Malaysian Journal of Chemistry, 2025, Vol. 27(3), 353-360
(Special Issue: *International Conference on Sustainable Materials and Technologies, ICSMT 2025*)

Thermal Performance Enhancement of Phase Change Material using Coconut Shell Biochar for Sustainable Thermal Energy Storage

Reji Kumar Rajamony[1]*, Kalidasan, B.[2], Subramaniyan Chinnasamy[3], Rajkumar Kamaraj[4], Asit Mohanthy[5] and Ramesh, R.[6]
[1]Institute of Sustainable Energy, Universiti Tenaga Nasional (The Energy University), Jalan Ikram-Uniten, 43000 Kajang, Selangor, Malaysia
[2]Research Centre for Nano-Materials and Energy Technology (RCNMET), School of Engineering and Technology, Sunway University, No. 5, Jalan Universiti, Bandar Sunway, 47500 Petaling Jaya, Selangor Darul Ehsan, Malaysia
[3]Department of Mechanical Engineering, Bannari amman Institute of Technology, Sathyamangalam, 638401, Tamilnadu, India
[4]Department of Mechanical Engineering, J.P. College of Engineering, Tenkasi-627852, Tamilnadu, India
[5]Centre for promotion of research, Graphic Era (Deemed to be University) Clement town, Dehradun, India
[6]Department of Mechanical Engineering, Annai Valankani College of Engineering, Azhagappapuram, Kanyakumari Dist, Tamilnadu, India
*Corresponding author (email: rejikumar.r2006@gmail.com)

The development of cost-effective, stable, and eco-friendly carbon-based nanoparticles derived from agricultural waste presents a sustainable alternative to conventional nanomaterials. This study focuses on synthesizing highly porous, three-dimensional honeycomb-structured carbon nanoparticles from coconut shells using green synthesis technique. The primary objective is to enhance the thermal properties of organic phase change materials (PCM) for improved energy storage applications. The coconut shell biochar (CSBC) nanoparticles were synthesized via a tube furnace process under controlled conditions and subsequently incorporated into RT54 PCM using a two-step dispersion approach to form RT54/CSBC nanocomposite PCM. The thermophysical properties of the nanocomposites were systematically analyzed using FTIR, thermal conductivity measurements, and thermogravimetric analysis. Experimental results shows the inclusion of CSBC particles significantly enhances the thermal conductivity of RT54 PCM by 80.19%, increasing from 0.212 W/(m.K) to 0.382 W(/m.K). Additionally, the formulated nanocomposite exhibits excellent thermal stability, maintaining structural integrity up to 170 °C. The 3D porous architecture of CSBC facilitates enhanced interfacial contact with the PCM, thereby reducing thermal resistance and promoting efficient heat transfer. These findings demonstrate the potential of CSBC-based nanocomposites as a sustainable and high-performance solution for thermal energy storage applications.

Keywords: Phase change materials; coconut shell biochar; thermal energy storage; thermal conductivity

Received: January 2025; Accepted: April 2025

Phase Change Materials (PCMs) play a crucial role in thermal energy storage (TES) by efficiently absorbing, storing, and releasing heat during phase transitions such as melting and solidification [1]. Their ability to maintain a nearly constant temperature throughout these processes makes them highly effective for temperature regulation across various applications [2]. Widely used to enhance energy efficiency, PCMs help regulate temperatures in different systems, thereby reducing the demand for active heating and cooling. In architectural design, they contribute significantly to passive thermal management, minimizing energy consumption and supporting sustainability efforts by lowering carbon emissions [3]. A wide range of PCMs is accessible on the market, including organic, inorganic, and eutectic types. Organic PCMs are particularly non-corrosive nature, thermal stability, and minimal or no supercooling, making them highly suitable for TES systems [4]. However, despite their numerous advantages, organic PCMs often suffer from low thermal conductivity (TC), limited optical absorption, and leakage issues, which hinder their widespread use in thermal management systems [5].

To address these challenges, researchers have explored the integration of various nanomaterials such as carbon nanotubes [6], graphene [7], expanded graphite [8], hybrid conductive polymers, and tetrapod's [9] to enhance the thermal performance of organic PCMs. These nanoparticles improve both optical and thermal

---

†Paper presented at the International Conference on Sustainable Materials and Technologies (ICSMT 2025)

properties by increasing thermal conductivity and enhancing heat transfer efficiency. Additionally, methods like encapsulating PCMs with silica gel and stabilizing their structure with materials such as wood powder or high-density polyethylene have been employed to mitigate leakage problems [10]. However, despite these advancements, nanomaterials pose challenges, including high production costs, scalability issues, and potential environmental risks. Once released, these nanoparticles can contribute to pollution, highlighting the urgent need for sustainable alternatives. A promising solution is the green synthesis of biochar nanoparticles, an environmentally friendly approach that converts agricultural and industrial waste such as manure, rice husks, corn cobs, eggshells, bamboo, old tires, and sawdust into functional nanoparticles [11]. Compared to activated carbon, biochar nanoparticles exhibit a higher concentration of functional groups (C–O and C=O), making them particularly effective for thermal applications [12].

While activated carbon is widely used due to its high surface area, chemical stability, and low density, it has drawbacks such as non-renewability, high production costs, and challenges related to regeneration [13]. In contrast, biochar presents a sustainable alternative derived from forestry and agricultural by products. Its key attributes include cost-effectiveness, renewability, ease of production, high sorption capacity, low environmental impact, large surface area, three-dimensional porous structure, corrosion resistance, and superior thermal and electrical conductivity [14-15] . As a result, biochar has gained significant attention in energy storage research, demonstrating great potential for widespread use in thermal management systems. Recent studies [16-19] have explored the integration of biochar with PCMs to enhance TES performance. Yadav et al. investigated the incorporation of wheat husk biochar into PEG-based PCMs, reporting a remarkable 103% increase in TC than pure PCM. Additionally, the energy storage capacity improved by 18.56% during heating and 5.4% during cooling, attributed to biochar's unique particle structure and large surface area, which enhanced thermal networking within the PCM matrix [20].

Similarly, researchers examined the combination of coconut shell biochar particles with PEG-based PCMs, observing a 75% improvement in thermal conductivity. This enhancement was linked to the strong intermolecular interactions between the 3D green-synthesized biochar and PEG, which strengthened heat transfer pathways [21]. In another study, Rajamony et al. found that incorporating coconut shell biochar into A46 PCM resulted in a 77.27% increase in TC. This increment was primarily due to two key factors: the exceptional conductivity of biochar, which established efficient thermal pathways, and its high surface-area-to-volume ratio, derived from its porous structure, which facilitated better heat conduction [22].

Naresh et al. [23] investigated the addition of fly ash aggregate to bio-based hexadecanol PCM, reporting a 19.3% increase in thermal conductivity without compromising other thermophysical properties. Although slight differences in melting enthalpy were observed, the overall performance remained stable. Meanwhile, Kalidasan et al. [24] exploited a eutectic PCM infused with coconut shell biochar for TES applications. Their findings revealed a significant increase in TC from 0.464 W/(m.K) to 0.714 W/(m.K), along with an enhancement in melting enthalpy from 202.3 J/g to 218 J/g. Chen et al. [25] formulated a shape-stabilized PCM using activated carbon and lauric acid for thermal energy storage. Microstructural analysis confirmed the effective adsorption of lauric acid into the porous structure of activated carbon. Heat conductivity tests demonstrated notable improvements, while DSC revealed, the composite retained the phase change characteristics of pure lauric acid, with an increased latent heat capacity. These advancements collectively underscore the potential of biochar-based PCM composites as sustainable and efficient thermal management solutions.

Extensive research has focused on enhancing the thermal properties of organic PCMs by incorporating commercially available metal, metal oxide, and carbon-based nanoparticles of various shapes, structures, and sizes. However, a thorough literature review highlights key challenges associated with these nanoparticles, including high costs, potential toxicity, and environmental concerns. Despite the increasing demand for sustainable alternatives, research on improving the thermal performance of organic PCMs using eco-friendly, green-synthesized nanoparticles remains limited. Naturally derived nanoparticles present a favorable solution for advancing TES materials in an environmentally responsible manner. This study focused on synthesizing biochar from coconut shell, an agricultural waste, and incorporating it into organic RT54 PCM at varying weight concentrations (0.1, 0.3, 0.5, and 0.7 wt%) to develop a novel composite PCM. The thermal conductivity, thermal and chemical stability of the resulting nanocomposites were systematically analyzed using high-precision instruments, including a thermal conductivity analyzer, TGA, and FTIR. The findings revealed a significant improvement in the thermal properties of the composite PCM. Notably, the RT54/coconut shell biochar (CSBC) nanocomposite exhibited lower density and cost-effectiveness, making it a promising material for heat management applications. The experimentally validated thermal properties confirm the potential of this organic nanocomposite PCM to enhance thermal management systems while promoting sustainability.

Table 1. Thermophysical properties of RT54 PCM.

Properties	Unit	PCM (RT54)
Thermal conductivity	W/(m.K)	0.210
Melting temperature	°C	52-54
Density	kg/m^3	850
Latent heat	J/g	183
Size	nm	-
Color	-	White

MATERIALS AND METHODOLOGY

Materials

Paraffin wax RT54HC, sourced from Rubitherm, Germany, was selected as the phase change material (PCM) with latent heat and melting temperature range of 183J/g and 52–54 °C. with n issues related to supercooling. The thermophysical characteristics of the PCM are presented in Table *1*. Meanwhile, the coconut shell biochar used in this study was obtained from Malaysia and synthesized at the Advanced Nanomaterials Laboratory of Sunway University.

Synthesis of CSBC and CSBC Enhanced PCM

This section outlines an environmentally friendly method for synthesizing nanopowders from coconut shell, making them suitable for TES applications. The process starts with sourcing coconut shells from agricultural waste, which are then reduced to smaller fragments (10–15 mm) using a mallet. To improve the quality of the resulting nanoparticles, the shells are thoroughly rinsed with deionized water to eliminate impurities such as dust and sand. After cleaning, they are dried under vacuum conditions at 125 °C for 12 hrs. The dried shells undergo carbonization in a nitrogen-controlled atmosphere at 1000 °C using a tube furnace, confirming a clean and efficient transformation into biochar.

Following carbonization, the biochar is further processed using size-reduction techniques, including manual crushing and wet ball milling. The milling operation is performed for 24 hrs at a 500 rpm, incorporating a dwell time of 5 mins after every 10 mins of milling. Once the process is complete, the material is subjected to oven drying at 200 °C to achieve the final nanoparticle form. The detailed process of synthesizing CSBS is illustrated in Figure *1*(a). The synthesized CSBC particles are then analyzed using a particle size analyzer and EDX to find out their size distribution and elemental composition. The resulting carbon nanoparticles exhibit a size range of 600–700 nanometers, with EDX confirming that they primarily consist of 92% carbon, along with trace amounts of oxygen, potassium, chlorine, calcium, sodium, and aluminum. The synthesized biochar is further used to prepare the composite PCM at various concentration.

Figure *1*(b) illustrates step-by-step procedure of preparing coconut shell biochar enhanced PCM at different concentrations. Approximately 25 grams of RT54 PCM is precisely measured PCM is placed in beaker. The beaker is then heated on a hot plate to 75 °C, allowing the PCM to transition from solid to liquid. Subsequently, coconut shell biochar (CSBC) is included into molten PCM at varying concentrations (0.1, 0.3, 0.5, and 0.7 wt.%) and subjected to sonication to ensure uniform dispersion. The sonication process is carried out in an ultrasonic bath (ELMASONIC) for 60 minutes to achieve a homogeneous mixture of CSBC within PCM. A commercial RT54HC, is denoted as RT54, while the composites with CSBC are labelled as RT54-0.1CSBC, RT54-0.3CSBC, RT54-0.5CSBC, and RT54-0.7CSBC, respectively.

Characterization Instruments

Various analytical instruments were used to assess the thermophysical properties of the formulated composite PCM. The chemical stability and functional groups of the samples were analyzed using a FTIR (Model: Perkin Elmer) within a wavenumber range of 400–4000 cm^{-1}. Thermal properties were evaluated using the TEMPOS technique and thermogravimetric analysis (TGA). TC measurements were conducted at room temperature with the TEMPOS system, employing a dual-needle SH-3 sensor. Additionally, the thermal degradation behavior of sample was examined using a Perkin Elmer TGA 4000. The samples were subjected to a controlled heating process, where the temperature was gradually increased to 430 °C at a rate of 10 °C/min in a nitrogen atmosphere.

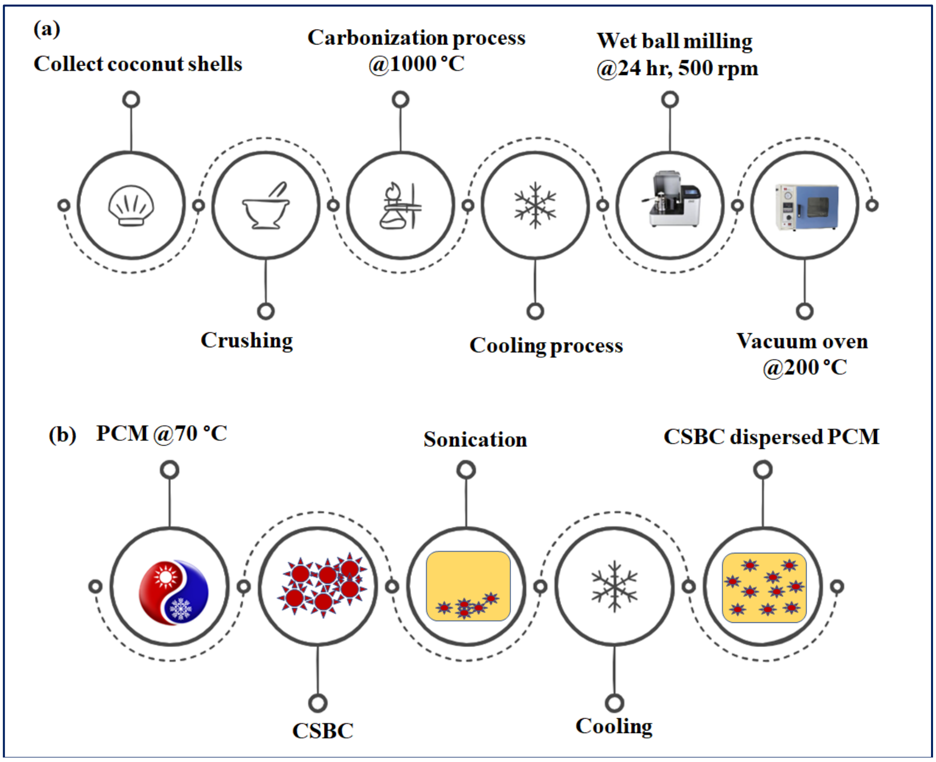

Figure 1. (a) Schematic diagram of synthesis procedure of CSBC and (b) coconut shell biochar dispersed PCM.

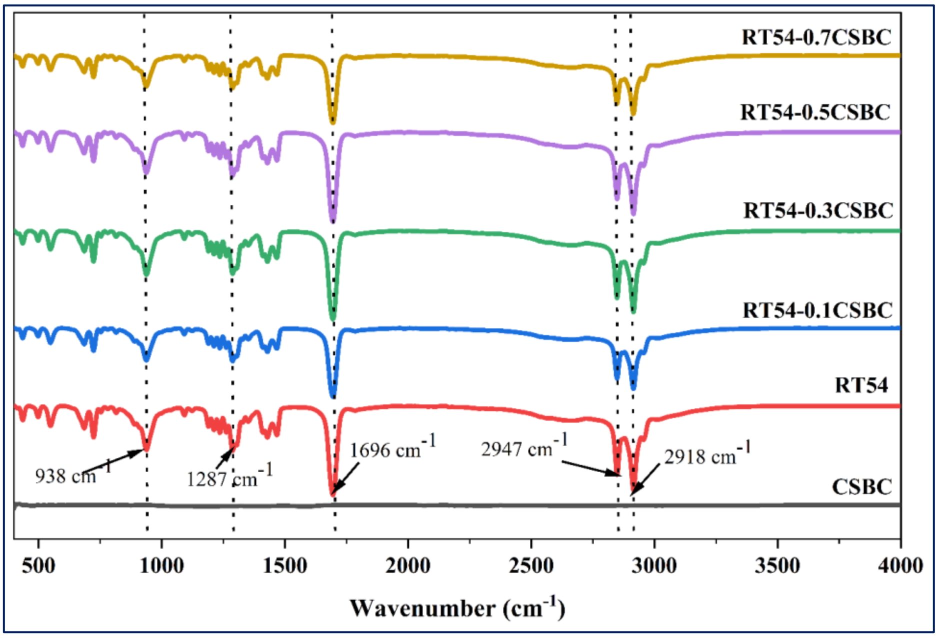

Figure 2. FTIR graph of PCM and CSBC enhanced PCM composite.

RESULTS AND DISCUSSION

Chemical Stability

Figure *2* presents the FTIR spectra of pure RT54 and CSBC-enhanced PCM, highlighting their functional groups. A transmittance of pure sample and CSBC-enhanced PCM composites within the wavenumber range of 400–4000 cm^{-1}. Upon infrared (IR) exposure, the PCM molecules exhibit four distinct vibration modes at wavenumbers: 2918 cm^{-1}, 2847 cm^{-1}, 1696 cm^{-1}, 1287 cm^{-1}, and 938 cm^{-1}. The peaks at 2918 & 2847 cm^{-1} relate to moderate anti-symmetrical stretching vibrations associated with $-CH_2$ and $-CH_3$ functional groups. Further, strong peak observed at 1696 cm^{-1} is attributed to the stretching vibrations of the C=O group. In addition, peak at 938 cm^{-1} correspond to the rocking-mode vibration of -CH$_2$ groups, while the wavenumbers of 1250–1470 cm^{-1} represents the deformation of -CH$_2$ and -CH$_3$ groups. Similarly, the FTIR spectra of PCM with varying concentrations of CSBC show no significant new peaks or spectral shifts. This confirms that the interaction between RT54 and CSBC nanoparticles is entirely physical, without any chemical bonding. Thus, the prepared CSBC-enhanced PCM nanocomposite exhibits excellent chemical stability, ensuring its suitability for thermal energy storage applications.

Thermal Conductivity

The heat transfer efficiency and overall thermal response of material are significantly influenced by TC. The TC of RT54 and its composite with CSBC particles is illustrated in Figure *3*. In its solid state, RT54 exhibits a low TC of 0.212 W/(m.K), suggesting restricted efficiency in thermal energy charging & discharging. However, the inclusion of CSBC substantially enhances the thermal performance of RT54. The samples containing CSBC at weight fractions of 0.1, 0.3, 0.5, and 0.7 wt% achieve TC values of 0.256, 0.345, 0.382), and 0.360 W/(m.K), respectively. This improvement is ascribed to two key factors; (a) The three-dimensional porous network of CSBC nanoparticles enhances interfacial contact with RT54, reducing thermal resistance and facilitating efficient heat transfer through well-established thermal pathways. (b) The uniform dispersion of highly conductive CSBC particles within the PCM matrix promotes the formation of thermal networks, further boosting heat transfer efficiency.

Elemental analysis confirms that the green-synthesized CSBC nanoparticles consist of approximately 92% carbon, with TC range of 118–160 W/(m.K) [26]. These nanoparticles generate multiple thermal hotspots within the RT54 matrix, improving overall heat transfer efficiency. However, at higher concentrations, such as 0.7 wt% CSBC, a slight decline in thermal conductivity is observed. This can be attributed to: (a) Increased cohesive attraction between nanoparticles, leading to cluster creation. Over time, these clusters grow denser and settle within the PCM matrix during repeated phase transitions, disrupting uniform dispersion and hindering effective thermal conduction. (b) A restricted mean free path for intermolecular diffusion due to the increase in density of the nanocomposite, limiting heat transfer efficiency [27]. From the results demonstrating the excellent thermal properties of the formulated material and reinforcing its novelty in TES applications.

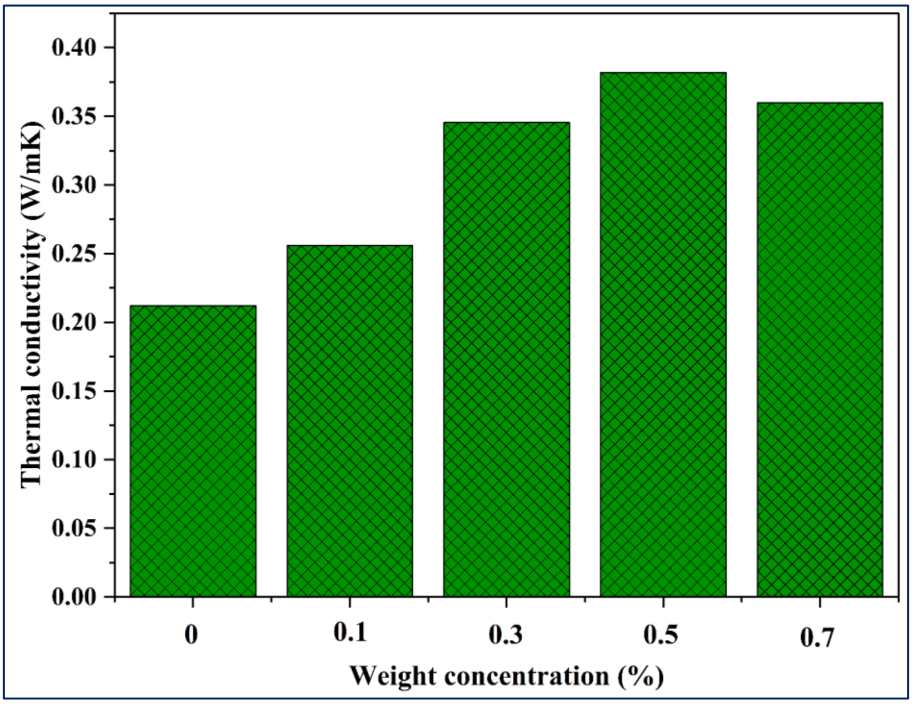

Figure 3. Bar chat of heat conductivity at various concentration of CSBC with PCM.

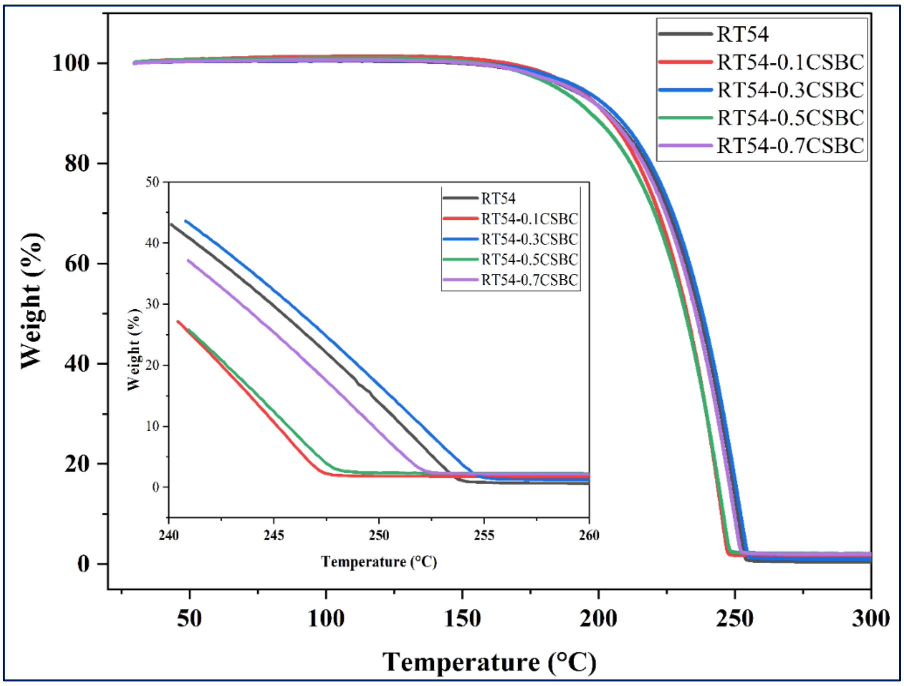

Figure 4. Step by step decomposition behaviour of PCM and CSBC enhanced PCM composite.

Thermal Stability

Thermogravimetric analyzer was led to evaluate the effect of incorporating CSBC nanoparticles on the thermal stability of composite samples. Thermal degradation behavior of the base material and CSBC-enhanced PCM composites is illustrated in Figure *4*. **Figure 4**The degradation process follows a one-step pattern, as indicated by the gradual reduction in weight fraction with increasing temperature.

The base RT54 PCM maintains thermal stability up to 167 °C, beyond which degradation begins. At 253.9 °C, nearly complete decomposition occurs, leaving only 0.6% residue, likely consisting of carbon remnants. The nanocomposite PCM samples, however, exhibit stable thermal behavior within the range of 167.5-170 °C before degradation initiates. The decomposition process is completed between 247.31 and 254.79 °C. The TGA findings designate a slight reduction in thermal stability as the concentration of CSBC particles increases. This decline is attributed to the formation of microcomposites instead of well-dispersed nanocomposites due to nanoparticle agglomeration. Moreover, a residual weight fraction of CSBC remains after the complete breakdown of PCM molecules, confirming the thermal resilience of the biochar component.

CONCLUSION

This study successfully synthesized 3D highly porous carbon-based CSBC using an environmentally friendly approach and integrated them into organic phase change materials (PCMs) via a two-step method. The inclusion of CSBC significantly enhanced thermophysical properties of the PCM, with a notable increase in TC by 80.19%, from 0.212 to 0.382 W/(m.K), particularly at a 0.5 wt.% concentration. Additionally, the formulated composite established excellent thermal stability, maintaining its structural integrity up to 170 °C, along with superior chemical stability, making it a promising material for TES systems, including medium-temperature waste heat recovery, building thermal regulation, and electronic cooling systems. Additionally, while thermal conductivity was significantly improved, the potential impact of biochar dispersion on the latent heat storage capacity and leakage test needs to be explored. This research contributes to Sustainable Development Goal (SDG) 7 – Affordable and Clean Energy by promoting the use of eco-friendly CSBC to enhance the thermal performance of phase change materials, thereby enabling more efficient and sustainable TES solutions. Future research will focus on conducting leakage tests, analyzing melting enthalpy, evaluating optical performance, and assessing the long-term thermal reliability of the biochar-enhanced PCM to further optimize its efficiency for practical TES applications.

REFERENCES

1. Shree, V., Dwivedi, A., Saxena, A., Pathak, S. K., Agrawal, N., Tripathi, B. M., Shukla, S. K., Kumar, R., and Goel, V. (2025) A comprehensive review of harnessing the potential of phase change materials (PCMs) in energy-efficient building envelopes. *J. Build. Eng.*, **101**.

2. Yadav, A., Samykano, M. and Kumar, A. (2024) Sustainable phase change material developments for thermally comfortable smart buildings : A critical review. **191**, 1918–1955 (September).

3. Wu, S., Li, T., Tong, Z., Chao, J., Zhai, T., Xu, J., Yan, T., Wu, M., Xu, Z., Bao, H., Deng, T. and Wang, R. (2019) High-Performance Thermally Conductive Phase Change Composites by Large-Size Oriented Graphite Sheets for Scalable Thermal Energy Harvesting. *Adv. Mater.*, **31** (49).

4. Reji Kumar, R., Samykano, M., Pandey, A. K., Kadirgama, K. and Tyagi, V. V. (2020) Phase change materials and nano-enhanced phase change materials for thermal energy storage in photovoltaic thermal systems: A futuristic approach and its technical challenges. *Renew. Sustain. Energy Rev.*, **133**, 110341(September).

5. R, R. K., Pandey, A. K., Samykano, M., Aljafari, B., Ma, Z., Bhattacharyya, S., Goel, V., Ali, I., Kothari, R. and Tyagi, V. V. (2022) Phase change materials integrated solar desalination system : An innovative approach for sustainable and clean water production and storage. *Renew. Sustain. Energy Rev.*, **165 (5)**, 112611.

6. Kumar, R., Koh, J., Paw, S., Pasupuleti, J., Pandey, A. K., Tak, C., Kiong, S., Yusaf, T., Samykano, M., Sofiah, A. G. N., Ali, I., Ahmed, O. A. and Kadirgama, K. (2024) Experimental investigation on the performance of binary carbon-based nano-enhanced inorganic phase change materials for thermal energy storage applications. *J. Energy Storage*, **86**, 111373 (PB).

7. Laghari, I. A., Samykano, M., Pandey, A. K., Kadirgama, K. and Mishra, Y. N. (2022) Binary composite (TiO2-Gr) based nano-enhanced organic phase change material: Effect on thermophysical properties. *J. Energy Storage*, **51 (5)**, 104526.

8. Bhutto, Y. A., Pandey, A. K., Islam, A., Rajamony, R. K. and Saidur, R. (2024) Lauric acid based form-stable phase change material for effective electronic thermal management and energy storage application. *Mater. Today Sustain.*, **28**, 100931 (April).

9. Balasubramanian, K., Pandey, A. K., Abolhassani, R., Rubahn, H. -G., Saidur, R. and Mishra, Y. K. (2022) Tetrapods Based Engineering of Organic Phase Change Material for Thermal Energy Storage. *SSRN Electron. J.*

10. Paneliya, S., Khanna, S., Utsav, Singh, A. P., Patel, Y. K., Vanpariya, A., Makani, N. H., Banerjee, R. and Mukhopadhyay, I. (2021) Core shell paraffin/silica nanocomposite: A promising phase change material for thermal energy storage. *Renew. Energy*, **167**, 591–599.

11. Kalidasan, B., Pandey, A. K., Saidur, R., Aljafari, B., Yadav, A. and Samykano, M. (2023) Green synthesized 3D coconut shell biochar/polyethylene glycol composite as thermal energy storage material. *Sustain. Energy Technol. Assessments*, **60**.

12. Zhu, X., Gao, Y., Yue, Q., Song, Y., Gao, B. and Xu, X. (2018) Facile synthesis of hierarchical porous carbon material by potassium tartrate activation for chloramphenicol removal. *J. Taiwan Inst. Chem. Eng.*, **85**, 141–148.

13. Dawood, S., Sen, T. K. and Phan, C. (2017) Synthesis and characterization of slow pyrolysis pine cone bio-char in the removal of organic and inorganic pollutants from aqueous solution by adsorption: Kinetic, equilibrium, mechanism and thermodynamic. *Bioresour. Technol.*, **246**, 76–81.

14. Magnacca, G., Guerretta, F., Vizintin, A., Benzi, P., Valsania, M. C. and Nisticò, R. (2018) Preparation, characterization and environmental/electrochemical energy storage testing of low-cost biochar from natural chitin obtained via pyrolysis at mild conditions. *Appl. Surf. Sci.*, **427**, 883–893.

15. Soffian, M. S., Abdul Halim, F. Z., Aziz, F., A. Rahman, M., Mohamed Amin, M. A. and Awang Chee, D. N. (2022) Carbon-based material derived from biomass waste for wastewater treatment. *Environ. Adv.*, **9**.

16. Park, J., Chang, S. J. and Kim, S. (2025) Enhancing thermal performance of cross-laminated timber using phase change materials and biochar composites. *J. Energy Storage*, **109**, 115198, (September 2024).

17. Hekimoğlu, G., Sarı, A., Arunachalam, S., Arslanoğlu, H. and Gencel, O. (2021) Porous biochar/heptadecane composite phase change material with leak-proof, high thermal energy storage capacity and enhanced thermal conductivity. *Powder Technol.*, **394**, 1017–1025.

18. Atinafu, D. G., Yun, B. Y., Choi, J. Y., Yuan, X., Ok, Y. S. and Kim, S. (2023) Introduction of sustainable food waste-derived biochar for phase change material assembly to enhance energy storage capacity and enable circular economy. *J. Energy Storage*, **72**, 108338 (PC).

19. Yadav, A., Pandey, A. K., Samykano, M., Kareri, T. and Tyagi, V. V. (2024) Wheat husk derived microparticle infused organic phase change material for efficient heat transfer and sustainable thermal energy storage. *J. Energy Storage*, **86**.

20. Yadav, A., Pandey, A. K., Samykano, M., Kareri, T. and Tyagi, V. V. (2024) Wheat husk derived

microparticle infused organic phase change material for efficient heat transfer and sustainable thermal energy storage. *J. Energy Storage*, **86**, 111204 (PA).

21. Yadav, A., Samykano, M., Pandey, A. K., Kareri, T. and Kalidasan, B. (2024) Optimizing thermal properties and heat transfer in 3D biochar-embedded organic phase change materials for thermal energy storage. *Mater. Today Commun.*, **38**.

22. Rajamony, R. K., Paw, J. K. S., Pandey, A. K., Sofiah, A. G. N., Yadav, A., Tak, Y. C., Kiong, T. S., Mohanty, A., Soudagar, M. E. M. and Fouad, Y. (2024) Eco-friendly approach to thermal energy storage: Assessing the thermal and chemical properties of coconut biochar-enhanced phase change material. *Energy Storage*, **6 (5)**, 1–14.

23. Naresh, R., Parameshwaran, R., Vinayaka Ram, V. and Srinivas, P. V. (2022) Bio-based hexadecanol impregnated fly-ash aggregate as novel shape stabilized phase change material for solar thermal energy storage. *Mater. Today Proc.*, **56**, 1317–1326.

24. Kalidasan, B., Pandey, A. K., Saidur, R., Kothari, R., Sharma, K. and Tyagi, V. V. (2023) Eco-friendly coconut shell biochar based nano-inclusion for sustainable energy storage of binary eutectic salt hydrate phase change materials. *Sol. Energy Mater. Sol. Cells*, **262**.

25. Chen, Z., Shan, F., Cao, L. and Fang, G. (2012) Synthesis and thermal properties of shape-stabilized lauric acid/activated carbon composites as phase change materials for thermal energy storage. *Sol. Energy Mater. Sol. Cells*, **102**, 131–136.

26. Murugesh, M. (2019) The elements of periodic table.

27. Shen, Z., Kwon, S., Lee, H. L., Toivakka, M. and Oh, K. (2021) Enhanced thermal energy storage performance of salt hydrate phase change material: Effect of cellulose nanofibril and graphene nanoplatelet. *Sol. Energy Mater. Sol. Cells*, **225**.