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Latest Progress in Utilizing Coconut Oil as Sustainable Phase Change Materials in Thermal Energy Storage Systems: Promoting Environmentally Sustainable Energy Systems

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Coconut oil; phase change materials; thermal energy storage; latest development.

Abstract

This review paper will present material concerning use of coconut oil with a phase change material (PCM) in thermal energy storage (TES) systems to meet increasing energy demands in different fields such as heating, ventilating, and air conditioning (HVAC) systems and building tem- perature control. The author provides a review of standard techniques of energy storage and shows their drawbacks, including low thermal efficiency and negative impact of some types of energy storage on the environment. Based on experimental results it can be concluded that coconut oil possesses good thermal characteristics illustrated by the large change in the melting point caused by natural convection and the process of solidification. The current study proves that integrating aluminum foams and nanoparticles can increase the TES unit's thermal charging rate by as much as 41% when design modifications are made to the TES unit. The conclusion made stresses the suitability of coconut oil as a PCM, along with its efficiency and the ability to act as a natural source of energy-boosting material other than fossil fuels. Recommendations for future research include studies concerning the applicability of hybrid PCM systems, the use of more sophisticated materials to improve the thermal conductivity and the evaluation of the permanency of coconut oil and the effectiveness of this product under different conditions. More to the point of this review, it highlights the need to embrace innovative concepts in TES in order to realise sustainable energy objectives..

Introduction

During their phase transition, phase change materials (PCMs) have the ability to both absorb and release heat. PCMs have the potential to bridge the gap between energy supply and demand, play a significant role in heat energy storage (e.g., waste heat energy recovery), and even out building temperature swings. More potential uses for phase change materials (PCMs) include sun cooling, energy storage, thermo-regulating fabrics, food preservation, and athletic and bedding accessories [1, 2]. Organic phase change materials have found extensive use because of their many desirable qualities, including but not limited to: cheap cost, high heat storage capacity, strong thermal stability, self-nucleating capabilities, absence of phase segregation, non-reactivity, non-corrosivity, and non-toxicity [3].

Fatty acids are very desirable organic non-paraffin phase change materials (PCMs) due to their many desirable properties, such as a wide temperature range, low supercooling, high heat capacity, congruent melting, lack of metal corrosion, low vapor pressure, excellent thermal and chemical stability, lack of flammability, and minimal volume change during phase transition [4, 5]. A solution to the problems of PCM interaction with the surrounding environment and leakage may be achieved by microencapsulation [6]. Improvements in storage, transportation, and a broader range of applications are also possible, as is an increase in specific surface area and, by extension, heat transmission [7]. One option for using the microencapsulated PCMs is to disperse them in a PCM slurry, while another is to use the powder form. Some common ways that PCMs are encapsulated include emulsion polymerization, complex coacervation, in situ polymerization, self-assembly, and interfacial polymerization.

The proper exploitation of renewable energy like sun and wind is complicated since these sources of power have a finite lifespan. Their availability is very unpredictable since it is influenced by elements of nature including wind, rain, and sunshine. Energy storage is the key to making the most of renewable sources, cutting down on fossil fuel use, maintenance expenses, and wasted power. To keep energy production and consumption in balance, it is required to store extra energy, whether it's for the short or long term [13–15]. The storage of thermal energy is less costly than electrical energy. While a surplus of thermal energy does lower peak demand on the power grid, it cannot be sold to the energy infrastructure. Materials for storing energy, such as batteries and PCMs. Because batteries don't store much energy, users and researchers are looking at PCMs. Energy storage provides a practical alternative to traditional energy sources, which in turn lowers energy consumption and costs, which has far-reaching economic advantages [16–20]. Figure (1) shows the energy storage dynamics.

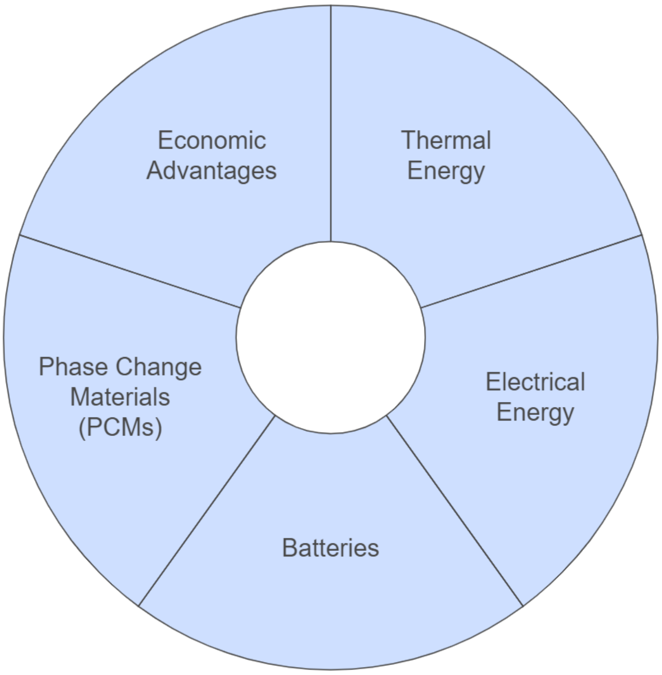

Figure 1Energy storage dynamics

Coconut oil and its derivatives are claimed in the literature for thermal energy storage application as phase change materials, because of their good thermal profiles and renewability. These applications covers all fields ranging from building temperatures where coconut oil could be used during the day to absorb heat and during night release the heat saving greatly on power used for cooling in the tropics. In solar energy systems, coconut oil stores excess heat produced during high sun radiation in order to improve energy density [21]. Further, it is employed for food preservation and temperature control in refrigeration and in textile industry to produce clothing materials that help the end consumer by being thermoregulatory. Coconut oil can also be used mixed with other materials to create composite PCMs improving thermal properties, good for waste heat recovery system whereby it will effectively capture excess heat from industrial processes. In general, the multifunctional and environmentally-friendly properties of coconut oil integrating itself into various possible applications for enhancing energy saving as a PCM. Figure (2) shows coconut oil in energy applications [22].

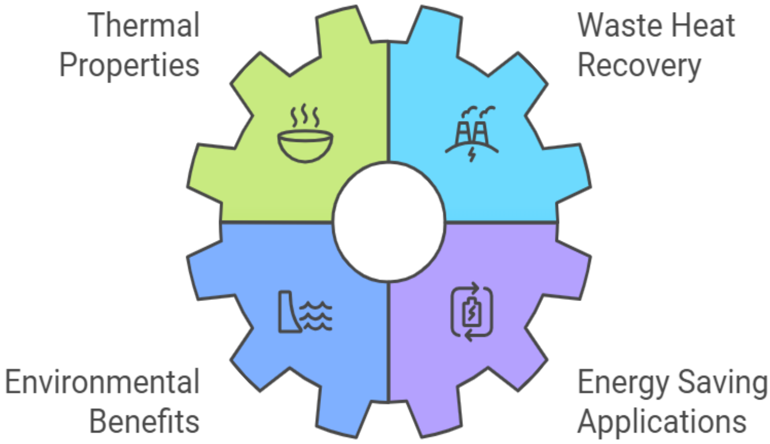

Figure 2 Coconut oil in energy applications

The purpose of this review paper is therefore to assess the applicability of coconut oil PCM for use in TES and discuss its use in building cooling and HVAC systems and drawbacks of its use. Also, the paper will try to discuss the proper techniques to utilize enhancement techniques for the better thermal characteristics of coconut oil which may include the use of additives and/or hybrid PCM systems, as well as the recommendations on the further studies to develop the optimum usages of coconut oil in the field of sustainable energy. By achieving these objectives, the review aims to enhance the knowledge concerning coconut oil as a PCM for thermal energy storage applications.

The applications of coconut oil in thermal energy storage systems

Coconut oil's (co_oil) capacity to retain substantial quantities of heat at temperatures close to its melting point was the primary emphasis of Wonorahardjo et al. (2018) [21] as a means of controlling the temperature of air conditioning systems in tropical nations like Indonesia. When studying the heat exchange between co_oil and the surrounding air, researchers took three things into account: the temperature differential between the two, the behavior of heat absorption and release from co_oil, and the amount of co_oil needed to make a noticeable difference. A thermal chamber was used to forecast the effectiveness of the co_oil mass in reducing room air temperature, and the sizes of the co_oil cells were developed in response to natural day and night air temperature profiles. Figure (3) shows that the charging capacity grew as the size of the co_oil cell rose. This is because the charging capacity is directly proportional to the quantity of co_oil contained in the cell.

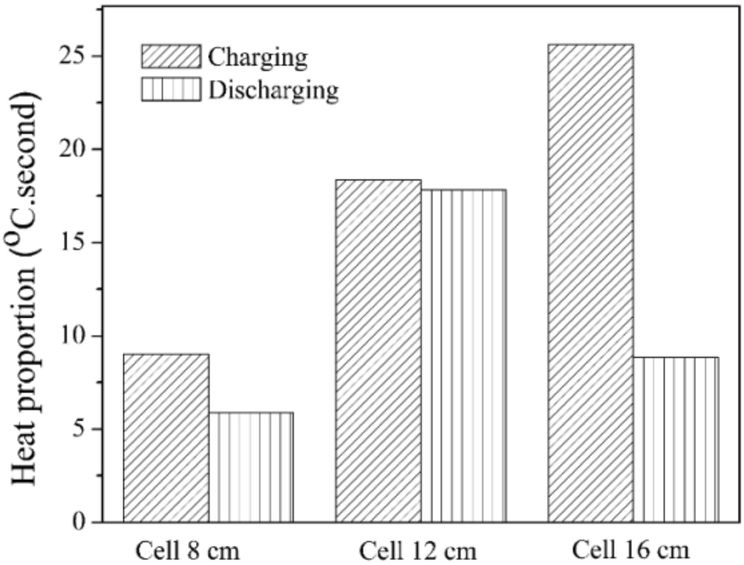

Figure 3 The predicted CO2 exchanges of three distinct cell sizes, including the capacity to charge and discharge the cell [21]

In their study, Faraj et al. (2019) [22] examined the efficacy of an underfloor heating system that employed coconut oil as a bio-based phase change material (PCM). The system was combined with a quarter-scale insulated prototype. The research looked at two separate instances. First, we looked at how the PCM adapted to the floor by placing it in an aluminum container and placing it over an electrical heater. A second example served as a control experiment that did not use PCM plates. We tested the prototype in an agricultural refrigerator to make sure the ambient temperature remained consistently low, much as in a genuine harsh winter. The findings demonstrate that the PCM increased the length of energy transfer between charging and discharging by 53.7%. In comparison to the control test, the usage of the bio-PCM allowed for a 58.9% yearly cost decrease by shifting power use from peak to off-peak times. As seen in Figure (4), the consumption of latent heats might be shifted into more efficient zones with the use of PCMs with greater solidification points.

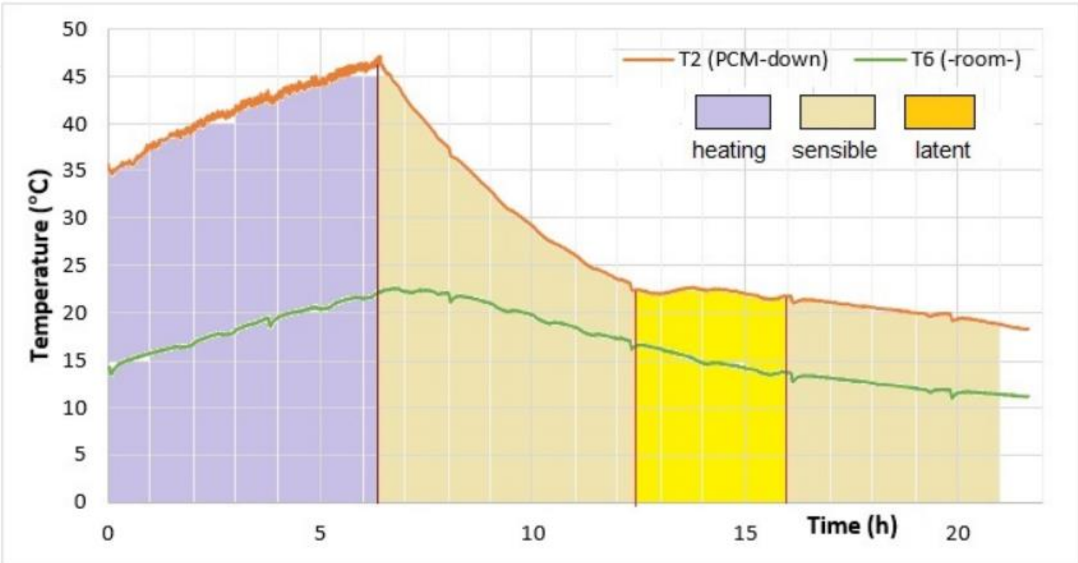

Figure 4 Surface temperature variation in the CO-PCM test as a function of time [22]

A new material that may be used as an insulator for latent heat storage that incorporates biochar was described by Jeon et al. (2019) [23] as latent heat storage biocomposite (LHSBC). The LHSBCs were prepared by vacuum impregnating biochars made from waste materials such as pine cones, pine saw dust, and paper mill sludge with coconut oil, a bio-based phase change material (PCM). Figure (5) shows that LHSBCs have a low thermal conductivity of 0.030 W/mK at maximum and a maximum latent heat storage capacity of 74.6 J/g, proving that they are good thermal insulators. Evidently, there was a lot of sensible heat storage, as the greatest specific heat was 1.69 J/gK. Furthermore, it was discovered that all LHSBCs exhibited thermal and chemical stability. This LHSBC has excellent thermal insulation and heat storage properties, making it a potential material for use in a variety of applications.

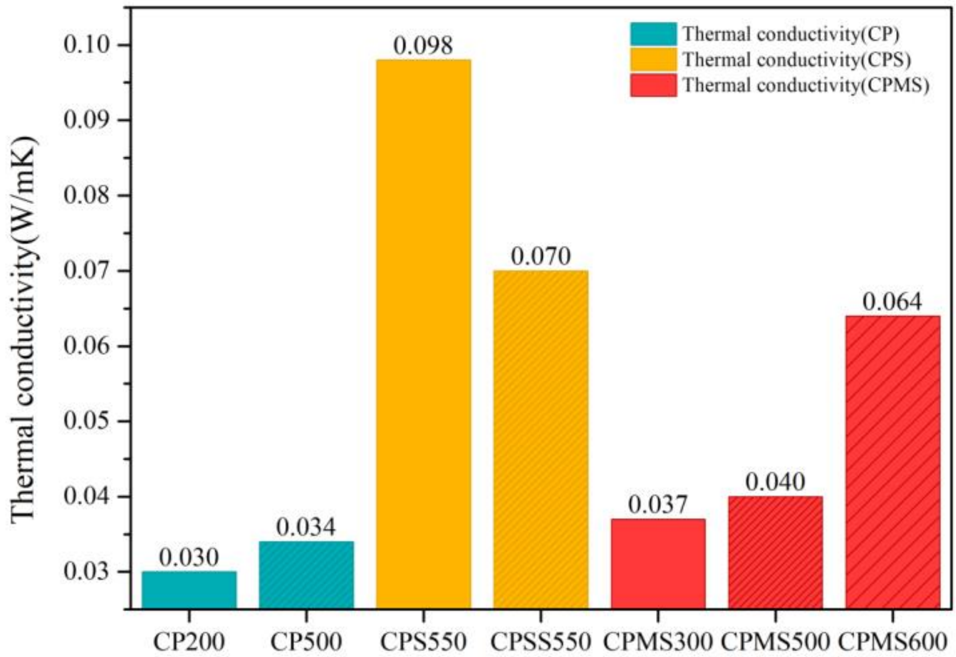

Figure 5 LHSBCs' thermal conductivity [23]

In a typical cold storage facility, Dhamodharan and Bakthavatsalam (2020) [24] investigated how to make the most of the energy that is available from air conditioning condensate. For a 17,580 kW cooling capacity, the expected amount of condensate is 150 to 170 liters per day, with an average temperature range of 9 to 11 °C. To extract energy from the cold condensate, two environmentally friendly phase transition materials—coconut oil and lauryl alcohol—were used. Both unprocessed samples and those that have undergone 250 cycles were examined for the thermophysical characteristics of chosen phase transition materials. After 250 cycles, the latent heat of fusion of coconut oil drops by 10.55% and that of lauryl alcohol drops by 52.9%. Prior to and during the thermal cycles, we tracked changes in thermal conductivity and specific heat capacity over the operational temperature range, and we talk about those findings. A constant temperature water bath with a 12-liter holding capacity was used to conduct the charging and discharging experiments on PCMs (1 kilogram each) at 11±1 °C. Results showed that coconut oil solidified at 22.3 °C and lauryl alcohol at 23.1 °C. The solidification process revealed that the coconut oil had been supercooled by 2.6 °C compared to its real freezing point. Figure (6) shows the results of the experimental investigation showing that the melting point of CO is 23.2 °C and that the melting process takes 784 minutes to finish.

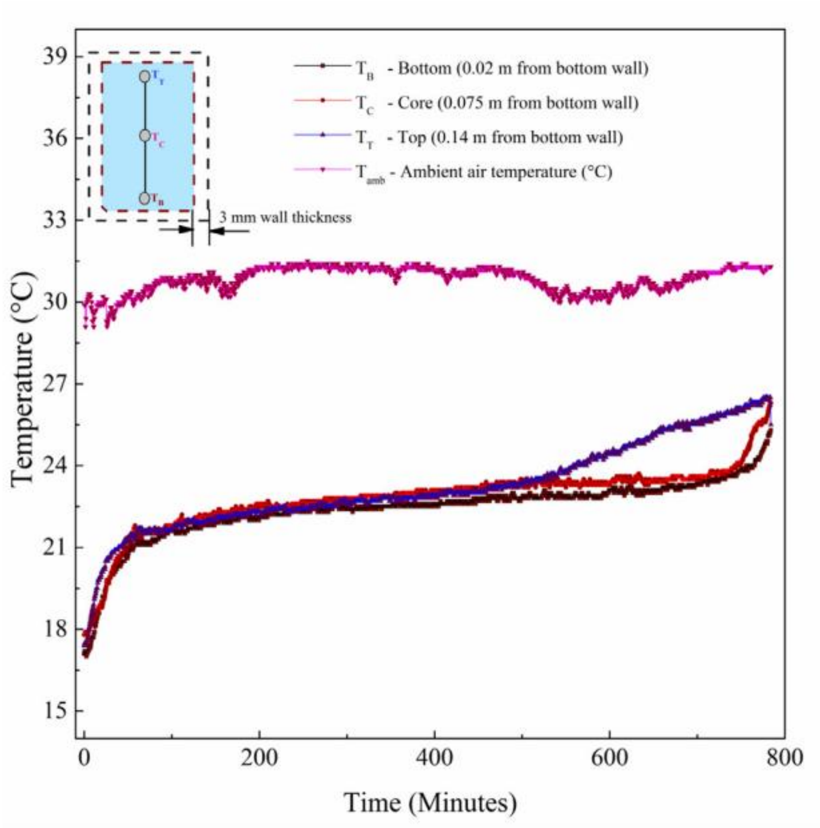

Figure 6 Coconut oil's (CO) melting properties [24]

After collecting condensate, Dhamodharan et al. (2021) [25] used the phase change characteristic of coconut oil to pre-cool apples while recovering energy. Coconut oil charging experiments yielded the following results: at condensate flow rates of 2.6 L/h, 4.25 L/h, 6.26 L/h, and 8.33 L/h, the charge time was determined to be 234, 126, 95, and 93 minutes, respectively. Studies were carried out to determine the efficacy of natural and forced convection in pre-cooling apples in two different scenarios: case i, where the apples were in direct touch with the container, and case ii, where the apples were in indirect contact with the container. A pre-cooling of 4 °C was accomplished with a discharge duration of 260 minutes under conditions of natural convection and direct contact. In the second scenario, a pre-cooling of 3.5 °C was accomplished after 304 minutes of discharge. Similarly, in example (i), 3.5 °C pre-cooling was accomplished in 189 minutes under forced convection, whereas in case (ii), it took 214 minutes. In example (i), the temperature differential between the apple's upper and lower halves was 1.5 °C, whereas in case (ii), it was 0.5 °C. In order to pre-cool apples before putting them into a cold storage unit, the results showed that coconut oil, when employed as a PCM, may recover energy from condensation.

A novel PCM composite of paraffin with beef tallow/coconut oil combination was used to enhance heat evacuation from the surface of a PV module by Karami et al. (2021) [26]. Initially, a PV module's temperature control is accomplished using a PCM composed of a composite of paraffin, beef tallow, and coconut oil (PBTCO). Researchers looked at how surface temperature and PV module power production were affected by PCM weights ranging from 2.1 to 4.1 kg. Step two involves increasing PBTCO's thermal conductivity by adding expanded graphite powders (EG) (X3 = 0.5-10.5 %wt.). According to the data, an uncooled system may reach temperatures of 64.02 °C and output powers of 4.875 W. The more efficient PCM is a composite of 63.1% paraffin and 36.9% BTCO, with a bulk fraction of 39% BT and 61% CO. More so, the data demonstrate that PBTCO, a mixture of paraffin and BTCO, produces a more uniform distribution of temperature than BTCO alone, owing to the increased thermal conductivity generated by the paraffin. Figure (7) shows that paraffin has a great capacity to transmit heat uniformly, and that the combination of 5.5% EG/PBTCO (50%BTCO/50%Paraffin) results in the lowest amount of TUi.

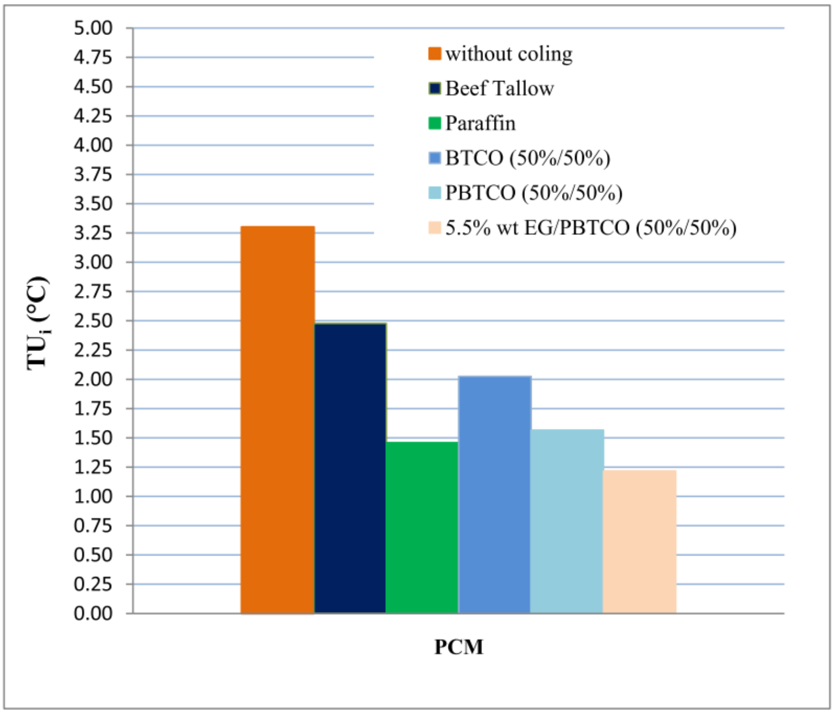

Figure 7 Temperature uniformity index (TUi) variation while utilizing PCMs and without a cooling system [26]

Using containers with improved thermal conductivity and a hydronic radiant floor heating system, Faraj et al. (2021) [27] created a bio-based PCM using macro-encapsulated coconut oil. The research is exploratory in nature, and it makes use of two small-scale modular test prototypes that are functionally equivalent. Current research focuses on determining how various weather conditions affect the thermal and energy storage capabilities of active CO-PCM systems, as well as how combining active and passive systems affects these performances, the impact of PCM choice/type, and the impact of PCM position within the active floor. Load shifting and energy savings may be achieved by tying CO-PCM to active floors, passive walls, and passive roofs. The method of control, weather, electricity tariff policy, and PCM location and type play a role in this process.

The experimental studies of the TES module for HVAC applications based on coconut oil were given by Andrzejczyk et al. (2021) [28] in the ambient and subambient temperature range. We now know that natural convective events have a significant impact on melting. It has been shown experimentally that the apparent melting point varies with the radial distance from the heat source. As the process of solidification progresses, the conduction heat transfer mechanism becomes more dominant, rapidly diminishing the impact of natural convection. The presence of subcooling temperature is indicative of the solidification temperature profile. In subcooling, the amount of temperature reduction is proportional to the radial distance from the heat source. Further confirmation of the shape of the phase-change profile appearing as a truncated cone (inverted in the case of melting) has been obtained for both the melting and solidification processes.

Using aluminum foams, nanoparticles (copper oxide), and geometric optimization, Zadeh et al. (2021) [29] reduced the thermal charging time of a latent heat TES unit. The TES unit used FEM to model the melting phase transition. During the two hours of thermal charging, the Taguchi optimization approach was used to maximize the melting rate. According to the findings, the two most important design criteria for thermal energy storage and melting rate are the unit's geometrical shape and the foam's porosity. The melting rate might be improved by 41% by adjusting the design parameters. The addition of nanoparticles might only result in a 2% increase to the melting rate. The ideal TES design allows for a complete charge in under two hours. Solar systems and temporary heat recovery might benefit from such rapid charging times.

Cutting fluid (taladrine, T) with phase change material (PCM) coconut oil (CO) in a 1:9 ratio (CO-0.1T) and hydrophilic silica in 0.01, 0.03 and 0.05 vol fractions was the focus of Gómez-Merino et al. (2022) [30]. Improved thermal conductivities with negligible changes to latent heat have been shown to result from the incorporation of solid particles. Optical polarized microscope pictures, which showed plate-like needles, corroborated the findings. Drilling performance was reduced by 11 °C and the gel strength was satisfactory in the 0.03 silica in CO-0.1T solution. If you choose not to use flood cooling or dry machining, you may use 2 grams of minimum quantity cutting fluid (MQCF). Because of its complex composition and high viscosity, it not only cleaned metal chips but also stopped evaporative loss.

The combination of activated carbon derived from coconut shells and food-grade coconut oil was introduced by Muchtar et al. (2022) [31] as a means of producing bio-based shape-stabilized phase change materials (bioSSPCM), as seen in Figure (8). In spite of the low melting point of the coconut-based components, a thermally stable bioSSPCM with anti-leakage properties may be reliably produced by simple physical blending by heating and mixing. When it came to SSPCMs, there was no discernible difference between analytical grade and food grade coconut oil. As an added bonus, when tested side by side with octadecane, a standard phase change material, coconut oil showed more stability and less leakage during phase change cycling, all while using the same synthesis conditions.

Figure 8 A diagram showing the process of creating shape-stabilized phase-change materials from coconut oil and coconut shell. The triangle diagram that shows the benefits and drawbacks of utilizing coconut against octadecane for SSPCM material [31]

The thermal characteristics of three different configurations of PCMs based on tamanu and coconut oils were reported by Paroutoglou et al. (2022) [32]: pure, emulsion, and encapsulated. Emulsions of coconut and tamanu oils, as well as mixes of these oils and commercial PCM paraffins, were shown to be encapsulated in fiber matrices made by a coaxial electrospinning process. The oils under study were mixed with polycaprolactone (PCL) to create a PCM emulsion, which was then further stabilized using polyvinyl alcohol (PVA) and sodium dodecyl sulfate (SDS). The latent temperatures of melting and solidification were 63.8 and 57.6 kJ/kg, respectively, when commercially available paraffin RT18 was added to a 70/30 combination of coconut and tamanu oil and effectively encapsulated in the core of a PCL shell.

Irsyad et al. (2023) [33] used a variety of methods to analyze the used cooking oil. These included thermal conductivity testing with the TCi Thermal Conductivity Analyzer C-Therm, Differential Scanning Calorimetry (DSC) with a DSC type 214 Polyma Brand NETZCSH, and PCM compound composition determination with an Agilent brand of Gas Chromatography (GC) type 7890 b. The frying process caused several modifications to the type and content of fatty acid molecules in cooking oil. For example, waste coconut cooking oil (WCCO) had an increase in methyl arachidate from 10.71% to 45.68%. Because of its similarities to CCO—for example, its 97.7 kJ/kg latent heat for melting and 0.155 W/m.K thermal conductivity—WCCO is likewise an intriguing candidate for development as a thermal energy storage. Changes in the content and type of fatty acid molecules in the materials were linked to the finding that WCCO had a somewhat lower freezing point, as seen in Figure (9).

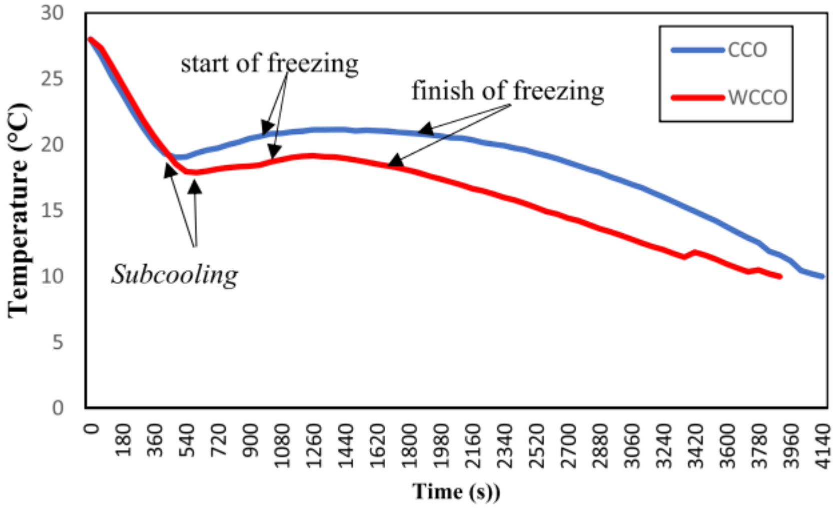

Figure 9 T-History test for WCCO and CCO freezing processes [33]

In their study, Baylis and Cruickshank (2023) [34] used full-house simulations in three distinct North American sites across various temperature zones to estimate the cost and emission impacts of using coconut oil instead of paraffins. During the lifespan of the home, paraffin PCM had a smaller carbon footprint than coconut oil because to its higher embodied carbon and better yearly heating and cooling savings. To reduce the overall carbon footprint of buildings, it is crucial to create bio-based PCMs with a latent heat capacity similar to paraffins. It was also shown that without reductions in capital costs or greater carbon price, the economic payback period of both PCMs might be longer than the house's lifespan, making them unfeasible. The results reveal that paraffin PCMs resulted in larger yearly savings in energy and emissions, whereas coconut oil exhibited lower emboided carbon.
Coconut oil PCM-loaded calcium alginate microcapsules with a double-layered shell were optimized for key process parameters by Németh et al. (2023) [35]. Important factors in optimizing the process and reducing waste were the viscosity of the alginate solution, the contact duration, and the concentrations of alginate and calcium ions. Following 200 cycles of heating and cooling, the microcapsules were determined to have retained all of the PCM. The waste alginate-containing material after partial gelation may be recycled into core formation, in addition to optimizing the usage of raw resources. In terms of both the chemicals used and the method used to create them, the synthetic PCM microcapsules are completely harmless to the environment.
A new shape-stable phase change material (SSPCM) was created by Gao et al. (2024) [36] by vacuum impregnating aluminum nitride (AlN) thermally conductive reinforcing particles into expanded graphite (EG) and combining coconut oil (CO) as a phase change material (PCM). The produced SSPCM had a thermal conductivity of 2.985 W·m-1·k-1, which was 1,765 times more than pure CO, according to the data. A latent heat of 83.67 J·g-1 was observed for SSPCM, which corresponds to 99 percent of the theoretical value. In addition, SSPCM demonstrated dependable performance over heat cycles and outstanding thermal stability. There is a lot of hope for the planned SSPCMs because of their renewable nature and the ease of their preparation.
Beeswax (BW) and coconut oil (CO) was created by Abdolahimoghadam and Rahimi (2024) [37] as a novel bio-PCM (bio-PCM) based on biology. Additionally, the potential of bio-PCM for thermal energy storage (TES) was investigated at0.5,1, and 2 weight percent of graphene-copper (Gr-Cu) hybrid nanoparticles. Researchers investigated bio-PCM and bio-nPCM thermal conductivity from 25 to 60 °C. Adding 2 weight percent Gr-Cu nanoparticles to Bio-PCM reduced its latent temperatures of melting to 172.3 kJ/kg and solidification to 173.11 kJ/kg, respectively. Conversely, at T = 25 °C, the thermal conductivity of bio-nPCMs is up to 604% greater than that of the base bio-PCM, and this difference increases as the concentration of Gr-Cu in the base PCM increases. Additionally, a novel model for thermal conductivity was put out, which, on average, was off by 5%. The calculated values of thermal conductivity and latent heat were obtained by use of machine learning. The first one had numerical values of 0.9996, 1.1253×10^{-4}, and 1.871 for R-squared, mean error (MSE), and average absolute relative deviation (%AARD), respectively, whereas the second one had values of 1, 4.7×10^{-10}, and 0.01, respectively.

Architectural envelopes may benefit from a new composite phase change material (PCM) called A-WF/CO/h-BN, which was created by Li et al. (2024) [38]. This material has excellent heat storage capabilities. It uses coconut oil (CO), which has an ideal phase transition temperature, as the PCM. The improvement in heat conductivity led to the selection of hexagonal boron nitride (h-BN). For the purpose of providing support, acetylated wood fiber (A-WF) was used. The A-WF/CO/h-BN sample that was developed has remarkable exothermic and heat storage capabilities, and it does so quickly. In the thermal performance assessment experiment, when both hot ends of the A-WF/CO/h-BN sample are heated, the cold end remains cooler than the A-WF. The results show that the A-WF/CO/h-BN sample can successfully prevent the increase and decrease of temperature and delay heat transfer. Applying the A-WF/CO/h-BN sample to building envelopes may reduce heat transmission to the interior and dampen indoor temperature fluctuations because of its outstanding features.

In their study, Dhamodharan et al. (2024) [39] used phase change materials (PCMs) such as waste coconut oil (WCO) and polyethylene glycol (PEG) in thermal energy storage systems. These systems were employed to pre-cool apples in cold storage facilities. The system's viability was determined by field evaluations of cold storage facilities and analysis of energy, exergy, economics, and the environment. At 11 ± 1 °C, with a pre-cooling temperature of 3 °C, the exergy efficiency rose from 11% to 90% for condensate flow rates ranging from 2.5 to 8.3 L/h. The solidification time of WCO was also shown to be reduced by 13% to 21%. Pre-cooling via natural and induced convection was achieved in PCM-apple direct contact discharging studies at 3.4 and 4.1 °C for PEG and 2.5 and 3.2 °C for WCO, respectively. Up to 75% energy savings were achieved by efficiently using condensate at 11 ± 1 °C. With a payback time of less than six months and savings of $168, WCO was the better choice than PEG 600 in terms of life cycle cost.

Research on the effects of nanoparticles and corrugation on energy storage was conducted by Alsabery et al. (2024) [40]. Using the enthalpy-porosity approach, the solid transformed into a liquid. The simulations were made more accurate and stable by using a mesh adaption approach to modify the mesh at the melting interface. More heat can be transferred from the NePCM inside the container to the working fluid because to the wavy surface design. To optimize melting (thermal charge), the Taguchi technique was used. We looked at how the melting rate and stored energy were affected by the porosity, volume percentage of nanoparticles, and wave number. The findings shown that the melting rate is reduced as the porosity increases, especially in the lower areas of the enclosure. Although changing the wave number altered the patterns of flow and heat transmission, it had no effect on the melting rate. At a nanoparticle volume fraction of 0.05, a minimum porosity of 0.05, and two undulations with a wave number of 2, the melting rate was at its highest.

To showcase a possible new use of CP in thermal energy storage, Ong et al. (2024) [41] created a batch of CP/polyethylene glycol (CP/PEG) composites as innovative shape-stabilized phase change materials (SSPCMs) using vacuum impregnation. A variety of imaging techniques, including scanning electron microscopy, thermogravimetric analysis, thermal cycling testing, a leakage test, and attenuated total reflection-Fourier transform infrared spectroscopy, were used to examine the composites. A composite with a CP/PEG mass ratio of 3:7 had a high relative enthalpy efficiency of 91.7% and a latent heat storage of 108.5 J/g, according to the data. The CP/PEG composites showed low PEG leakage. In the meantime, the thermal cycling test demonstrated outstanding thermal reliability even after 100 cycles, and the TG findings demonstrated strong thermal stability up to 150 °C.

By combining hybrid sun drying systems with phase-change materials (PCMs), Kumar et al. (2024) [42] developed a new method for drying wood fuel that improves thermal efficiency and is more environmentally friendly. The trials were conducted under a constant artificial radiation of 755 W m^{-2}, with coconut oil used as the PCM. A considerable increase in heat storage was shown by the hybrid system, which was able to maintain around 200 watts of usable heat for three hours after radiation. The results show that exergy efficiencies range from 13-14% and peak thermal efficiencies from 30-35%. According to the environmental and economic study, the system will last for five years, produce 64.09 kg of CO_2 per year, and cost 0.0058 EUR per kilogram of hot air.Table (1) shows a summary of studies related to applications of coconut oil as PCM in thermal energy storage systems.

Table 1–1 A summary of studies related to applications of coconut oil as PCM in thermal energy storage systems

Authors (year) [reference]	Study Type	Application	Results and remarks
Wonorahardjo et al. (2018) [21]	Experimental	Air temperature control in buildings.	Because the quantity of co_oil in a cell is directly proportional to its charging capacity, larger co_oil cells had a greater potential to store energy.

Faraj et al. (2019) [22]	Analytical	Underfloor heating system.	By using the bio-PCM, the transition from peak to off-peak power usage was made possible.
Jeon et al. (2019) [23]	Experimental	Latent heat storageinsulation.	At their highest, the LHSBCs exhibited a low thermal conductivity of 0.030 W/mK and a latent heat storage capacity of 74.6 J/g.
Dhamodharan and Bakthavatsalam (2020) [24]	Experimental	Energy recovery from cold condensate.	The solidification process revealed that the coconut oil had been supercooled by 2.6 °C compared to its real freezing point.
Dhamodharan et al. (2021) [25]	Experimental	Cold storage condensate forprecooling of apples.	To pre-cool apples before putting them into a cold storage unit, coconut oil may be used as a PCM for energy recovery from condensation.
Karami et al. (2021) [26]	Experimental and Numerical	Increasing the electrical efficiency and thermal management of PV module.	The more efficient PCM is a composite of 63.1% paraffin and 36.9% BTCO, with a bulk fraction of 39% BT and 61% CO.
Faraj et al. (2021) [27]	Experimental	Active heating.	Load shifting and energy savings may be achieved by coupling CO-PCM to active floors, passive walls, and passive roofs.
Andrzejczyk et al. (2021) [28]	Experimental and Numerical	Low temperature thermal energy storage.	As the process of solidification progresses, the conduction heat transfer mechanism becomes more dominant, rapidly diminishing the impact of natural convection.
Zadeh et al. (2021) [29]	Numerical	Multi-tube latent heat storage.	The addition of nanoparticles might only result in a 2% increase to the melting rate.
Gómez-Merino et al. (2022) [30]	Experimental	Drilling performance based on minimum quantity of cutting fluids.	Drilling performance was reduced by 11 °C and the gel strength was satisfactory in the 0.03 silica in CO-0.1T solution.
Muchtar et al. (2022) [31]	Experimental	Shape-stabilized PCM.	Phase change cycling reduced leakage and increased stability of the coconut oil.

Paroutoglou et al. (2022) [32]	Experimental	Electrospun fiber matrices.	The latent temperatures of melting and solidification were 63.8 and 57.6 kJ/kg, respectively, when commercially available paraffin RT18 was added to a 70/30 combination of coconut and tamanu oil and effectively encapsulated in the core of a PCL shell.
Irsyad et al. (2023) [33]	Experimental	Thermal energy storage.	Because of its similarities to CCO—for example, its 97.7 kJ/kg latent heat for melting and 0.155 W/m.K thermal conductivity—WCCO is likewise an intriguing candidate for development as a thermal energy storage.
Baylis and Cruickshank (2023) [34]	Analytical	Emissions reductions.	Paraffin PCMs resulted in larger yearly savings in energy and emissions, but coconut oil shows lesser emboided carbon.
Németh et al. (2023) [35]	Experimental	Latent heat energy storage.	In terms of both the chemicals used and the method used to create them, the synthetic PCM microcapsules are completely harmless to the environment.
Gao et al. (2024) [36]	Experimental	Thermal energy storage.	In terms of heat cycle reliability and stability, SSPCM performed very well.
Abdolahimoghadam and Rahimi (2024) [37]	Experimental and Numerical	Thermal energy storage.	The thermal conductivity of bio-nPCMs is much greater than that of the base bio-PCM at T = 25 °C, reaching a maximum of around 604% increase with increasing Gr-Cu content in the base PCM.
Li et al. (2024) [38]	Experimental	Thermal management in building envelopes.	Delaying heat transmission and inhibiting temperature rise and fall are both achieved by the suggested A-WF/CO/h-BN sample.
Dhamodharan et al. (2024) [39]	Experimental	Chilled energy recovery from air-conditioning condensate.	At 11 ± 1 °C, with a pre-cooling temperature of 3 °C, the exergy efficiency rose from 11% to 90% for condensate flow rates ranging from 2.5 to 8.3 L/h.
Alsabery et al. (2024) [40]	Numerical	Energy storage.	At a nanoparticle volume fraction of 0.05, a minimum porosity of 0.05, and two undulations with a wave number of 2, the melting rate was at

			its highest.
Ong et al. (2024) [41]	Experimental	Thermal energy storage.	A composite with a 3:7 mass ratio of CP to PEG has a high relative enthalpy efficiency of 91.7% and a latent heat storage of 108.5 J/g, while the CP/PEG composites show low PEG leakage.
Kumar et al. (2024) [42]	Experimental	Enhancing solar drying performance.	It was shown that the hybrid system could keep around 200 watts of usable heat for three hours after radiation.

Economic Analysis

In the present study, the prospects of using coconut oil as PCM in thermal energy storage systems depend on various factors such as cost of the material, energy saved and potential uses of the PCM in various markets. Compared to the paraffin and other synthetic material-based PCMs, cost effectively coconut oil is one of the renewable and biodegradable resources. The cost factor is often lower than the cost of many other commercial PCMs, which could be another selling point for industries trying to find a more environment friendly solution. For example, the cost of the coconut oil varies from 1.50to3.00 for a liter and the synthetic PCMs cost more than 10.00 dollars per litre show the economic benefits of coconut oil [10].

While the initial costs in thermal energy storage systems using coconut oil may be high they can be recovered from the long term energy costs. Due to the proper management of thermal loads, the systems also limit the peak energy demand and therefore decrease the amount to be paid for electricity bills and minimize the use of fossil products. Energy saving advantages of up to 30% in cooling have been observed in buildings that incorporates coconut oil based PCMs especially in regions that experience high demand of air conditioners. This savings has the twin benefits of saving the money of the consumers and reducing the emission of greenhouse gases which are parts of international sustainable development goals [15]. Fig. (10) reveals the benefits of coconut oil in thermal energy storage.

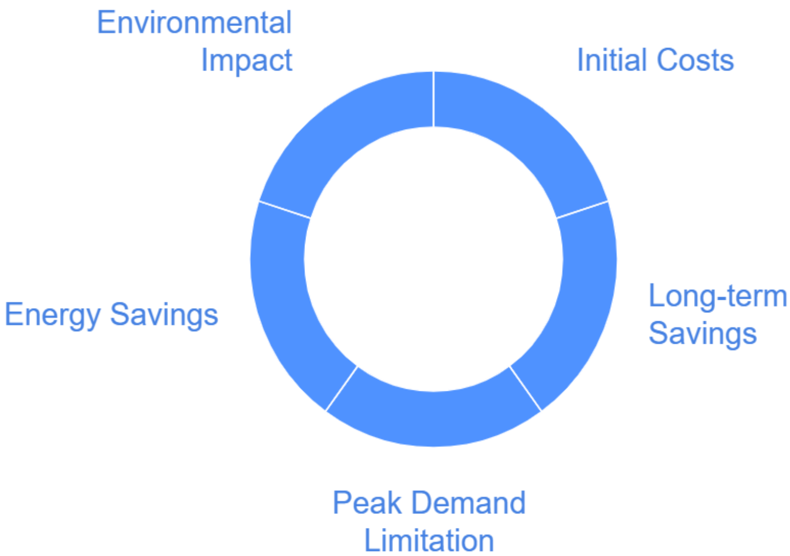

Figure 10 Benefits of coconut oil in thermal energy storage

Besides, it is possible to improve the performance of HVAC systems by using coconut oil as a phase change material with lower maintenance requirements and longer equipment durability. The control of excess thermal energy that accumulates during low demand and delivering it during high demand results to stabilization in power consumption, which is a critical factor in grid security especially in renewable energy generation [2]. For instance, Wonorahardjo et al. (2018) pointed out that ways that increases the size of the coconut oil cells enhances its energy storage performance and subsequently enhance the performance of AC systems in buildings [15].

There are therefore direct cost reductions and efficiency gains to be made from incorporating coconut oil in TES systems, and tap on new market applications across the building construction, food refrigeration, and textile industries. This has been due to increased awareness by customers as well as firms as sustainability becomes the future market trend of most products that contain coconut oil. To approve the global PCMs market increasing, it is expected to reach ahigher CAGR than 20% during 2021-2026 in terms of both volume and revenue owing to the growing trend towards energy management solutions [1]. Fig. (11) shows expanding horizons with coconut oil.

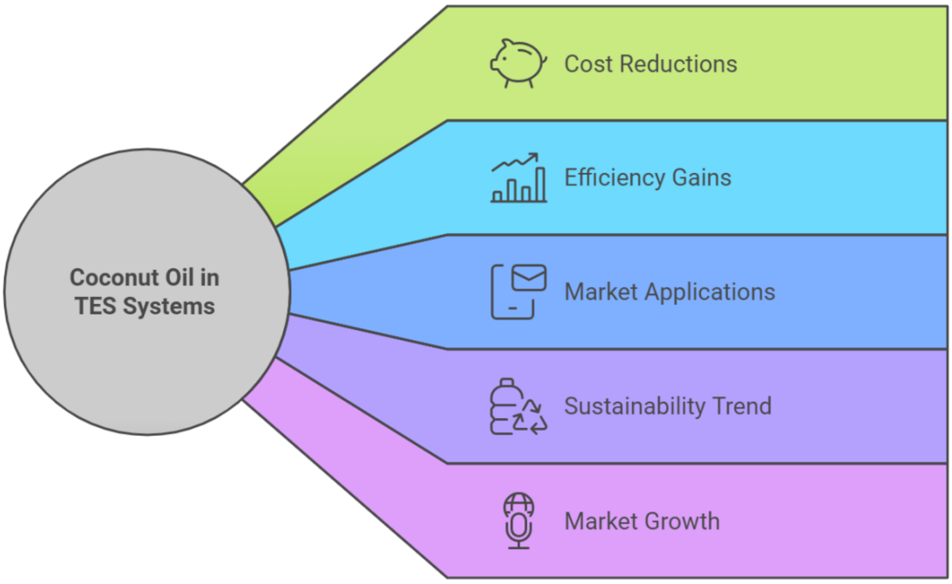

Figure 11 Expanding horizons with coconut oil

But higher attention should be paid with economic factors of coconut oil sourcing and processing such as changes in agricultural markets and supply chain issues. Sustenance of a sound supply of virgin coconut oil is therefore important in the continued sustainability of these systems. due to climate change fluctuations or fluctuation in the international market coconut oil prices can be a supreme threat to manufacturers and consumers [20].

Conclusions

This review paper has discussed in detail the possibility of using coconut oil as PCM in thermal energy storage systems and the pros. The following key conclusions can be drawn:

1.Coconut oil has a large specific heat capacity, and excellent conductivity in phase transitions and is, therefore, appropriate for energy storage that is vital in temperature management.

2.Compared to other synthetic PCMs, the cost of coconut oil is cheaper, the cost of the materials may be significantly lower resulting in large cost saving for energy systems.

3.Thermal energy storage systems with added coconut oil can yield up to 30% reduction in cooling costs more so in tropical regions where AC is most common.

4.Coconut oil is also renewable and biodegradable, hence cutting the use of fossil fuel and emissions of green house gases into the environment.

5.These increased needs for energy, opens opportunities to use coconut oil in different industries such as building construction, food storage, and textiles.

6. However, there are drawbacks like supply chain reliability and the fact that the performance of coconut oil as a PCM can still be improved with further research in that area, before it can become widely used.

7. Further investigation is required to unveil higher thermal capacity of coconut oil, to study the hybrid systems, and proper encapsulation methods to get the most out of it.

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