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A State of Art Review of Performance Evaluation of Solar Cooker with Thermal Energy Storage Materials

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ABSTRACT

Solar cookers are an alternative to the traditional cooking systems; they are clean and sustainable; however, the practical use of solar cookers is still limited by the intermittency of the sun and the lack of sufficient amount of heat during the sunset. The lack of successful thermal energy storage (TES) implementation ends up in the lack of consistent cooking performance and lower reliability in domestic application. In dealing with this challenge, the current review critically reviews solar cookers that have sensible and latent heat storage materials to improve effectiveness, reliability, and off-sunshine cooking abilities. The aims of this review are to: (i) determine the performance of solar cookers that use sensible, latent and hybrid TES systems; (ii) analyse thermo-physical characteristics and applicability of widely used phase change material (PCM), e.g. acetanilide and stearic acid and binary salt mixtures; (iii) determine the effectiveness of sensible heat storage materials such as granite, sand and thermal oils; and (iv) determine critical advancements in technology, limitations and gaps in research associated with heat transfer enhancement, system integration and long-term stability. Research literature shows that the latent heat storage with the help of PCMs significantly increases the thermal retention that allows cooking several hours after dark and increases the efficiency of the entire cooker by about 20-40% in comparison with traditional solar cookers. Sensible storage of heat utilizes reliable short term heat availability of three to five hours, as compared to hybrid storage systems that combine high heat storage capabilities and predictable heat output. Overall, the combination of sensible and latent TES resources improves the work of the solar cookers and encourages the use of energy resources in the households in a more sustainable way. The research in the future ought to concentrate on high-end storage materials, cost-efficient designs, and scalable systems to enhance efficiency and acceptance by the users.

Keywords: Solar energy; energy storage; sensible heat; latent heat; solar cooker

INTRODUCTION

The need to be green, clean, and energy efficient in cooking technologies has been heightened worldwide due to the growing consumption of the fossil fuel, greenhouse emission, and subsequent environmental and health complications. The traditional food preparation practices that are founded on biomass, liquefied petroleum gas, and electricity are major contributors to carbon emission and indoor air pollution, especially in developing countries. In this regard, solar cookers have come out as a more peaceful alternative that can be directly utilized through the application of the sensitive solar energy in the domestic cooking set up. Solar cooking, in turn, minimizes the reliance on energy sources that are non-renewable and provides a low-cost-of-operation and carbon-neutral solution (Vangeel et al. 2021; Patel and Sharma 2021; Khan et al. 2022; Patel and Patel 2020; Kumar A. et al. 2025; Fasinu E. B. et al. 2025).

Amid these strengths, the use of solar cookers has been low among people since they are highly dependent on the availability of sun rays. Traditional solar cookers tend to work best during the sunshine days and therefore they cannot be used to cook in the morning, evening, or on rainy days. This variability of solar power has been noted to be a leading technical challenge to its acceptability and practical usability. To overcome this drawback, in recent years, the incorporation of thermal energy storage (TES) materials into solar cooking systems has become the focus of a significant amount of attention (Sharma et al. 2022; Lee et al. 2021; Kumar and Verma 2022).

Solar cookers made using TES can store surplus thermal energy when the sun is shining intensely and release this thermal energy when the sun is not shining, thus providing prolonged and reliable cooking time. Recent studies have shown the effectiveness of both sensible and latent heat storage (LHS) storage materials and especially phase change materials (PCMs) in enhancing thermal performance based on sensible and latent heat storage (SHS) storage materials, respectively. PCMs have high energy storage capacity and almost constant temperature release of heat, which makes them particularly useful in domestic cooking temperatures. Most recently, hybrid TES systems (SHS + LHS material) have been suggested to even out between high storage capacity and consistent heat delivery and improved system performance (Malik et al. 2022; Patel and Patel 2022; Meena and Chauhan 2023; Rajput and Tiwari 2023; Yadav and Patel 2023; Saxena A. et al. 2025).

Similar developments have been noted in the design of TES containers, heat exchanger designs, and integration plans of box, parabolic and Scheffler reflector-based solar cookers. However, issues of thermal losses, low rates of charging and discharging, compatibility of materials, long term stability and economic viability are yet to be resolved. Additionally, the generalization of the research findings is undermined by the absence of standardized performance assessment measures and comparative analyse of the results of the different cooker configurations (Meena and Chauhan 2023; Rajput and Tiwari 2023; Malik et al. 2022; Yadav and Patel 2023; Adavi M. et al. 2025).

It is on this background that the current review systematically analyzes solar cookers that have been incorporated with thermal energy storage materials to be used in the domestic cooking activities. It is a study that summarizes recent experimental and review literature, categorizes TES materials, and solar cooker designs, estimates their thermal performance, and specifies outstanding research gaps. This review is set to give a reference to the researchers and practitioners interested in advancing efficient, reliable, and sustainable solar cooking technologies through the synthesis of current developments.

DESIGN-ORIENTED CLASSIFICATION OF SOLAR COOKERS WITH THERMAL ENERGY STORAGE

Figure 1 follows the history of solar-cooker typology since the early geometry-oriented schemes up to the modern architecture-oriented paradigm. The classification in the past has been based on optical designs, such as box type, parabolic dish, and Scheffler reflector designs, etc. Though this taxonomy explains the concepts of solar concentration, it does not encompass the new advances in terms of the integration of thermal-energy-storage (TES) and heat-transfer designs. In modern designs, functional features are put in the foreground (e.g. direct and indirect heat-transfer paths, integrated or decoupled TES modules, and hybrid) and have been integrated. The updated classification is more in line with the current design requirements: operational flexibility, indoor safety, post-sunset usefulness, and high thermal performance. The organization of the literature according to this framework of architecture provides more understanding of why modern hybrid and indirect cookers have already replaced their predecessors, and thus, the scaffold becomes more relevant when dealing with the evaluation of the current studies.

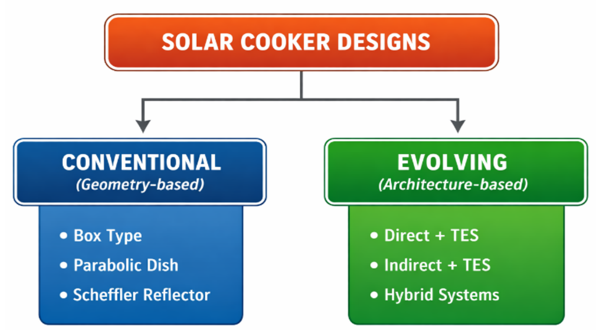

FIGURE 1. The representation of how the traditional and geometry-based categorization of solar cookers can be replaced by a dynamic and architecture-based model that presumes the inclusion of thermal-storage and heat-transfer paths (Patel & Patel 2024a)

SOLAR COOKER WITH THERMAL ENERGY STORAGE MATERIAL

The research by Buddhi and Sahoo (1997) discussed a solar box-type cooker with latent heat storage (LHS) to increase the cooking time. Figure 2 illustrates a schematic of the storage box of the cooker. The phase-change material (PCM) to store and release heat was the acetanilide of commercial grade, which was incorporated into a flat-plate collector. This experimental setup included a 0.44 m^2

collector area, 4 kg PCM, a blackened aluminum absorber plate and glass-wool insulation. A peak insolation (600-800 W/m^2) was attained; the absorber rose to 180 ^{o}C, and the PCM to 118 ^{o}C. Therefore, water temperature rose above 95 ^{o}C, and cooking efficiency improved by 20-25% compared to traditional systems. The heat stored kept the water temperatures above 60 ^{o}C at an average time of two hours after the sunset. The paper highlights the potential of PCM to be applied in prolonged periods of cooking and recommends future research concerning other PCMs, improved heat-transfer systems, and hybrid schemes. It maximizes PCM- sensible combinations of heat which are consistent with Scheffler-style cookers using reflectors.

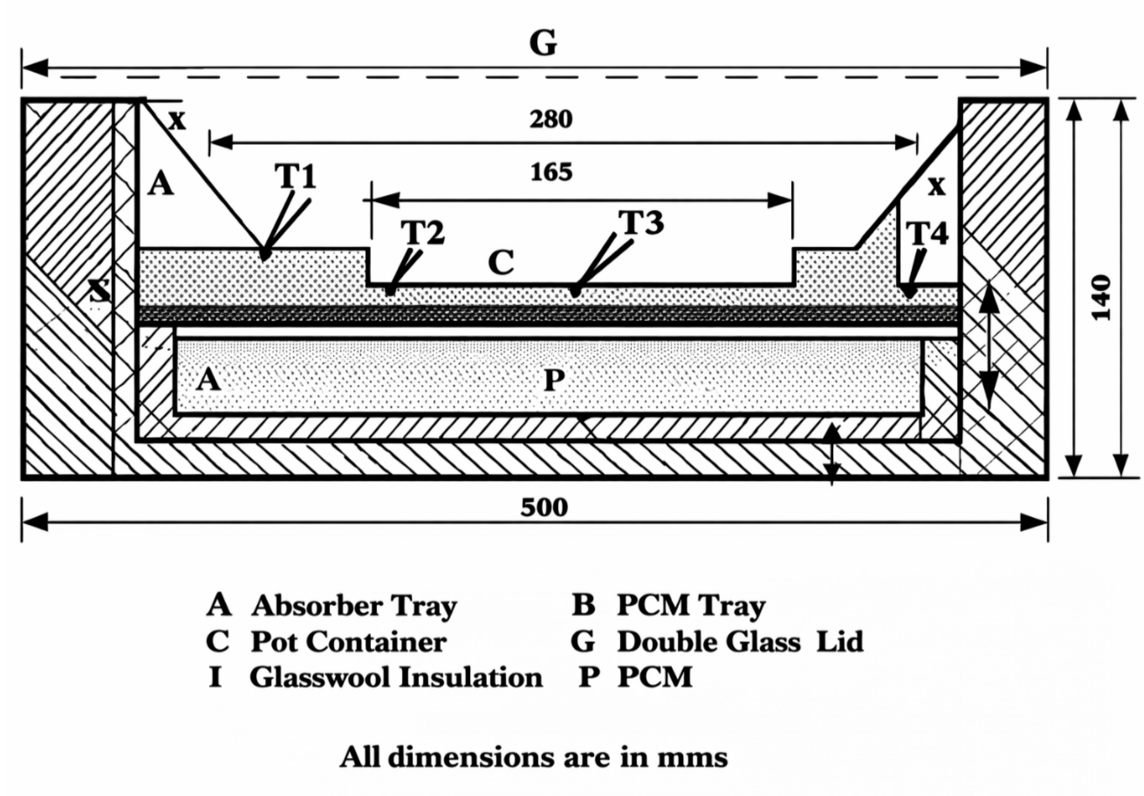

FIGURE 2. Schematic diagram of the box of a solar cooker with storage (Buddhi and Sahoo 1997)

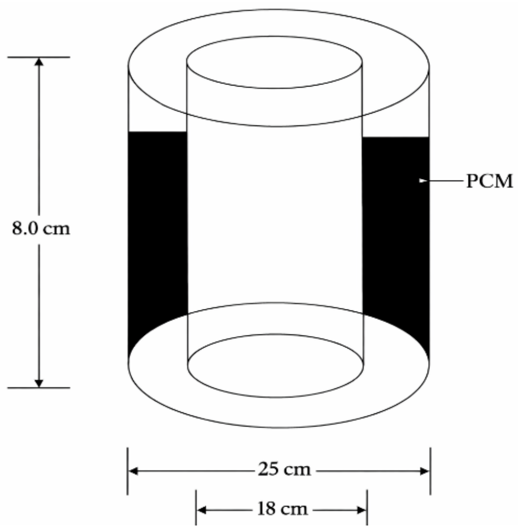

FIGURE 3. Schematic diagram of latent heat storage unit (Sharma et al. 2000)

Sharma et al. (2000) originally designed a latent heat storage (LHS) unit that used a box-shaped solar cooker to cook at night. The latent heat storage unit is illustrated in figure 3. Heat storage was done using stearic acid (PCM) that has a melting point of 69 °C. The system was designed with a flat-plate collector (0.6 m^2), 6 kg PCM, aluminum plate absorber made black and glass-wool insulation. The absorber plate reached 175 °C and PCM melted at 69 °C during operation with insolation ranged at 700 to 900 W/ m^2. in the air. The machine increased the cooking flexibility as it could maintain the water temperatures at over 80 °C over a period of just about three hours after the darkening process. The LHS system was 30% more heat-efficient than the traditional solar cookers. The research suggests the further studies around PCM-container materials, heat-transfer enhancement, and inclusion of the hybrid solar-cooking system, indicating the PCM incorporation to enhance the energy usage during the long-lasting working conditions outside of the peak sunshine. It optimizes PCM-sensible heat matchings of the Scheffler reflector method.

Buddhi et al. (2003) studied the combination of a latent heat storage (LHS) unit with a three-reflector solar cooker to enable cooking at night. Further thermal energy storage was done using stearic acid (PCM) which has a melting point of 69 °C. The experimental configuration featured a 0.72 m^2 collector area, 8 kg of PCM, blackened aluminum absorber plate and the insulation of glass wool. The insolation was 700-950 W/m^2 and the plate was exposed to the sun; the plate went to 200 °C and the PCM was melting at 69 °C. Late evening cooking became possible, and temperatures of the water were kept above 85 °C approximate 3.5 hours after sunset. The three-reflector design added to the efficiency and heat retention by 35% of the traditional cookers. The research recommends better designs in multilayer insulation, thermal-conductivity enhancing materials, and PCM containers. In line with Scheffler based cookers, it increases thermal storage with better performance by PCM sensible combinations of heat.

To test the thermal efficiency of a solar cooker, Sharma et al. (2005) used PCM storage unit and an evacuated tube solar collector (ETSC). Erythritol (melting point 118 °C, latent heat 339.8 kJ/kg) was used as PCM, and the experiments were done at Mie University, Japan. The ETSC (net absorber area of 3.64 m^2) conducted heat through a water loop of 370 W to a PCM storage unit (contained 45 kg of erythritol). The experiment showed the temperature of PCM reaching over 110 °C with the highest temperature of 138 °C, hence guaranteeing the availability of heat production during evening cooking. The time taken to cook decreased to between 96 and 120 minutes. Solar-energy utilization fractions of f1 = 15.7-21.9%, f2 = 22.1-30.8%, and f3 = 66.5-77.1% were obtained by energy analysis. PCM temperatures were lower than 100 °C, which limited winter performance. It is argued that improvement in insulation and design of heat-exchanger can lead to high efficiency levels, making the system a practical domestic solar-cooking.

Murty et al. (2007) evaluated the thermal performance of parabolic solar cooker with inclination cylindrical heat-exchanger unit to cook at off-site. The design utilized soya oil (density: 1075 kg/m^3) and mild steel tubing (length 157.5 cm, radius 2.07 cm) as the heat-transfer fluid (HTF) to transfer heat generated by the parabolic concentrator (TATA BP model) to another cooking chamber. Outcomes showed the maximum source-cylinder temperature to be 134 °C and the oil and food temperature was 120 °C and 95 °C, respectively. The overall duration of the cooking was 95 minutes. Energy analysis revealed that, out of 4726.80 kJ of incident solar energy, 159.20 kJ went to waste through cooking, and this equated to 3.47% increment energy to cooking efficiency and 99.17% increment energy to energy-transport efficiency. The design reduces glare and improves usability making the system to be appropriate in moderately sun insolated conditions.

Hussein et al. (2008) compared thermal performance of an indirect solar cooker equipped with PCM thermal storage to cook even after the sun goes down. The system had a flat-plate collector, wickless heat pipes, and magnesium nitrate hexahydrate (T_m = 89 °C, latent heat 134 kJ/kg) PCM. The apparatus used in the experiment included 15 elliptical wickless heat pipes to conduct heat, an indoor cooking device with PCM and steel wool (20% volume ratio) and two cooking pots (3L and 4L). The outcomes showed a PCM temperature of 109 °C at 3:00 PM, keeping 76 °C at 9:00 AM, thus, keeping evening and night cooking efficient. Noon cooking took 80 minutes on 420 W and evening cooking took 70 minutes on 300 W. The highest recorded incident solar radiation was 1300 W/ m^2. PCM retention-maintained meals at 65 °C overnight. The system is ideal in remote regions and more insulation and absorber-coating improvements might be beneficial.

Sharma et al. (2009) conducted an extensive survey of solar cookers with latent heat storage (LHS) systems, with a special focus on phase change material (PCM)-based thermal energy storage to improve the culinary output. They were able to discuss a range of PCMs, solar collector designs, and the corresponding thermal efficiencies of various cooker designs. PCM melting ranges ranged between 60 °C and 120 °C and storage capacities were between 150 kJ/kg and 250 kJ/kg. Experimental results showed the range of insolation between 600-1000 W/m^2 with an absorber plate taking temperatures of 150 to 200 °C. The water temperatures in integrated PCMs were sustained at temperatures exceeding 80 °C of 2-4 hours after sunset and this increased working life. The authors thus reported efficiency improvements of 20-40% as compared to traditional solar cookers. They suggested PCM thermal conductivity optimization, use of finned structures to increase heat transfer and the use of hybrid designs, which strengthened the pertinence of PCM-sensitive heat synergies in extending cooking times and overall heat transfer in solar cooking scenarios, a direction consistent with previous Scheffler reflector investigations.

To extend the time spent on cooking, Lecuona et al. (2013) developed a portable, parabolic solar cooker that uses a PCM as the latent heat storage and prolongs cooking time. To store the energy in high temperatures, sodium nitrate ($NaNO_3$) with the phase change temperature of 306 °C was utilized. The experimental installation included a parabolic reflector of 1.5 m^2, a storage module of 2.5 kg PCM loaded, an aluminum cooking kettle, and a multilayer insulation. Trials were conducted with solar irradiance of 600 W/m^2 to 900 W/m^2 obtain temperatures of the plate absorber in the range of 350 °C up to 400 °C, with the PCM stabilizing at room temperature of 310 °C. This allowed the cooker to maintain cooking-relevant temperatures more than 1.5 hours after dusk, with its high thermal retention, which increased efficiency by 25-35% relative to the standard systems. To complement the current PCM incorporated Scheffler reflector studies, the paper suggests improvement of the design of heat exchangers and the development of hybrid sensible-latent heat storage to enhance performance further.

Saini et al. (2016) examined a solar cooker with a built-in thermal energy storage (TES) unit in situ by using a parabolic trough collector (PTC). Sodium acetate trihydrate, which is a PCM with melting point of 58 °C was chosen to store excess thermal energy to cook in the night. Their experimental apparatus consisted of 2 m^2 PTC aperture, 10 kg PCM TES unit, stainless steel heat exchanger and aluminum cooking pot which was black. The range of solar irradiance was 650 to 900 W/m^2; the PCM was at its phase change temperature of 58 °C and the absorber plate was at 280 °C. Therefore, the system maintained the water temperatures at levels over 80 °C, 3-4 hours after sunset, which made cooking longer than traditional methods. An increase to 30-40% in efficiency compared to standard cookers was reported. The authors propose to include hybrid TES units in subsequent applications to increase heat transfer and storage time.

Nkhonjera et al. (2017) have carried out a stringent evaluation of TES architectures, storage constituents, and cooking efficiencies in solar cookers with heat storage. Their test analyzed an array of sensible heat storage (SHS) and latent heat storage (LHS) systems, which examined the effect on the cooking time and efficiency. PCM melting points were 50 to 350 °C in materials, and PCM based systems have been reported to increase thermal efficiency by 20 to 40 °C. Due to their stability and large latent heat capacity (~200 kJ/kg), sodium acetate trihydrate and erythritol became the PCMs of choice. The storage units of sensible heat like rocks or oil storage units prolonged the period of cooking to three to five hours after sunset. The authors determined that hybrid storage (PCM+SHS) is more effective in increasing the heat retention and transfer, thus making solar cooking feasible even outside of the peak hours of irradiation. Recommendations should be made on the further improvement of heat-exchanger designs and improvement of PCM thermal conductivity to obtain better performance.

Coccia et al. (2018) consider a solar box cooker with a high temperature with a thermal storage unit (TSU) based on solar-salt that is aimed at making it possible to cook during the night. The TSU contains 4 kg of a ternary blend of nitrite/ nitrate salt (53% KNO_3, 40% $NaNO_2$, 7% $NaNO_3$) as PCM, with a 145 °C phase transition temperature. The system uses a solar- box cooker having a concentration of 10.78 and a two-walled stainless steel storage tank, which is loaded with PCM and a 3 kg silicone oil heat-transfer medium. Findings showed that the PCM reached 145 °C in 1.73 h and spent 2.27-3.39 h in the range of above 130 °C and significantly extended cooking times. The heating efficiencies were reported to be ranging between 4-12%, and cooling time extension to the performance of PCM between 65.12 and 107.98%.

A solar thermal storage and cooking device based on magnesium chloride hexahydrate (melting point 118 °C, latent heat 167 kJ/kg) used as PCM is introduced by Bhave and Thakare (2018). The system is made of 84 cm aperture parabolic dish concentrator (45 cm focal length) and a thermal storage vessel, which consists of 21 aluminum PCM tubes immersed in 660 ml of heat-transfer fluid (HTF). The experimental tests were done in Mumbai, India. The PCM obtained 135 °C in 50 minutes to cook after sunset. The appliance was able to cook 140 g of rice in 30 minutes. The documented cooking efficiency was 5.41% and the thermal storage efficiency was 32.38% and the utilization efficiency was 32.66%. The system can be described as small, efficient, and fit in the home environment.

Cuce (2018) applied a thermodynamic analysis of box-type solar cookers and made a comparative study through a thermodynamic analysis and experimental study using sensible thermal energy storage (TES) materials. The main aim was to determine the efficacies of three different storage materials namely, concrete, pebbles, and sand. The system used an aluminum absorber plate, an insulated cooking chamber and a 0.4 m^2 collection area. The highest temperature of the absorber plate under trial was 165 ^oC and the solar insulation was between 600 and 900 W/m^2. The TES substance affected the boiling time of water: in the absence of TES, it took up to 50 minutes, with concrete, stones, or sand, it took 65 to 85 minutes and once it got dark, the water was boiling over 60 °C two to three hours. The results revealed that TES made of pebble had better performance compared to traditional cookers in thermal performance, and it increased efficiency by 30%.

In off-sunshine cooking, Mawire et al. (2020) were able to make a comparison between two solar cooking storage pots and the Wonderbag slow cookers. Figure 4 is a photo of a parabolic dish solar cooker that was used in the experiment. The aim of the study was to enhance the performance of slow cookers in terms of efficiency and heat retention by using TES materials and insulated slow cookers. The experimental parameters were the following: storage pot materials, rock based and oil-based TES; solar insulations, 700-950 W/m^2. The highest temperatures obtained were 160 °C in the case of oil-based TES and 145 °C in the case of rock-based TES. This was found to be beneficial to cooking efficiency with oil-based TES being found to be 30% more efficient than rock-based TES. The use of a Wonderbag slow cooker with heat retention ensured that food could remain over 65 °C with a minimum of four hours remaining until it went bad. The authors made the conclusion that oil-based TES is better to be used in solar cooking, and the slow cookers addition enhances thermal efficiency, which allows further cooking when the sun is at its best.

FIGURE 4. A photograph of the parabolic dish solar cooker used in the cooking tests

Milikias et al. (2021) analyzed the performance of an improved box-type solar cooker with sensible TES to improve the level of heat retention and cooking performance. The main goal of the study was to optimize the thermal storage system regarding its ability to cook longer during periods when there was no direct sunlight. Important experimental findings are: TES materials-sand, granite stones; insolation of the sun 600 to 900 W/m^2; top temperatures-absorber plate 175 °C, cooking vessel 100 °C or above. Without TES, boiling took 55 minutes and with TES, boiling took 70 minutes. The heat storage increased cooking efficiency by 15 to 20%. The high-temperature of the cooking vessel was sustained at more than 60 °C during the night over 3 hours. The authors concluded that granite stones are an efficient and low-cost TES material with a better thermal performance than sand.

Lentswe et al. (2022) experimentally measured the energetic and exegetical performance of a solar cooking system that makes use of TES to boost off-sunshine cooking. The system used latent heat storage unit and the parabolic dish collector. Among the important conclusions are: the solar radiation- 700-900 W/m^2; PCM- erythritol (melting point 118 °C); the maximum temperatures- PCM, above 118 °C, cooking vessel, above 100 °C, absorber plate, above 195 °C. Boiling was realized in 45 min and 60 min without TES and with TES respectively. Efficiency of cooking was found to be 25 to 30% higher in comparison to traditional methods. Depending on PCM thermal characteristics and heating losses, exergy efficiency was 12 to 18%. The cooking pot was maintained at a temperature exceeding 60 °C with the aid of heat retention, and it took the pot an estimated 3.5 hours after the dark. The research confirmed that the TES integration does increase the efficiency of solar cookers allowing cooking after the sun goes down and favoring sustainability.

Verma et al. (2022) constructed an analytical model to predict the thermal performance of a box-type solar cooker using sensible TES in different conditions. This model takes into consideration the radiative, convective, and conductive radiative losses. Important discoveries are: solar radiation-500 to 900 W/m^2; sensible heat storage medium- oil and sand mixture; physical and geometrical-glass wool insulation, black coated aluminum absorber plate, collector area 0.5 m^2. Highest temperatures cooking vessel, above 95 °C, absorber plate, 190 °C. It took around 70 minutes to boil. Efficiency in cooking was 20 to 30% greater than a traditional sun cooker. Retention of heat stayed at 60 °C or more approximately three hours after the darkness. The authors determined that sensible heat storage increases the energy retention, which ensures the extension of cooking times when the sun sets.

To achieve efficient storage and exploitation of the required heat, Papade and Patil (2022) investigated the thermal properties of a concentrated solar cooker combined with binary salt phase change material (PCM). The study was aimed at enhancing thermal stability and storage capacity of PCM to achieve culinary applications beyond the scope of daylight. The major findings are as follows:

solar insolation: 700 to 900 W/m^2; PCM composition: 60% $NaNO_3$ + 40% KNO_3 binary ion mixture; physical and geometrical aspects: 10 kg PCM mass, concentrator collector, stainless-steel cooking pot with black coating. Thermal performance-PCM melting temperature- 222 °C, absorber plate- more than 250 °C, cooking vessel- more than 100 °C. Insulation maintained the temperatures at above 80 °C well into the night after the sunset of about four hours. The effectiveness of conventional solar cookers was 30 to 40% lower than that of cooking with the device. The research highlights the efficiency of binary salt PCM during the high temperatures so that it can be utilized to cook over a long duration beyond the daylight hours.

The article by Tawfik et al. (2022) is a critical evaluation of the performance of a solar cooker that has a tracking-type bottom reflector, and an innovative thermal storage-built-in absorber plate. The major aim is to add to the heat storage and cooking capacity to sustain operations even during cloudy seasons when the sun is not shining optimally. It consists of an experimental apparatus made of a modified box-type solar cooker that has a tracking bottom reflector; the plate of absorber is combined with a thermal storage medium made of a new mixture of phase change material (PCM) and sensible heat storage. The size of the collector is 0.8 m^2. The insolation of the sun at the time of tests was 700 to 900 W/m^2. In these conditions, the highest temperature was reached by the absorber plate was 200 °C, PCM melting point was 130 °C, and the cooking utensil was hot with temperatures above 90 °C after 2.5 hours of sunset. The thermal efficiency was 30 to 35% higher than the efficiency of the conventional solar cookers and that the use of more efficient heat storage was sufficient to allow evening cooking and furthermore make solar cooking systems more reliable.

Anilkumar et al. (2022) investigated a thermal energy storage (TES) unit that can be utilized in solar cookers but used an iterative design algorithm to optimize thermal behavior. The paper projected phase change materials (PCM) and their abilities to store heat during off-sun cooking. The ability to optimize heat storage and release by the TES unit provided long usage after sunset. They were compared with standard configurations and demonstrated an added heat retention as well as an increased energy efficiency of about 60%. The indicators of key performance were an optimal PCM temperature (max 220 °C, but an optimal between 110 °C and 140 °C). There was an increase of 10 to 15% in heat storage capacity as compared to the usual arrangements. The geometry and choice of materials used in the TES unit was refined as well through the iterative process giving an economically viable and effective solution which the authors state to increase the reliability of solar cooking and further encourage the use of sustainable energy sources.

Getnet et al. (2023) performed an experimental study of an indirect solar cooker with and without reflectors having heat storage. A phase change material (PCM) that is used to store thermal energy during the off-sunny hours was used in cooking. The analysis covered the performance of cooking, heat transfer effectiveness, and temperature change. It was resulted that the highest temperature of the absorber plate was more than 210 °C with reflectors, and 175 °C with no reflectors. The thermal storage device was able to keep the cooking temperatures above 80 °C even after being exposed to sunlight up to three hours. The system with the reflector had a 32.5% improvement in efficiency over the non-reflector system. The cooking power of the system varied between 45 and 55 W depending on the conditions of the environment. The authors conclude that the inclusion of thermal storage substantially enhances the practicality of solar cooking in the night and under cloudy weather, and it can be considered a sustainable alternative to traditional ways of cooking.

A comparison analysis of experiment conducted by Saxena et al. (2023) used the viability of different sensible heat storage materials in solar cooking applications. The research has discussed granite, copper, aluminum, and stainless steel, and has discussed its thermal properties such as energy efficiency, temperature variation, and the heat retention capacity. Thermal performance measurements have been made based on heating time, maximum temperature, and cooling rate with the help of a solar cooker with a Scheffler reflector. Results showed that granite was more effective in terms of its ability to retain heat, thereby maintaining cooking temperature longer after sunset, and aluminum was the fastest heating material (up to about 250 °C) within 30 minutes. The authors conclude that the high-specific-heat materials used in solar cookers should be combined with the high-conductivity ones as this could lead to an improvement of solar cookers. The study offers a good contribution to the enhancement of thermal efficiency and off-sun-hours performance of solar cookers by choosing the right sensible heat storage materials.

Paying close attention to the improvement of thermal energy storage and heat retention, the study by Papade and Patil (2023) examined the characterization of nano-mixed phase change materials (PCMs) in terms of solar cooker use. To enhance thermal conductivity and latent heat capacity, nanoparticles including $Al2O_3$ and CuO were added into organic and inorganic PCMs as a part of the study. The thermal conductivity of a 2–5 weight percent. nanoparticle was enhanced by 15 to 20% as tested using the differential scanning calorimetry (DSC). The improved PCM had constant phase transition temperature between 140 and 160 °C and energy storage capacity that was higher (~180-220 kJ/kg). Experimental evaluation using a solar cooker apparatus has shown an increase in the ability to absorb heat and longer cooking durations which show that nano enhanced PCMs are promising solutions to provide efficient solar cooking. It is indicated in the study that it is possible to make solar cookers work significantly better by reducing the duration that it takes to charge the device and increase the amount of heat that is retained during the off-sunny hours.

Patel and Patel (2024) shows, the incorporation of thermal energy storage (TES) is a significant enhancement of the performance of a solar cooker in households. PCM-based systems have been reported to boost total thermal efficiency up to 20 to 40% and cooking time after sunset up to 2-5 hours with melting temperatures ranging between 50 and 120 °C. Sand, pebbles, and iron pieces are sensible heat storage (SHS) materials that are very dependable in the retention of heat up to 2-4 hours which in most cases maintains the temperature of food above 60-80 °C. The TES systems based on hybrids that include PCM and SHS have additional positive feedback on the stability of heat, as well as charging-discharging efficiency. The experimental studies of box, parabolic, evacuated tube, Fresnel, and Scheffler reflector cookers show that the top absorber temperature can be 150 to 400 °C and hence prove the technical viability of off sunlight solar cooking as a source of domestic and rural cooking.

As it can be seen, Patel and Patel (2024) prove that inclusion of thermal energy storage (TES) is central to the effectiveness of solar cookers in residential settings. It has been shown that phase change material (PCM)-based systems increase the total thermal performance by about 20 -40% and increase the cooking time by 2-5 hours after sunset with PCM melting temperatures ranging 50 to 350 °C. Approximately 450-1200 kJ of energy is stored in sensible-heat storage (SHS) medium like sand, pebbles, and iron pieces to provide dependable store of heat over a 2 to hour duration. High-tech solar cookers using box, parabolic, evacuated-tube, Fresnel, and Scheffler refractors reach up to 150 and 400 °C of maximum absorber temperature respectively. Hybrid TES configurations that incorporate PCM/SHS provide enhanced heat stability and reliable cooking performance, which upholds food temperatures over 60 °C during later evening cooking and hence, has a great potential of sustainable household and rural energy usage.

PHASE CHANGE MATERIAL (PCM) SELECTION CRITERIA IN SOLAR COOKER APPLICATIONS

When considering the phase change materials that can be incorporated into the box-type, parabolic, and Scheffler reflector cookers, the main rank factor should be the correspondence of the melting temperature of the PCM to the operating temperature range of the gadget. The issues of thermal stability and cycling durability should be evaluated as the key aspects in the comparison between organic and inorganic PCM candidates since they are directly dependent on temperature and this dependency directly affects the long-term performance. In addition, practical factors like availability, affordable cost as well as integration into home cooking set-ups, cannot be ignored. Lastly, suitability to domestic cooking needs, such as anticipated cooking times, and the need to operate effectively at night, gives the ultimate test of achievability.

HEAT TRANSFER ENHANCEMENT MECHANISMS IN THERMAL STORAGE-BASED SOLAR COOKERS

The total thermal efficiency of solar cookers with thermal energy storage (TES) will also depend not only on the selected storage medium, but also on the processes that allow the transfer of heat between the solar absorber, the storage system, and the cooking vessel. In a comprehensive analysis of the literature that the most effective TES-integrated cookers can perform at an adequate level because of the conscious optimization of heat transfer but not just an increase in storage capacity. Other factors like longer surfaces, often made possible through use of fins, will always enhance the overall area over which convection can occur, which in turn lowers process of thermal resistance and speeds up both charge and discharge process of the PCM. Heat-pipe and thermosyphon systems also enhance performance by enhancing almost isothermal transportation of heat with low losses, which is of special importance in indirect and concentrator-based systems where the isothermal temperature distribution has a direct impact on safety and reliability. To overcome the intrinsic low thermal conductivity of PCMs, scholars have added nano-additives, such as Al_2O_3, CuO and graphite, to produce composite PCMs with up to 15-30% increases in conductivity and quick heat removal, though with cost, and stability over time problems and possible sedimentation. Besides, the geometry and material structure of PCM containers is decisive; metallic housings with a high conductivity, and geometries of encapsulation minimization, conductivity pathways, enhancing the charging efficiency and heat retention. Synthetically, there is no single enhancement strategy that is universally most effective, instead, strategies of a hybrid that incorporate finned surfaces, optimized containment, heat-pipe, and additives that are conductive will always provide better efficiency, thermal stability and long post-solar radiation cooking duration. This highlights the fact that optimization of heat-transfer is the crucial factor behind the development of performance improvements in state-of-the-art TES-integrated solar cookers.

SOLAR COOKER COMPARATIVE SYNTHESIS OF THERMAL ENERGY STORAGE STRATEGIES IN TYPES OF SOLAR COOKERS

The ability of thermal energy storage in solar cookers fundamentally depends on the design of the cooker, the temperature at which it will operate, and the amount of time the energy store requires, and not just the storage medium. A systematic review of literature defines specific performance curves of sensible heat storage (SHS), latent heat storage (LHS) and combined heat storage (CHS) strategies if these are coupled with diverse cooker geometries.

THE TES PERFORMANCE IN BOX-TYPE SOLAR COOKERS WAS EVALUATED IN THIS STUDY

Box-type cookers are usually run at temperatures of absorbers ranging between 120 to 180 ^{o}C, thus limiting the storage choices. Literature using SHS materials like sand, granite, pebbles, and oil has shown a marginal efficiency increase (around 15-30%), and reduced post-solar evening heat storage, usually 2-3 hours. Although both these media are economical and simple to execute, they have high thermal losses and storage capacity that varies with temperature thus restricting their application to long cooking processes. On the other hand, low/medium temperature PCMs such as stearic acid, acetanilide and erythritol, which have melting points of 60-120 ^{o}C, e.g. stearic acid, -acetanilide and erythritol, offer significant enhancement in post-sunset culinary abilities with retention times of 2-4 h and efficiency increases of 20-40%. However, PCM based box cookers are limited by non-optimal charging temperatures and slow heat transfer especially at variable insulation thus are more applicable to short evening meals and not to long term domestic application.

TES INTEGRATION IN PARABOLIC AND CONCENTRATOR-BASED COOKERS

Parabolic dish, trough, and Scheffler reflector cookers have absorber temperatures ranging between 200 and 400 ^{o}C, allowing the use of high-temperature PCMs and hybrid storage schemes. LHS material such as sodium nitrate, binary mixtures of salts and magnesium chloride hexahydrate have better thermal stability and longer storage at these systems and can maintain cooking temperature within 3-5 hours after sunset with 30-40% efficiency improvements. The synthesis highlights the high operating temperature as the determining factor determining the efficacy of storage and not PCM type. The concentrator-based cookers are more capable of providing quicker PCM charging, intense melting, and greater stability of heat release and therefore would suit domestic cooking requirements. However, the benefits associated with these positive characteristics include the complexity of the system, higher costs, and thermal management issues.

ADVANTAGE OF COMBINED HEAT STORAGE (CHS) SYSTEMS

Hybrid systems combining SHS and LHS are better than single mode storage across all types of cookers. SHS modules counteract the sensible heat at high temperatures whereas PCMs offer close and isothermal release during cooling stages. The empirical evidence has shown that CHS systems would be able to increase productive cooking duration up to 5-6 h, reduce thermal variations and increase overall reliability. The high-temperature stability of CHS, in combination with the domestic cooking window, can be used in the Scheffler based cooker. CHS represents an increased initial expense and design complexity but its greater functionality and sustainability make it the most promising TES strategy to use in the implementation of solar cooking in practice.

NEW INSIGHT BASED ON THE SYNTHESIS

An essential comparison of TES solutions in cooker settings indicates that no universal solution to storage exists. SHS is best at low cost, short duration cooking; LHS will allow significant after sunsets operation when paired with suitable temperature ranges; and CHS will provide the most robust one when long domestic cooking is required. This means that an organised system that balances TES strategy with type of cooker and operating conditions is essential in designing and optimising the solar cooker in the future.

EXERGY AND THERMODYNAMIC EVALUATION OF SOLAR COOKERS WITH THERMAL STORAGE

The most recorded indicator of solar cookers is energy efficiency; however, this may not be a true measure of the usability or quality of stored thermal energy. The traditional analysis of energy based determines the amount of heat absorbed and then used, but it does not take into consideration temperature levels, entropy creation, and irreversible phenomenon. Thus, the exergy analysis has recently become more widely used to determine the thermodynamic efficiency of solar cookers combined with thermal energy storage (TES).

Exergy efficiency provides a better measure of how much of the available solar energy is finally used to provide useful cooking heat. The exergy efficiencies reported are generally less than energy ones (10-20%), indicating a significant amount of irreversibility in capturing, transferring, and storing solar energy. Solar cookers based on concentrators, which run at higher temperatures, are always characterized by better exergy performance compared to box-shaped configurations; this fact explains the high importance of operating temperature on the quality of heat.

Key causes of irreversibility in TES -integrated solar cookers are optical losses, heat transfer between large temperature differences, charging-discharging of the thermal storage substance and heat loss to the environment. Phase-change material (PCM) latent heat storage can address fluctuations in temperature on discharge and thereby lessen entropy generation and improved use of exergy when the sun is off. As a comparison, sensible heat storage systems exhibit greater exergy destruction because of the continuous deterioration of heat.

Overall, the synthesis shows that a combination of energy and exergy analysis provides a deeper analysis of the thermodynamic performance. The use of exergy-based metrics will allow distinguishing better the different designs of solar cooker and will give a better understanding of the impact of TES and system configuration on the performance of the cooking.

OPERATIONAL AND RELIABILITY THE TES INTEGRATED SOLAR COOKERS HAVE LONG-TERM

OPERATIONAL DIFFICULTIES AND RELIABILITY CHALLENGES

Despite the significant enhancement of the solar cooker performance through TES, the long-term reliability is a major issue on its possible practical implementation in the domestic setting. The thermal cycling associated with charging and discharging of PCMs daily can wear out the PCMs reducing latent heat capacity and changing the melting behavior over time. Organic PCMs are typically reasonably stable at moderate temperatures; inorganic, salt-based PCMs can tend to degrade or depreciate when used at high temperatures over a long period of time.

Phase segregation and supercooling are common issues particularly in salt hydrate PCMs. The phenomena result in uneven melting and uneven heat release, thus decreasing the effective storing capacity, as well as lowering the reliability of cooking. The risk of leakage due to the expansion of volume during the phase change and the encapsulation material failures is also an added safety and maintenance issue especially in the domestic context. Metallic containment enhances thermal conductivity; however, it brings about corrosion issues of the PCM, especially in instances where nitrate or chloride-based PCM is used at high temperatures.

Long service life therefore requires compatibility of material between PCMs, container materials and heat-transfer enhancers. Protective coating, composite PCMs and optimized encapsulation designs have been proposed as methods of overcoming these problems but at a premium in cost and complexity to the system. Moreover, frequent handling, exposure to the external environment, and low user maintenance ability in domestic applications are also additional factors that affect durability.

CONSIDERATION OF SAFETY, CONTAINMENT AND MATERIAL COMPATIBILITY IN TES-INTEGRATED SOLAR COOKERS

High temperature PCMs and salt-based TES systems used in solar cookers pose very high safety and material compatibility concerns especially when used in the household. Most inorganic PCMs such as nitrates and chlorides are used at high temperatures and can be dangerous source of thermal instability, corrosion and leakage unless properly contained. Such risks are of an acute concern when it comes to domestic settings where users do not always have technical training or are at a loss of routine maintenance. The design of containment is thus critical in containing safety issues. When subjected to reactive salt-based PCMs, metallic encapsulation increases the thermal conductivity and increases the likelihood of corrosion. Incorrect sealing or material incompatibility may result in leakage when you go through repeated melt-solidification cycles that will create burn hazards and system failure. Organic PCMs usually are safer to handle at moderate temperatures but have lower upper operating temperatures and 2 cause flammability problems in poorly ventilated areas. Another important consideration is thermal stability during a long time of high-temperature operation. PCMs that are close enough to their stability limits to cause chemical degradation, the formation of gases, or phase separation may have a detrimental impact on both performance and safety. It has been shown in the literature that these risks can be mitigated using protective coatings, corrosion-resistant alloys, composite PCM, and designs that provide pressure relief at the cost of higher costs and design complexity. In general, the synthesis indicates that the concept of safety, the integrity of the containment, and the compatibility of materials should be considered as one of the major design considerations, instead of a secondary issue regarding the success of the responsible implementation of TES-integrated solar cookers in households.

THE ECONOMIC VIABILITY, SCALABILITY, AND ADOPTION OF TES INTEGRATED SOLAR COOKERS BY USERS

There have been massive advancements in the thermal efficiency of solar cookers using TES but the implementation of the solar cooker on a large scale is dependent on the economic viability and acceptance by the users particularly in the rural and off-grid locations. Numerous solar cookers of high-performance use concentrators, PCMs and sophisticated heat-transfer improvements, which add to the cost of capital and complexity of fabrication. Being able to cook longer and more efficiently, these systems are not affordable to low-income families, but their initial cost is higher.

Scalability and manufacturability are also determinants. Systems which can be built upon locally available materials, which can be built easily and systems based on modular TES designs have higher chances of being accepted at the community level. On the other side, complicated hybrid systems with precision parts can have transportation, installation, and repair problems in remote locations. Long term usability is also influenced by maintenance requirements such as containment integrity of PCM, inspection and replacement of worn-out parts.

Non-technical factors like cooking habits, timing of meals, ease of operation, safety and cultural acceptance also affect user adoption. Research indicates that indirect solar cookers and installations that permit in-door cooking are usually the most desired, since their use does not expose individuals to the elements of the outside world and because they conform more to traditional cooking methods. In addition, the technologies that allow cooking after the sunsets, minimal activity during the process, and can be used with regular utensils have more acceptance potential.

AN OVERVIEW OF SOLAR COOKERS WITH MATERIALS TO STORE HEAT

Table 1 summarizes PCM-based TES solar cookers, Table 2 summarizes SHS-based TES solar cookers and Table. 3 contains information on hybrid TES solar cookers. The literature review has shown that thermal energy storage significantly increases the viability and usability of solar powered cookers in the home. PCM systems offer high energy density and almost isothermal heat release enabling longer cooking times of 2-4 hours after sunset and are 20-40% more efficient. Heat storage Sensible-heat storage (SHS) media including sand, granite, rocks, and oils provide durable and low-cost heat storage of 240-400 mins (oil and granite typically better than sand). The Hybrid TES systems which combine PCM and SHS can be used to balance high storage capacity, constant heat output, and enhanced thermal reliability to a considerable extent. In sum, hybrid designs have a great potential of off-sunshine cooking but more optimization must be done to improve heat transfer, longevity, and affordability to give it wide usage in households.

TABLE 1. Summary of PCM-based TES solar cookers

Study	Cooker Type	PCM Material	Collector Area (m²)	PCM Mass (kg)	Max Temp (°C)	Heat Retention	Efficiency (%)	Key Findings
Buddhi & Sahoo (1997)	Box-type	Acetanilide	0.44	4	180 (Abs)	~2 h	20–25	Extended cooking duration
Sharma et al. (2000)	Box-type	Stearic acid	0.60	6	175 (Abs)	~3 h	30	Improved evening cooking
Buddhi et al. (2003)	Three-reflector	Stearic acid	0.72	8	200 (Abs)	~3.5 h	35	Late-evening cooking

TABLE 2. Summary of SHS-based TES solar cookers

Study	Cooker Type	SHS Material	Collector Area (m²)	Max Temp (°C)	Heat Retention	Efficiency (%)	Key Findings
Murty et al. (2007)	Parabolic	Soya oil	-	134	-	3.47	Off-place cooking
Cuce (2018)	Box-type	Pebbles	0.40	165	2–3 h	30	Best SHS material
Milikias et al. (2021)	Box-type	Granite stones	-	175	~3 h	15–20	Granite superior to sand

TABLE 3. Summary of Hybrid TES solar cookers

Study	Cooker Type	TES Type	Max Temp (°C)	Heat Retention	Efficiency (%)	Key Findings
Sharma et al. (2009)	Review	PCM + SHS	150–200	2–4 h	20–40	Hybrid TES effective
Nkhonjera et al. (2017)	Review	PCM + SHS	50–350	3–5 h	20–40	Best reliability
Tawfik et al. (2022)	Tracking box-type	PCM + SHS	200	-	-	Improved hybrid design
Patel & Patel (2024a)	Concentric type	SHS + SHS	95–110	2-3 h	25-30	Dual SHS offers stable heat retention with low cost
Patel & Patel (2024b)	Concentric type	PCM + SHS	105-120	3-4 h	30-37	Hybrid TES improves late-evening cooking performance

COMPARISON OF SENSIBLE HEAT STORAGE, LATENT HEAT STORAGE, AND COMBINED HEAT STORAGE IN SOLAR COOKERS

The abridged heat-retention characteristic and huge thermal losses of sensible-heat storage (SHS) compared to latent-heat storage (LHS) and combined heat storage (CHS of solar cookers limits the cost-effectiveness of SHS. LHS is efficient and it is a better heat retention method; however, it requires proper thermal control and PCM choice. CHS is more complicated and expensive to build, but it helps to optimize the benefits of both technologies to be used over a long period of time. A comparative discussion of the sensible, latent, and combined heat storage of solar cookers is shown in table 4.

TABLE 4. A comparative analysis of solar cookers' sensible, latent, and combined heat storage

Parameter	Sensible Heat Storage (SHS)	Latent Heat Storage (LHS)	Combined Heat Storage (CHS)
Definition	Stores thermal energy by increasing the temperature of a material.	Stores thermal energy during phase change (solid-liquid transition).	Utilizes both SHS and LHS for enhanced thermal performance.
Common Materials	Sand, rocks, water, oil, concrete.	Phase change materials (PCMs) like stearic acid, erythritol, sodium nitrate.	A combination of sensible heat materials and PCMs.
Energy Storage Mechanism	Sensible heat absorption and release based on temperature change.	Latent heat absorption and release during phase transition.	Synergistic storage through both sensible and latent heat mechanisms.
Storage Capacity	Moderate; depends on specific heat capacity.	High; depends on latent heat of fusion.	Higher than SHS and LHS alone due to combined effects.
Heat Retention Duration	2–3 hours post-sunset.	3–5 hours post-sunset.	5–6 hours post-sunset.
Maximum Temperature Achieved	120–190°C (depending on material).	60–350°C (depending on PCM type).	150–300°C (optimized performance).
Cooking Efficiency Improvement	15–30% over conventional solar cookers.	20–40% over conventional solar cookers.	30–50% over conventional solar cookers.
Thermal Losses	High due to continuous heat dissipation.	Moderate; depends on PCM insulation.	Low; optimized heat transfer and retention.
System Complexity	Simple; requires basic thermal insulation.	Moderate; requires PCM containment and heat exchanger.	High; requires integration of SHS and LHS for efficient operation.
Cost	Low; widely available materials.	Medium to high; PCMs can be expensive.	High; complex design and additional materials required.
Experimental Examples	Milikias et al. (2021), Verma et al. (2022).	Buddhi & Sahoo (1997), Sharma et al. (2000), Lecuona et al. (2013).	Hussein et al. (2008), Saini et al. (2016), Papade & Kanase-Patil (2022).
Suitability	Effective for short-duration cooking and direct heat utilization.	Ideal for evening/night cooking due to extended heat release.	Best for all-day cooking, ensuring continuous availability of stored heat.

KNOWLEDGE GAPS AND FUTURE RESEARCH DIRECTIONS

Even though significant progress has been made in the sphere of solar cooker technologies that use thermal energy storage (TES) solutions, it is possible to point out several key gaps that still must be addressed to make the project consistent and sustainable when applied to a domestic environment. One of the most outstanding shortcomings is associated with the continuously low levels of exergy efficiencies characteristic of most solar cooker designs despite relatively strong energy efficiency values. As a result, the strong call on future research to reduce irreversibility through optimization of operating temperatures, heat transfer conduits and use of an exergy-focused system structure is essential.

A second glaring gap is the losses in the heat transfer and inconsistent thermal charging particularly in phase change material (PCM) based and hybrid storage systems. Future studies should then lean towards advanced methods of enhancing a basic concept of heat transfer, like refined fin patterns, integration of internal heat pipes, and design of thermally conductive composite PCMs that are supported by complementary experimental and numerical studies.

Material degradation issues and operation reliability problems are also not well characterized, and there is little empirical evidence on PCM stability in repeated thermal cycles. In this regard, future research should focus on durability testing, accelerated ageing tests, and the development of degradation-resistant PCMs and protective encapsulants that can be developed to withstand long-term domestic use. Correspondingly, the safety issues, material compatibility underlying high-temperature, salt-saturated PCMs require the establishment of standardized corrosion-proofed containment systems and material systems.

Finally, the literature points out that there is a gap between laboratory scale performance measurements and the field implementation, with the constraints put on the economic, maintenance and user-acceptance. To bridge this gap, future research work should combine entire techno-economic analyse, life-cycle analysis, and user-oriented design approaches, particularly in rural and off-grid settings.

Overall, it will be critical to fill these identified gaps systematically through targeted application-based research, to transform the current TES -integrated solar cookers beyond the laboratory prototypes into widely used domestic technologies.

CONCLUSION

1. Solar cookers with thermal energy storage (TES) have also shown a significant enhancement in reliability, efficiency, and usability of cooking even after the sun has gone down.
2. Phase-change-material (PCM) based TES systems offer strong performance advantages, including a thermal efficiency increase of about 20 to 40% and good heat storage at a wide melting temperature range (50-350 ^{o}C) to allow cooking after the sun sets.
3. Sensible heat storage (SHS) media like thermal oils, granite and sand are stable and relatively economical, which traps the heat and improves the cooking time and constant temperature.
4. Hybrid TES designs that combine PCM and SHS provide a balanced solution by enhancing heat transfer, increasing cooking time and possessing a constant thermal output.
5. TES is also integrated with high end solar collectors, such as evacuated-tube collectors, Scheffler reflectors and parabolic trough systems, which also increase overall thermal performance.
6. Some of the research issues, which are still important in enhancing PCM thermal conductivity, minimizing thermal losses and maximizing charging discharging efficiency are: Innovative storage materials, new designs of heat-exchangers, and scaled hybrid systems should be put at the forefront of future work, to benefit cost-effectiveness and longevity.
7. These improvements put TES-based solar cookers at the forefront of viable, environmentally neutral substitutes of traditional cooking technologies, to the specific rural and off-grid household settings.
8. Overall, exergy-based performance metrics, when combined with traditional energy efficiency metrics, provide a more realistic and thermodynamically sound framework of comparing solar cookers with thermal storage, which will allow a clearer understanding of designs that provide superior and utilizable heating to domestic cooking.

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DECLARATION OF COMPETING INTEREST

None.

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