrimps. The maximum water temperature obtained was 73.5 ℃. The maximum η_{th} and η_d were found to be 42.37% and 37.09%, respectively.

Singh and Gaur [85] conducted an environmental and economic analysis of an HSD dryer integrated with an evacuated solar collector. The heat exchanger was placed inside the greenhouse dryer where it supplied hot air by taking hot water from an evacuated solar collector (kind 2). The maximum air temperature in the drying chamber was observed to be 46.9 ℃. The drying times saved were 34.09, 47.36 and 61.90% during the drying of ginger, tomato and bottle gourd, respectively, compared to traditional greenhouse dryers. The energy payback period was found to be 2.87, 1.79 and 0.69 years fewer than the traditional dryer during the drying of bottle gourd, ginger and tomato, respectively.

It is concluded that HSD dryers used auxiliary sources such as electric heaters [81,83,88], biomass burners [80,82,86,87] and LPG cylinders [84] to dry different food products. The use of auxiliary sources enables one to maintain the required drying air temperature constantly and maintain higher values of drying air temperatures compared to MSD, ISD and OSD methods. If the desired temperature is maintained, it produces quality food products due to uninterrupted drying day and night. This avoids cracking, moisture reabsorption and mold growth in food products [82]. If the products are overheated in the HSD dryer due to high air temperatures, the drying time reduces enormously but the quality of food products becomes poor. The natural energy storage materials used in HSD dryers were granite, water, pebbles, etc. Water is the most commonly used natural energy storage material in the HSD dryer [83–85, 88] since higher temperatures were obtained using auxiliary sources. Almost 50 to 70% of the drying time was saved in the HSD dryer compared to the OSD technique.

5. Highlights, perspectives and challenges of solar drying with natural energy storage materials

5.1. Highlights and perspectives of solar dryers with natural energy storage materials

Drying increases the shelf life of food products without deteriorating their quality. Solar energy is renewable and free of cost. Different types of solar dryers have been designed invented to overcome the limitations of the OSD method. Solar drying of food products can occur during periods of sunshine. The storage of energy during day time enables continuous drying of food products during day and night. Natural energy storage materials are freely available in nature and can be accessed by anyone. An extensive literature review has been carried out on various natural energy storage materials in solar drying applications and the highlights are given in Table 6.

The various natural energy storage materials used in solar dryers were rock, concrete, sand, pebbles, gravel, granite, limestone, water, etc. These materials have a range of working temperatures from 20 to 1200 ℃ and have thermal conductivity ranging from 1 to 10 W/m-K. Rocks maintain the same thermal performance for more than 20 years. Sand is used as a storage material due to its higher thermal inertia. Clay is used

Table 6
Highlights from literature.

Studies	Highlights
Soprani et al. [17], Okello et al. [18]	The amount of heat stored in natural energy storage materials depends on thermo-physical properties, shape and size of the rocks.
Ahmed et al. [29], Kousksou et al. [30]	Water has high specific heat than other solid states natural energy storage materials and it can be mixed up with rocks or sand to provide large scale energy storage.
Ahmed and Prakash [45], Ayyappan et al. [4]	Black painted gravel bed is the most energy efficient than gravel, concrete and sand beds.
Natarajan et al. [46]	The drying efficiency is increased and drying time is decreased due to the storage system in the solar tunnel dryer.
Prakash et al. [47]	The floor is covered with a black PVC that gains more thermal energy than the black coated floor and barren floor in a greenhouse dryer with concrete as storage material.
Amer et al. [48], Deeto et al. [49]	DSD dryer was made with a water tank and heat exchanger to store heat during the day and generate heat at night.
Mohanraj and Chandrasekhar [35], El-sebaii et al. [34]	Natural energy storage materials were used below the absorber plate to store energy during daytime and release it during off-sunshine hours.
Vijayan et al. [40], Atalay [57]	Exergy performance of ISD dryers was improved and the payback period was decreased due to storage materials.
Vlachos et al. [67], Shanmugam and Natarajan [70]	Natural energy storage materials are placed in the drying chamber to store up the heat during the day and release heat energy at night.
Jain [72], Abubakar et al. [75]	Higher drying air temperatures were achieved in MSD dryers due to convection and radiation.
Komolafe et al. [77], Leon and Kumar [82]	A Temperature controller was used to maintain constant air temperature for drying.
Madhlopa and Ngwalo [80], Hossain et al. [81], Murali et al. [84]	Electricity, biomass and LPG were used as auxiliary energy sources in HSD dryers.
Mohajer et al. [83], Leon and Kumar [82]	At very high drying air temperatures, poor quality end products were obtained.

for low temperature applications due to its ability to absorb water. Water is abundantly available, it has high specific heat and good thermal stratification and therefore, it is also one of the effective natural energy storage materials.

In the DSD dryer, the black painted gravel bed can store more thermal energy and the drying time is lower compared to rock or sand bed on the floor [3,45]. Forced convection DSD takes less time to reach the final MC of food products than natural convection [47].

The degradation of food products due to direct exposure to solar radiation in DSD dryers was overcome by ISD dryers. Most of the studies used natural energy storage materials below the absorber plate (kind 1) since a higher amount of energy can be stored. In ISD dryers with heat exchangers, the natural energy storage tank is charged with separate SAC at day time and heat is recovered from the natural energy storage tank at night to dry food products. In some cases, the water storage tank is provided between either solar water collector (or SAC) and drying chamber.

In the MSD dryers also, the natural energy storage materials were used below the absorber plate (kind 1), separate storage unit via a heat exchanger (kind 2) and inside the drying chamber (kind 3). As per the literature, the HSD dryers used auxiliary sources such as electricity, biomass and LPG cylinder. The water in the storage tank can be heated by electric heaters inside the tank or by using a heat exchanger from the biomass stove and LPG cylinder. The HSD dryers produce higher drying air temperatures than DSD, ISD and MSD dryers. The overheating of food products leads to cracks on the food surface and poor-quality products. So, it is suggested that one uses a control system and temperature controller to maintain the required drying air temperature.

The use of natural energy storage materials in solar drying applications reduces carbon dioxide emissions since it saves fuel or energy consumed to manufacture other storage materials. The use of natural energy storage materials in solar dryers enables continuous drying of food products which prevents moisture reabsorption and mold growth. It also saves drying time to reach the final MC of food products so that more amount of food products can be dried. Higher thermal stability of natural energy storage materials provides a long-life span for solar dryers.

The various natural energy storage materials available in nature can be used in solar dryers for storing and releasing heat. It is observed that higher thermal diffusivity (α) of natural energy storage materials is the key property to determine the order of the proposed natural energy storage materials. The proposed natural energy storage materials that can be used in solar dryers (in decreasing order) are quartz, sand and gravel, soil minerals, sandstone, rocks, limestone, granite stone, soil, clay, waste concrete, fire bricks and water. Dry clay, dry bricks, water and dry sand exhibit lower thermal conductivity (k) which causes lower α. Water has higher mass specific heat than other solid-state natural energy storage materials and it is used for storing a higher amount of energy storage at higher drying air temperatures. However, storage system design and maintenance need to be taken care of properly where water is used as storage material due to the involvement of water pipes.

5.2. Challenges of solar dryers with natural energy storage materials

The biggest challenge in using natural energy storage material in drying applications is, that it increases the volume of the solar dryer due to the lower energy density of natural energy storage materials, which needs to be optimized and further studies are required in this respect. Since the size and total mass of solar dryers with natural energy storage material are huge, it is difficult to transport the dryer from one place to another. The design calculations to find the exact amount of natural energy storage materials such as rocks and sand are difficult to arrive at compared to PCM since it is affected by many parameters such as relative humidity of the air, size of particles, void fraction and mass flow rate of air [61]. There is always energy loss in natural energy storage materials due to pressure drops in packed bed storage. The non-isothermal behavior during storage and release of energy from natural energy storage materials cannot produce constant drying air temperature. The solar dryers with natural energy storage materials always need to use a control system and temperature controller to maintain constant drying of air temperature to get high quality food products.

Most of the studies used rocks, concrete, sand and water as natural energy storage materials for food drying applications. Rock &, stones or pebbles are among the most suitable natural energy storage materials, but their poor thermal conductivity and higher pressure drop under large flow rates are major concerns. For long-term applications, concrete is not suitable due to the chances of thermal cracking and the cracking widens for a longer thermal cycling duration. Sand has a peculiar property to absorb as well as radiate heat quickly. Therefore, its temperature increased rapidly during sunshine. However, during off-sunshine hours or cloudy weather, the stored temperature is likely to be radiated rapidly and this makes the sand very cool. The main challenges of water as natural energy storage material are its high vapor pressure and corrosion of the storage tank in high temperature applications (more than its boiling point).

The lack of awareness in the farmers concerning to natural energy storage materials in the solar dryer is also another challenge. The governing bodies, academic institutions and industries have a great responsibility to take this simple and free-of-cost technology to farmers. There are limited numerical studies available in the literature on evaluating the thermal storage capacity and optimum storage bed thickness. The lack of studies on the mixture proportion of natural energy storage materials for various ranges of applications along with volumetric heat storage data is another challenge.

6. Conclusions and recommendations for future studies

A state-of-the-art review was carried out on solar dryers with natural energy storage materials. It included a comprehensive review of various natural energy storage materials, thermo-physical properties and recent progress on various solar drying applications. Further, the performance evaluations of various types of solar dryers (direct, indirect, mixed mode and hybrid dryers) integrated with natural energy storage materials were briefly discussed. Finally, the highlights, perspectives and challenges in natural energy storage materials for solar drying applications were signposted. The following important conclusions were made from this review.

- The majority of the studies used sand, rock and water as storage materials for drying applications as they could store thermal energy up to 108 MJ per m^3 vol for heating and cooling applications and also showed excellent thermal stability at high temperature applications. The proposed natural energy storage materials that can be used in solar dryers (in decreasing order) are quartz, sand and gravel, soil minerals, sandstone, rocks, limestone, granite stone, soil, clay, waste concrete, fire bricks and water.
- The thermal energy storage (TES) system carrying natural energy storage materials was integrated into solar dryers either below the absorber plate (kind 1) or with a heat exchanger between SAC and drying chamber (kind 2) or inside the drying chamber (kind 3). In most of the studies, kind 1 and kind 2 setups were used.
- The drying kinetics improved and drying time was saved significantly with the use of natural energy storage materials in direct solar dryers (DSD). A drying time of 55.2 − 69.5% was saved for coconut drying, 51.7% for grapes, 47% for bitter gourd in DSD integrated with natural energy storage compared to the open sun drying (OSD) process. However, 47.2% and 24.3% of drying time were saved for grape and bitter gourd, respectively, with the use of natural energy storage material, compared to without storage system.
- Similarly, in an indirect solar dryer (ISD), drying time was saved 60% for rosella, 51.2% for copra, 40.3% for grapes, 30% for bitter gourd and 10% for potato when the ISD dryer was integrated with natural energy storage compared to OSD. Also, 9.52% drying time was saved during the drying of green peas in ISD with natural energy storage compared to without storage.
- The drying efficiency (η_d) and thermal efficiency (η_{th}) of the DSD system with natural energy storage was in the range of 2.85−42% and 9.9 − 58.2%, respectively, for various food materials. Similarly, for ISD system with natural energy storage, the same was in the range of 1.6 − 53% and 12−78.02%, respectively.
- Higher drying rate and lower drying time were achieved in mixed mode solar dryer (MSD) compared to the ISD system. In most of the MSD systems, kind 1 setup was used as it was a higher temperature region than other locations. During unfavorable weather conditions, the use of a hybrid solar dryer (HSD) played an important role. HSD system integrated with auxiliary sources (such as biomass, electric heater, PV panel, LPG cylinders, etc.) maintained a constant drying temperature inside the dryer.
- Water was the most commonly used natural energy storage material in HSD. Higher temperatures were obtained using auxiliary sources and heat exchanger integrated dryers to transfer the heat from the water to drying air. Almost 50 to 70% of the drying time was saved in the HSD dryer to dry food products compared to OSD.

Overall, it can be concluded that natural energy storage materials have promising advantages for different modes of solar drying applications. Instead of using expensive storage materials and chemical PCMs, these freely available materials can be used as energy storage materials in solar dryers. However, further studies are required to explore suitable storage material. More studies are required to estimate the optimal thickness of the storage bed to avoid excessive use of storage materials and decrease the volume of the setup.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] A.A. El-Sebaii, S.M. Shalaby, Solar drying of agricultural products: a review, Renew. Sustain. Energy Rev. 16 (2012) 37–43, https://doi.org/10.1016/j.rser.2011.07.134.
[2] A. Lingayat, V.P. Chandramohan, V.R.K. Raju, A. Kumar, Development of indirect type solar dryer and experiments for estimation of drying parameters of apple and watermelon: indirect type solar dryer for drying apple and watermelon, Therm. Sci. Eng. Prog. (2020) 16, https://doi.org/10.1016/j.tsep.2020.100477.
[3] V.R. Mugi, V.P. Chandramohan, Shrinkage, effective diffusion coefficient, surface transfer coefficients and their factors during solar drying of food products – A review, Sol. Energy. (2021), https://doi.org/10.1016/j.solener.2021.07.042.
[4] S. Ayyappan, K. Mayilsamy, V.V. Sreenarayanan, Performance improvement studies in a solar greenhouse drier using sensible heat storage materials, Heat Mass Transf 52 (2016) 459–467, https://doi.org/10.1007/s00231-015-1568-5.
[5] S. Yadav, A.B. Lingayat, V.P. Chandramohan, V.R.K. Raju, Numerical analysis on thermal energy storage device to improve the drying time of indirect type solar dryer, Heat Mass Transf 54 (2018) 3631–3646, https://doi.org/10.1007/s00231-018-2390-7.
[6] S. Yadav, V.P. Chandramohan, Performance comparison of thermal energy storage system for indirect solar dryer with and without finned copper tube, Sustain. Energy Technol. Assessments. 37 (2020), 100609, https://doi.org/10.1016/j.seta.2019.100609.
[7] L.M. Bal, S. Satya, S.N. Naik, Solar dryer with thermal energy storage systems for drying agricultural food products: a review, Renew. Sustain. Energy Rev. 14 (2010) 2298–2314, https://doi.org/10.1016/j.rser.2010.04.014.
[8] L.M. Bal, S. Satya, S.N. Naik, V. Meda, Review of solar dryers with latent heat storage systems for agricultural products, Renew. Sustain. Energy Rev. 15 (2011) 876–880, https://doi.org/10.1016/j.rser.2010.09.006.
[9] G. Srinivasan, P. Muthukumar, A review on solar greenhouse dryer: design, thermal modelling, energy, economic and environmental aspects, Sol. Energy. (2021), https://doi.org/10.1016/j.solener.2021.04.058.
[10] M. Goud, M.V.V. Reddy, V.P. Chandramohan, S. Suresh, A novel indirect solar dryer with inlet fans powered by solar PV panels: drying kinetics of Capsicum Annum and Abelmoschus esculentus with dryer performance, Sol. Energy. 194 (2019) 871–885, https://doi.org/10.1016/j.solener.2019.11.031.
[11] A.B. Lingayat, V.P. Chandramohan, V.R.K. Raju, V. Meda, A review on indirect type solar dryers for agricultural crops – Dryer setup, its performance, energy storage and important highlights, Appl. Energy. 258 (2020), 114005, https://doi.org/10.1016/j.apenergy.2019.114005.
[12] Y. Mohana, R. Mohanapriya, T. Anukiruthika, K.S. Yoha, J.A. Moses, C. Anandharamakrishnan, Solar dryers for food applications: concepts, designs, and recent advances, Sol. Energy. 208 (2020) 321–344, https://doi.org/10.1016/j.solener.2020.07.098.
[13] V.P. Chandramohan, Convective drying of food materials: an overview with fundamental aspect, recent developments, and summary, Heat Transf. - Asian Res. (2020), https://doi.org/10.1002/htj.21662.
[14] S. Vijayan, T.V. Arjunan, A. Kumar, M.M. Matheswaran, Experimental and thermal performance investigations on sensible storage based solar air heater, J. Energy Storage. 31 (2020), 101620, https://doi.org/10.1016/j.est.2020.101620.
[15] N. Ahmed, K.E. Elfeky, L. Lu, Q.W. Wang, Thermal and economic evaluation of thermocline combined sensible-latent heat thermal energy storage system for medium temperature applications, Energy Convers. Manag. 189 (2019) 14–23, https://doi.org/10.1016/j.enconman.2019.03.040.
[16] P. Tatsidjodoung, N.Le Pierrès, L. Luo, A review of potential materials for thermal energy storage in building applications, Renew. Sustain. Energy Rev. 18 (2013) 327–349, https://doi.org/10.1016/j.rser.2012.10.025.
[17] S. Soprani, F. Marongiu, L. Christensen, O. Alm, K.D. Petersen, T. Ulrich, K. Engelbrecht, Design and testing of a horizontal rock bed for high temperature thermal energy storage, Appl. Energy. 251 (2019), 113345, https://doi.org/10.1016/j.apenergy.2019.113345.

[18] Y. Jemmal, N. Zari, M. Asbik, M. Maaroufi, Experimental characterization and thermal performance comparison of six Moroccan rocks used as filler materials in a packed bed storage system, J. Energy Storage. 30 (2020), https://doi.org/10.1016/j.est.2020.101513.

[19] H.P. Garg, S.C. Mullick, A.K. Bhargava, Sensible heat storage, Solar Therm Energy Storage (1985) 82–153, https://doi.org/10.1007/978-94-009-5301-7_2.

[20] Y. Tian, C.Y. Zhao, A review of solar collectors and thermal energy storage in solar thermal applications, Appl. Energy. 104 (2013) 538–553, https://doi.org/10.1016/j.apenergy.2012.11.051.

[21] V. Becattini, T. Motmans, A. Zappone, C. Madonna, A. Haselbacher, A. Steinfeld, Experimental investigation of the thermal and mechanical stability of rocks for high-temperature thermal-energy storage, Appl. Energy. 203 (2017) 373–389, https://doi.org/10.1016/j.apenergy.2017.06.025.

[22] K.G. Allen, T.W. Von Backström, D.G. Kröger, A.F.M. Kisters, Rock bed storage for solar thermal power plants: rock characteristics, suitability, and availability, Sol. Energy Mater. Sol. Cells. 126 (2014) 170–183, https://doi.org/10.1016/j.solmat.2014.03.030.

[23] H. El Ferouali, A. Zoukit, I. Salhi, S. Doubabi, N. Abdenouri, Investigation of the efficiency of a solar dryer with thermal storage by rock salt and by pebble bed, Int. J. Renew. Energy Technol. 10 (2019) 283, https://doi.org/10.1504/ijret.2019.102845.

[24] F.J. Pettijohn, P.E. Potter, R. Silver, Sand and Sandstone, 2nd ed, Springer, New York, 1987, https://doi.org/10.1007/978-1-4612-1066-5.

[25] B. Dhifaoui, S. Ben Jabrallah, A. Belghith, J.P. Corriou, Experimental study of the dynamic behaviour of a porous medium submitted to a wall heat flux in view of thermal energy storage by sensible heat, Int. J. Therm. Sci. 46 (2007) 1056–1063, https://doi.org/10.1016/j.ijthermalsci.2006.11.014.

[26] O.M. Sadek, W.K. Mekhamer, Ca-montmorillonite clay as thermal energy storage material, Thermochim. Acta. 363 (2000) 47–54, https://doi.org/10.1016/S0040-6031(00)00598-0.

[27] S.S. Rathee, R. Kaushal, A. Swarup, Analysis of soil suitable for thermal energy storage media in renewable energy applications, in: 2016 7th India Int. Conf. Power Electron., 2016: pp. 1–6. https://doi.org/10.1109/IICPE.2016.8079479.

[28] H. Hailemariam, F. Wuttke, Effects of drying and shrinkage on the mechanical performance of unsaturated fine/medium- grained soils used as heat storage media, MATEC Web Conf 337 (2021), https://doi.org/10.1051/matecconf/202133701022.

[29] S.F. Ahmed, M. Khalid, W. Rashmi, A. Chan, K. Shahbaz, Recent progress in solar thermal energy storage using nanomaterials, Renew. Sustain. Energy Rev. 67 (2017) 450–460, https://doi.org/10.1016/j.rser.2016.09.034.

[30] B. Xu, J. Han, A. Kumar, P. Li, Y. Yang, Thermal storage using sand saturated by thermal-conductive fluid and comparison with the use of concrete, J. Energy Storage. 13 (2017) 85–95, https://doi.org/10.1016/j.est.2017.06.010.

[31] K. Vijayaraghavan, F.D. Raja, Design and development of green roof substrate toimprove runoff water quality: plant growth experiments and adsorption, Water Res 63 (2014) 94–101, https://doi.org/10.1016/j.watres.2014.06.012.

[32] P.M. Chauhan, C. Choudhury, H.P. Garg, Comparative performance of coriander dryer coupled to solar air heater and solar air-heater-cum-rockbed storage, Appl. Therm. Eng. 16 (1996) 475–486, https://doi.org/10.1016/1359-4311(95)00038-0.

[33] S. Aboul-Enein, A.A. El-Sebaii, M.R.I. Ramadan, H.G. El-Gohary, Parametric study of a solar air heater with and without thermal storage for solar drying applications, Renew. Energy. 21 (2000) 505–522, https://doi.org/10.1016/S0960-1481(00)00092-6.

[34] A.A. El-Sebaii, S. Aboul-Enein, M.R.I. Ramadan, H.G. El-Gohary, Experimental investigation of an indirect type natural convection solar dryer, Energy Convers. Manag. 43 (2002) 2251–2266, https://doi.org/10.1016/S0196-8904(01)00152-2.

[35] M. Mohanraj, P. Chandrasekar, Drying of copra in a forced convection solar drier, Biosyst. Eng. 99 (2008) 604–607, https://doi.org/10.1016/j.biosystemseng.2007.12.004.

[36] M. Mohanraj, P. Chandrasekar, Performance of a forced convection solar drier integrated with gravel as heat storage material for chili drying, J. Eng. Sci. Technol. 4 (2009) 305–314, http://jestec.taylors.edu.my/Vol%204%20Issue%203%20September%2009/Vol_4_3_305_314_Mohanraj.pdf.

[37] M. Mohanraj, P. Chandrasekar, Performance of a solar drier with and without heat storage material for copra drying, Int. J. Global Energy Issues (2009) 112–121, https://doi.org/10.1504/IJGEI.2009.023888.

[38] W.B. Chaouch, A. Khellaf, A. Mediani, M.E.A. Slimani, A. Loumani, A. Hamid, Experimental investigation of an active direct and indirect solar dryer with sensible heat storage for camel meat drying in Saharan environment, Sol. Energy. 174 (2018) 328–341, https://doi.org/10.1016/j.solener.2018.09.037.

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

[40] S. Vijayan, T.V. Arjunan, A. Kumar, Exergo-environmental analysis of an indirect forced convection solar dryer for drying bitter gourd slices, Renew. Energy. 146 (2020) 2210–2223, https://doi.org/10.1016/j.renene.2019.08.066.

[41] I. Dincer, Thermal energy storage systems as a key technology in energy conservation, Int. J. Energy Res. 26 (2002) 567–588, https://doi.org/10.1002/er.805.

[42] I. Dincer, M.A. Rosen, Thermal Energy Storage: Systems and Applications, 2nd ed, John Wiley & Sons, Ltd, 2011.

[43] K. Kant, A. Shukla, A. Sharma, A. Kumar, A. Jain, Thermal energy storage based solar drying systems: a review, Innov. Food Sci. Emerg. Technol. 34 (2016) 86–99, https://doi.org/10.1016/j.ifset.2016.01.007.

[44] R. Kumar, S.Kumar Gaurav, A. Afzal, A. Muthu Manokar, M. Sharifpur, A. Issakhov, Experimental investigation of impact of the energy storage medium on the thermal performance of double pass solar air heater, Sustain. Energy Technol. Assessments. 48 (2021), 101673, https://doi.org/10.1016/j.seta.2021.101673.

[45] A. Ahmad, O. Prakash, Performance evaluation of a solar greenhouse dryer at different bed conditions under passive mode, J. Sol. Energy Eng. Trans. ASME. 142 (2020) 1–10, https://doi.org/10.1115/1.4044194.

[46] K. Natarajan, S.S. Thokchom, T.N. Verma, P. Nashine, Convective solar drying of Vitis vinifera & Momordica charantia using thermal storage materials, Renew. Energy. 113 (2017) 1193–1200, https://doi.org/10.1016/j.renene.2017.06.096.

[47] O. Prakash, A. Kumar, V. Laguri, Performance of modified greenhouse dryer with thermal energy storage, Energy Reports 2 (2016) 155–162, https://doi.org/10.1016/j.egyr.2016.06.003.

[48] B.M.A. Amer, M.A. Hossain, K. Gottschalk, Design and performance evaluation of a new hybrid solar dryer for banana, Energy Convers. Manag. 51 (2010) 813–820, https://doi.org/10.1016/j.enconman.2009.11.016.

[49] S. Deeto, S. Thepa, V. Monyakul, R. Songprakorp, The experimental new hybrid solar dryer and hot water storage system of thin layer coffee bean dehumidification, Renew. Energy. 115 (2018) 954–968, https://doi.org/10.1016/j.renene.2017.09.009.

[50] Y. Raja Sekhar, A.K. Pandey, I.M. Mahbubul, G. Ram Sai Avinash, V. Venkat, N. R. Pochont, Experimental study on drying kinetics for Zingiber Officinale using solar tunnel dryer with thermal energy storage, Sol. Energy. 229 (2021) 174–186, https://doi.org/10.1016/j.solener.2021.08.011.

[51] P. Nimnuan, S. Nabnean, Experimental and simulated investigations of the performance of the solar greenhouse dryer for drying cassumunar ginger (Zingiber cassumunar Roxb.), Case Stud, Therm. Eng. 22 (2020), 100745, https://doi.org/10.1016/j.csite.2020.100745.

[52] V.R. Mugi, V.P. Chandramohan, Energy and exergy analysis of forced and natural convection indirect solar dryers: estimation of exergy inflow, outflow, losses, exergy efficiencies and sustainability indicators from drying experiments, J. Clean. Prod. (2021) 282, https://doi.org/10.1016/j.jclepro.2020.124421.

[53] V.R. Mugi, V.P. Chandramohan, Energy, exergy and economic analysis of an indirect type solar dryer using green chilli: a comparative assessment of forced and natural convection, Therm. Sci. Eng. Prog. 24 (2021), 100950, https://doi.org/10.1016/j.tsep.2021.100950.

[54] M.W. Kareem, K. Habib, M.H. Ruslan, B.B. Saha, Thermal performance study of a multi-pass solar air heating collector system for drying of Roselle (Hibiscus sabdariffa), Renew. Energy. 113 (2017) 281–292, https://doi.org/10.1016/j.renene.2016.12.099.

[55] A.K. Bhardwaj, R. Kumar, R. Chauhan, S. Kumar, Experimental investigation and performance evaluation of a novel solar dryer integrated with a combination of SHS and PCM for drying chilli in the Himalayan region, Therm. Sci. Eng. Prog. 20 (2020), 100713, https://doi.org/10.1016/j.tsep.2020.100713.

[56] S. Vijayan, T.V. Arjunan, A. Kumar, Mathematical modeling and performance analysis of thin layer drying of bitter gourd in sensible storage based indirect solar dryer, Innov. Food Sci. Emerg. Technol. 36 (2016) 59–67, https://doi.org/10.1016/j.ifset.2016.05.014.

[57] H. Atalay, Assessment of energy and cost analysis of packed bed and phase change material thermal energy storage systems for the solar energy-assisted drying process, Sol. Energy. 198 (2020) 124–138, https://doi.org/10.1016/j.solener.2020.01.051.

[58] A.J. Cetina-Quiñones, J. López López, L. Ricalde-Cab, A. El Mekaoui, L. San-Pedro, A. Bassam, Experimental evaluation of an indirect type solar dryer for agricultural use in rural communities: relative humidity comparative study under winter season in tropical climate with sensible heat storage material, Sol. Energy. 224 (2021) 58–75, https://doi.org/10.1016/j.solener.2021.05.040.

[59] S. Kesavan, T.V. Arjunan, Experimental study on triple pass solar air heater with thermal energy storage for drying mint leaves, Int. J. Energy Technol. Policy. 14 (2018) 34–48, https://doi.org/10.1504/IJETP.2018.088276.

[60] S. Kesavan, T.V. Arjunan, S. Vijayan, Thermodynamic analysis of a triple-pass solar dryer for drying potato slices, J. Therm. Anal. Calorim. 136 (2019) 159–171, https://doi.org/10.1007/s10973-018-7747-0.

[61] H. Atalay, M. Turhan Çoban, O. Kıncay, Modeling of the drying process of apple slices: application with a solar dryer and the thermal energy storage system, Energy 134 (2017) 382–391, https://doi.org/10.1016/j.energy.2017.06.030.

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

[63] H. Essalhi, M. Benchrifa, R. Tadili, M.N. Bargach, Experimental and theoretical analysis of drying grapes under an indirect solar dryer and in open sun, Innov. Food Sci. Emerg. Technol. 49 (2018) 58–64, https://doi.org/10.1016/j.ifset.2018.08.002.

[64] D. Luna, J.P. Nadeau, Y. Jannot, Model and simulation of a solar kiln with energy storage, Renew. Energy. 35 (2010) 2533–2542, https://doi.org/10.1016/j.renene.2010.03.024.

[65] R. Poblete, O. Painemal, Improvement of the solar drying process of sludge using thermal storage, J. Environ. Manage. 255 (2020), 109883, https://doi.org/10.1016/j.jenvman.2019.109883.

[66] B. Lamrani, A. Draoui, Thermal performance and economic analysis of an indirect solar dryer of wood integrated with packed-bed thermal energy storage system: a case study of solar thermal applications, Dry. Technol. 39 (2021) 1371–1388, https://doi.org/10.1080/07373937.2020.1750025.

[67] N.A. Vlachos, T.D. Karapantsios, A.I. Balouktsis, D. Chassapis, Design and testing of a new solar tray dryer, Dry. Technol. 20 (2002) 1243–1271, https://doi.org/10.1081/DRT-120004050.

[68] G.N. Tiwari, P.S. Bhatia, A.K. Singh, R.F. Sutar, Design parameters of a shallow bed solar crop dryer with reflector, Energy Convers. Manag. 35 (1994) 535–542, https://doi.org/10.1016/0196-8904(94)90094-9.

[69] D. Chaatouf, M. Salhi, B. Raillani, S. Amraqui, A. Mezrhab, Assessment of a heat storage system within an indirect solar dryer to improve the efficiency and the dynamic behavior, J. Energy Storage. 41 (2021), 102874, https://doi.org/10.1016/j.est.2021.102874.

[70] V. Shanmugam, E. Natarajan, Experimental study of regenerative desiccant integrated solar dryer with and without reflective mirror, Appl. Therm. Eng. 27 (2007) 1543–1551, https://doi.org/10.1016/j.applthermaleng.2006.09.018.

[71] S.F. Dina, H. Ambarita, F.H. Napitupulu, H. Kawai, Study on effectiveness of continuous solar dryer integrated with desiccant thermal storage for drying cocoa beans, Case Stud, Therm. Eng. 5 (2015) 32–40, https://doi.org/10.1016/j.csite.2014.11.003.

[72] D. Jain, Modeling the system performance of multi-tray crop drying using an inclined multi-pass solar air heater with in-built thermal storage, J. Food Eng. 71 (2005) 44–54, https://doi.org/10.1016/j.jfoodeng.2004.10.016.

[73] S.N. Ugwu, B.O. Ugwuishiwu, O.V. Ekechukwu, H. Njoku, A.O. Ani, Design, construction, and evaluation of a mixed mode solar kiln with black-painted pebble bed for timber seasoning in a tropical setting, Renew. Sustain. Energy Rev. 41 (2015) 1404–1412, https://doi.org/10.1016/j.rser.2014.09.033.

[74] V. Subbian, K.K. Murugavel, R.S. Raja, A.M. Shanawaz, Experimental investigation and the performance evaluation of a mixed mode solar dryer for coconut, Mater, Today Proc 45 (2021) 3662–3665, https://doi.org/10.1016/j.matpr.2021.01.157.

[75] S. Abubakar, S. Umaru, M.U. Kaisan, U.A. Umar, B. Ashok, K. Nanthagopal, Development and performance comparison of mixed-mode solar crop dryers with and without thermal storage, Renew. Energy. 128 (2018) 285–298, https://doi.org/10.1016/j.renene.2018.05.049.

[76] J.K. Andharia, B. Markam, D. Dzhonova, S. Maiti, A comparative performance analysis of sensible and latent heat based storage in a small-scale solar thermal dryer, J. Energy Storage. 45 (2022), 103764, https://doi.org/10.1016/j.est.2021.103764.

[77] C.A. Komolafe, M.A. Waheed, S.I. Kuye, B.A. Adewumi, A.O. Daniel Adejumo, Thermodynamic analysis of forced convective solar drying of cocoa with black coated sensible thermal storage material,, Case Stud. Therm. Eng. 26 (2021), 101140, https://doi.org/10.1016/j.csite.2021.101140.

[78] C.K.K. Sekyere, F.K. Forson, F.W. Adam, Experimental investigation of the drying characteristics of a mixed mode natural convection solar crop dryer with back up heater, Renew. Energy. 92 (2016) 532–542, https://doi.org/10.1016/j.renene.2016.02.020.

[79] K.M. Aguilar-Castro, J.J. Flores-Prieto, M.E. Baltazar-Lopez, E.V. Macias-Melo, Design and experimental evaluation of a mixed-mode continuous solar dryer for plaster molds, J. Mech. Sci. Technol. 26 (2012) 2969–2976, https://doi.org/10.1007/s12206-012-0707-x.

[80] A. Madhlopa, G. Ngwalo, Solar dryer with thermal storage and biomass-backup heater, Sol. Energy. 81 (2007) 449–462, https://doi.org/10.1016/j.solener.2006.08.008.

[81] M.A. Hossain, B.M.A. Amer, K. Gottschalk, Hybrid solar dryer for quality dried tomato, Dry. Technol. 26 (2008) 1591–1601, https://doi.org/10.1080/07373930802467466.

[82] A.M. Leon, S. Kumar, Design and performance evaluation of a solar-assisted biomass drying system with thermal storage, Dry. Technol. 26 (2008) 936–947, https://doi.org/10.1080/07373930802142812.

[83] A. Mohajer, O. Nematollahi, M.M. Joybari, S.A. Hashemi, M.R. Assari, Experimental investigation of a hybrid solar drier and water heater system, Energy Convers. Manag. 76 (2013) 935–944, https://doi.org/10.1016/j.enconman.2013.08.047.

[84] S. Murali, P.R. Amulya, P.V. Alfiya, D.S.A. Delfiya, M.P. Samuel, Design and performance evaluation of solar - LPG hybrid dryer for drying of shrimps, Renew. Energy. 147 (2020) 2417–2428, https://doi.org/10.1016/j.renene.2019.10.002.

[85] P. Singh, M.K. Gaur, Environmental and economic analysis of novel hybrid active greenhouse solar dryer with evacuated tube solar collector, Sustain. Energy Technol. Assessments. 47 (2021), 101428, https://doi.org/10.1016/j.seta.2021.101428.

[86] E. Tarigan, Mathematical modeling and simulation of a solar agricultural dryer with back-up biomass burner and thermal storage, Case Stud, Therm. Eng. 12 (2018) 149–165, https://doi.org/10.1016/j.csite.2018.04.012.

[87] M.C. Ndukwu, M. Simo-Tagne, F.I. Abam, O.S. Onwuka, S. Prince, L. Bennamoun, Exergetic sustainability and economic analysis of hybrid solar-biomass dryer integrated with copper tubing as heat exchanger, Heliyon 6 (2020) e03401, https://doi.org/10.1016/j.heliyon.2020.e03401.

[88] B.M.A. Amer, K. Gottschalk, M.A. Hossain, Integrated hybrid solar drying system and its drying kinetics of chamomile, Renew. Energy. 121 (2018) 539–547, https://doi.org/10.1016/j.renene.2018.01.055.