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# Natural energy materials and storage systems for solar dryers: State of the art

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ABSTRACT

Inappropriate food conservation practices along with insufficient and inefficient storage systems are often responsible for the deterioration in food quality of agricultural products leading to food insecurity and economic loss. Open sun drying is a well-known traditional food preservation technique but is limited in use due to its low efficiency and long drying times. Solar drying is considered the most effective, economical, green and sustainable technology available to preserve farm produce. In this regard, an attempt has been made in this study, to review the solar dryer technologies, natural energy materials and storage systems available for persevering food products and reported in detail. An extensive classification and comparative analysis of solar dryers have been presented. Evolutionary classification and performance assessment using various indicators has been carried out for solar dryers employing natural energy materials for energy storage. Polices, challenges, risks and recommendations for the improvement of existing solar dryers as well as the development of new technologies impacting the quality, economic, social and environmental aspects of solar dried products have been discussed in detail. The study concluded that solar drying processes with thermal energy storage devices based on natural materials are most preferred for delivering extended shelf life for farm produce in an energy-efficient and sustainable manner.

## 1. Introduction

To ensure food security for the ever-growing global population, food wastage must be monitored and reduced during harvesting, handling, promoting, and circulation. Inadequate storage units and handling processes cause the flavor, color, taste and quality of food items to deteriorate. Many developing nations are losing a lot of agricultural food production and allied products owing to the above reasons. The overall post-harvest losses in vegetable and fruit produce are estimated to be 30% to 40% of the total production which is one of the prime reasons for the rise in inflation in agriculture products [1,2]. In the United States, 30% of food, totalling US$48.3 billion (€32.5 billion), is wasted annually. Since water is the main source of farming, it is estimated that almost half of the water utilized to create this food is also lost. Depending on the sector, farm-level losses are probably between 15 and 35%. Unexpectedly super-markets, trailing about 1%, and the retail sector have rather significant loss rates of roughly 26%. Losses total between US$90 billion and US$100 billion annually [3]. 300 million people might be fed with the food that is presently lost or wasted in Latin America [4]. An estimated 6.7 million tonnes of food are wasted by British homes each year, or around one-third of the 21.7 million tonnes that are bought. This indicates that over 32% of the food purchased each year is wasted. Currently, municipal governments collect the majority of this (5.9 million tonnes, or 88%). If it had been handled more effectively, the majority of the food waste (4.1 million tonnes, or 61%) might have been consumed [5,6]. Europe's current food waste can feed 200 million people [4].

The Australia Institute surveyed more than 1600 Australian families and found that $10.5 billion was spent on things that were either never utilized or were thrown away nationwide. This comes to more than

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$5000 per person every year [7]. Food cereal post-harvest losses in several African nations are reported to be 25% of the whole produced crop. Post-harvest losses for some crops, such as fruits, vegetables, and root crops, which are less resilient than cereals, can exceed 50% [8]. Economic losses in the dairy industry from spoilage and waste could amount to US$90 million on average per year in East Africa [9]. Every year, Kenya loses over 95 million litres of milk, which is worth about $22.4 million. In Tanzania, annual losses total around 59.5 million litres of milk or more than 16% of total dairy production during the dry season and 25% during the rainy season. About 27% of the milk produced in Uganda is wasted, costing the country US$23 million annually [9]. Africa's current food loss could feed 300 million people [4]. The Food Corporation of India (FCI) reports that losses for cereals and oil seeds are smaller, at 10–12%. A total estimated worth of 240 billion Rupees is wasted annually in the form of food cereals (23 million tons), fruits (12 million tons) and vegetables (21 million tons). According to a recent estimate by the Ministry of Food Processing Industries, India, the country trashes agro-products valued at 580 billion Rupees annually [10].

Globally, each year, almost 1.3 billion tonnes, or 1/3 of food cultivated for human feeding worldwide, is squandered. Food waste and losses total around US$ 310 billion in underdeveloped nations and US$ 680 billion in wealthy nations. The amount of food wasted by both developing and industrialized nations is approximately equal to 670 million tons. Vegetables, tubers, fruits and roots are among the major agricultural products having the maximum depletion rates of food. The global food-waste rate is about 30% for cereals, 45% for root crops, 20% for fruits, 20% for vegetables, 20% for oilseeds, 20% for meat, 20% for dairy products and 30% for fish. Consumer waste per person varies between 95 and 115 kg annually in North America and Europe, compared to 6–11 kg in Southeast & South Asia and Sub-Saharan Africa. Overall food cultivation for human feeding per capita is approximately 900 kg/year in developed countries, which is nearly twice the food production in underdeveloped countries (460 kg/year). In industrialized countries, more than 40% of losses occurring at the retail and consumer levels, compared to 40% of losses in poor countries at the post-harvest and processing stages.

Food loss and wastage lead to a substantial waste of natural resources, which includes land, labour, water, capital and energy. Additionally, because of this waste unnecessary emissions like greenhouse gas levels are increasing in the environment, which leads to climate change and global warming. Large amounts of food are wasted at the retail level as a result of quality standards that place an excessive emphasis on appearance. If 1/4 of food that is presently wasted or lost worldwide might be salvaged, 870 million hungry people would be able to eat. Food waste in poor nations primarily occurs at the beginning and is caused by technical, managerial, and financial limitations in harvesting methods as well as cooling and storage facilities. Famine is a big concern, according to the Food and Agriculture Organization (FAO), population expansion and management of waste food (≅ 1.3 billion tonnes) can enhance the critical consequences. This is almost 30% of world nutrition manufacturing, which is thrown away every year [11,12]. Food loss and waste could be decreased by bolstering the supply chain through direct support for farmers and investments in transportation, infrastructure, and an expansion of the food and packaging industries. Food is lost and wasted primarily after the supply chain in medium and high-income nations. In contrast to the situation in developing nations, consumer behavior has a significant impact on developed nations. Literature research revealed that lack of cooperation amongst supply chain entities is a contributing element. Agreements between farmers and buyers may help to improve coordination. The quantity of losses and waste can be reduced by increasing attentiveness between consumers, retailers and businesses as well as by defining the use of food which is currently wasted [13,14].

Drying food products is the most sought-after method for preserving agricultural produce. The conventional drying technologies presently used in the food industry are hot-air-based systems that are normally considered energy intensive processes with higher Greenhouse Gas (GHG) emissions. The popular conventional drying methods are hybrid drying systems, heat pump drying, super-heated steam drying, vacuum drying, microwave drying, refractance window dehydration method, electro technologies, ohmic heating/drying, adsorption mediated drying systems and impingement drying. Around 35–45% of the energy input is wasted as the hot exhaust gases, incur high energy losses and emit high GHG emissions [15,16]. The other drawbacks of conventional drying systems are longer drying times, non-uniform exposure to the temperature and hardening of the food materials. To avoid these issues, the food industry is motivated to work on the improvement of the existing drying technologies and the development of alternative drying technologies. It is expected that the new generation of dryers and drying technologies promote more sustainable development with higher thermal and energy efficiency, lower operation costs and improved product quality. With the world progressing towards the application of green technology and sustainable methods, the use of alternative energy-efficient drying systems is of paramount importance. Due to the above reasons, solar drying processes are found to be the best suitable methods for the dehydration of food products and eliminate the environmental issues rising due to conventional drying processes [17,18]. In this context, an extensive review of solar dryers and natural materials for thermal energy storage has been carried out in this paper and the subsequent sections are organized as follows. Section 2 deals with the classification and review of solar dryers along with their comparative analysis. Section 3 deals with various energy storage systems used in solar dryers. Section 4 analyses the performance of various natural materials used for energy storage in solar dryers along with evolutionary classification of these materials. The various performance indicators used in the performance assessment of solar dryers were discussed in Section 5. Section 6 discusses the quality, economic, social and environmental impact of solar dried products. Polices, challenges, risks and recommendations for the improvement of existing solar dryers as well as development of new technologies were discussed in Scetion7 and finally, Section 8 highlights the salient features discussed in this paper as conclusions. The study concludes that solar drying processes with thermal energy storage devices based on natural materials are most preferred for delivering extended shelf life for food production in an energy-efficient and sustainable manner.

## 2. Solar drying technologies

Drying is a process of food preservation that includes evaporating water from harvested products to prevent the growth of bacteria. Owing to the free and abundant energy from the sun, open solar drying is one of the oldest known food processing and storage strategies for drying agro-goods. However, technological advancement led to thermal processes for use in agro-industry for processing and storage of food [19]. The inherent drawbacks of conventional energy sources and the benefits associated with solar energy such as cost effectiveness and efficiency provided long-term solutions for ecological development. Solar radiation was abundantly available globally, which replaced the traditional way of drying for preserving fruits and vegetables for a maximum number of days. Food drying is also a difficult process that involves inconsistencies in heat and mass transmission, as well as physical and chemical reactions that might impair product quality [20,21]. It is a difficult process that includes simultaneous mass and heat transmission along with physicochemical changes. A crucial step in the production of many different kinds of chemical products is the adjustment and control of moisture levels in solid materials by drying. Since it is employed in almost every plant and facility that produces or processes solid materials, in the form of powders and granules, drying solid materials is one of the most popular and significant unit operations in the chemical process industries. The quality of the final product and the effectiveness of the drying operations can both be significantly impacted by the chemical process industries [22,23].

Food drying is a diversified field as different foods require different types of drying processes. A natural or manufactured substance can be dried to remove surplus water and bring it up to the required moisture content. It requires a lot of energy to operate. Reducing the moisture level of foods is especially important because they often have substantially larger water contents than those appropriate for long-term storage. Enzymes, bacteria, yeasts, and moulds take longer to develop when there is less moisture in the meal. As a result, food can be kept and stored for a long period without going bad. The process of completely removing moisture from food until there is none left is another example of drying. When ready for usage, dehydrated food is rehydrated and nearly returns to its original state [24,25]. For agricultural products, especially those produced in medium to small quantities, solar energy drying is a fairly cost-effective method for preserving extra output. It is eco-friendly and it is still used to dry foodstuffs, agricultural products and crops on a domestic up to small commercial scale, greatly boosting the income of small agricultural farms and communities. Based on this, a variety of solar drying processes have evolved as follows [26]: a) Natural or Direct Sun Drying, b) Indirect sun drying and c) Mixed mode sun drying. Fig. 1 illustrates the classification of solar dryers into several categories.

Open sun drying (OSD) using Open dryers is the process of drying materials which are positioned on trays of thin layers, ground, concrete floors or mats. The process of exposing the drying materials to open wind and sun is illustrated in Fig. 2 [27]. It is the best traditional and favorable method because OSD is not dependent on other sources of energy, no additional provisions are required for drying products, is the most cost-effective process and skilful labor is also not required. However, OSD has several drawbacks, prompting researchers to hunt for alternatives. The potential for product damage from birds, insects, and animals is one of the main drawbacks. Rain, air humidity, and dew can all cause product degradation. Loss as a result of over-drying, spoilage due to the proliferation of microorganisms etc. can take place. A slightly modified method of OSD is natural or direct solar drying which is also considered traditional for dehydrating agricultural produce. It consists of a translucent cover, as illustrated in Fig. 3, which is intended to diminish temperature losses and to safeguard the foodstuff from rain and dust [28,29]. Its working principle is based on a direct solar dehydration strategy, and it is used to dry a variety of items, as shown in Table 1. A portion of the solar energy reflected on the transparent cover is transmitted within the box dryer, while the remainder is reflected. Furthermore, the food surface reflects the amount of solar radiation. The temperature of the substance rises, and it dehydrates. The air blasted into the cabin drier removes the moisture in the food substance [30,31]. The indirect method of sun dehydration is more competent than the direct dehydration method, illustrated in Fig. 4, and it is used to dry a variety of items, as represented in Table 2. Through indirect sun dehydration, ambient air temperature is raised with a flat-plate collector in this method. Forced-convection and Natural-convection systems are the two types of indirect sun dryers, depending on how the air is passed over food. Material quality necessitates low temperatures. The disadvantages of direct solar dehydration are mitigated by using an indirect solar dehydration method [32–34]. Caramelisation and localized heat damage are rare since sun radiations are not openly striking the agro-products. These are ideal for preserving vitamins as well as color in highly pigmented goods. A flexible insulated conduct is commonly used to connect the separate air heater and drying rooms [35]. The north side of the drying chamber has a door that allows loading. The air collector can be angled to capture the optimum amount of solar energy at the time of year when the dried crop is collected.

Mixed mode drying generates the necessary heat for the drying process by combining the effects of solar radiation impacting the material to be dried with air heated by a solar collector. Solar dryers have used a range of phase transition and sensible thermal energy storage methods, with a focus on the usage of rock beds [36]. Many self-contained solar dryers do not require supplementary heating since thermal mass enables short-term storage of heat to allow drying processes even in bad weather [37]. Agro-goods which are quickly drying are the most suitable products for thermal energy storage methods, as thermal mass is hardly enough to withstand the overnight drying process [38,148]. Agricultural materials are dried in a hybrid dryer using direct sun radiation and backup heat stored in the event of a power outage. A variety of items are dried in this process, as shown in Table 3.

Alternative supporting energy sources, such as diesel, LPG, electricity, biomass and solar energy P–V module are used to pre-heat the air. It's possible to use this in the single dryer and mixed-type dryers like direct-type and indirect-type dryers [170]. Hybrid drying has the potential to reduce material microbe contamination [39,40,171]. In comparison to conventional electric resistant dryer, a heat pump drier can save up to 40% on energy [41]. In a study of banana drying, researchers discovered that hybrid drying takes less time than artificial or open drying [42,43]. And also, when related to the open dehydration process

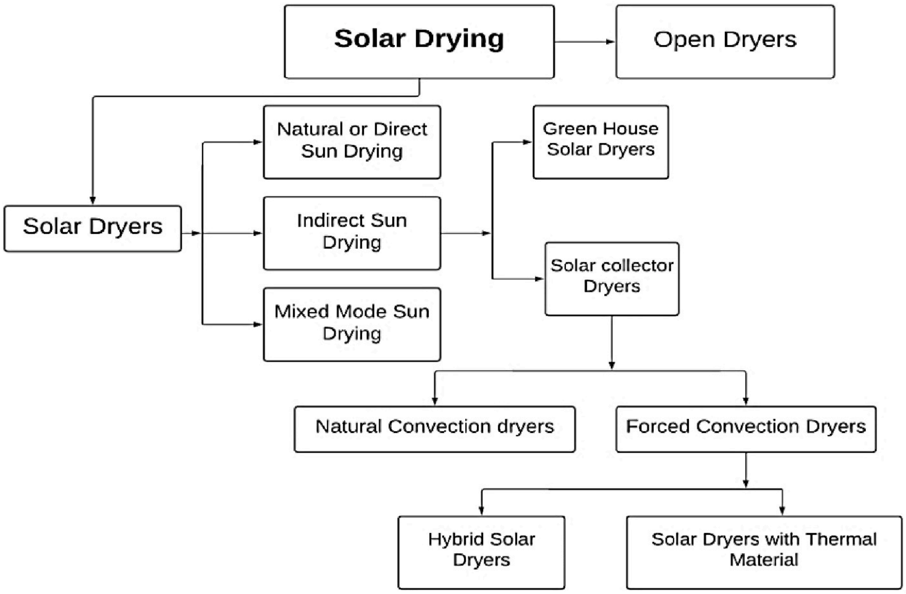


**Fig. 1.** Classification of solar drying process.

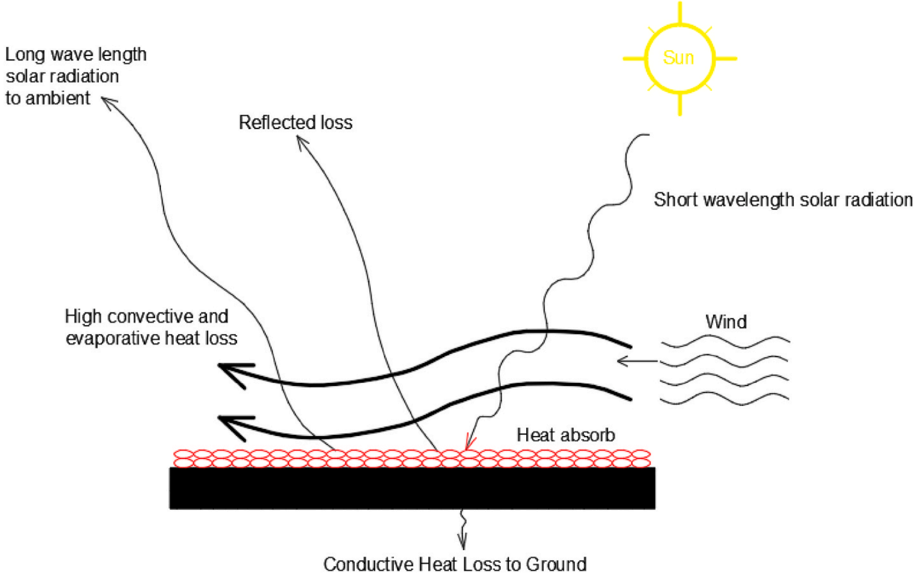


**Fig. 2.** Open sun drying.

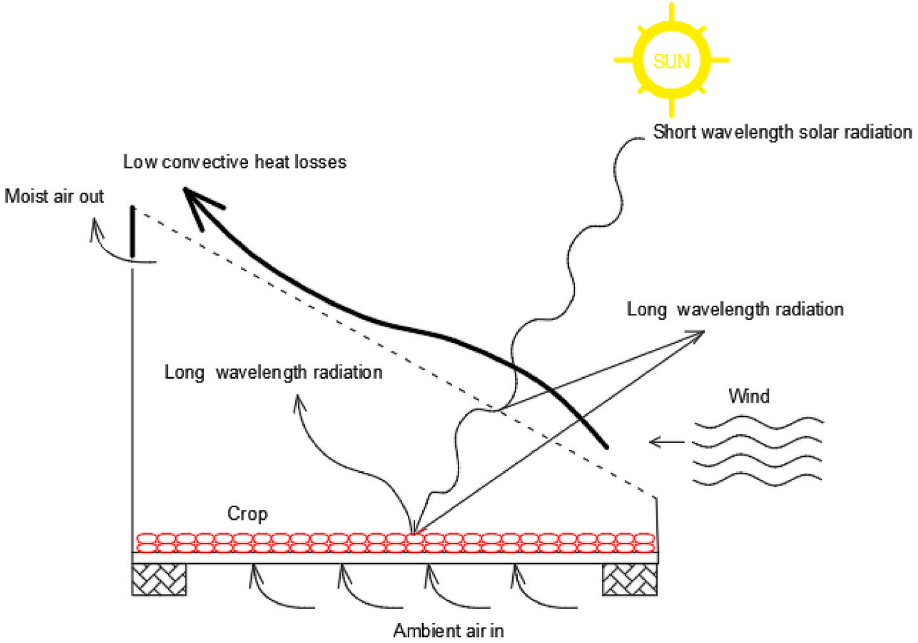


**Fig. 3.** Natural or Direct solar drying Process.

(Solar-drying), hybrid dried bananas had improved color, aroma, and texture [44]. Another hybrid portable tunnel drier uses a solar non concentrating type collector (Flat palte) and solar system P–V module to improve the drying performance of the peppermint [45,172]. They discovered that hybrid-dried peppermint had a greater quality than open-air-sun-dried 'peppermint'. These hybrid dryers had diminished 32 tonnes of $CO_2$ and 31% productivity over their lifetime. The hybrid dryer has also been used on a variety of agro-goods, including cashew nuts, pineapples and mushrooms [46,47]. It is ideal for drying crops quickly while maintaining great product quality.

The majority of the studies looked at individual solar drying methods; some looked at indirect methods, while others looked at direct methods [48,49]. Meanwhile, other studies used experimental and numerical methods to evaluate the various forms of dehydration performance to determine their benefits and downsides, as well as to identify future research possibilities. These studies, on the other hand, examined the various types of solar dryers in depth, focusing on their uses and benefits. In addition, this study examines solar-dryers with thermo-physical features of several "Natural Energy Storage Materials". Solar dryers' performance in "direct, indirect, hybrid-mode and mixed-mode" is examined by considering and without considering natural-energy-storage materials, is examined. Also examined are the performance of commonly used natural energy storage materials such as water, pebbles, limestone, rocks, concrete, sand, quartz, gravel bricks, soil, clay and sandstone. Solar-air accumulating system dehydrating performances are highlighted as mechanical needs for improving solar dehydration technologies for food. The solar drying process has different advantages and as well as disadvantages, similarly different types of dries, and various dried products. The key observations for the review conducted in this section have been summarized and tabulated in

**Table 1**
Several dehydrated agro-products by applying various direct solar-dyers.

| S. No. | Type of Solar Dryer | Dried Product | Observations | Remarks | Ref |
|---|---|---|---|---|---|
| 1 | Direct Solar Dryer | Banana | The models of Pabis and Henderson were shown to be the best fit for explaining banana sun dehydration curves. | The bananas took 21 h to dehydrate. | [84] |
| 2 | Direct Solar-Dryer: | Cocoa | The grade analysis revealed that a 20 kg treatment was capable of producing high-quality food. Brown beans were found in greater abundance in the lower loading regimens. | This is the utmost basic low-capacity solar-dryer. | [85] |
| 3 | Solar Assisted Heat Pump | Corn | In 240Hrs, lower the materials moisture content from almost 16%–14% (w.b). To reduce the moisture level by 1%, 1.24 kW were consumed for every grain tonne. | One of the best methods for dehydrating using a heat pump with low consumption of power which is 1.24KW/tonne. | [86] |
| 4 | Direct Solar Dryer | Mango | Mango dried in the sun for 12Hrs to reduce the moisture content from 95% to 13% (w.b). | It is simple and efficient, and it takes longer to dry than open sun drying. | [87] |
| 5 | Natural Convection Solar Dryer | Onions | After 43Hrs and 32Hrs, the moisture content of full-size and cut onions drops from 35% to 57% and 6%, respectively. After 24Hrs, the moisture content of preserved onions reaches 46% for full size and 6% for chopped onions. | Chopped onions are dehydrating faster than full size onions. | [88] |
| 6 | Solar Tunnel Dryer | Tomatoes | Tomato moist concentration almost diminished from 11 kg to 0.1 kg of water per kilogram when it is dried for 101 h in the open sun, but it takes only 86Hrs in the solar tunnel dryer. | A combination solar dryer is recommended for tomatoes. Insects, rain, and dust were removed from the samples dried in the solar tunnel drier, and the dried samples were of outstanding color and hygienic quality. | [89] |
| 7 | Solar Tunnel Dryer | Pineapple | This dryer can handle 120 kg–150 kg of pineapple at a time. | Rain, insects, and dust were kept out of the pineapple and dried in a die solar tunnel drier, and the dried pineapple was of great quality | [90] |
| 8 | Solar Tunnel Dryer | Fish | Silver jewfish dried from 71.56% to 14.75% on 3 days in the solar tunnel drier, compared to 71.56%–23.63% in 3 days in open sun dehydrating. | Solar tunnel dryer process is more efficient than the open sun drying technology which is consuming less time to remove moisture from silver jewfish | [91] |
| 9 | Solar Assisted Drying | Tea | Fresh leaves of tea are dried at a rate of 15.1 $m^3$/min and it is observed that primary moist concentration is reduced from 87% to 54%. Dehydration at a higher temperature causes the key element in tea to be lost, resulting in the loss of medicinal effects. | Quick dehydration process for tea leaves is not acceptable due to the loss of key medicinal elements, | [92] |
| 10 | Solar Tunnel Dryer | Apples | The open-sun dehydration reduced the moist concentration by 32%–11% in 32Hrs, however, the solar tunnel dryer took just 28Hrs. | The solar tunnel dryer worked best for drying apples, whereas open-air drying took a lengthy time. | [93] |
| 11 | Solar Cabinet Dryer | Chilies | Solar dehydrating reduced the moisture content from 06% to 4% in only 9 days, but open-sun drying took 13-days to dehydrate 12 kg of chilies. | When relating to open-sun drying and cabinet-drying, the time consumed by cabinet-drying is less than open-sun drying. Conventional solar dryers are better at predicting temperature and moisture content at a steady pace. | [94] |
| 12 | Natural Convection Solar Dryer | Chilies | Dehydrating 2 kg of chilies took 4 days in the solar dryer versus 15 days in the open-sun. | Concentrated drying process is more efficient than the conventional process. | [95] |

Table 4 [173]. The advantages and disadvantages of different solar dryers like natural, indirect and mixed mode drying processes are discussed by representing their level of construction dehydration rate and economy.

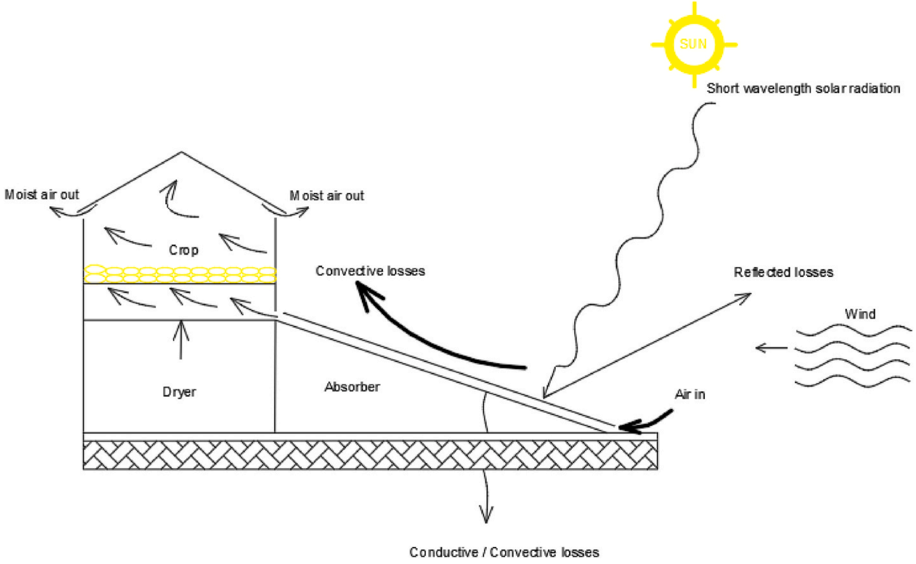


**Fig. 4.** Indirect solar drying.

## 3. Energy storage systems in solar dryers

The preservation of agro-products necessitates the use of a drying process. Hot-air at a range of temperatures (45 $^{O}$C – 60 $^{O}$C) is required for the safe dehydrating process, particularly for vegetables and fruits. Drying agro-products under controlled humidity and temperature settings allow them to dry quickly to the safest moisture level while maintaining optimum product quality. Solar-dryer system is coupled to a thermal backup division in hybrid solar thermal dryers. Thermal energy can be stored as a change in the material's internal energy, phase change material (PCM), thermochemical heat, or a mixture of these in well-insulated materials [50,174]. When there is no solar energy available, thermal energy dryers are used to keep the dehydration process going while maintaining a steady state temperature of the air. Heat energy storage forms a critical basis because it permits solar energy (also other renewable energy sources) with intermittent energy nature to balance the demand and supply. There are several methodologies for energy storing in numerous ways, including thermal, electrical, and mechanical [51–53]. Thermal energy can be stored as thermo-chemical heat, practical heat, latent heat a change and core energy of material in fine-shielded liquids or solids. Thermal storage is highly dependent on the usage of the type of solar-collector and demand. The solar air collector's estimated employed air temperature is crucial in determining the storage material's range [175]. To pick the precise material for heat storage, the thermo-physical parameters of the storage materials are regulated based on the temperature of the air [54–56]. The basic strategies for solar thermal energy storage are summarized in Fig. 5.

Agricultural and commercial goods can be continually dried using solar dryers based on thermal energy storage materials at steady state temperatures between 40$^{O}$C - 60 °C. Due to their use of clean energy resources and affordability, these dryers have gained popularity as a potentially feasible alternative to solar dryers that use fossil fuels [176]. These dryers use storage materials that can store energy during daylight hours and deliver that energy throughout the night. It plays a crucial part in ensuring the sustainability of the energy system by reducing the current burden on the energy supply-demand gap. Research on the thermal energy storage concept has been conducted in the last few decades for drying agricultural and food goods using a solar dryer [54,177]. A change in the material's internal energy, such as sensible heat or latent heat, can be used to store thermal energy. LHS stores thermal energy at the time of phase transition from liquid to vapour and solid to liquid in the form of latent heat of vaporization and fusion respectively [57]. PCMs have been widely studied and used for a wide range of applications due to their property of heat absorption and discharging during the melting and solidification process respectively [178]. The term "thermal energy storage" (TES) refers to the process of storing energy by cooling, heating, melting, solidifying, or vaporizing a substance. Storage by varying materials' temperature to rise or to lower is known to be Sensible Heat Storage (SHS) [57,58]. Due to the high moisture level and inexpensive price, bentonite clay and $CaCl_2$ were chosen as desiccant materials for a drier to dehydrate maize [58,59]. Moisture sorption of the 'desiccant materials' is almost 45%(w.b) and also, and they might be renewed at 45$^{O}$C. Using solar-collectors hot-air, the dehydration process was carried out during the day. And dehydration process was maintained at night by forcing hot-air from end to end of desiccant layer [179,228]. During the day, solar radiation replaced the saturated desiccant layer. Using this solar drier, 38% of the original moisture concentration level of 90 kg of corn was dropped down to 15% (w.b) in 24Hrs. Similarly, another study looked into the construction of a can-based absorbing solar air heater. The energy efficiency of three different varieties of double-flow solar heat collectors was calculated in different operating situations. Table 5 shows the differences in temperatures between Type-I, Type-II, and Type-III at 0.05 and 0.03 kg/s mass flow rates. At 0.05 kg/s air flow rate, the average temperature difference of air inlet and outlet ($T_a$) of Type-I, Type-II, and Type-III was determined to be 16.7 $^{O}$C, 13.01 $^{O}$C, and 12.27 $^{O}$C respectively. The temperatures at inlet and outlet ($T_a$) differences for Type-I, Type-II, and Type-III were 20.07 $^{O}$C, 17.19 $^{O}$C, and 15.14 $^{O}$C respectively, at 0.03 kg/s flow-rate. At 0.05 kg/s of mass flow rate, the collector efficiency for type I was found to be ideal. The Type I flat-plate collector consistently outperforms the Type II and Type III flat-plate collectors in testing results for efficiency. By generating turbulence and preventing dead zones in the collector, the barriers or cans guarantee that air flows freely over and beneath the absorber plates [60].

The designed system is installed at two positions that are below the dehydration compartment and below the solar-collector [180]. The sensible heat-storage component increased the air thermal efficiency of the solar collector to 28%, while the dehydration chamber's thermal-efficiency was 11.8%. Dehydrating camel meat was used to conduct a performance study. For dehydrating Valeriana Jatatnansi, another researcher used an indirect type sun-dryer with sensible-heat storage with engine oil material and latent-heat storage with paraffin RT- 42 material, with this 89%–9% (w.b) Jatamansi's moisture level is reduced. By integrating the energy-storage materials the dehydration

**Table 2**
Several dehydrated agro-products by applying various indirect solar-dyers.

| S. No. | Type of Solar Dryer | Dried Product | Observations | Remarks | Ref |
|---|---|---|---|---|---|
| 1 | Indirect Solar Dryer: | Straw berries | The dehydration times for the whole, halves, quarters, and discs strawberries were 28, 26, 20, and 24 h respectively. | Small farms can use an indirect sun drier, which yields top quality strawberries even in unfavorable weather. | [96] |
| 2 | Indirect Solar Dryer | Grapes | At a dehydrating flow of 31.3 $m^3/h.m^2$, the dehydration period was 13Hrs. | The thermal transfers, which in turn affect the output temperature and collector performance, are significantly better as compared to the collector without obstructions. | [97] |
| 3 | Indirect Solar Dryer: | Granny Smith apples | In an indirect type natural convection solar-dryer, Granny Smith apples of 1 kg are dehydrated for 8–10 h at 45.5 $^{O}$C to 50.5 $^{O}$C, with a final moisture content of 5%. | Small farms can use an indirect solar drier, which produces high-quality products even in adverse weather. | [98] |
| 4 | Indirect Solar Dryer | Beans | Whenever beans are dehydrated without any storage elements for 32Hrs and with the integration of storage elements for 24Hrs, the moisture content drops from 65% to 18%. | The findings indicate that the ambient air temperature within the cabinet has the greatest impact on the drying rate. The drying cabinet's internal air speed change has a minor impact that can be disregarded. | [99] |
| 5 | Indirect Solar Dryer | potatoes | The moisture content of figs declines from 70% to 20% when dried without storage material for 32Hrs and with storage substance for 12Hrs. | The relative correctness of seven theoretical models was examined and verified using experimental data. The drying curve of potato slices using the two dryers was found to be best fitted by two new dimensionless models. | [100] |
| 6 | Indirect Solar Dryer | tomatoes | At a temperature of 65 $^{O}$C, 0.3 m/s velocity of air, and relative humidity of 30%, the optimum dehydration results for tomatoes are obtained. The moisture level of tomatoes dropped from 80% to 18% in just two and a half days. | Predicted the kinetics and thermodynamics of tomato drying process. | [101] |

rate is improving when compared with open-sun dehydration. Therefore, the Jatamansi dehydration processing time is 120Hrs, whereas in the absence of energy-storage materials the dehydration processing time is 216Hrs, while open-sun dehydration took 336Hrs [61]. An indirect type solar-dryer integrated with energy-storage medium of a packed-bed was built, and the design efficiency was evaluated by dehydrating slices of orange. The efficiency of dyer exergy ranged from 50.18% to 66.58% without energy storage and 54.71%–68.37% with energy storage, respectively [62].

An indirect type solar-dryer with a system of forced-convection and an absorbent bed (sensible-heat) packing medium was created and evaluated [63,181]. By drying the Slices of bitter-guard the dryer's effectiveness was estimated under the environmental conditions of Coimbatore. As illustrated in Fig. 6, the dryer had a hot-air solar-collector with a 2 m surface area, fan and dehydrating space. At 0.063 kg/s air-flow, the moisture level of the slices of bitter-gourd dropped from 92% to 9% (w.b) in 7Hrs. At 0.014 kg/s to 0.087 kg/s air-flow, the regular efficiency of exergy changed from 28.74% to 40.67% respectively. Bitter gourd slices had an effective moisture diffusivity of 8.62 x $10^{10}$ to 12.95 x $10^{10}$ $m^2/s$ with the present setup, whereas with open-sun drying it is having the least value of 0.95 x $10^{10}$ $m^2/s$. At 0.014–0.087 kg/s mass-flows the normal efficiency of pickup is increased from 17.12% to 54.29% and for exergy, it is increased from 28.27% to 40.68% [64]. Similarly, for crop dehydration, an indirect type solar-dryer with a thermal-energy storage device has been manufactured. The dryer was used to help determine the color and flavor of the produce after continual dehydration [182]. As illustrated in Fig. 7, the dehydrator is developed with a 1.5 m area solar-collector and 6 portions of trays which can hold 12 kg of agro-goods. The dryer had PCM of 50 kg, which is used to preserve 6 °C more dehydrating air-temperature than ambient air-temperature. After sunset, the heat storage device came in handy for completing the dehydration process. As a result, the dehydration period could be greatly reduced [65,66].

## 4. Natural materials for energy storage in solar dryers

Generally, liquids and solids are capable of storing thermal energy. Substance enthalpy is because of thermo-chemical, latent heat and sensible heat and a combination of all. Various energy-storage systems in solar dryers have been illustrated in Fig. 5 [122,123,183]. Continuously, materials of Sensible Heat Storage (SHS) cause a rise/drop in temperature. These SHS materials are generally used as 'TES' materials in the applications of low/high temperatures due to their comparatively strong thermal stability and heat transmission capabilities [184,226]. Due to their suitability, stability, low cost of investment and effortlessness execution, SHS materials in solid state are employed in a variety of practical applications for storing energy. The topic of naturally available storage materials is covered in this article. Because solid materials have a higher heat capacity, SHS in solid state is a preferable choice for storing thermal energy [185]. Natural materials utilized in SHS can store heat energy without altering phase. Equation (1) governs the amount of solid state thermal energy storage in materials [29–31]:

$$Q = \int_{Tf}^{Ti} mC_p dT \tag{1}$$

**Table 3**
Dehydrated agro-products under mixed mode and hybrid solar dyers.

| S. No. | Type of Solar Dryer | Dried Product | Observations | Remarks | Ref |
|---|---|---|---|---|---|
| 1 | Mixed Mode Dryer | Potato | The drying temperature ranged from 53.8 $^{O}$C to 52.6 $^{O}$C. The air velocity, on the other hand, was set at 0.15 and 0.45 m/s. | For drying potatoes, a mixed-type solar dryer is better, and agro-goods are dried perfectly in a mixed-mode dryer. The thermal storage efficiency is more effective than indirect type dryer | [100] |
| 2 | Mixed Type Dryer | Tomatoes | For flat slices, the drying time ranged from 5Hrs to 21.25Hrs. For the wedges, the drying time ranged from 8.5Hrs to 23.25Hrs. | Predicted the kinetics and thermodynamics of tomato drying process. | [101] |
| 3 | Mixed Type Dryer | Paddy | Solar-dried rice had a higher degree of whiteness than sun-dried rice. | Results showed that quality factors weren't impacted by the solar dryer's operating parameters, except rice's whiteness, which was superior to samples dried in the sun. In comparison to those of the sun drying process, the final product's other quality attributes were all satisfactory. | [102] |
| 4 | Mixed Type Dryer | Mango | The moisture content of the mango was decreased to 23% by utilizing mixed-mode dehydrating and by 46.9% when exposed to the open sun for the same amount of time. | This drier is considered to remove moisture from mango during the time of the cold season, and there are different collectors. A combined solar dryer produces high quality dried items. | [82] |
| 5 | Hybrid Solar Dryer | Banana | The drier could dry banana slices of 30 kg in 8 h and identified that the moisture level diminished from 82% to 18% (w.b). The color, aroma, and texture of the solar-dried items were superior to those of the sun-dehydrating products. | The hybrid Solar Dryering process holds the color, aroma, and texture of the solar-dried items | [83] |
| 6 | Hybrid Solar Drier | Onions | Dehydrating an onion from a moisture level of 36%–7% (w.b.) results in a total energy of 23–62 MJ/kg water. By reutilizing the exhaust hot air, total energy savings of up to 70.7% can be obtained. | In a hybrid solar dryer, recommend recycling the hot exhaust air system to save overall energy. The hybrid sun dryer is ideal for drying onions at a controlled temperature. | [103] |
| 7 | Hybrid Solar Dryer | Pineapple | In the biomass, solar, and solar-biomass modes the day-end moisture level efficiency was 11%, 15%, and 13% respectively. | Recommends drying pineapple with a hybrid solar drier and utilizing a hybrid solar dryer in bad weather. | [104] |
| 8 | Hybrid Solar Dryer | Tea | A total of 60.2 kWH is required to maintain a temperature of 50 $^{O}$C in the air. | At low temperatures air, the hybrid sun dryer is recommended. | [105] |

Where.

$T_i$ = Iniital Temperature(K)
$T_f$ = Final Temperatures(K)
m = Materials Mass (kg)
$C_p$ = Specific Heat(kJ/kg.k)
dT = Change in Temperature

Since the non-boiling and freezing nature the following materials are used as soil, bricks, concrete, clay, gravel, sand and rocks are solid state natural energy storage for the applications of high/low temperatures [189–192]. These natural materials cannot be affected by the limitations of fluids and superheated steam. The flow rate, heat-transfer rate, packing density and size all have a role to enhance the efficiency of energy storage [122–124]. Some of the readily available natural energy storage materials include reinforced concrete, quartz, bricks, soil, clay, limestone, pebbles, rocks, gravel, sandstone, sand etc. Various natural materials for energy storage are used in different solar applications like solar water-heating, solar air-heating, solar drying etc., by integrating several storage strategies throughout the previous two decades. The development of solar-dryers that are combined with natural materials for energy storage is shown in Table 6 [125]. The results of the study revealed that sustainable methods were introduced for a variety of thermal-energy storing processes [126]. Environmental impact examination on indirect type solar dryers (ISD) coupled to a porous-bed SHS material yielded an estimated energy payback period of 2.2 years [127]. And it is claimed that the forced-convection solar dryer (FCSD) produced hygienic copra slices [128–130].

NES materials, which supply efficient and ecologically friendly energy during sun heating applications, can significantly meet society's needs. They ensure certain significant advantages over thermo-chemical energy storage systems [131,132], like low $CO_2$ emissions, enhanced ambient temperature, low CFC emissions, low cost for space cooling and heating, low electricity charges etc. NES materials like clay, gravel, soil and rocks may store up to 108 MJ/$m^3$ vol. of thermal energy [133,193]. Since these materials have exceptional thermal stability, they do not lose weight or degrade at high temperatures >100 $^{O}$C, resulting in a lengthy life span. Due to stratification being conserved over extended periods, the energy storing material cost is insignificant, and solutions underground have some benefits so, the ground is used as insulation. Their utilization allows solutions efficiently over large scale applications through Underground Thermal Energy Storage (UTES) systems. A system which is integrated with energy storage and solar-dryer is mostly

**Table 4**
Advantages and disadvantages of solar dryers.

| S. No. | Type of Dryer | Advantage | Disadvantage |
|---|---|---|---|
| 1 | Natural or Direct Solar Drying | • Simple construction,<br>• Loading and unloading are straightforward,<br>• The dryer is rain and dust resistant, and<br>• Agro-products can be dried at night or in the rain.<br>• There is less product contamination as a result of the enclosure's clear lid.<br>• Provide shelter from the rain, dew, and other elements.<br>• The acquired product quality is superior to drying outdoors in the sun. | • Crop damage is caused by rodents, birds, and other animals.<br>• Degradation is brought on by exposure to the sun's direct rays as well as to rain, storms, and dampness.<br>• Pollution from the environment, wind-borne debris, and dirt and dust contamination<br>• Damage from excessive drying<br>• Insect infestations development of microbes.<br>• Additional losses during storage as a result of inadequate or uneven drying |
| 2 | Indirect Solar Drying | • The rate of dehydration is faster when using a direct dryer.<br>• Slightly elevated dehydrating commodities, and conserved flat plate solar collectors were used and gave an excellent outcome, dehydrating performance,<br>• It is also appropriate for low or small-scale farms.<br>• This method prevents contamination of the finished product.<br>• It is a far more effective method of solar drying than the direct form.<br>• Prevent direct solar radiation exposure to preserve product quality.<br>• Some products dry more quickly than others.<br>• Final product conditions are not based on the conditions of a natural phenomena | • Construction costs are high.<br>• After a certain time, maintenance is required. |
| 3 | Mixed mode sun drying | • Accelerated drying with safe product moisture levels.<br>• Compared to other drying methods, drying takes less time. | • Agro-food capacity is very less.<br>• Grain dried over a year has a worse quality than grain dried using an indirect form of dryer.<br>• The cost of maintenance.<br>• The required capital cost is higher. |

beneficial for allowing the drying process continuously even after sunset, with this the dehydrating time is significantly minimized [134]. SHS or LHS systems can collect and store solar thermal-energy. As shown in Fig. 5, two types of energy storage technologies are now being explored and developed in solar dryers and the evolution of NES materials in different solar-dryers is shown in Table 6. The NES materials are positioned in a solar air collector (SAC) below the absorber plate in the first configuration [188,193]. The absorber sheet is in direct contact with it, and the absorbed thermal energy is delivered to 'TES' system via conduction mode of heat-transfer. The NES materials are retained in a heat exchanger of box type among the SAC and the second type is having a drying chamber [135–137]. The heat exchanger collects and stores energy, which is then utilized for drying products with incoming hot-air shown in Fig. 8. The NES system is located under the drying chamber in the third design [138]. The charged air from the SAC passes via the TES structure; there it is captivated by the NES materials and used for drying purposes during the hours when the sun is not shining [139,140].

## 5. Performance indicators for solar dryers

To evaluate the performance of solar dryers, numerous methods and processes were developed based on many merits, such as energy efficiency, time to dry and product quality. In solar drying, thermal performance is a reliable indicator to study the system's merits and can be quantified using energy analysis. Energetic performance is based on the first law of thermodynamics, which takes in to account the quantity of energy and the energy change with respect to the change in surroundings [144,187]. However, the drawback of energy analysis is that it only considers energies at the inlet and outlet of the system, and sometimes is redeemed as insufficient for system optimization as it neglects the irreversibility and thermodynamic losses [145–148]. In general, energetic analysis on solar dryers can be done on two main components: the drying systems and the drying materials. Drying systems of solar dryers include the solar absorber unit, drying chamber, and movement of heated drying air throughout the system. In short, energy analysis of solar dryer components is commonly done by applying heat transfer and energy balance based on the principle of energy conservation of the first law of thermodynamics. Determination of the thermal performance of solar dryers is important to achieve maximum moisture removal while using minimum amount of energy [149,227].

In literature, several indicators are commonly used to evaluate the thermal capacity of solar dryer components, especially for solar collector units. The amount of useful heat that can be harnessed from solar collectors can be calculated using heat removal factor ($F_R$) and incident solar radiation ($I_t$). $Q_u$ value is depended on the material of construction used for collector, as well as the surface area, as suggested by Eq. (2) [150].

$$Q_u = F_R A_C [I_t(ra) - U_L(T_t - T_a)] \tag{2}$$

The energy used for moisture evaporation can be calculated as [151].

$$E_{vap} = M_{water} \text{ X } H_{fg} \tag{3}$$

Thermal efficiency of a solar collector is the ratio of heat gain by air passing through the collector to the energy gained due to solar irradiation, given by Refs. [152,153].

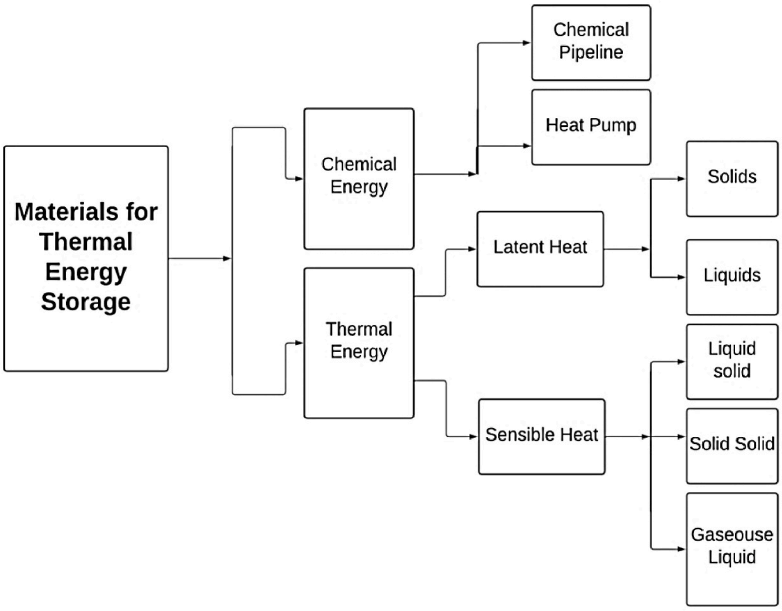
$$\eta_C = \frac{m_c(T_{out} - T_{in})}{A_c I} \text{ X } 100\% \tag{4}$$

Another indicator commonly used in energetic analysis is the thermal efficiency of solar dryers $\eta_d$. Essentially $\eta_d$ is the ratio of energy required to evaporate product's moisture to the energy consumed for the drying process. In short, thermal efficiency of the drying system is the ratio of the energy used for moisture evaporation to the energy input to the drying system.

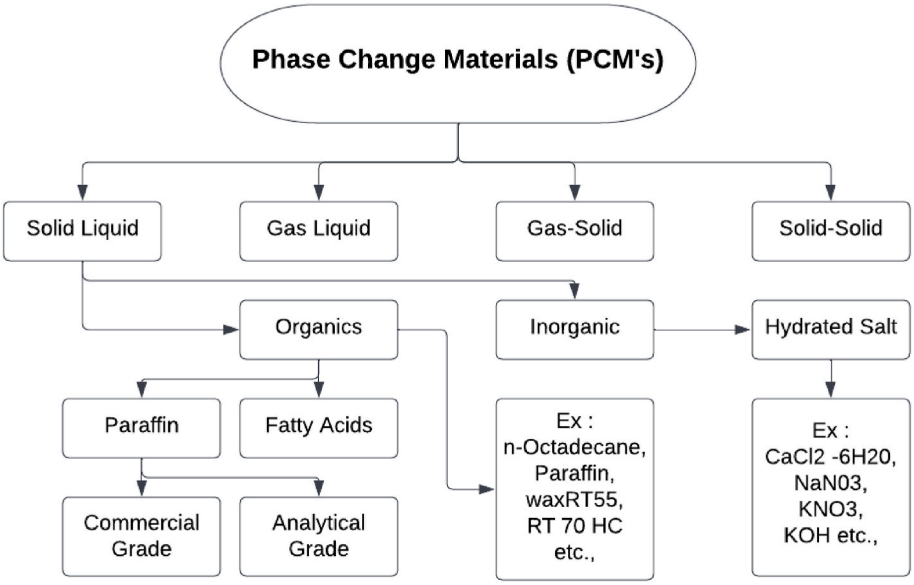
$$\eta_d = \frac{E_{evap}}{E_{input}} \tag{5}$$

In passive convection dryers, dryer efficiency calculation is based on the air movement due to natural buoyancy, whereas active dryers take into account the energy input through electrical fans or blowers, given by respectively [154,155]. Depending on the type of solar drying system, the energy consumed for the drying process would need to account for all sources of energy generated in the system. In hybrid systems, usually photovoltaic-thermal (PVT) hybrid dryers, the electrical efficiency of the solar collector is quantified as the system takes electricity into energy generation.

$$\eta_{d,P} = \frac{mL_V}{A_c I t_d} \tag{6}$$



(a) Thermal Energy Storage Materials



(b) Phase Change Materials

**Fig. 5.** Materials for thermal energy storage and Phase Change Materials.

$$\eta_{d,A} = \frac{mL_v}{A_c It + P_f} \tag{7}$$

The relationship between energy input to solar dryer and amount of water evaporated can also be used to define the performance of the dryer and to compare performance of the dryers, is Specific moisture extraction rate (SMER) in kg kWh$^{-1}$ relates how much moisture can be removed per unit of energy, whereas specific energy consumption (SEC) is the reciprocal of SMER with units of kWh $^{\mathrm{kg}-1}$ [156]

$$\mathrm{SMER} = \frac{\text{Amount of moisture evaporated}}{\text{Energy input to the dryer}} \tag{8}$$

$$\mathrm{SEC} = \frac{\text{Energy input to the dryer}}{\text{Amount of moisture evaporated}} \tag{9}$$

Pickup efficiency, or moisture removing efficiency of drying air is the efficiency measure of moisture extraction using hot air, and it can be calculated using

$$\eta = \frac{h_o - h_i}{h_{as} - h_i} = \frac{W}{\nu\rho(h_{as} - h_i)} \tag{10}$$

In hybrid systems where energy source comes from other than solar energy, solar fraction is determined to quantify the ratio of energy extraction of heat from solar collector to the overall energy available for the drying process [151]. Solar fraction can be expressed by

$$\mathrm{SF} = \frac{Q_S}{Q_t} = \frac{\text{Heat gain at collector}}{\text{Total heat supplied to dryer}} \tag{11}$$

From the drying material components, effectiveness of drying can be associated with moisture reduction within the samples. The mass of water removed (W) from a wet product can be calculated by [149].

**Table 5**
Solar collectors of Type-I, Type-II, and Type-III temperature differences in various air-flows [60].

| m (kg/s) | Type | I (W/m$^2$) | Time (Hrs) | $T_a$ in °C | T1 °C | T2 °C | T3 °C | T4 °C | $T_a$ Out °C |
|---|---|---|---|---|---|---|---|---|---|
| 0.03 | III | 420 | 9:00 | 23 | 25 | 27 | 26 | 28 | 29 |
| | III | 950 | 13:00 | 40 | 46 | 49 | 56.5 | 59 | 64 |
| | III | 650 | 16:00 | 30 | 32 | 35 | 36 | 33 | 39 |
| | II | 420 | 9:00 | 23 | 25 | 27 | 27 | 27 | 29 |
| | II | 900 | 13:00 | 40 | 42 | 60.5 | 54 | 48.5 | 64 |
| | II | 650 | 16:00 | 30 | 33 | 41 | 39 | 35 | 44 |
| | I | 480 | 9:00 | 23 | 24 | 26 | 26 | 28 | 32 |
| | I | 950 | 13:00 | 39 | 43 | 46 | 52 | 59.5 | 67.5 |
| | I | 690 | 16:00 | 32 | 33 | 35 | 39 | 44 | 48 |
| 0.05 | III | 450 | 9:00 | 23 | 24 | 26 | 27 | 26 | 28 |
| | III | 940 | 13:00 | 40 | 42 | 45.5 | 48 | 53 | 57.5 |
| | III | 660 | 16:00 | 29 | 31 | 33 | 36 | 37 | 38 |
| | II | 420 | 9:00 | 23.5 | 24 | 26.5 | 26.5 | 27 | 27.5 |
| | II | 900 | 13:00 | 39 | 44 | 46 | 50 | 54 | 57 |
| | II | 650 | 16:00 | 31 | 32.5 | 35 | 37 | 38 | 41 |
| | I | 450 | 9:00 | 23 | 24 | 25 | 28 | 29 | 30 |
| | I | 990 | 13:00 | 39 | 44.5 | 49 | 58 | 61 | 65 |
| | I | 680 | 16:00 | 31 | 32 | 34 | 37 | 45 | 42.5 |

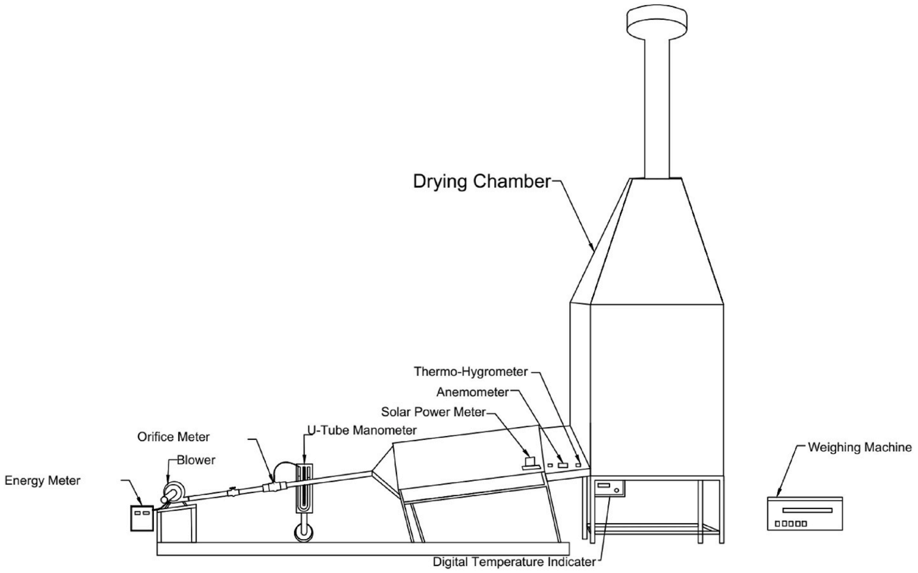


**Fig. 6.** Various instruments and configurations of bitter gourd slices were used in an experimental setup [63].

$$W = \frac{M_0\left(M_i - M_f\right)}{100 - M_i} \quad (12)$$

Moisture ratio, which is a dimensionless form of moisture content, explains the ratio of remaining moisture to be removed at time t over initial total moisture present. In the study of drying, MR is an important tool to understand the kinetics and drying profile as they vary from one material to another. MR is found to be mostly adequate to describe the diving behavior of some fruits and vegetables as it translates to drying constant, k ($s^{-1}$). This is an important parameter widely used in thin-layer modelling, to obtain drying curves as a function of time [157].

$$MR = \frac{(M - M_e)}{(M_o - M_e)} \quad (13)$$

TES is one of the most practised technologies to store energy in the form of heat to eliminate the gap between the energy supply and demand. As shown in Fig. 5, there are two main thermal energy storage technologies: sensible heat storage through a temperature change (sensible heat) of a material, latent heat storage through phase change (latent heat) of a material and thermochemical heat (chemical energy) by thermally induced changes in materials' chemical states. As compared in Table 7, the choice of TES method depends on a variety of factors such as the storage capacity, cost, temperature range, duration requirement as well as the specific application.

### 5.1. *Pros and cons of sensible heat storage*

Sensible heat storage materials are typically based on relatively low cost materials and thus extensively used, except the liquid metals. Due to the relatively good thermal stability, heat transfer performance and transport properties, sensible heat storage materials are the most used TES materials for high-temperature applications. Compared to latent heat storage, the specific heat of sensible heat storage materials is 50–100 times smaller, leading to the requirement of large volumes or quantities to deliver the amount of energy storage necessary for high temperature thermal energy storage applications. The other main issue of sensible heat storage is that the temperature of the storage medium decreases during discharging process, so the heat transfer fluid temperature also decreases with time.

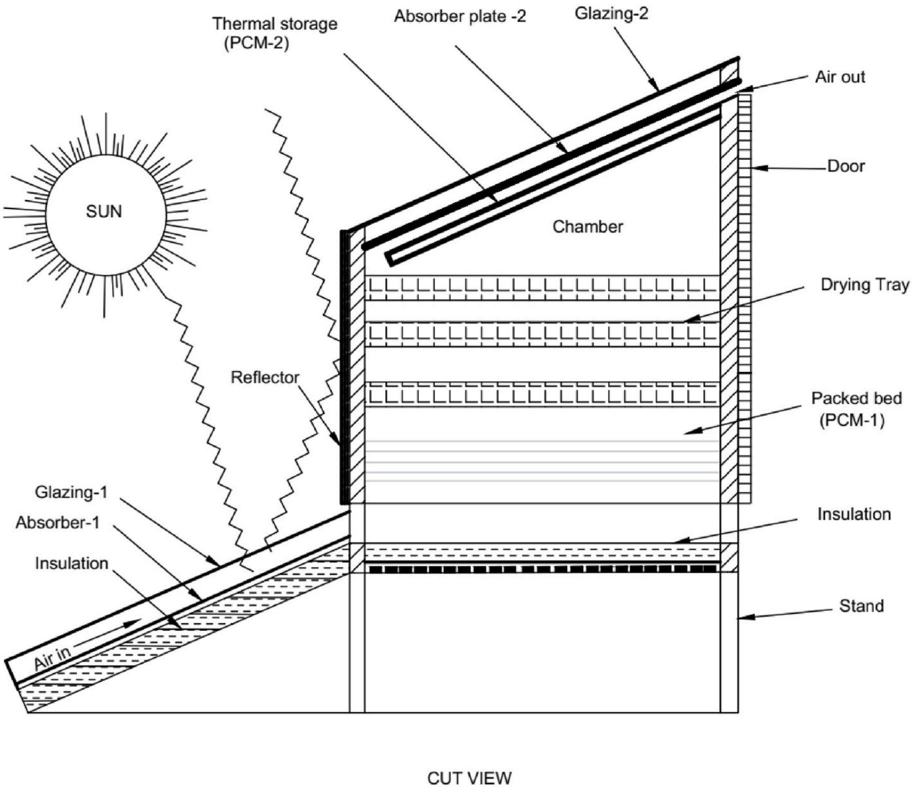


**Fig. 7.** A flat plate absorber with thermal storage [35].

### 5.2. *Pros and cons of latent heat storage*

Latent heat storage with PCM has a large latent heat of fusion so it can store more amount of heat than sensible heat storage. This large difference gives PCMs the advantage of a high energy storage density, which reduces the volume of the TES vessel and the outer wall surface area, and minimizes heat loss. Compared to sensible heat storage, the discharging process of the latent heat storage can maintain the temperature constant and make the contacting medium like HTF or the adjacent space temperature stable. However, the main drawback of latent heat storage is the low thermal conductivity of PCMs. Moreover, the heat transfer design and media selection are more difficult, and the experience with low temperature PCMs like inorganic salts has shown that the performance of the materials can degrade after moderate number of freezing-melting cycles.

### 5.3. *Pros and cons of thermochemical heat storage*

The thermochemical heat storage system is unique and suitable for solar energy storage owing to its advantages: high volumetric storage density, low volume requirement, long energy preservation duration periods with limited heat loss, low storage temperature (ambient temperature) and unlimited transport distance. However, it also has some issues to be tackled, such as poor reactivity and reversibility of reactions, harsh reaction conditions, toxic and corrosive products from reactions, etc. Currently, most studies are conducted at laboratory scales. Large-scale tests are needed to verify the feasibility and durability of long-term thermal energy storage. Furthermore, the criteria of material selections for thermochemical heat storage should be established.

## 6. Quality, economic, social and environmental impact of solar dried products

Due to the wide availability of solar drying systems in practice, the development of solar dryer technologies needs to be based on empirical knowledge of its energy profile and the anticipated performance over its expected lifetime. The information acquired from the literature is to identify and improve the quality of the products, plant operation costs, energy conservations, fuel versatility and pollutants [194]. In addition, selection of the right dryers must take into consideration the user's need and the end use of dried products, thus requiring the evaluation of the following domains. The impact of solar dried products on quality of the dried products, the economics of the dried products, social impact and environmental issues are studied for a better understanding of the solar energy conversion for post-harvesting process. Due to the widespread use of sun drying systems in daily life, the advancement of solar dryer methods must take their energy profile and predicted performance over their estimated lifetimes into consideration. Literature-based knowledge is used to evaluate and enhance product quality, plant operating costs, energy efficiency and emissions. The user's needs and the intended use of the dried goods must also be taken into account when choosing the appropriate dryers, necessitating an assessment of the following domains.

### 6.1. *Quality assessment parameters*

Physical, biological, chemical and nutritional quality qualities of dried agricultural produce can be classified. These quality factors play a big role in dried product specification. In general, improper dehydration processing conditions lead to significant nutritional loss and material degradation [67]. Although dehydrated materials are a good nutrient source, the dryness procedure may alter the quality. Color, flavor, and nutrient preservation are all quality characteristics. The market value of food is determined by these factors. Pretreatments and novel dehydration processes can aid in the production of good-quality food [68–70]. The color factor is an important qualitative attribute that determines customer approval. The total color changes of food during dehydration are influenced by color and enzymatic browning [71,72]. At high

**Table 6**
Evolution of NES materials in different solar-dryers.

| S. No | Type of Dryer | Dried Product | Energy Material | Observations | Ref |
|---|---|---|---|---|---|
| 1 | Indirect Solar Dryer | Fruits and Vegetables | Sand | When compared to drying time without storage material, the TES system with a dryer reduced drying time by 12Hrs. | [141] |
| 2 | Indirect Solar Dryer Forced Convection Solar Drier | Copra | Sand | A dryer was used to dry the copra integrated with sand. In the bottom and top trays, moisture content was reduced from 51.78% to 7.77% and 9.63% after 32Hrs. When compared to a dryer without sand material, the drying rate was faster. | [136] |
| 3 | Solar Green House Dryer | Coconuts | Sand | In 73Hrs, the drier concrete as a natural energy storage component and reduced the moisture content from 52% to 7%. The OSD took 174Hrs to complete. | [142] |
| 4 | Indirect Solar Dryer | Copra | Sand | For SAH with and without energy storage components, the specific moisture removal rate (SMRR) was calculated to be 0.81 and 0.94 kg/kWh, respectively. | [128] |
| 5 | Flat Plate Solar Air-Heater | Agro-Products | Sand | According to reports, the thermal qualities of air heaters made of SHS materials were the best. | [129] |
| 6 | Solar Air-Heater | Coriander | Rock Bed | By integrating rock-bed, the coriander is dried for more than 13Hrs and the moisture level is lowered from 73% to 53%. Without a rock-bed, the drying process is completed in 3-days. | [137] |
| 7 | Indirect Solar Dryer Forced Convection Solar Dryer | Bitter Gourd | Pebbels | A maximum drying rate of 2.3 kg of moisture is removed with pebbles. | [127] |
| 8 | Indirect Solar Dryer | Camel Meat | Pebbels | The drying time has been slashed by 10Hrs. | [143] |
| 9 | Solar Dryer integrated with the packed bed | orange slices | Pebbels | Die drying system exergy efficiency increased from 54.7% to 68.4% while using TES. | [126] |
| 10 | FCSD combined with gravel | Chillies | Gravel | The use of NES material increased the dehydrating time by 4H/day. | [144] |

temperatures, the process of dehydration is sped up by increasing the air's moisture-holding capacity. However, depending on fresh product thermal-sensitivity, high temperatures exceeding 80 °C damage the color and texture of fruits and vegetables [73].

Between 50 °C and 30 °C, the effect of dehydrating air temperature on dry chilli has been investigated [74]. In this research, the dehydration period was shortened, and the effective moisture diffusivity was increased, thanks to the higher temperatures. High air temperatures, on the other hand, had a significant impact on chilli quality, resulting in losses in volatile chemicals, nutrients, and color factors. Several food aromatic chemicals influence taste in the flavour of foodstuff. Several taste components become volatile when moisture is removed using the dehydration process, which needs to be controlled. The food microstructure has a significant impact on the texture and shape that affect flavor expression during the dehydration process. Chemical analyses or sensory evaluations can be used to investigate a food material's taste components. Organic analyses can deliver quantitative information on fragrant compounds, but they are invalid in terms of human taste perception. As a result, sensory evaluation plays an important part in determining whether or not food products are ultimately acceptable [71].

Industrialization of an indirect solar dryer for drying apples and watermelon slices [75]. The apple's initial moisture content dropped from 6.16 to 0.799 kg. Under the indirect sun drier, the watermelon's moisture level dropped from 10.76 kg to 0.496 kg. The color change of the watermelon and apple dried in the open sun was different for the watermelon and apple dehydrated in the indirect type solar dryer as shown in Fig. 9. The drying kinetics of turmeric is studied using direct and convection solar dryers. The direct sun dryer reduced the browning index of the samples by 25.65%, whereas hot air convection drying decreased it by 21.53%. In the direct sun dryer, the spherical particles examined with electron microscopies were more exposed and smoother, showing that the flow ability spots had been improved through packing processing [76]. The physical properties of the product are frequently affected by drying, resulting in variations in texture, color, shape and size. During dehydration, many enzymatic and chemical reactions will take place. Even though not all of these phase changes are worse, only a few of them turn the product into taste bad. It's important to compare the quality of solar dryers because it might vary greatly based on the air-flow rate, dryer design and drying temperature. Sensory and nutritional factors, as well as rehydration capabilities, are frequently assessed as part of a dried product's quality assessment [77–79]. Table 8 summarizes the attributes used for assessing the quality of the dried product.

### 6.2. Economic assessment

Evaluating the solar dryer methodologies for technical and financial viability involves economic and financial analysis. The solar-dryers are recognized as capital-intensive compared to other industrial dryers [106,167]. Solar dryers also provide various financial advantages over traditional sun drying processes, such as cheaper expenses for combustion equipment and fossil fuel materials. They also provide high-quality outputs, increasing market value and ensuring steady and high revenue despite varying climatic circumstances [186]. Solar dryers, in particular, allow small-scale farmers to minimize post-harvest wastage in an energy-saving and cost-effective manner, and also improved quality of products may propose new ways for employment and income opportunities. Payback period, life cycle savings and annualized expenses have all been used to assess the economic possibilities of solar-dryers in the literature [107,168]. However, it should be emphasized that numerous factors influence these calculations, including dryer system, climate conditions and physical qualities of the dehydrating materials [108,109]. Solar drying, for example, is economically viable for cash-type crops like coffee and tea in India, but unfortunately not economically viable for the vegetables like tomatoes and cabbage. The anticipated payback period for a 1000 kg volume greenhouse type drier for fresh

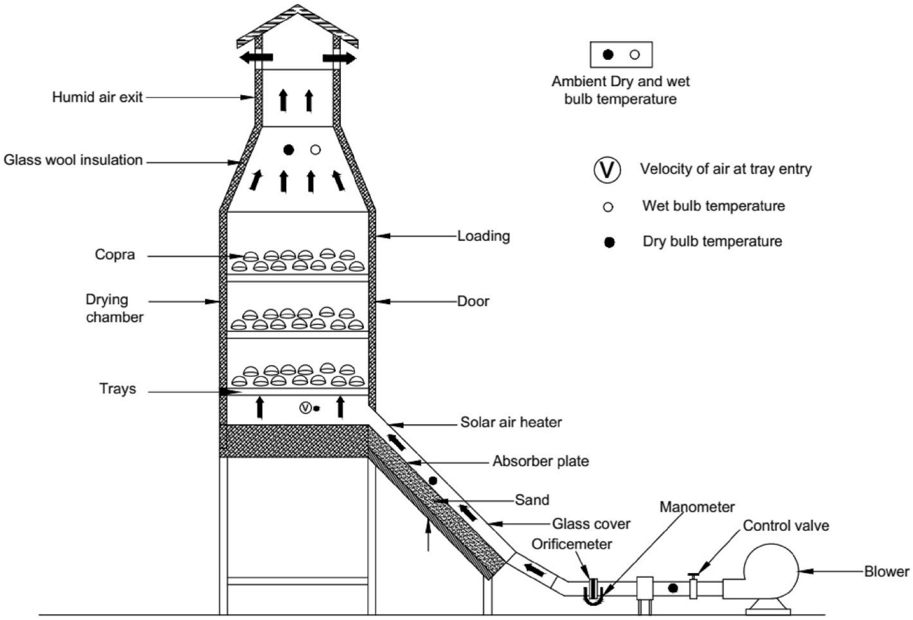
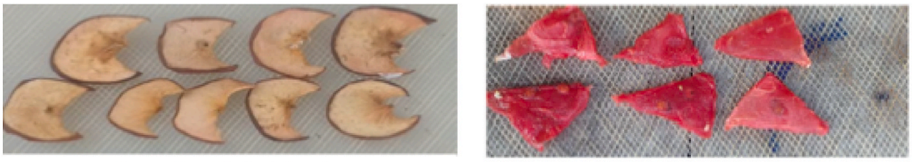


**Fig. 8.** Solar drier used for copra drying [128].

**Table 7**
Available energy storage materials used in the thermal energy storage systems [164,165].

| Material | Type | Density (kg/m$^3$) | Thermal conductivity (W/m-K) | Heat capacity (kJ/kgK) | Cost (€/m$^3$) |
|---|---|---|---|---|---|
| Rock | Solid | 1500–2800 | 0.85–3.5 | 1 | 64–742 |
| Concrete | Solid | 2000 | 1.35 | 1 | 76 |
| Sand and gravel | Solid | 1700–2200 | 2 | 0.910–1.180 | 6–8 |
| Ceramic tile | Solid | 2000 | 1 | 0.8 | 1600–3500 |
| Gypsum (coating) | Solid | 1000 | 0.4 | 1 | 78 |
| Ceramic brick | Solid | 1800 | 0.73 | 0.92 | 36–64 |
| Wood | Solid | 450 | 0.12 | 1.6 | 404 |
| Water | Liquid | 990 | 0.63 | 4.19 | 1.6 |
| Oil | Liquid | 888 | 0.14 | 1.88 | 6560 |
| Nitrite salts | Liquid | 1825 | 0.57 | 1.5 | 2200 |
| Carbonate salts | Liquid | 2100 | 2 | 1.8 | 6050 |
| Liquid sodium | Liquid | 850 | 71 | 1.3 | 2000 |



Open Sun Dried Apples
Open Sun Dried Watermelon

Indirect Solar Dried Apples
Indirect Solar Dried Watermelon

**Fig. 9.** Drying of apple and watermelon slices in IDSD and OSD [75].

items like chilli in Thailand is roughly 2 years [110,169]. In general, projections for solar dryer technologies' economic returns priced at market prices and ignoring any potential good environmental benefits, are substantially greater than traditional drying technologies. Other benefits, like low land use, larger yields and greater quality should be addressed to provide a more realistic cost-benefit analysis [195–198].

While energy analysis is a common approach used to minimize thermodynamic efficiencies within dryer systems, thermo-economic is a different take to estimating the cost-optimal structure and the optimal values of thermodynamic efficiencies in each component [158]. Thermo-economic is viewed as a promising diagnostic tool, even for complex systems [147]. Through economic analysis, solar dryer application has been proven to have an undeniable improvement in carbon footprint reduction associated with the energy-intensive drying process.

**Table 8**
Different attributes for measuring the quality of the dried product.

| S. No | Attributes | Observations | Type of attributes | Remarks | Ref |
|---|---|---|---|---|---|
| 1 | Sensory attributes | Sensory assessment for quality is a mixture of multiple perception senses that comes into play while deciding what to eat and how much to eat | Color, size, shape, homogeneity | Chemically, taste attributes may be approximated, but their optimum in terms of customer choice differs | [80] |
| 2 | Nutritional attributes | Organic characteristics are analyzed | Sugar and ash level, Vitamin-C and ascorbic acid level, acidity level and beta-carotene level | High amount of acidity level indicates degraded quality because of fermentation | [80] |
| 3 | Rehydration attributes | Rehydration capacity describes the amount to which it can restore lost moisture. | appearance, texture, aroma and flavor | The rehydration capacity of dried fruits is discovered to be influenced by cell wall, intercellular tissue and pectin component | [80]<br>[81]<br>[82] |

Solar dryers are highly effective devices with low investment to produce good quality dried products. The unit costs of useful energy for solar dryers were found to vary from 0.0034 to 0.015 USD per MJ of energy for different types of drying products [159]. An economic study to evaluate monetary savings due to the application of industrial solar dryers under the Lebanese climate indicates that the energy cost saving is determined on monthly basis, where it is dependent on the percentage of time when the solar dryer is used ($P_r$) the dryer energy consumption for operation $E_{month}$ and the cost of electricity for one unit of kWh, $P_{kWh}$, depending on the $P_r$ value which ranges from 0.1 to 1, the energy cost reduction records savings between \$130 to \$4160 per month for drying of 120 kg of various vegetable samples.

$$SM = P_r \quad X \quad E_{month} \; X \; P_{kwh} \tag{14}$$

From the determined SM and capital cost of the solar dryer, simple payback period for the dryer system was determined as follows

$$PP = \frac{C_{dryer}}{SM} \tag{15}$$

Another approach for economic analysis is the incorporation of cost-benefit analysis to compare the cost and benefits of solar drying to other means by taking into consideration the size, materials for construction, efficiency, operation, sophistication and sustainability of the driers which vary from country to country. Table 9 presents a comparison of economic analysis methods applicable to solar drying systems.

### 6.3. Social assessment

Global warming poses a huge danger to the world, especially because of high GHG emissions levels. Transferring to solar based energy from fossil-fuel energy has been attempted by governments and enterprises all around the world [111,199]. Most governments deal with the problem by enacting energy policies that include laws, international treaties, and

**Table 9**
Comparison of economic analysis methods for solar drying systems.

| S. No | Solar Dryer | Drying material | Economic Indicator | Findings | Ref |
|---|---|---|---|---|---|
| 1 | Mixed mode greenhouse SD | Red pepper and grape | Annualized cost of dryer Annualized capital cost (Cac) Annual electricity cost for Annual savings (Sj) for drying the typical product in the jth year Payback period | Dryer capital cost rs 660 USD. and Payback period is 1.6 years compared to 20 years of lifetime. | [160] |
| 2 | Modified greenhouse dryer | Potato chips | Payback period | Payback period is 1.11 years. | [155] |
| 3 | Indirect cabinet SD | Carrot, Corn, Mushrooms, Potatoes, Apples. Banana Cherries. Peaches | Amount of saved money Payback period (PP) | The capital cost of dryer is 8000 USD. and savings recorded range from 1400 USD to 12500 USD depending on mass and type of drying sample and percentage of dryer utilization. From this, the payback period range from 0.9 to 62 months. | [161] |
| 4 | Mixed mode SD | Various agri-produce | Capital cost of dryer Unit cost of drying Unit cost of useful energy Valuation of benefits | | [162] |
| 5 | Low cost SD -Direct and indirect passive dryers | Fish | Fixed cost - construction and maintenance cost Qualitative performance evaluation | | [163] |
| 6 | Direct and indirect passive dryers | Agro Products | Carbon savings | Life-cycle assessment on environmental performance of industrial solar thermal system (ISTS). Large-scale ISTS applications were found to achieve energy and carbon savings ranging from 35 to 75 GJ and 2–5 tonnes of C02 per kWth. depending on the geographical location. | [166] |

financial incentives for investors [112,113]. Most countries like Malaysia, China, Spain Canada, Germany and France are supporting and implementing clean and renewable energy for various applications. Renewable energy sources accounted for most of the global energy depletion which is 19%, with solar, geothermal, biomass and wind [114,200]. Almost 9.8 million jobs are available in the renewable energy sector. The majority of possible jobs are from Asia, especially from China [115]. Furthermore, solar-energy is considerably having benefit to public health and is eco-friendly, since several studies have discovered that greenhouse gas emissions (GHG) can increase the risk of allergies, cancer, cardiovascular morbidity and non-allergic respiratory disorders [116,201].

### *6.4. Environmental assessment*

Most drying systems use electricity and fossil fuels as sources of energy, resulting in high operating costs and environmental issues due to increased GHG emissions. Because of this reason, farmers and scientists have turned their focus to clean energy technologies like solar and thermal energy, which can be used directly or indirectly. The consumed energy of the solar dryer is advised to be calculated with help of indicators like carbon mitigation, $CO_2$ emission and embodied energy [116,117]. It has been discovered that a solar dryer system with a 40% efficiency level can reduce conventional energy usage by 27%–80% [118,202]. The fan consumes 5% of the total energy used in the forced ventilation greenhouse drier. Conventional and Solar energy collectively can save energy up to 20%–40% [119]. By utilizing electrical energy for 275 days at 100 kWH per day, the drying system with hot air produces carbon dioxide of around 15 tonnes per year [120,181]. Finally, it was determined that using solar dryers possibly will diminish emissions of $CO_2$ when related to general non-conventional drying methods [121].

## 7. Policies, challenges, risks and recommendations

### *7.1. Polices*

Recently, solar applications have significantly been considered due to the importance of protecting environment by governments. Government policies can reduce the energy crisis and the effects of global warming. Governments can provide great interest and motivation in using solar technologies, which include solar drying systems by applying policies such as renewable portfolio standards (RPS), feed-in-tariff (FIT), and incentives [204]. Some researchers also studied the solar energy related policies that were implemented in various countries including the united states, Germany, Spain, China, Australia, Pakistan, France, Malaysia, and Canada. Most of these policies deal with environmental issues and using energy efficiently [205]. Globally, numerous policies have been created and put into place to encourage the use of renewable energy for various processes apart from generating electricity alone, including feed-in tariffs (FIT), renewable portfolio standards (RPS), tax credits, pricing legislation, production incentives, quota restrictions, trading systems etc. (RE) [206]. Primary goals of these include minimizing the negative effects of energy and its allied sectors on the environment, decreasing dependency on fossil fuels, and promoting new industrial development [207,208]. However, the feed-in tariff (FIT) and the renewable portfolio standard (RPS) are the most widely implemented policies. Despite the numerous arguments around their efficacy, in general, a decision must be taken amongst them. In this case, the countries could choose which RE policy is appropriate given their unique situations and goals [209].

Industry statistics state that worldwide and in the United States, solar energy deployment grew at a record rate in 2008. The "2008 U S. Solar Industry Year in Review" report from the Solar Energy Industries Association revealed that the country’s solar energy capacity expanded by 17% in 2007 to reach a total equivalent of 8775 MW (MW). In 2007, the United States installed 342 MW of solar photovoltaic (PV) electric generation according to a report by the Solar Energy Industry Association (SEIA) [210,211]. As of 2010, 12% of the country’s electricity came from all renewable sources (solar, wind, geothermal, hydroelectric, biomass, and waste). By 2030, the DoE (Department of Electricity) wants to produce 10–15% of the country’s energy from solar sources [212]. By 2025, solar energy might supply up to 10% of the country’s energy requirements. According to a forecast created by the organization Co-op America and the research and publishing company Clean Edge, solar photovoltaic systems will produce more than 8% of the country’s electricity, while concentrating solar power systems would produce close to 2% [213].

**Renewable portfolio standard**: In its 28 states, the United States of America has implemented the RPS mechanism, which calls for the use of renewable energy sources including solar, wind, geothermal, and biomass for the maximum amount of production energy. Most policy goals seek to encourage the diversity of power-generating sources, lessen reliance on fossil fuels by the state, boost the use of renewable energy, cut carbon emissions, or other combinations of these goals [214,215]. For the most part, jurisdictions with RPS regulations permit utilities to trade renewable energy certificates (RECs) to meet their RE responsibilities.

**Feed-in tariffs:** Feed-in tariffs (FITs) have proven as the most successful government incentive programme for renewable technologies. In reality, FITs are responsible for half of all PV installations worldwide [216]. Around the world, FITs for PV are in use; in early 2009, FITs were available in 45 nations and 18 Canadian states, provinces, and territories. The paper creates the FITs system in Germany with a 20-year contract period and consistent payment for the energy produced. For the various types and rated powers of the generation system, different values of FITs are established. In late 2008, it was agreed to revise the Erneuerbare-Energien-Gesetz (EEG) to encourage a stronger price decrease. For new PV systems, a rate of FIT values depreciation was chosen [217]. FITs for electricity produced in Spain from PV systems, according to Real Decreto 436/2004. One of the primary policies for PV in France is the FIT. This system was released in July 2006. It entails a utility’s responsibility to buy electricity produced by renewable energy producers in its service area at a price set by public authorities and secured for a set amount of time. The value of a FIT is the total amount paid to an independent producer for each kWh of electricity generated by a RES-based system, including any premium over or above the market price but excluding any tax credits or other government-funded production subsidies. In both Europe and the USA, FITs have been the primary method for assisting RES development. They are now being used in 20 EU member countries [218]. While various Australian governments and territories have looked into FITs, only Queensland and South Australia now have programmes in place [219,220]. Queensland’s Solar Bonus Scheme rewards small power users, who are those that use less than 100 MWh per year. AU$ 0.44 $kWh^{-1}$ from photovoltaic systems less than 10 kVA for single phase and 30 kVA for 3-phase systems until 2028 [221,222]. Similar rules apply in South Australia, although the small electricity user must use less than 160 $MWhyr^{-1}$.

**Government incentives**: Government has a significant role to play in slowing the trend of GHG emissions. The government may enhance the adoption of PV through thoughtful policy initiatives, which will encourage related innovation and boost economic competitiveness through economies of scale. Governments of any size can lessen the environmental impact of their regions through a reduction in GHG emissions from carbon usage by increasing their reliance on distributed sources of renewable energy, especially roof-mounted PV. Overall, it is clear that the government is interested in expanding distributed renewable energy production in its regions, such as roof-mounted solar power [223]. Credit terms and tax incentives favour additional subsidies. They vary depending on whether the PV installations are carried out by an individual or a business investor. Commercial systems are exempt from VAT (value-added tax; 19% VAT in Germany). Additionally, some German areas offer investment grants.

**Renewable energy law**: The Law on Renewable Energy was passed by the National People's Congress in 2005 [224]. The growth of renewable energy in China has entered a new phase thanks to this regulation. Since REL was first introduced, numerous enabling laws and directives have been adopted to put it into practice. Guidelines for Using the Public Fund for Renewable Energy Development were published in 2006 by the NDRC (National Development and Reform Committee). Three priorities are listed in these rules. One is promoting the use of renewable sources of electricity (including wind, solar, and ocean). The other two goals are assistance with the use of renewable energy in building heating and cooling systems and research into energy alternatives that can replace oil. They agreed that there are two ways the public fund can be utilized. It may first be given out as a grant. Such grants are used by the recipients to conduct research and development on renewable energy sources. It can also be used to pay the interest on loans. Renewable energy projects that qualify may receive public funding to cover some of their loan interest.

### 7.2. Challenges

The design, construction, operation and examination of solar dryer systems as well as projects associated with them involve several issues, including structure [203–206], Political and social issues [229,230], economic provision, marketing, environmental condition [231,232], knowledge and efficiency [233]. Six potential criteria are examined, and the proposed factors are briefly described in Fig. 10. The quality and rate of drying of agricultural goods are efficiency factors. Geographical conditions relate to solar radiation quality and the use of solar dryers as a means of preventing climate change, as well as infrastructure factors that include things like infrastructures, the potential for luring private investors, the expertise of local engineers, economic sanctions, and the financial advantages of solar dryer use [225]. The shortcomings also include a lack of adequate production experience, a lack of executive management experience for the implementation of solar dryer projects, a lack of competition in the design, production, and supply of solar dryers, as well as other factors like loan borrowing and government financial support for related projects. Finally, the social, cultural and political aspects covered in the suggested questionnaire include farmer knowledge of solar dryers, indigenous people's choices about foreign-made dryers and their readiness to adopt the technology, as well as political hazards.

The quality of dried goods produced by solar dryers is superior to that of goods produced by conventional dryers. In sun dryers, product drying occurs quickly. A benefit of erecting solar dryers is adequate sun radiation. It is a good idea to use energy resources in solar dryers to stop climate change. Building solar dryers involve infrastructure (such as the required skills, tools, and so forth). To install solar dryers, it is feasible to entice private investors. Engineers need the appropriate tools, skills, and

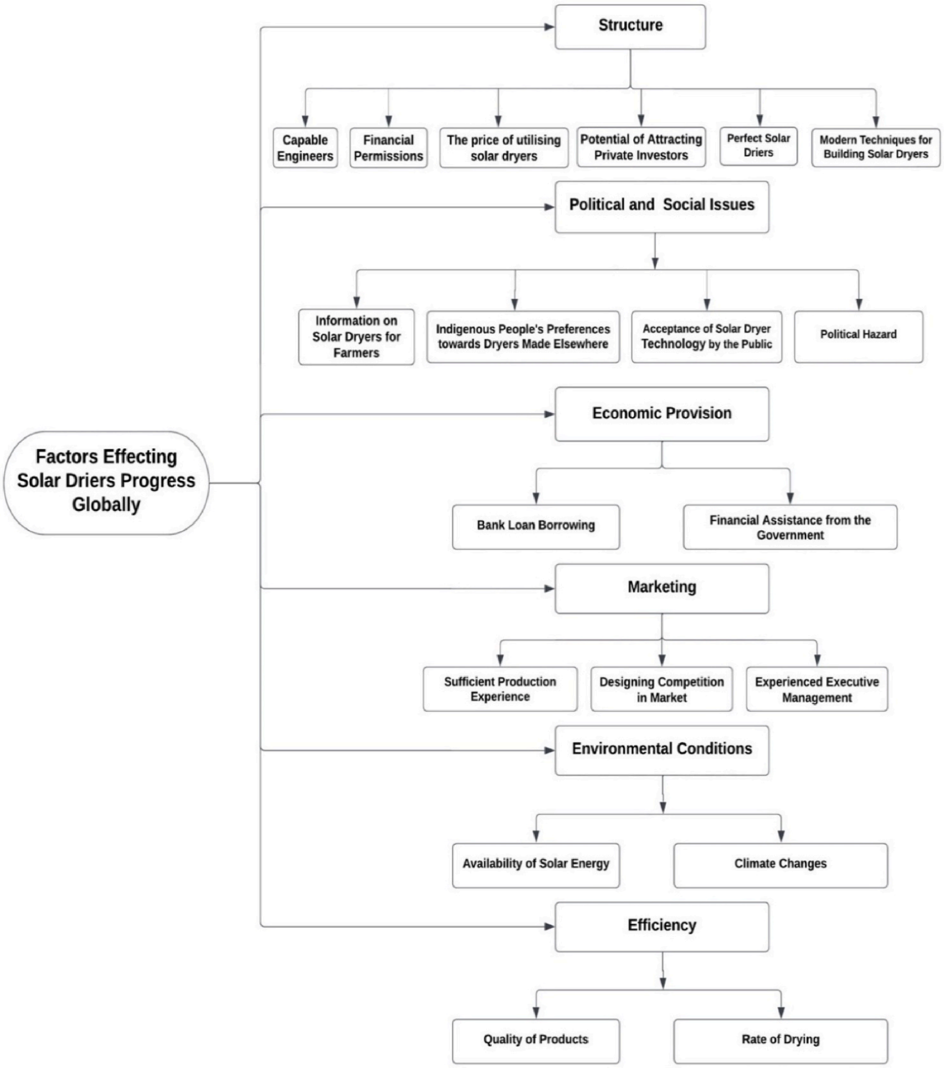


**Fig. 10.** Factors affecting the Solar Dryers Progress.

resources to create solar dryers. The main obstacle to the use of solar dryers, notwithstanding their low cost, is economic sanction. The government is giving solar projects significant funding. Farmers are not sufficiently informed about solar dryers and their advantages.

### *7.3. Risks*

In addition to all the significant project-related considerations, several project-related dangers could interfere with the effective completion of associated activities. Therefore, in addition to the associated components, three distinct types of the aforementioned risks—financial, external, and building risks—have also been analyzed [234]. Fig. 11 presents the risk-related factors that were previously mentioned. According to the figure, budget and pricing risks, inflation, interest rates, currency rates, and executive risks are included in economic risks. Structural risks include construction hazards which take into account discrepancies between designing and building, environmental and safety issues and risks associated with project execution. Finally, external risks consist of economics and environment, laws, political risks and demand concerns [235].

### *7.4. Recommendations*

Authorities must pay more attention to the characteristics that have been found and look into how they affect the advancement of projects related to solar dryers to increase the application of these systems. The elements and risks impacting the accomplishment or failure of connected projects in the world have been identified in this study. Therefore, it is advised that the influencing elements suggested in this study be given more consideration by governments and businesses. The results show that to decrease the effectiveness of these solar plants, the government and businesses must concentrate on the important elements affecting solar dryers. Solar dryers with higher efficiency would be built and manufactured by raising and updating the level of engineers' expertise and information and developing the designing and producing procedures. The results show that to decrease the effectiveness of these solar plants, the government and businesses must concentrate on the important elements affecting solar dryers. Solar dryers with higher efficiency would be built and manufactured by raising and updating the level of engineers' expertise and information and developing the designing and producing procedures.

More investors would be enticed to invest in solar drying systems if more people, including consumers, managers, and officials, were aware of their cost-effectiveness. On the other hand, as more private investors are drawn to projects using solar dryers, more attention will be paid to the fundamental framework for their execution, including the acquisition of the most recent information, design, and manufacturing technology. In the end, this will boost the effectiveness of solar drying systems. Therefore, one strategy that might be suggested in this situation is to educate and increase public awareness of the advantages of using solar dryers, particularly among farmers. Farmers' willingness to accept solar dryers will rise as their knowledge of them rises. As a result, it was easier to promote these systems to both niche and broad consumers. Furthermore, the government should be aware of this problem to further develop solar dryers as interventions have a direct impact on their implementation. The likelihood of completing solar dryer-related projects will rise as more expertise is gained in their design, building, operation, and management. However, as competition in this field grows, officials and staff members' efforts to enhance these systems' performance will also grow.

## 8. Conclusions

A detailed review of recent studies on solar dryer systems involving natural energy materials and storage systems has been presented. A review of traditional solar drying procedures and their improved versions, and an examination of research needs based on various techno-economic-socio-enviro-policy factors have been consolidated. The necessity to produce higher quality foods in large quantities is currently pushing the development of innovative dehydration technologies. This goal can be achieved by integrating solar dryers with natural energy storage materials to produce high-grade dehydrated food-stuff at a low cost. Agro-Products pre-treatment is very much required before the drying process to diminish the ultimate food quality deterioration. The combined dryer setup with PCM and forced-convection produces the finest output with the highest dehydration rate and maximum quality among the different dryer categories. The dehydration rate is permanently increased by employing a dryer with a forced hot-convection capability. The performance examination for several types of solar-dryers like 'direct, indirect, hybrid dryers and mixed mode' combined with the natural energy storage materials explored. The use of diverse types of sun dehydration technologies can greatly reduce postharvest damages for agro-products in underdeveloped nations. In addition, this paper summarizes the procedural guidelines for the development and

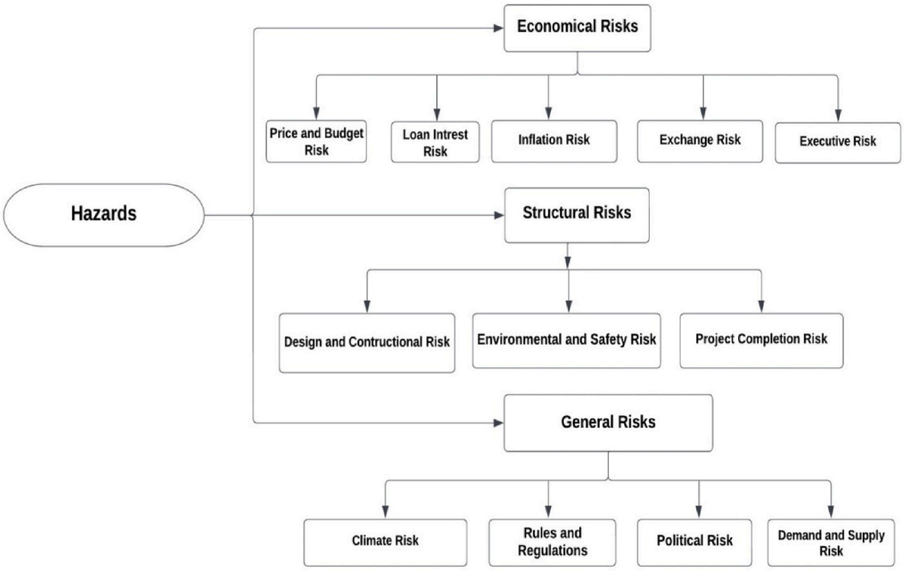


**Fig. 11.** The effective risks of the solar dryer systems implementation.

design of solar aided drying methods for agro-products. The usage of greenhouse dryers when it is integrated with hybrid solar-collectors is progressively recognized in the present research.

Novel thermal storage and desiccant materials are thus required for hybrid solar drying structures. But with the integration of NES materials with solar drying setups may increase the size of the solar dryer due to the low density of NES materials, which needs to be improved and more research is needed in this area. For food drying applications, the majority of the researchers considered water, sand, concrete and rocks. Pebbles, stones and rock are among the most suited materials, but high-pressure drop and low thermal conductivity at high flow rates are important issues. Sand has the unusual ability to absorb and reflect heat quickly. As a result, when it was sunny, the temperature rose quickly. The stored heat is expected to be discharged quickly during gloomy weather or no-sunshine hours. With this, a successful solar energy system can be employed for pollution-free drying processes by focusing on these areas. Finally, the challenges, advantages and prospects of NES materials integrated with solar-drying applications are discussed. From an economic standpoint, the system may operate after the sun has set, allowing food to be dried constantly and at a lower cost. Future research could look into different pretreatment procedures to provide the chemical and physical changes needed to increase mass and heat transmission. In addition, research is needed to determine the best storage material to avoid overusing storage materials and reducing the setup's volume.

## CRediT authorship contribution statement

**Bade Venkata Suresh:** Writing – original draft, Formal analysis, Data curation, Conceptualization. **Yegireddi Shireesha:** Writing – original draft, Formal analysis, Data curation. **Teegala Srinivasa Kishore:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Gaurav Dwivedi:** Writing – review & editing, Visualization, Investigation, Data curation. **Ali Torabi Haghighi:** Writing – review & editing, Visualization, Investigation. **Epari Ritesh Patro:** Writing – review & editing, Visualization, Supervision, Project administration, Methodology, Conceptualization.

## 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.

## Data availability

No data was used for the research described in the article.

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