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Recent innovations and developments concerning the beeswax as phase change material for thermal energy storage: a review

Farhan Lafta Rashid[1] · Mudhar A. Al-Obaidi[2,3]

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Abstract

It is possible to store heat energy and extract it from materials in the form of internal energy changes such as sensible heat, latent heat, and thermo-chemistry, or in any combination of these three. In systems of insensible heat storage, energy is stored by raising the temperature of the medium to which it is being stored. During the process of heat absorption and release, this system makes use of the heat capacity of materials as well as variations in the temperature of those materials. The quantity of energy that is deposited within the system is dependent on the specific heat of the medium, as well as variations in temperature and the amount of medium that is used. The principle behind the operation of latent heat storage is that the storage medium absorbs or releases heat depending on whether or not it is undergoing a phase transition from solid to liquid, liquid to gas, or vice versa. Beeswax is a naturally occurring phase change material (PCM) that has its greatest phase transition enthalpy in the temperature range of 60–68 °C. It has the potential to be used in a wide number of applications that include the storage of thermal energy. Researchers are interested in the durability and temperature resistance of beeswax. This study aims to deliver a comprehensive review that provides a rundown of experimental, numerical, and experimental and numerical studies on beeswax and Nanoparticles-beeswax as PCM for thermal energy storage (TES). The review will also provide a summary of recent developments in research. This article also discusses a few other concerns pertaining to setting up, researching parameters, and discovering results. Studies on beeswax are presently being conducted, and based on the results of the most recent one, suggestions have been made for other research projects to be carried out.

Keywords Beeswax · Nano-enhanced beeswax · Phase change material (PCM) · Thermal energy storage (TES) · Energy

Abbreviations

CPCMs	Composite phase change materials
DSC	Differential scanning calorimetry
DTA	Differential thermal analysis
FTIR	Fourier-transform infrared spectroscopy
HTF	Heat transfer fluid
LHTES	Latent heat thermal energy storage
LPM	Liter per minute
MWCNTs	Multiwall carbon nano-tubes
PCM	Phase change material
TES	Thermal energy storage
TGA	Thermo-gravimetric analysis
TSU	Thermal storage unit
SEM	Scanning electron microscope

✉ Mudhar A. Al-Obaidi
dr.mudhar.alaubedy@mtu.edu.iq

1 Petroleum Engineering Department, College of Engineering, University of Kerbala, Karbala 56001, Iraq

2 Technical Institute of Baquba, Middle Technical University, Baghdad 10074, Iraq

3 Technical Instructor Training Institute, Middle Technical University, Baghdad 10074, Iraq

Introduction

Consumption of final energy continues to rise in tandem with the expansion of the Indonesian economy, the country's population, rising energy costs, and the policies enacted by the Indonesian government. During the period of 2010–2015, there was only a moderate growth in total energy use, which averaged just approximately 1.3% annually. The residential sector accounted for the largest percentage of total energy consumption (35%) in 2015, followed by the transportation sector (31%), the industrial sector (29%), the commercial sector (4%), and other sectors (2%). The transportation industry has conducted the highest annual growth rate of 5.2% between 2010 and 2015, followed by the residential sector with 3.8% growth and the business sector with 2.9% growth [1, 2]. The rate of expansion in the industrial sector and in other sectors both slowed to be 4.6% and 10%, respectively. Building legislation and regulation are arranged in Law 28/2002, Government Regulation 36/2005, and regulation no 02/PRT/M/2005 issued by the Ministry of Public Works and Housing. These pieces of legislation and regulation are what enable energy-saving efforts to be carried out in the building sector. A green building is one that complies with building codes and exhibits notable, quantifiable efficiency in the conservation of energy, water, and other resources [3]. The function and categorization at each stage of the facility's operation are used to use green building concepts to attain this performance.

It is possible to store heat energy and extract it from materials in the form of internal energy changes such as sensible heat, latent heat, and thermo-chemistry, or in any combination of these three. In systems of insensible heat storage, energy is stored by raising the temperature of the medium to which it is being stored. During the process of heat absorption and release, this system makes use of the heat capacity of materials as well as variations in the temperature of those materials. The quantity of energy that is deposited within the system is dependent on the specific heat of the medium, as well as variations in temperature and the amount of medium that is used. The principle behind the operation of latent heat storage is that the storage medium absorbs or releases heat depending on whether or not it is undergoing a phase transition from solid to liquid, liquid to gas, or vice versa. In thermochemical systems, the process of altering molecular bonds as a result of chemical reactions is what causes energy to be absorbed or released, and the process that takes place is completely reversible [4].

The substance that may be extracted from the honeycomb is known as beeswax. The production of soap, batik, and candles are all possible applications for this material. In addition to this, beeswax may be utilized as a material for the storage of thermal energy, since it is able to store latent heat throughout the phase shift process from solid to liquid and vice versa. This makes it a potentially useful substance. According to the findings of a number of experts, beeswax has a melting point that ranges from 61.8 to 67 °C [5–8] and a latent heat that ranges from 122 to 395 kJ kg^{-1} [5, 9–12].

Beeswax is mostly made up of a combination of esters of hexadecanoic and octadecanoic acids, with the chain lengths of its fatty alcohols ranging between 38 and 52 carbon atoms, and between 46 and 54 carbon atoms, respectively [13]. Beeswax also contains a small amount of fatty acids. If a wide melting temperature range is not a problem, these molecular structural features of beeswax, which lead to a relatively high melting enthalpy, make it an intriguing option for energy storage as a PCM [14]. Because of these molecular structural traits, beeswax has a comparatively high melting enthalpy.

The capacity of beeswax to absorb heat more effectively has led researchers to conclude that it is superior than paraffin wax as an alternative material [15]. It is comparable to paraffin wax in that it similarly has a high melting point and poor heat conductivity, however it has a greater melting point than paraffin wax does. Adding additional components, such as carbon Nano-tubes, expanded graphite, graphene, and copper Nanoparticles, has been the subject of a number of studies [16–18] that have been carried out with the goal of increasing its thermal conductivity. According to the findings of Putra et al. (2016) [19], adding CuO Nanoparticles to PCM accelerated the melting process more than without adding any.

Despite this, the beeswax in both categories (beeswax and Nanoparticles-beeswax) has not been comprehensively examined for a variety of configurations in the published research that is available to the public. As a direct result of this, the purpose of this research is to address this problem. The use of beeswax as a phase transition material for the storage of thermal energy is the subject of this investigation, which covers a wide range of technical, investigative, and development techniques. With the aid of a comprehensive understanding of the variables that were discussed, the quality of the beeswax can be increased further, and as a result, it may be used in a variety of applications. In the realm of beeswax as a phase transition material for TES, which has achieved significant breakthroughs but still need additional refinement, the results of this study may give a road map for future research.

Studies on beeswax as PCM for TES

Researchers who investigated the use of beeswax as a phase transition material for various applications involving the storage of thermal energy are addressed in the following paragraphs:

In 2016, a single slope solar still was constructed by Kuhe and Edeoja [20] with the goal of boosting output. The still was coupled with a latent heat TES system and connected to a parabolic concentrator. In order to keep the still's operating temperature high enough to produce distilled water even during the hours of sunset, 14 kg of beeswax had to be used as a PCM underneath the absorber plate. The bottom of the still was covered with a 0.2 m-thick metal sheet that is painted black on the side facing the parabolic concentrator to help gather solar energy reflected from the concentrator and conduct it to the PCM. In order to have a better understanding of the single slope solar still's potential, experiments were run on it both with and without the PCM effect. Measurements were made of the PCM's temperature as well as the temperatures of the water, the air, the inner surface of the glass, and the

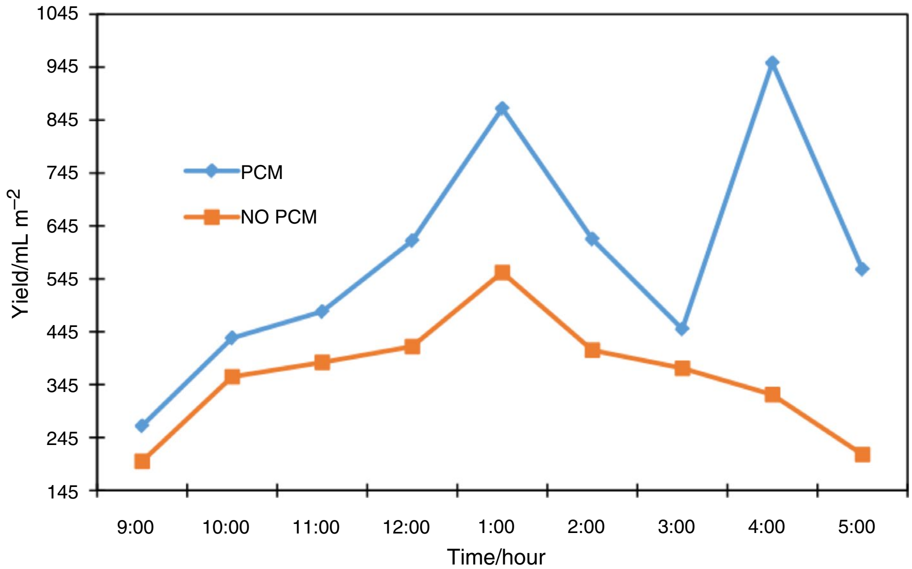

Fig. 1 Yield of distillate water with respect to time [20]

outside surface of the glass. Figure 1 illustrates the experiment findings, which show that adding thermal storage to a parabolic concentrator connected to a single slope solar array still resulted in a 62% increase in overall output.

Sinaringati et al. [11] in 2016 focused on the comparison between the use of paraffin and beeswax materials as the sources of heat energy on newborn incubators. The findings showed that the PCMs are able to keep the heat energy at a temperature of more than 32 °C for a period of more than 8 h in the neonatal incubator environment. However, it was discovered that beeswax performed far better than paraffin when it came to the storage of heat energy. This research recommended the use of beeswax as the primary component material (PCM) for newborn incubators, as well as perhaps for any other practical use.

Beeswax was used by Dinker et al. [21] in 2017 as a thermal storage unit in a novel rectangular shell and tube type design. Beeswax is a natural latent heat storage material (TSU). In this geometry, the rectangle shell was filled with beeswax and implanted with a copper helical coil carrying hot heat transfer fluid. Through a series of charging and discharging tests, using water as the heat transfer fluid in each one, the thermal performance of beeswax was examined (HTF). We looked explored the impact of HTF flow rates (0.25 LPM, 0.5 LPM, 0.75 LPM, and 1.0 LPM) and inlet temperatures (60 °C, 70 °C, and 80 °C) on the beeswax's ability to store heat and how long it takes to charge. The flow rates range from 0.25 to 1.0 LPM, while the inlet temperatures range from 60 to 80 °C. It was found that increasing the fluid flow rate decreased the amount of time needed to charge the system while increasing the fluid intake temperature increased the amount of time needed to charge the system. This was seen to be the case. When HTF was flowing through the TSU at a rate of 0.5 LPM at a temperature of 80 degrees Celsius, the TSU reached its maximum efficiency of 84%.

Nugraha et al. [22] enhanced the functionality of a non-electric beeswax newborn incubator in order to create a model that is more dependable and useful. The design of the first beeswax cartridge, which took the shape of copper boxes, was later altered to make use of tubes made of stainless steel. Both the shape and position of the air openings were altered as part of the redesign. In order to bring down the overall mass of the incubator, the body material, which had previously been made of wood, was switched out for polyurethane. In order to melt the beeswax, the cartridges containing the beeswax were heated using boiling water. According to the findings, a newborn incubator made of polyurethane may be made smaller, lighter, and more user-friendly. The newly developed concept for a non-electric newborn incubator was able to maintain a temperature ranging from 32 to 36 °C for a period of two hours.

Cheng et al. [23] created beeswax-tetradecanol/expanded perlite composited with carbon fiber (BW-TD-CF/EP) composite phase change materials (CPCMs) for the use of solar energy utilizing a vacuum impregnation procedure. The physical combination of the raw materials rather than a chemical interaction is demonstrated by the characterization and measurement of the CPCMs' chemical compatibility, microstructure, and thermal properties. It also demonstrates that BW-TD-CF is sufficiently absorbed into the porous structure of EP with no leakage even in the molten state. As shown in Fig. 2, the inclusion of CF results in an increase in the thermal conductivity of the BW-TD/EP composite from 0.443 to 1.245 W $m^{-1}K^{-1}$. As a result, the form-stable composite PCMs have stronger thermal stability in buildings and more favorable thermal characteristics for the use of solar energy.

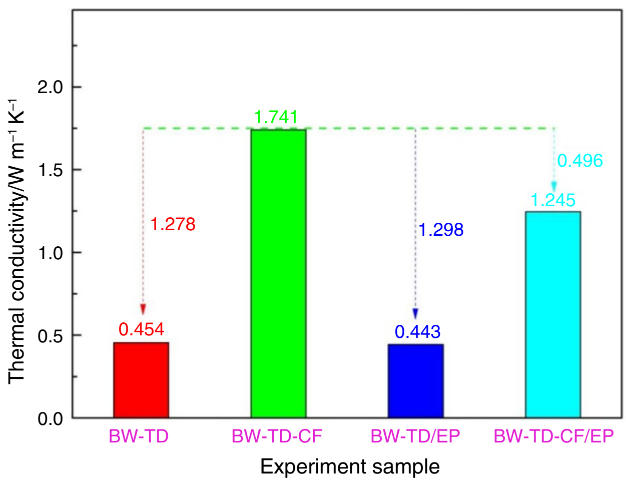

Fig. 2 Thermal conductivities of BW-TD, BW-TD-2 mass%CF, BW-TD/EP and BW-TD-2 wt%CF/EP composites [23]

An experimental effort was provided by Thaib et al. [24] in 2017 to explore the behavior of PV-PCM systems in actual outside uncontrolled settings in order to establish how successful they are. In addition, the PV-PCM systems were evaluated in Banda Aceh, Indonesia, which is located at a low latitude and has a warm environment. Experiments were carried out in the open air at the Engineering Faculty of Syiah Kuala University, which is situated in the city of Banda Aceh in Indonesia (05:57 N, 95.37 E). As a phase transition substance, paraffin wax and beeswax were both put to use in this particular investigation. The conclusive research found that photovoltaic (PV) panels operating without PCM have an electrical efficiency that ranges between 6.1 and 6.5%. However, the efficiency of PV panels that use PCM may vary anywhere from 7.0 to 7.8%. This demonstrated that the technique of cooling PV panels with water is capable of enhancing their efficiency to a greater degree.

Dinker et al. (2017) [15] presented beeswax as a natural phase transition material that might be used for the storage of low-temperature thermal energy. Differential Scanning Calorimetry was used in order to investigate the thermal characteristics of beeswax (DSC). A thermal storage unit of the tube and shell type was built to conduct research on the thermal performance of employing beeswax as a thermal storage material. A heated fluid was permitted to flow through the copper tube that was positioned in the center of the storage material shell. The rate of temperature change over time was investigated at nine distinct locations across the thermal storage units. The results of Fig. 3 indicated that the flow rate of the heat transfer fluid had little effect on how long it took to charge the beeswax. However, as the temperature of the heat transfer fluid at the inlet climbed, the time required to charge the beeswax reduced.

Umar et al. [25] investigated the mechanical characteristics of concrete mixtures that included PCM (PCM). The PCM combination that the researchers utilized consisted of beeswax, tallow, and dammar gum. According to the findings of the PCM characteristics test, the latent heat energy content of beeswax and tallow have a great potential to be used as PCM. On the other hand, dammar gum is beneficial in boosting the thermal conductivity of concrete that contains PCM. According to the findings of the tests, the concrete compressive strength was reduced by between 3 and 24% in comparison with the PCM-0% concrete compressive strength. As is seen in Fig. 4, the PCM-tallow concrete mixture has a tendency to experience a significant decrease in compressive strength.

Thaib et al. [26] assessed the effect that applying beeswax and bentonite PCM had on the concrete walls of the building. The purpose of this experiment was to determine the amount of concrete's compressive strength that would be lost if coarse aggregates were partially substituted with PCM beeswax/bentonite. It has not been possible to improve the strength of the concrete by including PCM-beeswax into the mixture. Even more concerning, evidence suggests that their presence lowers the compressive strength of PCM mixed concrete (Fig. 5). The results of heat absorption tests

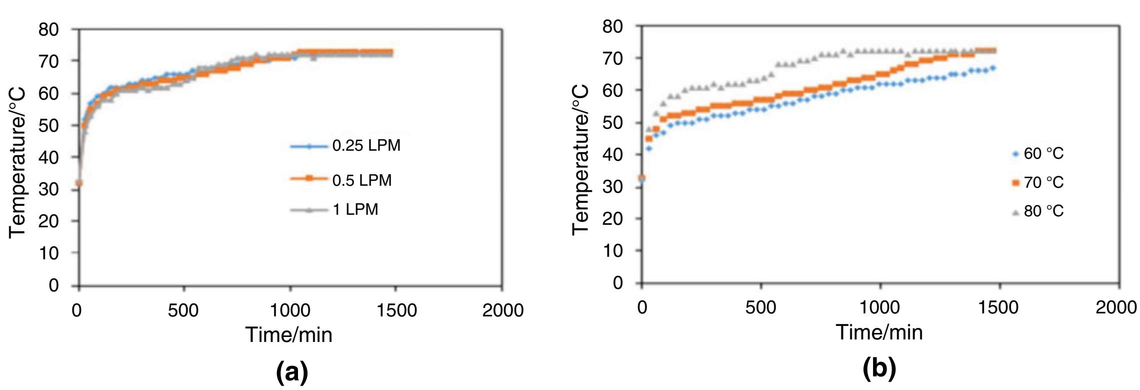

Fig. 3 Charging history **a** at different rates of flow, **b** at different inlet temperatures [15]

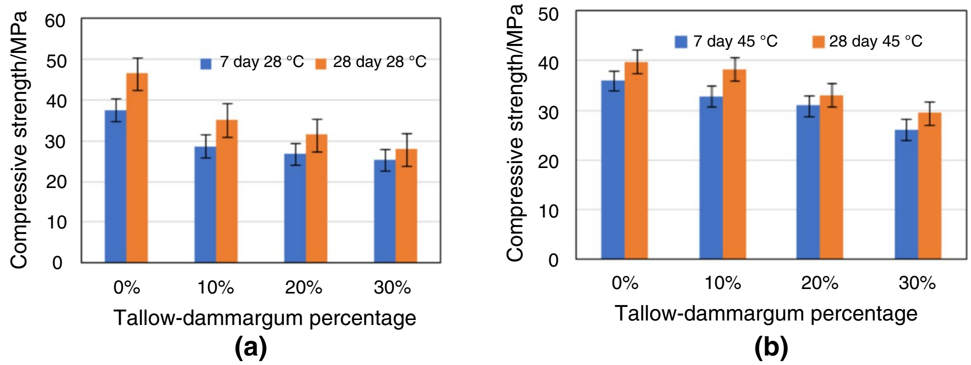

Fig. 4 Compressive strength evaluation of concrete containing PCM-TD **a** at a temperature of 28 °C; **b** at a temperature of 45 °C [25]

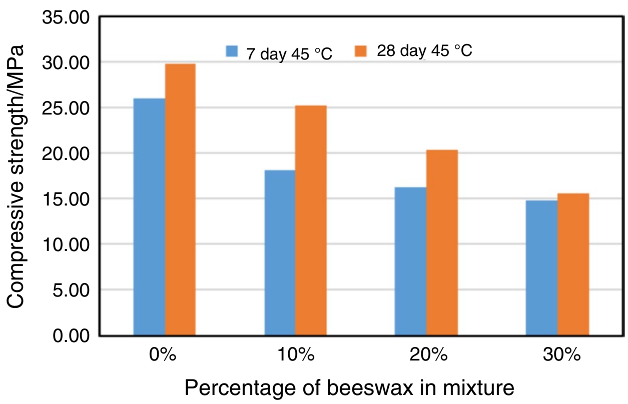

Fig. 5 The compressive strength of the concrete mixture after it is heated to 45 °C [26]

indicated that the addition of PCM beeswax/bentonite to concrete may reduce the temperature of the concrete by up to 6.67% when compared to concrete without PCM. It also suggests that PCM presented in this research has a significant amount of potential for use as an additive in lightweight concrete.

In 2019, Putra et al. [27] created a technique for thermal cycling test in which the polarity of the thermoelectric material was automatically altered to correspond with the temperature of the sample being tested. In addition, a newly designed cartridge that can be used with this apparatus only needs a minimal amount of sample space (1.53 cm^3) and is simple to install and dismantle. As a potential candidate for the PCM sample, the suggested device was evaluated using beeswax. This is quite significant for cost reductions on PCMs material, which is often rather pricey. The findings demonstrated that the equipment had automatically cycled between the temperatures necessary for melting and chilling the beeswax. The thermal data indicated that after 1000 cycles, beeswax maintains the same temperatures for melting and freezing; nevertheless, its heat of fusion decreases after repeated thermal cycling, as illustrated in Fig. 6.

Beeswax has been used as a low-temperature phase transition material for the storage of thermal energy, according to studies by Kabir and Yola [28] in 2020. It has been concluded that there is a chance that beeswax could be used to store thermal energy. This study examined the heat stability and life cycles of three various beeswax kinds. These three types of nesting habitats provided the beeswax samples. The techniques that might be used to determine whether or not these materials were suitable for use in an application that included the storage of low-temperature thermal energy were differential scanning calorimetry (DSC), thermogravimetric analysis (TGA), and differential thermal analysis (DTA). The obtained results demonstrated that beeswax

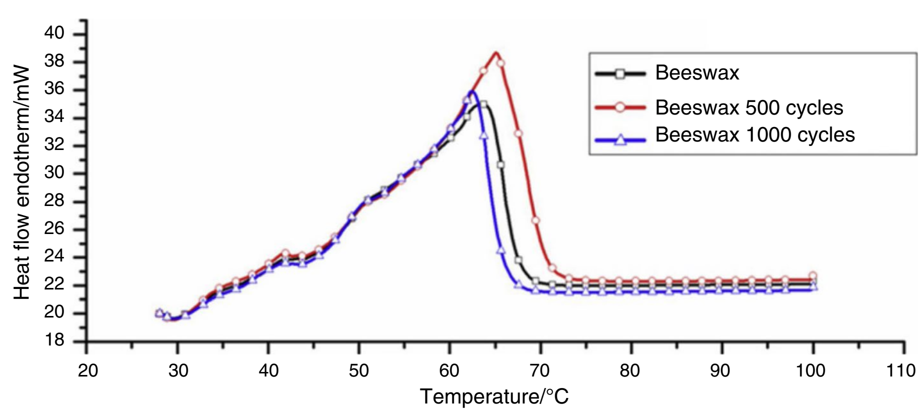

Fig. 6 Endothermic differential scanning calorimetry (DSC) curves for beeswax melting [27]

was stable for samples A, B, and C at operating temperatures of 60–270 °C, 60–260 °C, and 60–250 °C, respectively. The material can last 34.76 service years while staying within the beeswax stable temperature range, according to the results of a life-cycle research that used the Coffin Mason equation.

Using a heat pipe and PCM, Putra et al. [29] built a passive cooling system, and then used battery simulators to study how well it worked. The objective of this study was to evaluate the performance of the cooling system and choose the most suitable PCM (beeswax or Rubitherm RT 44 HC) for an operating temperature range of 25–55 °C. As can be seen in Fig. 7, the implementation of a heat pipe may bring the temperature of the battery down by 26.62 °C when subjected to a heat load of 60 watts, in comparison with the scenario in which a passive cooling system was not present. Furthermore, the addition of RT 44 to a heat pipe resulted in a maximum temperature drop of 33.42 °C. As a result, an RT 44 HC is more efficient than beeswax because its melting temperature is within the acceptable range for the battery working temperature and because it can absorb more heat than beeswax thanks to its latent heat. Additionally, an RT 44 HC's melting temperature falls within the acceptable range for the battery's working temperature.

Beeswax, transistorized beeswax methyl esters, and combinations of beeswax with paraffin were the subjects of research conducted by Baptista et al. [30] in 2020. In addition, waste vegetable cooking oil, which is abundantly accessible but not put to its full potential as a renewable raw material, was completely hydrogenated, and the resulting product and its mixes with beeswax were studied as potential candidates for use as PCMs. The melting and crystallization enthalpies of transistorized beeswax are about 15% higher than those of the beeswax that is already appropriate. It was discovered that the addition of beeswax to hydrogenated waste cooking oil was effective in boosting the creation of the most stable triacylglycerides polymorph. As a result, mixes of these two renewable raw materials are viable candidates for LHTES. As can be seen in Fig. 8, mixes of beeswax and paraffin that include forty percent of the former have a thermal behavior that is very close to being perfect for a PCM, while at the same time reducing the quantity of the crude derivative. In addition, the volume change that occurs during melting, which is one of the most significant issues that paraffin presents as a PCM, is significantly reduced for this combination (by about 50%).

In 2021, Amberkar and Mahanwar [31] employed the Taguchi technique to analyze the influence of process parameters in the microencapsulation process of beeswax with resorcinol modified phenol–formaldehyde shell. This was done in order to determine the optimal values for each of the process parameters. In order to investigate the influences that the ratio of the core to the shell of the process parameters, the concentration of the surfactant, and the agitation speed have on the control parameter core content, an orthogonal array of 53 was developed. The quantity of heat that may be stored in microcapsules is directly proportional to the amount of core material that they contain. The optimal values for the concentration of the surfactant, the ratio of the core to the shell, and the agitation speed were respectively 3%, 1:1, and 800 rpm. Within the temperature range of 35–62 °C, the microcapsules that were produced with process parameter values that were optimized exhibited a spherical shape and a heat transition enthalpy of 148.93 J g^{-1}. Figure 9 illustrates the versatility of the MPCM thanks to its spherical form and micrometer dimensions, which enable it to be employed in a broad variety of contexts.

Thaib [32] in 2021 described an experimental study to ascertain the compressive strength of the concrete if the coarse aggregate (gravel) was partially replaced by the gravel material using the PCM of Beeswax (beeswax) according

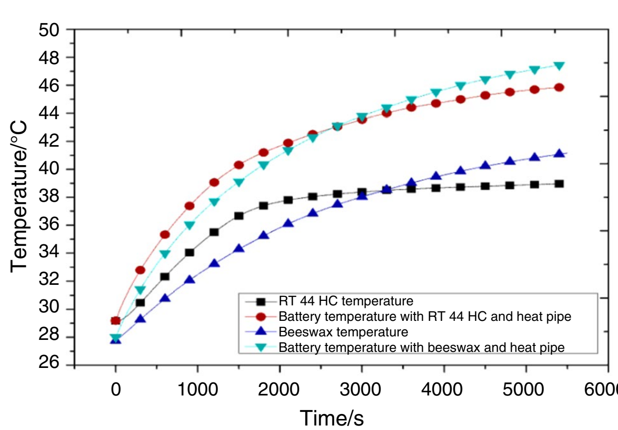

Fig. 7 Temperature comparisons on the surface of the batteries under a heat load of 60 W [29]

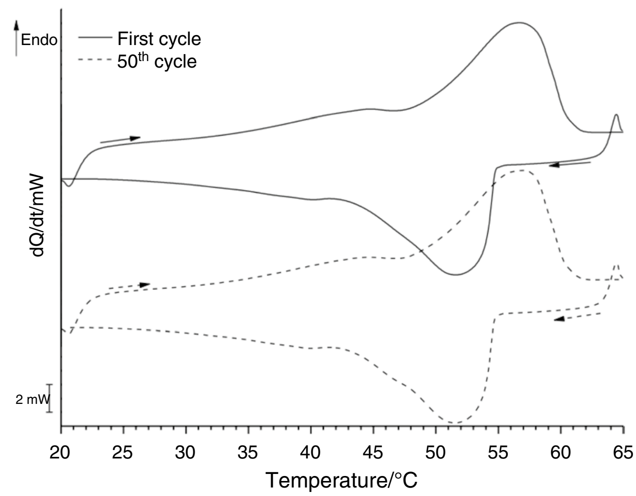

Fig. 8 DSC curves were generated for a combination of beeswax and paraffin that included 40% beeswax [30]

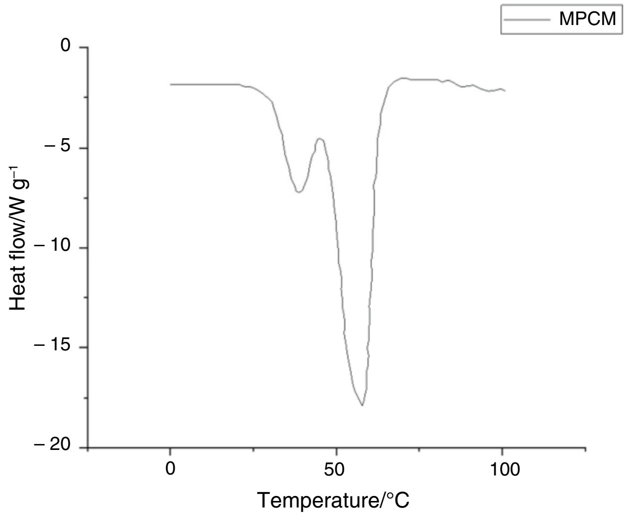

Fig. 9 An optimized DSC curve of the batch [31]

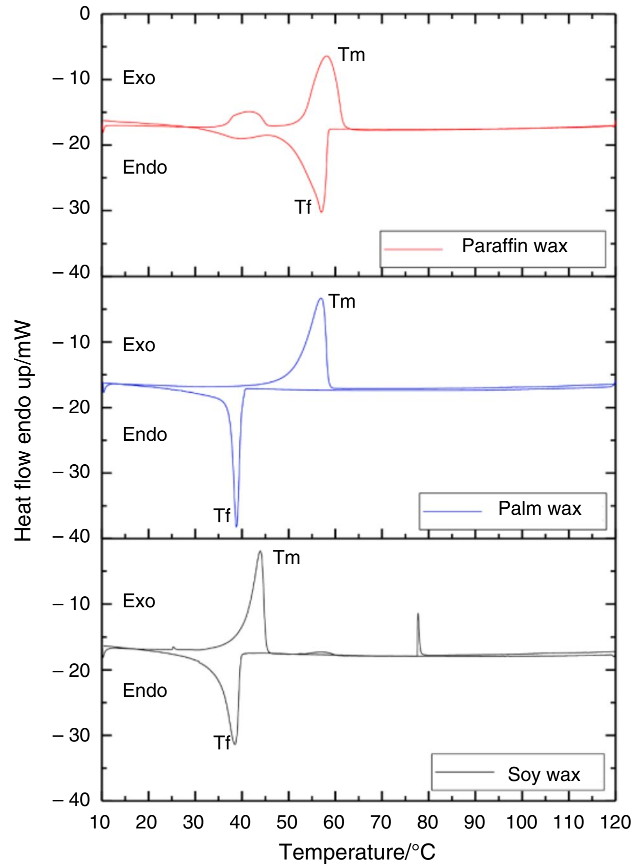

Fig. 10 DSC graphs of the waxes made from soy, palm, and paraffin [33]

to the required percentage starting from 0%, 5%, 10%, and 15% and if the aggregate was fine. The purpose of the study was to ascertain the concrete's compressive strength in the event that the coarse aggregate (gravel) was changed. As a partial substitute for sand, rice husk ash was utilized in a variety of various ratios, ranging from 0 to 15%. This usage is also an excellent choice because it will allow for the use of previously wasted rice husk ash, which can then be used or processed to be added to the concrete mix. This use is a good substitute since a procedure will be used to make use of previously discarded rice husk ash.

Thermal cycle testing was carried out by Trisnadewi et al. [33] to examine the characteristics of PCM and establish its thermal stability. By using thermoelectric as a heating and cooling medium with a total of 500, 1000, 3000, and 5000 cycles, respectively, a thermal cycle test procedure has been developed to assess the thermal stability of PCM. This approach was used to evaluate PCM's thermal stability. Palm wax, soy wax, and paraffin wax are three different types of natural waxes that were used to make their PCM. They used these waxes in their investigation. Soy wax has the lowest melting and freezing points, according to research using differential scanning calorimetry (DSC). According to Fig. 10, these temperatures are 43.92 °C and 38.49 °C, respectively. The addition of the test module to 4 modules and the use of the thermoelectric as a thermal cycle test device may both enhance the overall efficacy of the test. Palm wax, soy wax, and paraffin wax all produce 24, 13, and 45 cycles after an hour of thermoelectric characterization, respectively. Each module can be tested with this thermal cycle tester for up to 5000 cycles. The waxes' thermal properties steadily decreased and became less favorable after 5000 cycles. The soy wax, which saw a 60% decrease in H upon freezing, was found to have the highest value of H reduction.

A computational research of beeswax-based PCM was reported by Mishra et al. [34] for the resolution of thermal control of the li-ion battery cell. In order to enhance the heat transfer performance of beeswax-based battery thermal management systems, a numerical model of beeswax melting in a square cavity has been developed, and the influences of the phase conversion process have been investigated. This was done in order to improve the heat transfer behavior of the systems. The findings showed that the location of the heating wall had a significant impact on the phase change process. When heated from separate locations, the beeswax in the cavity melts in a manner that is distinct from one another. The change of temperature with time is also researched, and it was discovered that the temperature initially climbed quickly, but that after some time had passed, the increment rate dropped, as shown in Fig. 11.

Table 1 shows summary of studies outline studies on beeswax as PCM for TES.

Life cycling analysis using the Coffin Mason equation revealed that the material can endure for 34.76 service years while remaining within the beeswax stable temperature region. These findings were based on the findings of

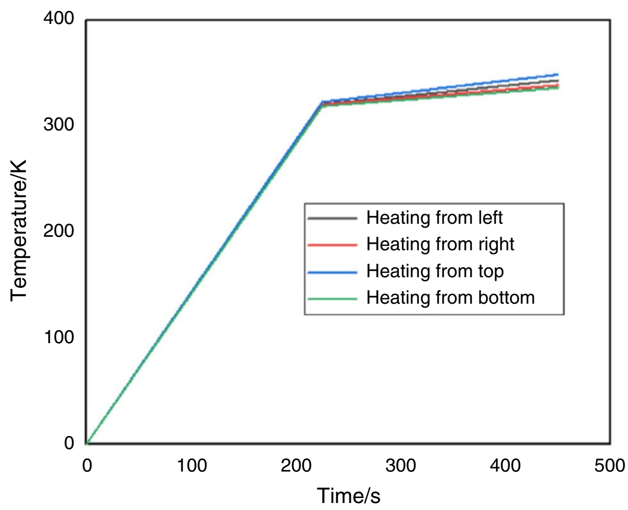

Fig. 11 Temperature changes throughout the course of time [34]

associated studies that looked at the use of beeswax as a TES medium. In addition, as compared to concrete that does not include PCM, PCM beeswax/bentonite has the ability to reduce the temperature of the concrete by up to 6.67%. Also, the use of thermal storage (beeswax) in a parabolic concentrator paired with a single slope solar system managed to bring about a 62% increase in the system's output.

Studies on nanoparticles-beeswax as PCM for TES

PCM materials have either had a metal oxide or metal particles added to them in order to increase their thermal conductivities. This has been done by incorporating/adding the metal particles. The thermal characteristics of beeswax were tested by researchers, and the results indicated that the thermal conductivity of the beeswax was improved when graphene and CuO were added. Researchers who introduced the use of Nanoparticles combined with beeswax as a phase transition material for various applications involving the storage of thermal energy are addressed in the following paragraphs:

The thermo-physical characteristics as well as the heat transport qualities of a beeswax Nanoemulsion were investigated by Anderson et al. [35] in 2013 when it was subjected to forced convection in a circular tube. First, the beeswax Nanoemulsion was created by combining surfactants and water. This resulted in the Nanoemulsion having a low viscosity, which improved its ability to be pumped, as well as a high proportion of beeswax by mass, which resulted in a better capacity for latent heat storage. The testing portion consisted of a circular tube made of stainless steel with a diameter of 11.3, and it was heated in a homogeneous manner using an ohmic heating technique. Figure 12 depicts the experimental results that suggest that a stable beeswax Nanoemulsion has adequate heat transfer coefficients. This makes the Nanoemulsion a promising candidate for charging and discharging thermal energy in applications involving thermal storage.

Within a rectangular shell and tube thermal storage unit, Dinker et al. [36] in 2016 investigated the thermal performance of beeswax and its composite as a heat storage medium. Beeswax was investigated as a potential novel energy storage material, along with its composite with expanded graphite. This combination was then manufactured, tested for its surface and thermal characteristics, and described. Characterization of the surface revealed that beeswax and expanded graphite do not interact chemically with one another. The thermal conductivity of the composite material saw a 117% improvement after being treated. The composite's melting point remained virtually the same as that of beeswax, but the melting time was significantly decreased from 540 to 360 min when the input water temperature was 80 °C and the flow rate was 2 LPM.

Putra et al. [37] investigated the thermal properties and behaviors of beeswax/CuO Nano-PCM by using beeswax as a high thermal-capacity phase-change material. In this work, equipment for differential scanning calorimetry was used to determine the temperature at which Nano-PCMs melt as well as their overall thermal capacity. The research discovered that the melting temperatures of Nano-PCM were 63.62 °C at 0.05 mass percent, 63.59 °C at 0.1 mass percent, 63.66 °C at 0.15 mass percent, and 62.45 °C at 0.25 mass percent. According to the results of FTIR tests, there was no chemical interaction between CuO and beeswax. The presence of CuO Nanoparticles in beeswax has resulted in an increase in the material's thermal conductivity but a decrease in its heat capacity. However, the variation in latent heat has not generated any substantial changes in the performance of the beeswax/CuO combination. In light of these findings, it can be deduced that the heat transmission of the composite beeswax/CuO melts quicker than the basic phase-change material.

The research conducted by Amin et al. [38] has the objective of measuring and analyzing the thermal characteristics of graphene and beeswax as a phase transition material. A differential scanning calorimeter (DSC) was used to estimate the melting temperature, thermal capacity, and latent heat. A thermal conductivity measuring instrument was also used to explore the thermal conductivity. The viscosity of the material was analyzed in order to get insight into the alteration of the material's physical characteristics that was brought on by the presence of Nanoparticles. According to the findings of the DSC, there was a 22.5% rise in the latent heat of 0.3% beeswax/graphene. The combination of 0.3 mass percent beeswax and graphene has a heat conductivity of

Table 1 Summary of studies outline studies on beeswax as PCM for TES

Authors (year) reference	Configuration/composition	Studied parameters	Highlighted results/findings
Kuhe and Edeoja (2016) [20]	Under the absorber plate of the single slope solar still that was attached to a parabolic concentrator and combined with a latent heat TES system, 14 kg of beeswax served as the PCM	The effect of thermal storage	The use of thermal storage, namely beeswax, in conjunction with a parabolic concentrator connected to a single slope solar array managed to achieve a 62% improvement in overall production
Sinaringati et al. (2016) [11]	Materials made of beeswax were used in the newborn incubator as sources of heat energy	Impact of using paraffin and beeswax as source of heat energy	Beeswax performed much better than paraffin when it came to the storage of heat energy. The PCMs were able to keep the temperature in the neonatal incubator chamber at more than 32 °C for more than 8 h
Dinker et al. (2017) [21]	Beeswax is a natural latent heat storage substance that may be used in a new rectangular shell and tube type shape as a thermal storage unit (TSU)	Effect of flow rates (0.25 LPM, 0.5 LPM, 0.75 LPM, 1.0 LPM) and inlet temperatures (60 °C, 70 °C, 80 °C),	The system's charging time was cut down, and its storage capacity was increased, as a result of the increased fluid flow rate. However, the charging time was lengthened as a result of the increased fluid intake temperature. When HTF is flowing through TSU at 80 °C and 0.5 L per minute, the TSU achieves its maximum level of efficiency, which is 84%
Nugraha et al. (2017) [22]	In a baby incubator that does not need electricity, beeswax is used	Impact of using beeswax in non-electric infant incubator	The newly developed model of non-electric newborn incubator was able to maintain a temperature range of 32–36 °C for a period of two hours
Cheng et al. (2017) [23]	In the field of solar energy usage, CPCMs made of beeswax-tetradecanol/expanded perlite and carbon fiber are referred to as BW-TD-CF/EP	Impact of adding CF to BW-TD/EP composite	Thermal conductivity of BW-TD/EP composite is enhanced from 0.443 to 1.245 $Wm^{-1} K^{-1}$ by adding CF
Thaib et al. (2017) [24]	Both paraffin wax and beeswax were used in PV-PCM systems as the PCM	Influence of using paraffin wax and beeswax in PV-PCM systems	Without the use of PCM, the electrical efficiency of PV panels falls somewhere in the region of 6.1–6.5%. However, the efficiency of PV panels that use PCM may vary anywhere from 7.0 to 7.8%
Dinker et al. (2017) [15]	Wax from beehives may be used as a natural phase transition material for the storage of low-temperature thermal energy	Flow rate and temperature of inlet heat transfer fluid	The flow velocity of the heat transfer fluid has no effect on the amount of time it takes beeswax to charge, but the time to charge dropped as the temperature of the heat transfer fluid entering the system rose
Umar et al. (2018) [25]	The incorporation of beeswax, tallow, and dammar gum into concrete as a PCM combination	The impact of using beeswax, tallow, and dammar gum in concrete	Beeswax and tallow both have high latent heat energy contents, indicating a tremendous potential for use as PCM. Dammar gum, on the other hand, has a positive impact on improving the thermal conductivity of concrete that contains PCM due to its capacity to do so
Thaib et al. (2019) [26]	Applying a beeswax and bentonite PCM coating to the building's concrete walls	The effect of using PCM beeswax/bentonite on the concrete walls of the building	When compared to concrete that does not include PCM, PCM beeswax/bentonite has the ability to reduce the temperature of the concrete by up to 6.67 percent

Table 1 (continued)

Authors (year) reference	Configuration/composition	Studied parameters	Highlighted results/findings
Putra et al. (2019) [27]	Beeswax was used to test a new cartridge design using the PCM method	Impact of using beeswax in cartridge	Beeswax maintains the same temperatures at which it melts and freezes even after one thousand cycles of thermal cycling; however, its heat of fusion decreases with each additional cycle
Kabir and Yola (2020) [28]	Utilizing beeswax as a TES material that undergoes phase shift at low temperatures	Impact of using beeswax	According to the findings of a life-cycle study that made use of the Coffin Mason equation, the material is capable of enduring 34.76 service years while remaining within the beeswax stable temperature area
Putra et al. (2020) [29]	Heat pipes and PCMs used in conjunction with passive cooling systems (beeswax)	Impact of using heat pipe and beeswax	The usage of a heat pipe had the ability to reduce the battery's temperature by 26.62 °C when subjected to a 60-W heat load when compared to a case with a passive cooling system. The maximum temperature drop attainable was 33.42 °C when RT 44 was added to a heat pipe. As a result, an RT 44 HC is more effective than beeswax since its melting temperature is within the acceptable limit for the operation temperature of the battery
Baptista et al. (2020) [30]	Wax, beeswax methyl esters that have been transistorized, and combinations of beeswax and paraffin are all types of beeswax	Influence of using beeswax	Beeswax and paraffin combinations with a composition of 40% beeswax exhibit thermal behavior that is close to being optimal for a PCM, while at the same time reducing the quantity of the crude derivative
Amberkar and Mahanwar (2021) [31]	Beeswax was microencapsulated using a technique that used resorcinol-modified phenol–formaldehyde shells	Influence of presence beeswax in the process of Microencapsulation	The parameters of 3% for the concentration of the surfactant, 1:1 for the ratio of the core to the shell, and 800 rpm for the agitation speed were found to be ideal
Thaib (2021) [32]	Beeswax was used as a PCM in lieu of some of the coarse aggregate (gravel) in the material that comprised the gravel (beeswax)	Impact of adding beeswax	Since of the reduction in compressive strength caused by the addition of 15% diangka beeswax and rice husk ash, the combination cannot be used because it falls short of the 4.33 MPa brick wall compressive strength requirement
Trisnadewi et al. (2021) [33]	The PCM that was utilized was comprised of three different kinds of waxes that originated from natural sources: palm wax, soy wax, and paraffin wax	The impact of using 3 types that derived from natural waxes, namely palm wax, soy wax and paraffin wax	The value of H reduction was found to be at its maximum for the soy wax, which achieved a decrease of 60% in *H* during freezing
Mishra et al. (2021) [34]	PCM made of beeswax for the purpose of regulating the temperature of the li-ion battery cell	Impact of using beeswax	When heated from separate locations, the beeswax in the cavity melts in a manner that is distinct from one another. The change of temperature with time is also explored, and it was discovered that the temperature initially climbed fast, but that after some time, the increment rate dropped

2.8 W m^{-1} K^{-1}. As can be seen in Figs. 13 and 14, the presence of graphene Nano-platelets in the beeswax led to an increase in both the latent heat and the thermal conductivity of the material.

A pure beeswax and its unique composite with expanded graphite (10% mass) were both evaluated for their ability to efficiently store heat in a storage unit consisting of a rectangular shell and helical tubes by Dinker et al. [39]. Beeswax has a low heat conductivity; however, this may be enhanced by adding 10% by mass of expanded graphite. Utilizing differential scanning calorimetry and thermo-gravimetric analysis, a thermal characterization of beeswax and its composite was carried out. The effect of hot fluid flow rates (0.25 L per minute [LPM], 0.5 LPM, and 1.0 LPM) and inlet temperatures (60 °C, 70 °C, and 80 °C) on the charging time of beeswax and its composite was researched and compared. Inlet temperatures ranged from 60 to 80 °C. The shorter charging time of beeswax and its composite was achieved by increasing the fluid flow rate as well as the temperature at the intake. The charging time of the composite was lowered by 630 min when compared to charging with pure beeswax at a flow rate of 0.5 LPM and an intake fluid temperature of 8 0 °C.

Beeswax and multi-walled carbon Nano-tubes were combined to create a form-stable Nanocomposite phase-change material for TES that was developed by Putra et al. [40]. Because it has a high latent heat, beeswax was employed as the PCM, and multi-walled carbon Nano-tubes (MWCNTs) were used as the supporting material because of their high thermal conductivity. This study makes use of three distinct preparations of MWCNTs: pristine MWCNTs, MWCNTs that have been ball-milled, and MWCNTs that have been treated with acid. Samples of a beeswax/carbon Nano-tube composite were made with ratios of 5 and 20 mass%. Samples of composites were evaluated with regard to their structural modification and thermal performance. These evaluations included testing for thermal conductivity, melting point, and solidifying point, as well as latent heat, sensible heat, melting point, and solidifying point testing. Figure 15 displays the findings of the trials, which showed that the new shape-stable Nanocomposite PCM's thermal conductivity increased by a factor of two and that neither the melting temperature nor the solidification temperature experienced any discernible phase transitions.

An experimental investigation of using the beeswax as PCM was given by Sravani and Reddy [41]. The beeswax was contained inside capsules made of stainless steel. Because of its poor thermal conductivity value, beeswax has a delayed thermal reaction; thus, an attempt is made to dope PCM with copper, aluminum, and graphite particles individually in order to improve its ability to transport heat. An insulated tank is used to keep the capsules, and hot water is poured into the tank periodically. The experimental design is constructed by taking into consideration characteristics such as the flow rate, number of capsules, and temperatures at the inlets of the heat transfer fluid. Experiments are carried out in accordance with the findings of the Taguchi analysis, and the results are documented. Analysis of experimental data was used to study the influence of various factors on the TES system. The goal of this study was to identify the parameters that should be used when constructing an efficient TES system.

The thermal conductivity, melting temperature, latent heat, and heat capacity of beeswax containing ZnO, CuO, and soot particles at various concentrations of 0.0, 0.064, 0.326, 1.304, and 3.260 g per 20 g of beeswax were studied by Andoshe et al. [42]. When ZnO, CuO, and soot particles were added, the thermal conductivity of the beeswax increased, going from 0.2502 to 2.89 W $m^{-1}K^{-1}$, according to the examination of thermal conductivity. Additionally, the research utilizing differential scanning calorimetry demonstrated that the addition of ZnO, CuO, and soot particles decreased the melting temperature, latent heat, and heat capacity of the beeswax, as shown in Fig. 16.

In 2021, Agarwal et al. [43] looked into beeswax as a potential PCM for the storage of heat due to its high latent heat. Two of the difficulties of using this material were its poor heat conductivity and high melting point. Al_2O_3, ZnO, and FeO Nanoparticles of PCMs were mixed with other phase change elements to lower the melting point of beeswax and improve its thermal conductivity. An examination was carried out with the purpose of determining how the charging time of a beeswax composite was affected by the flow rates of hot fluid (1 LPM and 2 LPM) and the temperatures at the intake (60 °C, 70 °C, and 80 °C). According to the findings of the research, out of all of the different composites, the one containing 50 mass% beeswax and 50 mass% coconut oil together with 1 mass% of FeO Nanoparticle produced the greatest results. It was discovered that the material had a charging time that was 15 min faster than the composite that did not include Nanoparticles. It was possible to achieve an increase in thermal conductivity of 112.77% by utilizing FeO Nanoparticles for 3 mass% of Nanoparticles, which represented a more than twice increase, as represented in Fig. 17.

Mishra et al. [44] evaluated computationally the composite-beeswax strategy to overcome the poor efficiency in heat transmission caused by the low thermal conductivity of beeswax. This was accomplished by combining composite materials with beeswax. In order to increase the heat conductivity of the pure beeswax, three distinct metal oxides (Al_2O_3, MgO, and SiO_2) were scattered throughout the beeswax at three different volume concentrations: 1%, 3%, and 5%. According to the findings, the melting rate as well as the heat transmission were marginally enhanced when the geometry of the annulus was a rectangular–rectangular

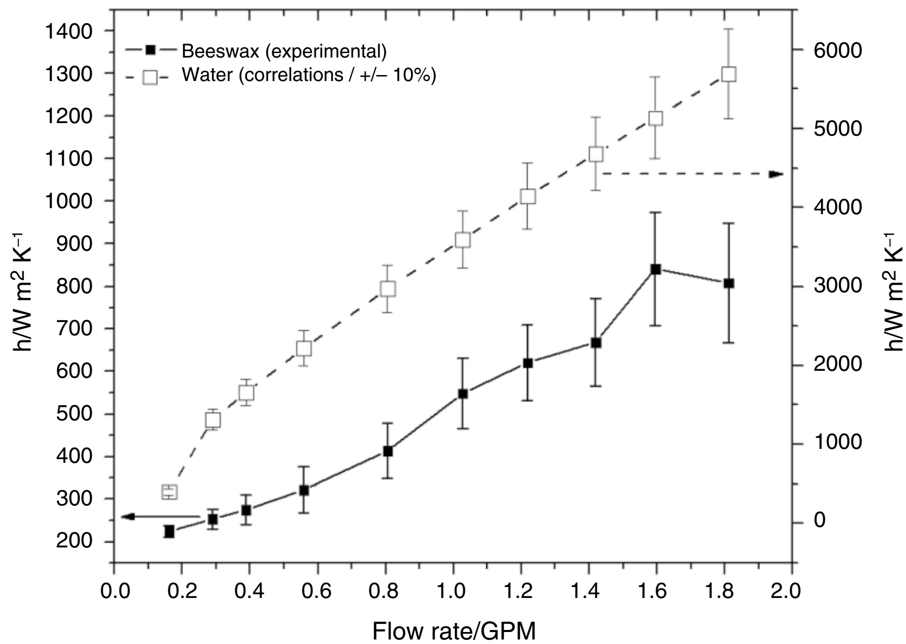

Fig. 12 Experimentally determined average coefficients of heat transmission for flow rates ranging from 0.16 to 1.81 gallons per minute (0.61 to 6.85 L per minute) [35]

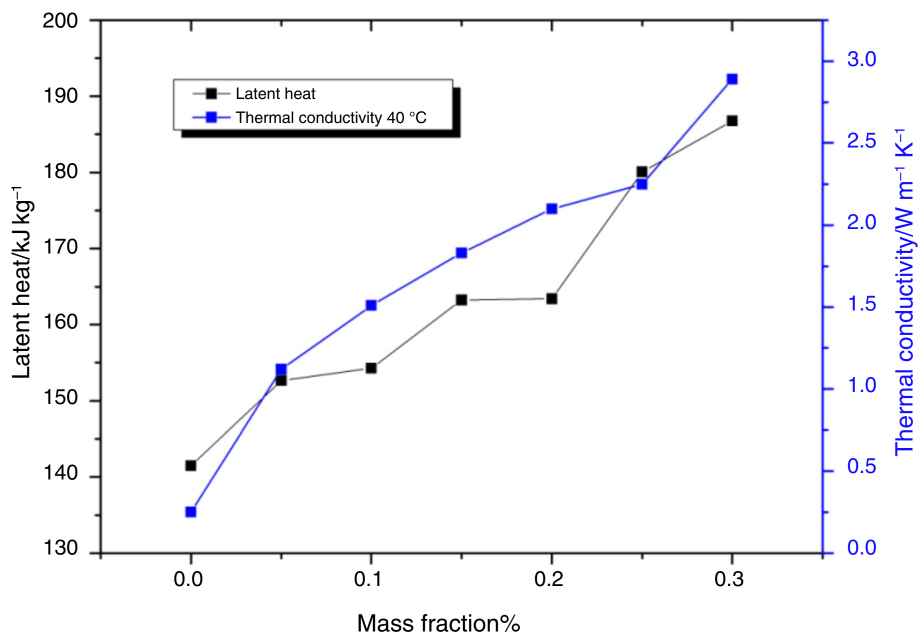

Fig. 13 Latent heat enhancement and the relationship between thermal conductivity [38]

combination. The results also showed that the presence of metal oxide particles results in a considerable increase in the rate of melting as well as an improvement in the heat transmission. Additionally, it was discovered that the different sorts of particles have not significantly altered the pace at which heat was transferred or melted. At the same time, it is 341 K as observed for the beeswax, which demonstrated an improvement of 1.4% in the case of circular-circular annulus and Al_2O_3. The temperature of the system reached 346.4 K at 15,000 s of process for all three Nanoparticles that were under investigation.

The integration of carbon Nano-tubes (CNT) into beeswax led to an increase in the material's ability to transfer heat, as shown by Amberkar and Mahanwar [45]. By putting it on recycled paperboard, the researchers were able to reduce the amount of molten beeswax that leaked out. The Nanocomposite made of recycled paperboard, beeswax, and carbon Nano-tubes was then covered with silicone adhesive. It made certain that melted wax would not escape. The FTIR spectrum of the Nanocomposite and the SEM morphology of it both demonstrate the physical dispersion of CNT into the matrix. The TES enthalpy was found to be reduced to

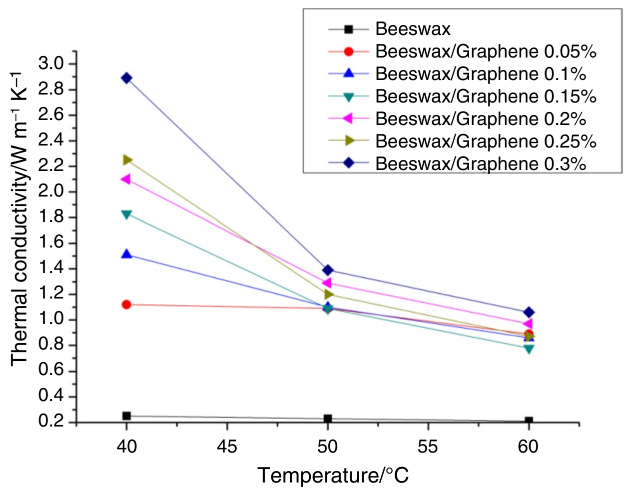

Fig. 14 Beeswax/graphene thermal conductivity [38]

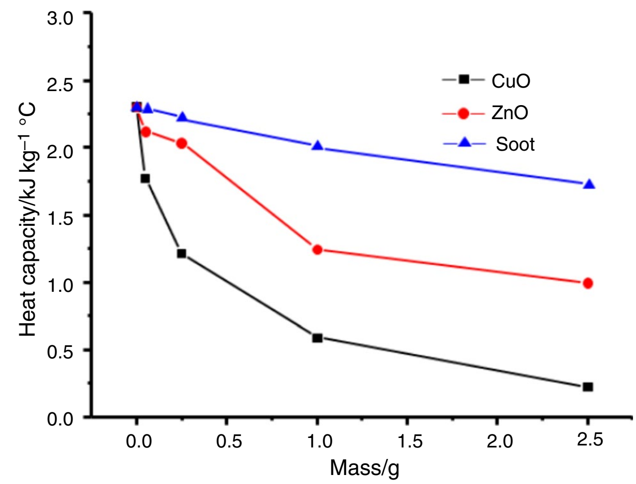

Fig. 16 Beeswax-metal oxide composite's heat capacity [42]

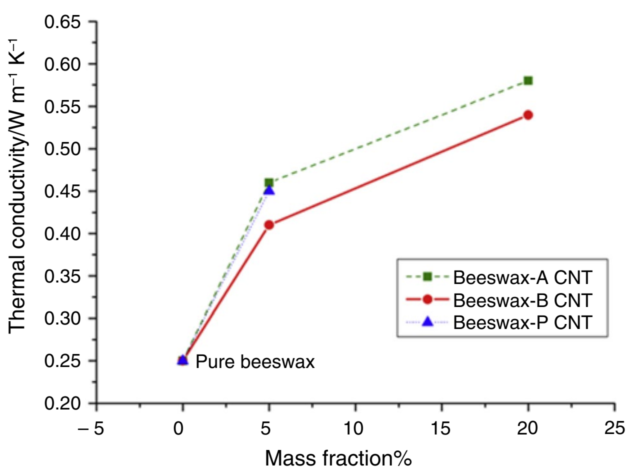

Fig. 15 Composite materials' thermal conductivity at a temperature of 40 °C [40]

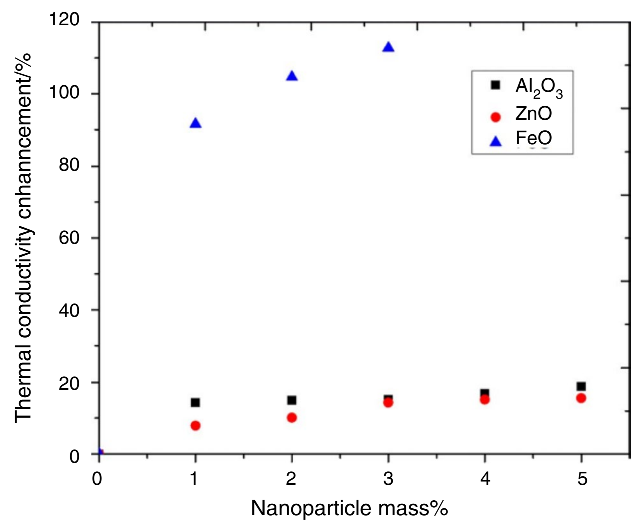

Fig. 17 Analyses of the differences in the augmentation of heat conductivity between the various Nanoparticles [43]

98.52 J g^{-1} after being analyzed by DSC for Nanocomposites. As can be shown in Fig. 18, the use of PCM Nanocomposite sheets may extend the amount of time required to keep food at a temperature that is quite near to the composite's phase transition temperature.

Table 2 shows summary of studies outline studies on Nanoparticles-beeswax as PCM for TES.

Critical evaluation of utilizing beeswax and nanoparticles-beeswax as PCMs for TES

The improvement of the effectiveness and sustainability of different energy systems depends heavily on TES. It entails capturing, holding, and releasing thermal energy for later use, which aids in balancing the supply and demand of energy. The use of natural substances like beeswax and cutting-edge technologies like nanoparticles to boost the effectiveness and efficiency of TES systems has garnered a lot of attention in recent years.

Honeybees naturally create a material called beeswax. Throughout history, it has served a number of uses, such as serving as a component for candles, cosmetics, and even food preservation. Beeswax is a naturally occurring, non-toxic, renewable resource that may be collected safely without endangering the environment. It also degrades naturally, reducing its negative effects on the environment. The potential of beeswax as a PCM in TES applications has drawn attention more recently. Specifically, having materials that can transform from a solid to a liquid or vice versa at a given temperature is a key component of PCM-based TES.

Beeswax has a relatively high latent heat capacity, allowing it to store a substantial amount of energy in a small volume. Furthermore, beeswax has a high degree of thermal stability over numerous cycles. These are key features that make beeswax as a desirable material for TES and durable for long-term use. In other words, beeswax is a reliable and secure option to store heat since it can store and release a substantial quantity of thermal energy during the melting and solidification process.

While beeswax is a good material for TES, adding nanoparticles can interestingly improve it even more. Due to their high surface area to volume ratio, nanoparticles, which are extremely small particles, have special features that make them useful additions to improve materials' thermal conductivity and heat transmission. Nanoparticles can be dispersed into the beeswax matrix in beeswax-based TES. This increases the rate of heat transmission between the solid and liquid states of beeswax, increasing the process' overall effectiveness as a means of storing thermal energy. Graphene, carbon nanotubes, and metal oxides are materials that are frequently employed as nanoparticles in TES.

The current review elucidated the innovations and progress made in the field of utilizing Nanoparticles- based beeswax as PCM for TES systems. The following points summarize these benefits;

- Beeswax's improved thermal conductivity thanks to nanoparticles makes it possible for thermal energy to be charged and discharged more quickly. This is specifically an enhanced of heat transfer.
- Higher energy densities, which enable more energy to be stored in a smaller volume, have been achieved by incorporating nanoparticles into beeswax matrices.
- The temperature range at which the beeswax undergoes phase shift can be customized to certain uses by carefully selecting nanoparticles and altering their level of concentration.
- The melting temperature, latent heat, and heat capacity of the beeswax were all shown to be decreased as a result of the inclusion of ZnO, CuO, and soot particles.
- Beeswax's latent heat and thermal conductivity may both rise as a result of the presence of graphene Nano-platelets in the material.

In a summary, the advancement of thermal energy storage technology has showed significant potential when beeswax and nanoparticles are combined. These developments may make a substantial contribution to more sustainable and energy-efficient systems as research and development in this area continues, assisting in the shift to cleaner energy sources. In the race for a greener future, the utilization of organic materials like beeswax in conjunction with cutting-edge nanoparticle technology is an example of how traditional knowledge and contemporary innovations can coexist peacefully.

Recommendation for further research

An overview of contemporary research literature on the use of beeswax for the storage of thermal energy has been offered in this article. The discussion of beeswax and Nanoparticles-beeswax began with their respective classifications, selection criteria, and property testing. Subsequently, their numerous ideas were analyzed and debated. Two tables were compiled to serve as a summary: the first table covered research on beeswax as a PCM for the storage of thermal energy, and the second table covered research on Nanoparticles-beeswax as a PCM for the storage of thermal energy. It is possible to draw the following recommendation based on the findings of the data that are

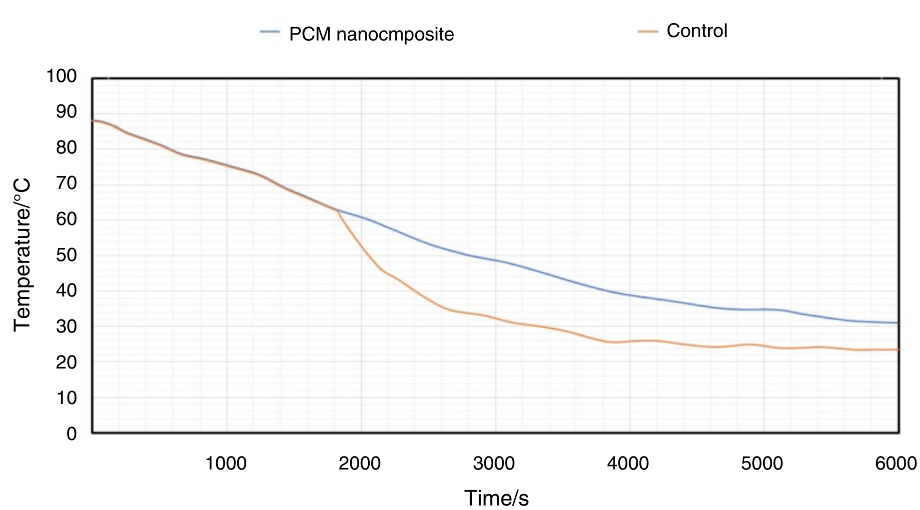

Fig. 18 PCM Nanocomposite sample and control sample temperature–time profiles [45]

Table 2 Summary of studies outline studies on Nanoparticles-beeswax as PCM for TES

Authors (year) reference	Configuration/composition	Studied parameters	Highlighted results/findings
Anderson et al. (2013) [35]	Nanoemulsion of beeswax formed in a circular tube by the process of forced convection	Impact of adding Nanoemulsion to beeswax	A stable beeswax Nanoemulsion with suitable heat transmission properties might be used in thermal storage applications to charge and discharge thermal energy
Dinker et al. (2016) [36]	A rectangular shell and tube heat storage unit containing beeswax along with its composite, which is a composite including expanded graphite	Impact of applying beeswax and its composite in a rectangular shell and tube thermal storage unit	Composite material's thermal conductivity was increased by 117%. With intake water at 80 °C and a 2 LPM flow rate, the composite's melting point remained almost identical to that of beeswax, and the melting time was decreased from 540 to 360 min
Putra et al. (2016) [37]	Beeswax/CuO Nano-PCM	Impact of using Nano-CuO with beeswax	The performance of beeswax/CuO was unaffected by the change in latent heat. Beeswax/CuO composite material melts more quickly than basic phase-change materials under heat
Amin et al. (2016) [38]	Beeswax/graphene as a PCM	The existence of graphene Nano-platelets in beeswax	Because of the presence of graphene Nano platelets, beeswax's latent heat and thermal conductivity were both improved
Dinker et al. (2018) [39]	In a storage unit consisting of a rectangular shell and a helical tube, pure beeswax and its unique composite with expanded graphite (10 mass%) are kept	Effect of hot fluid flow rates and inlet temperatures	The shorter charging time of beeswax and its composite was achieved by increasing the fluid flow rate as well as the temperature at the intake
Putra et al. (2019) [40]	beeswax/multi-walled carbon Nano-tubes	Influence of adding multi-walled carbon Nano-tubes to beeswax	The melting and solidifying temperatures of the new shape-stable Nanocomposite PCM did not exhibit any notable phase transitions, despite the fact that the thermal conductivity of the material rose by a factor of two
Sravani and Reddy (2019) [41]	Beeswax as PCM enclosed in stainless steel capsules	Inlet temperatures of heat transfer fluid, flow rate, and number of capsules	Heat transfer fluid at a temperature of 75 °C and a flow rate of 4 L per minute is more concerned with charging and discharging times
Andoshe et al. (2020) [42]	Beeswax that has ZnO, CuO, and soot particles incorporated into it, with 0.0, 0.064, 0.326, 1.304, and 3.260 g of each present in 20 g of beeswax	Impact of adding Nanoparticles to beeswax	Because ZnO, CuO, and soot particles are now a component of the beeswax, its melting temperature, latent heat, and heat capacity have all been reduced
Agarwal et al. (2021) [43]	Beeswax with Nanoparticles (of Al_2O_3, ZnO, and FeO)	Impact of adding Nanoparticles (of Al_2O_3, ZnO, and FeO) to beeswax	An increase in heat conductivity of 112.77% was shown by Nanoparticles, which is more than twice as much as before
Mishra et al. (2022) [44]	The pure beeswax has various volume concentrations of three distinct metal oxides—Al_2O_3, MgO, and SiO_2—scattered throughout it. The concentrations range from 1 to 3% to 5%	Influence of adding metal oxides to beeswax	With metal oxide particles present, the rate of melting and heat transport are greatly enhanced
Amberkar and Mahanwar (2022) [45]	Beeswax with carbon Nano-tube incorporation	Impact of adding carbon Nano-tube to beeswax	Food temperature maintenance around the phase transition temperature of the composite might take longer when PCM Nanocomposite sheets are used

included in Tables 1 and 2 and the thermal performance analysis that was included in each of the studies that were analyzed:

1. In order to facilitate more research and development, rice husk ash and beeswax PCM are not combined together all at once. It is suggested that future research and development use capsules (comprised of beeswax and rice husk ash contained inside capsules).
2. Due to its promising results of rising the thermal conductivity of the material by a factor of two, it would be interesting to direct the next research to improve the synthesis and characterization of beeswax/multi-walled carbon Nanotubes PCM for TES.
3. The entire dispersion of nanoparticles into beeswax can be made more uniform and homogenous over a long period of time if appropriate porous media with micro-scale holes are used. It may be possible to use this to address the issue of unstable beeswax nanoparticles.
4. Solar thermal systems can be connected with beeswax-based TES, with or without Nanoparticles, enabling the effective storage of solar energy for subsequent use.

Conclusions

Beeswax is a naturally occurring PCM that has its greatest phase transition enthalpy in the temperature range of 60–68 °C. It has the potential to be used in a wide number of applications that include the storage of thermal energy. Researchers are interested in the durability and temperature resistance of beeswax. In a scenario with three changes each day, beeswax may continue to function for 37 years. The melting point of beeswax is around 250 °C. The capacity of beeswax to absorb heat more effectively than paraffin wax has led researchers to conclude that it is superior to paraffin wax as an alternative. It is comparable to paraffin wax in that it similarly has a high melting point and poor heat conductivity, however it has a greater melting point than paraffin wax does. Adding additional components such as carbon Nano-tubes, expanded graphite, graphene, and copper Nanoparticles has been the subject of a number of experiments that have been carried out in an effort to boost the thermal conductivity of the material. One could potentially reach the following findings after reviewing a summary of the data presented in the evaluated articles:

1. The productivity of the parabolic concentrator-coupled single slope solar still has been improved by 62% as a result to the use of thermal storage (beeswax).
2. The PCMs have the ability to keep the heat energy at a temperature higher than 32 °C for more than eight hours in the room that houses the neonatal incubator. Beeswax fared better than paraffin in terms of storing heat energy.
3. The system's charging time and storage efficiency have been improved as a result of an increase in the fluid flow rate. Nevertheless, the charging time became longer as a result of a rise in the fluid input temperature.
4. The flow rate of heat transfer fluid has insignificant impact on the amount of time required for charging beeswax. However, the amount of time required for charging can be decreased when the temperature of the input heat transfer fluid increases.
5. Beeswax and tallow both have a high potential for use as PCM due to their latent heat energy content, whereas the addition of dammar gum improves the thermal conductivity of concrete containing PCM.
6. When compared to concrete that does not include PCM, PCM beeswax/bentonite has the ability to lower the temperature of the concrete by up to 6.67%.
7. A beeswax stable temperature area was used in the life cycle study, which revealed that the material can last 34.76 service years at that temperature range. The Coffin Mason equation was used to conduct the analysis.
8. A stable beeswax Nano-emulsion has adequate heat transfer properties, making it a potential candidate for thermal energy charging and discharging in applications involving thermal storage.
9. The composite's melting point remained about the same as that of beeswax, but the time required to melt it decreased from 540 to 360 min when the input water temperature was set at 80 °C and the flow rate was set at 2 L per minute.
10. The variation in beeswax/performance CuO's was not significantly affected by the change in latent heat. The basal phase-change material melts more slowly than the composite beeswax/CuO, which transfers heat more quickly.
11. The presence of graphene Nano-platelets in the beeswax led to an increase in both the latent heat and the thermal conductivity of the material.
12. As the fluid flow rate and intake temperature increased, the charging time for beeswax and its composite decreased.
13. The beeswax has a lower melting temperature, lower latent heat, and lower heat capacity as a result of the inclusion of ZnO, CuO, and soot particles.
14. The presence of metal oxide particles resulted in a considerable increase in both the pace at which the material melts and the amount of heat that it transfers.

Author contributions FLR contributed to conception and design, analysis and clarification of the data, and approval of the final version. MAA-O contributed to analysis and clarification of the data, drafting the article or revising it critically for important intellectual content, and approval of the final version.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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