Food, cloth and shelter are three basic necessities of life. Food can be regarded as essential component for growth and survival of human being. So, the source of cooking is one of the most important things in our daily lives. There are various cooking sources of energy like kerosene, LPG, Firewood and Renewable sources etc. and one of them is solar cooking which is a renewable source of energy. Solar cooks are limited by the fact that cooking can only take place during daytime. If a thermal energy storage system is provided to solar cookers, food can be cooked during hours of evening or night. In the last few decades, the cooking sector has used various solar cookers, including the box type solar cooker, flat plate type solar cooker, parabolic dish type solar cooker, evacuated tube type solar cooker and Scheffler dish solar cooker with sensible heat, latent heat and Combined heat storage technologies for the solar cooker. As a result, this paper summarizes the investigation and analysis of the available thermal energy storage materials (sensible heat, latent heat and combined heat storage materials) to store heat during the daytime and use it for purposes other than daytime hours for use in solar cooking application. The current study also compares the Sensible heat, Latent heat and combined heat storage systems for cooking.

Keywords: Solar energy, Solar cooker, Sensible heat storage materials, Latent heat storage materials, Combine heat storage materials, Evening cooking, Energy storage

INTRODUCTION

Everyone in the world needs to know how to cook. 75% of rural Indians use non-commercial fuels like forest wood to cook their food, which causes deforestation and increases the greenhouse effect. LPG prices, on the other hand, are steadily rising as a major source of cooking energy. As a result, using renewable energy sources to cook is an alternative option. India is fortunate in that it receives plenty of sunlight. As a result, solar cooking becomes a viable option (Garg (1978), Mullick et al. (1987), Thulsidas et al. (1997)). Figure 1 shows the classification of solar cooker.

![Classification of solar cooker (Garg 1978)](image1.jpg)
A solar cooker, as well as other solar applications such as a solar still, solar dryer, solar water heater, and others, necessitate the use of an energy storage system. In solar stills, more energy can be stored and re-used during the day so that it can be used later in the evening and at night. [Panchal and Shah (2012), Panchal and Patel (2017), Panchal and Mohan (2017), Panchal and Shah (2014), Panchal et. al. (2018), Panchal et. al. (2018), Panchal et. al. (2018), Patel and Patel (2020)] It is economically viable to use energy storage when it lowers energy consumption and can be used to replace another energy source. Figure 2 illustrates the various types of energy storage materials.

![Energy Storage Systems Diagram](https://doi.org/10.17576/jkukm-2022-34(5)-01)

**FIGURE 2. Classification of Energy Storage System (Mohjir et. al. 2019)**

Thermal energy storage can be stored as a change in internal energy of a material as sensible heat, latent heat and combination of these.

**Sensible heat storage:**

In sensible heat storage (SHT), thermal energy is stored by raising the temperature of a solid or liquid. SHT system utilizes the heat capacity and the change in temperature of the material during the process of charging and discharging. The amount of heat stored depends on the specific heat of the medium, the temperature change and the amount of storage material [Sharma et. al. (2009)].

\[
Q = \int_{T_i}^{T_f} m \cdot C_p \cdot dT \tag{1}
\]

\[
Q = \int_{T_i}^{T_f} m \cdot C_p \cdot (T_f - T_i) \tag{2}
\]

Where, \( Q \) = quantity of heat stored (J), \( T_i \) = initial temperature (°C), \( T_f \) = final temperature (°C), \( m \) = mass of heat storage medium (kg), \( C_p \) = specific heat (J/kg K).

**Latent heat storage:**

Latent heat storage (LHT) is based on the heat absorption or release when a storage material undergoes a phase change from solid to liquid or liquid to gas or vice versa [Sharma et. al. (2009)].

\[
Q = \int_{T_m}^{T_f} m \cdot C_p \cdot dT + \int_{T_m}^{T_i} \cdot C_p \cdot dT + a_m \cdot \Delta h_m \tag{3}
\]

\[
Q = m \cdot C_p \cdot (T_f - T_m) + a_m \cdot \Delta h_m + \int_{T_m}^{T_i} \cdot C_p \cdot dT \tag{4}
\]

Where, \( Q \) = quantity of heat stored (J), \( m \) = mass of heat storage medium (kg), \( T_f \) = final temperature (°C), \( T_m \) = melting temperature (°C), \( C_p \) = average specific heat between \( T_m \) and \( T_f \) (J/kg K), \( a_m \) = fraction melted, \( \Delta h_m \) = heat of fusion per unit mass (J/kg).

Solar box cooker with thermal energy storage unit developed by Anilkumar et. al. (2021) for solar cooking in off-sun hours. Multi-criteria decision making (MCDM) techniques was used for selection of phase change material and selected erythritol as a PCM because erythritol required lesser quantity (6.06 kg) compared with magnesium chloride hexa-hydrate (16.02 kg) and acetanilide (13.25 kg).

The novel box type solar cooker integrated PCM was experimentally developed by Palanikumar et. al. (2021) for solar cooking application. Three different experiments [Solar box type cooker with PCM (waste cooking oil and C_12H_{22}O_2), with Nanocomposite – PCM (MgAlO/NaFeO_2-PCM) and without Nanocomposite – PCM] study by the researchers. From study resulted that, the overall thermal performance of solar box cooker without Nanocomposite – PCM, with PCM, and with Nanocomposite – PCM was obtained as 24.90-33.90%, 24.77-45.20% and 31.77-56.21% respectively.
Evacuated tube solar collector with cooking pot and phase change material (palm oil) deloved and investigated by Hebbar et. al. (2021) for off-sunshine hours cooking application. From study resulted that, temperature of oil reaches a maximum value during late afternoon oil will remain high in the evening time.

The objective of this review paper is to review about solar cooking and its applications to preserve fresh foods using sensible heat, latent heat and combined heat storage. The review paper makes a comparison of the solar cooking systems with sensible heat, latent heat, and combined heat storage materials.

REVIEW ON LATENT HEAT STORAGE MATERIALS

Phase change materials (PCMs) have recently gained a lot of attention as a component of latent heat thermal energy storage units (LHTES). Many researchers have worked into the effects of solar cookers using PCMs.

Cooking during the night is a challenge, so Domanski et al. (1995) investigated the effectiveness of materials that store latent heat. A phase change material (PCM) was used in a solar cooker made of two cylindrical vessels with a gap filled with stearic acid or magnesium nitrate hexahydrate. An experiment was conducted using a solar simulator to produce the desired amount of solar radiation and concluded that important parameters like solar intensity and the mass of the cooking medium are in terms of cooking performance.

Box type solar cooker with three reflectors and PCM storage unit designed and manufactured by Buddhi et al. (2003) for storing energy during the day and cooking food at night during the winter, commercial acetanilide has been used as a phase change material. Cooking experiments has been done with and without PCM. The experimental results have shown that evening cooking is possible in a solar cooker with three reflectors along with latent heat storage unit.

An evacuated tube solar collector (ETC) with a PCM storage unit was used by Sharma et al. (2005) to investigate the thermal performance of a prototype solar cooker. Cooking experiments with various loads and loading times were conducted throughout the day and evening. Cooking with a PCM storage unit in the evening versus noon was found to be faster. Using erythritol as a PCM, researchers were able to cook food to a temperature of 130°C during dinner time.

A novel indirect solar cooker based on a flat plate collector (FPC) with PCM storage and cooking unit was investigated by Hussein et al. (2008). Wickless heat pipes were used in the solar cooker, which had an elliptical cross section. As a PCM, magnesium nitrate hexa-hydrate was used. The results shows that the feasibility of elliptical cross-section indirect solar cooker can be used to cook in the evening and to heat food in the daytime using wickless heat pipes and PCM. Figure 3 illustrates the main components of solar cooker.

FIGURE 3. Cross sectional side view of the indirect solar cooker based on a flat plate collector (Hussein et al. 2008)
Using a parabolic collector with solar thermal system, Umanand and Prasanna (2011) developed a hybrid cooking system. The band graph method was used to model the system. For various flow rates (2 m³/s, 3 m³/s, 4 m³/s, 5 m³/s, 6 m³/s, 7 m³/s) examined the simulation results against the experimental results to see which was more accurate. Thermosyphon flow rate efficiency is increased by approximately 6% at optimum flow rate.

They presented literature on various box type solar cooker developments by Saxena et al. (2011), considering major parameters such as box cooker geometries and glass systems as well as cooking vessel designs that store heat efficiently while also being thermally insulated. These developments have led to improvements in box cooker performance, even at low ambient temperatures. As well as being a good way to cook at night, paper suggests that PCM is an excellent way to store solar energy.

Using a box-type solar cooker, Yuksel et al. (2012) investigated the use of paraffin wax with metal shavings as a PCM in the daytime and/or night. It was resulted that the designed cook can be used effectively at a 30° at a reflecting angle with a thermal efficiency of 18.35% when tested under various isolation conditions and on different days.

Solar cooking was used to evaluate the new design of a portable parabolic type heating system by Lecuona et al., (2013). Making the dish required the two traditional coaxial cylindrical cooking pots. the hollow space between the two conical pots is filled with phase change material (PCM). The results show that it is possible to cook the three meals for family during sunny days in summer as well as in winter.

Mussard and Nydal (2013) used solar parabolic trough collector with two different kinds of thermal storage systems (thermal oil storage and aluminium based storage). The loop connecting the collector and storage unit served as a self-circulating thermal fluid for the latent heat storage unit. Thermal oil storage reduces thermal losses in the pipe and absorber much better than an aluminum-based storage unit. Figure 4 illustrates Schematic representation of self-circulated loop used in experiment.

Chaudhary et al. (2013) investigated a solar cooker based on a parabolic dish collector with phase change material (acetanilide). It was noted that a solar cooker with a dark colored (Black) exterior and glazing stores 32.3% more heat compared to PCM in a standard solar cooker.

Farooqui Suhail (2013) developed a Fresnel lens collector-based solar cooker. Mirror strips mounted on a wooden framework to make up the cooker and required single axis solar tracking system. In experiment’s maximum temperature was 250 °C. The heat absorption capacity of this collector was five times higher than the conventional box type solar cooker. Fig. 5 Shows Schematic diagram of the cooking chamber with various components.
Ashmore Mawire et al. (2014) test the thermal performance of three different types of solar thermal oil (Sunflower Oil, Shell Therma C and Shell Therma B) during the charging period. A 20 L insulated tank was used for the experiment. The results show that Sunflower Oil was better than other thermal oils under high power charging.

This study used an experiment by Singh et al. (2015) to investigate the effects of using acetanilide as a latent heat storage material in solar cookers. They circulate heat through a thermosiphon using two different types of heat transfer fluid (water and thermal oil). When using thermal oil as a working fluid, it was observed that the temperature of the thermal oil was 10-24°C higher than the water as a working fluid. Food was cooked twice daily, with the evening cooking rate being higher than the noontime.

REVIEW ON SENSIBLE HEAT STORAGE MATERIALS

Sand was used as a sensible heat storage material in an experiment by Ramadan M.R.I. et al. (1998) on a flat plate solar cooker (FPSC) during clear sunny days. Temperatures in the solar cooker and sand were measured using thermocouples. After experimentation, Sand has been found to be an effective storage material and a reliable source and provide three hours per day indoor cooking.

Using engine oil as a sensible heat storage material, Nahar N. M. (2003) investigated the conventional box type solar cooker. Using engine oil as a sensible heat storage medium increased the solar cooker efficiency by 27.5%.

Schwartz K. and Silva. MEV. (2003) studied a flat plate solar cooker using vegetable oil as a sensible heat storage. Vegetable oil has been found to be an effective ingredient in keeping food warm for an extended period of time.

REVIEW ON COMBINED (SENSIBLE & LATENT) HEAT STORAGE MATERIALS

Nallusamy et al. (2007) had experimentally studied the thermal efficiency of a packed bed of a combined thermal energy storage unit for sensible and latent heat energy as thermal energy storage (TES). A TES unit has been designed,
constructed and integrated with constant temperature bath/solar collector to study the performance of the storage unit. The TES device contains paraffin as a PCM filled with spherical capsules packed in a cylindrical isolated storage tank. In order to transfer heat from the constant bath/solar collector to the TES tank, the water used as HTF. Charging tests are performed at constant and varying input fluid temperatures to determine the effects on the efficiency of the storage unit of the inlet fluid temperature and HTF flow rate. Discharge experiments are conducted by both continuous and batchwise processes in order to recover the stored heat. The discharge experiments show that the combined storage system employing batchwise discharging of hot water from the TES tank is best suited for applications where the requirement is intermittent. Figure 6 shows the experimental setup of combined storage with use of solar collector.

In order to ensure continuous energy supply in the absence of the availability of solar energy, the intermittent existence of solar energy needs an energy storage system with solar collector units. The use of phase change material (PCM) and heat storage rock beds has been investigated by Okello et al. (2014). They carry out the thermal behaviour of thermal energy storage with rocks and PCM, through an experimental comparison. The PCM material ratio was 60:40 percent mixture of NaNO3 and KNO3. The results showed that the injection of PCM cylinders into a rock bed to store heat not only increases the storage energy content, but also the vertical thermal conductivity. The increase in vertical thermal conductivity is due to the PCM container material having a high thermal conductivity.

Andrea Frezzica et al. (2016) had conducted experiments, the research work on the hybrid combined storage for the hot water applications for domestic purpose. They used two PCMs (commercial paraffin and a mixture of hydrate salts). They checked various volume ratios between PCM and water. The resulting showed that the heat storage capacity per unit volume improved dramatically, except for small fractions of the PCM used, to 10% of heat storage increases with the addition of a 1.3 dm³ hydrate salt mixture. Figure 7 shows the vertical heat storage with thermocouples location.
FIGURE 7. The vertical heat storage with thermocouples location (Andrea Frezzica et al. 2016)

Table 1 shows comparison sensible, latent, combined (sensible and latent) heat storage systems.

Table 2 shows summary of comparisons and various research works on sensible, latent, combined (sensible & latent) heat storage systems.

### TABLE 1. Comparison of sensible, latent, combined sensible-latent heat storage systems

| Features          | Sensible heat storage                                                                 | Latent heat storage                                                                 | Combined heat storage (Sensible and latent) |
|-------------------|---------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|---------------------------------------------|
| Principle         | Unlike storage media which changes in temperature, energy is not stored by any phase shift. | Energy is stored as latent heat of fusion by adjusting the phase of the storage medium. | The latent heat of fusion determines the amount of energy contained. |
| Storage material  | Rocks, sand, bricks, molten salt, and sunflower oil are some of the materials used.    | Eutectic products, paraffin, non-paraffin, nitrate salts, hydrates salts.            | Combination of sensible and latent materials. |
| Working temperature | Low (Up to 50 °C-200 °C)                                                                 | Medium (Up to 400 °C)                                                               | Medium (Up to 400 °C)                      |
| Merit             | No threat of obsolescence                                                               | moderate charging and discharging                                                    | Temperature on charge and during discharging |
| Demerits          | Thus, lower energy density is needed                                                   | Due to reduced thermal conductivity, Vitality of existence is bounded                | Thermal waste losses are greater           |
| Material cost     | Low                                                                                    | High                                                                                | Medium                                    |

### TABLE 2. Comparison of various researchers work on sensible, latent and combine heat storage systems

| Sr. No. | Author's name         | Type of Solar Cooker | Application | Type of Material | Name of Material        |
|---------|-----------------------|----------------------|-------------|------------------|-------------------------|
| 1       | Buddhi and Sahoo (1997) | Box type solar Cooker | Cooking     | Latent heat storage material | Commercial grade stearic acid |
| 2       | Buddhi et al. (2003)  | Double glazed (glass covers) box type solar cooker | Cooking | Latent heat storage material | Commercial grade acetonilide |
| 3       | Sharma et al. (2005)  | Evacuated tube solar collector | Cooking | Latent heat storage material | Commercial grade erythritol |
| 4       | Ramadan MRI et. al. (1998) | Flat plate solar cooker | Cooking | Sensible heat storage material | Sand |
| 5       | Nallusamy et al. (2007) | Solar flat plate collector | Heat storage | Combined heat storage | Packed bed and paraffin |
| 6       | Andrea Frezzica et al. (2016) | Boiler | Hot water for domestic purpose | Combined heat storage | Macro-encapsulated, commercial paraffin and hydrate salts |
CONCLUSION

Solar cooking is an efficient, economical, Pollution-free, easily accessible and low-maintenance system used by solar energy. But due to a lack of awareness, it is unpopular in the domestic sector. From the previous literature study, the following points are concluded:

1. Thermal energy storage materials have good ability to store the energy during the sunshine hours and release heat during off sunshine hours for solar cooking.
2. Sensible heat storage materials are easily available and low in cost but energy storage time is 2 to 3 hours only.
3. Comparing sensible and latent heat storage materials, the time needed to store energy in latent heat storage materials is longer.
4. Sensible heat storage material required more quantity than latent heat storage material for the same amount of heat storage.
5. In comparison to a single heat storage system, a combined heat storage system performs better because it utilizes both sensible and latent heat benefits.

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DECLARATION OF COMPETING INTEREST

None

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