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Synthesis of Waste-Derived Biochar-Based Phase Change Material for Thermal Energy Storage Applications

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Abstract

This study analyzes the transformation of organic waste into biochar, used as a supporting matrix for phase change materials (PCMs). This approach not only valorizes waste but also aligns with sustainability and the circular economy by reducing waste and offering a cost-effective solution for energy storage applications in areas such as building energy management, electronics cooling, and solar thermal systems. The work contributes not just technically but also environmentally by reducing reliance on petrochemical or synthetic supports for PCMs. Nanocomposites were synthesized using a melt blending technique by adding 1% of aluminum oxide (Al_2O_3) nanoparticles and 10% of biochar by weight, derived from biomass wastes: coconut fiber and water hyacinth. The composites were characterized using Fourier-transform infrared spectroscopy (FTIR), Scanning Electron Microscopy (SEM), thermal conductivity analysis and moisture absorption test. FTIR results confirmed the structural integrity and chemical compatibility of the composite, with the integration of Al_2O_3 nanoparticles and biochar into paraffin, which can be suitable for long-term thermal cycling applications. SEM micrographs revealed the uniform dispersion of the additives and the structural stability of the matrix. The coconut fiber biochar composite exhibited the highest thermal conductivity of 0.24 W/m·K, followed by the water hyacinth biochar of 0.23 W/m·K, and the paraffin-Al_2O_3 composite of 0.17 W/m·K. The moisture absorption test showed negligible weight gain after 12 hours of immersion, indicating a strong moisture resistance. Finally, the integration of agricultural and aquatic waste with PCMs not only improves thermal performance but also contributes to the sustainable waste management solution.

Keywords

Paraffin Wax, Biochar, Alumina Powder, Thermal Conductivity, PCM

1. Introduction

The huge waste generation in Bangladesh due to the rapid expansion of urbanization, industrialization in the metropolitan cities has become a serious concern. These wastes are generated from multiple sources with chemicals, solid/liquid food waste, agro-waste, etc. These wastes are dumped frequently in open landfills causing environmental degradation in the urban areas. This poor waste management pollutes air, water, and soil, and creates huge pollution, which is a common phenomenon in most cities in Bangladesh. In many areas of Bangladesh, coconut husks contribute largely to air and water pollution when they are burned or dumped in open fields or water, releasing harmful gases like carbon dioxide, methane, and particulate matter. The decomposition of coconut shell waste in stagnant water causes unpleasant odors and greenhouse gases that worsen the local environment. Sometimes it blocks drainage systems that are the main causes of flooding during the monsoon season. However, these crucial issues highlight the need for improved waste management and processing industries to prevent ecological damage in Bangladesh. It was reported that a densely populated city like capital Dhaka, produces more than 7000 metric tons of waste per day [1]. The author also formulated a conceptual framework for zero-waste management for entrepreneurs and researchers to initiate further research on waste recycling processes.

The sustainable management of coconut fiber and its byproducts, especially coir fiber, offers Bangladesh an opportunity to integrate environmental conservation with rural economic development. Van Dam *et al.* (2004) [2] investigated the manufacture of fiberboards from coconut husks. It was observed in their analysis that a high percentage of lignin is present in coconut coir and fiber. However, a high thermo-durability character was obtained at temperatures over 140˚C, used to manufacture fiberboards. Santos *et al.*, 2014 [3] developed a medium-density fiberboard (MDF) by adding synthetic resins, formaldehyde (UF) as binders with coconut husks, at a lower pressing temperature. Despite the immense potential of coconut and its byproducts such as coir fiber, the sector faces multiple environmental, technical, and economic challenges in Bangladesh [4].

The ripe or unripe coconut is an important element of the rural economy and its fibers can be used in sustainable industries as a potential raw material. However, due to the lack of proper management of its byproducts, it can create many forms of waste and environmental hazards. For example, unripe green coconut (Cocos nucifera) produces a large amount of fibrous waste, named as unripe green coconut husks, and the amount is around 80% of the total coconut mass [5]. It was also estimated that the global coconut industry generated 408,216,000 tons of husk in 2013, in the tropical areas where coconuts are produced [6].

Presently, the technology and industrial capacity for the extraction of coconut coir fiber are not sufficient in Bangladesh. The traditional manual retting methods are used to process coir fibers, which are time-consuming, labor-intensive, and the retting water contaminates the aquatic ecosystems and poses an environmental hazard. These challenges range from coconut coir waste and environmental pollution to economic inefficiency and modern technological limitations that hinder the potential of coconut. However, the absence of modern technology in fiber extraction limits the use of coir fiber in industry. Due to the high lignin content and fibrous structure, coconut coir provides rigidity, dimensional stability and resistance to degradation features that are essential for materials having effective thermal and acoustic insulation. These materials are suitable for both structural and non-structural architecture and also help reduce agricultural waste and address disposal issues [7]. The coir-based composites can be a remarkable solution for coconut waste management and can reduce the dependency on virgin wood resources. Due to the hydrophilic nature of coconut fiber, it faces difficulty in adhering to a hydrophobic matrix. This adhesion to the matrix can be improved by typical chemical treatment and can be used to develop highly efficient coir-based composites [8]. The strength and dimensional stability of coir fiber are very suitable for material's mechanical stability while reducing material waste [9]. Furthermore, coir-fiber cement boards produced from coir-based raw materials can reduce transportation related emission, promote the economy, and reduce waste [10].

The Hydrophytes plant Eichhornia crassipes, known as water hyacinth is a member of the Pontederiaceae family. These are free floating, fast growing, perennial plant, growing plentifully in the water, and are indigenous to Brazil, Ecuador region and Amazon basin. These aquatic plants are the main causes of multiple hazards ranging from ecological, economic, to social. The biodiversity nature of these plants, causes eutrophication, clogs fresh waterways, shelters pests, also affects aquaculture and agriculture [11]. The aggressive propagation of this water hyacinth blocks sunlight and reduces oxygen penetration in water, leading to the death of submerged vegetation and also destroys fish breeding and feeding. The water hyacinth alters microclimatic conditions and affects climate change by increasing humidity. The plant's accumulation along the riverbanks is the main cause of erosion and sedimentation, which creates challenges to the long-term sustainability of riverine and wetland ecosystems of Bangladesh. The decaying biomass emits methane and carbon dioxide, both potent greenhouse gases, contributing to local air pollution and climate warming. Water hyacinth is prevalent in Southeast Asia including Bangladesh, Central and Western Africa and Central America, the Southeastern United States [12]-[15].

To ensure long-term effectiveness, water hyacinth management must be integrated into national policies on water resources, agriculture, and waste management in Bangladesh. By aligning control measures with the United Nations Sustainable Development Goals (SDGs), Bangladesh can address multiple priorities simultaneously [16]. Promoting hyacinth-based biogas and compost programs directly contributes to renewable energy and sustainable agriculture targets in Bangladesh. Due to the presence of organic matter in water hyacinth, it can be converted into biogas and several pilot projects in Bangladesh have successfully generated methane for household cooking and electricity production. Here water hyacinth is an invasive alien species and considered as waste material. To make it environmentally friendly globally, these wastes are being recycled or reused as resources. In addition, water hyacinth can absorb heavy metals such as arsenic, lead, and mercury from contaminated water, making it an effective phytoremediation agent for treating wastewater from tanneries, dyeing industries, and agricultural runoff in Bangladesh. Thus, integrating hyacinth-based treatment systems in rural and industrial areas could improve water quality and support environmental health.

Water hyacinth also contains a high level of cellulose and hemi-cellulose, which can serve as a high-energy source [17]. These available resources are used in several small cottage industries in the Indonesia, Philippines and India for making paper, basket, rope, mats, shoes, wallets, sandals, bags, vases, etc [18] [19]. The House and Building Research Institute in Dhaka, Bangladesh has conducted research on the production of fiber boards from water hyacinth fiber and other indigenous materials [20]. However, the effective management of coconut coir and water hyacinth in Bangladesh requires a combination of scientific, technological, and community-based approaches. Due to the lack of weed-based green technology, Bangladesh needs an integrated management strategy combining biological, mechanical, and socio-economic utilization approaches aligned with its sustainable development goals (SDGs). The decomposition of coconut coir and water hyacinth produces unpleasant odors and greenhouse gases, worsening the local environment, sometimes it blocks the drainage systems creating localized flooding during the monsoon season. In many areas, they are dumped near water bodies or burned in open spaces, releasing carbon dioxide, methane, and particulate matter that cause air and water pollution. Thus, the sustainable management of coconut coir and water hyacinth in Bangladesh can play a crucial role in early detection, removal, utilization and finally enhance both social inclusion and environmental resilience.

Presently, the illimitable capacity of solar energy attracts researchers to design and develop an effective system that is capable of storing the maximum amount of energy for its better utilization. Storing heat with phase change materials has the potential for several modern-day applications such as building thermal regulation, isothermal solar drying, electronic cooling, etc. Since a significant number of researchers have tried to trap solar energy in the last decades, the improvement of energy storage capacity as well as the analysis of the overall performance of the materials, is still a crucial need. However, suitable latent heat energy storage materials need to be addressed. The biochar derived from biomass feedstock, in this regard, can be explored as a stable, environmentally compatible energy storage material. Biochar can be produced from various feedstocks and serves as a sustainable alternative to conventional carbon-based supports. The biochar is synthesized here from two abundant biomasses, which are coconut coir (CC) and water hyacinth (WH). The morphological and structural studies confirmed the suitability of biochar as a phase change material (PCM), and it can be used as the most efficient alternative for an energy storage system with comparatively higher time of energy holding. Biochar is a carbon-rich, porous byproduct of biomass, capable of absorbing molten paraffin and its porous architecture also promotes heat flow and structural integrity [21] [22].

PCMs are substances that absorb or release significant amounts of latent heat during their phase transition, typically between solid and liquid states. PCMs are broadly classified into three categories: organic (like paraffin wax, fatty acids), inorganic (like salt hydrates), and eutectic mixtures. Researchers are now focusing on the development of thermally enhanced PCM composites, using paraffin waxes, aluminum oxide (Al_2O_3) nanoparticles, together with waste-derived biochar additives [23]. It was also observed that the thermal conductivity of the PCM was increased up to 13.82 times with the inclusion of water hyacinth biochar as a supporting matrix [24].

Among the organic PCMs, paraffin waxes and fatty acids are chemically stable, non-corrosive, and possess good thermal reliability, making them highly suitable for low to medium-temperature applications. Inorganic PCMs like salt hydrates offer higher latent heat per volume but are often corrosive and prone to super-cooling. Eutectic PCMs combine organic-organic or organic-inorganic materials to achieve customized points [25]. To overcome these downsides, researchers have incorporated nanoparticles into PCMs to improve their thermal conductivity. Nanoparticles such as Al_2O_3, CuO, and SiO_2 act as thermal bridges in the paraffin matrix [26]. Among them, aluminum oxide (Al_2O_3) is low-cost, abundant, and thermally stable, making it a promising additive for enhancing heat transfer performance with paraffin wax [27]. The high-porosity biochar derived through the pyrolysis process, makes it suitable for strengthening the PCM. In this regard, the structural strength of paraffin wax in PCM was improved by a dual-additive produced from the combination of biochar with Al_2O_3 nanoparticles [28]. The nanoparticle into PCMs still suffers from some difficulties like phase separation, sedimentation, and reduced structural integrity and these problems were solved by introducing biomass-derived porous materials like biochar as shape-stabilizing agents in the PCMs [29]-[31]. Biochar derived from agrarian waste is lightweight, porous, and has good thermal properties. It also offers financial benefits, as it is produced from waste biomass like coconut shells, sawdust, and aquatic weeds [16] [32] [33]. Coconut fiber and water hyacinth are two biomass sources for Biochar, available abundantly in Bangladesh, which act as an auxiliary matrix to reduce leakage and increase heat flows in PCMs. The aluminum oxide (Al_2O_3) nanoparticles which have high thermal conductivity and chemical stability, are used with paraffin wax to improve its heat transfer characteristics. The carbon-rich porous material, biochar derived from biomass waste, is also used here as a form-stabilizing additive to prevent leakage.

The large surface area and porous structure of biochar enhance capillary retention and heat storage efficiency. This increases the energy storage capacity of the

PCM composites and improves thermal stability and leakage resistance. Traditional PCMs often suffer from low thermal stability, leakage during phase changes, and environmental issues associated with their supporting materials. This biochar-based composite PCM overcomes those issues, displaying improved shape stability, high thermal cycling durability, and little to no leakage in thermal tests. Therefore, this work contributes not just technically but also environmentally by reducing reliance on petrochemical or synthetic supports for PCMs, promoting carbon sequestration via stable biochar formation, and offering a cost-effective route for thermal energy storage applications in areas such as building energy management, electronics cooling, and solar thermal systems.

However, the ultimate goals of this study are to investigate the thermal and structural properties of paraffin wax-based PCM on the combined effects of Al_2O_3 nanoparticles (1 wt%) and biochar (10 wt%) derived from the coconut fiber and water hyacinth. FTIR and SEM analyses were conducted to analyze the chemical consistency and microstructure, respectively, and the thermal conductivity was measured by the hot-wire method. The thermal and structural architecture of the composite PCM is improved when combined with biochar additives. This finally solves the sedimentation, poor dispersion, and leakage issues.

2. Materials and Methods

2.1. Synthesis of Biochar

The approach of selecting materials is based on the alignment of waste valorization and its sustainability. In this work, biochar was synthesized from two local biomass waste sources: coconut fiber, a byproduct of domestic use, and water hyacinth, an invasive aquatic weed. The sequential steps involved in the preparation of the nanocomposite PCM-biochar composite are illustrated in **Figure 1**. These materials are typically discarded, contributing to solid waste and waterway pollution. Their translation into biochar offers a dual benefit: like waste management and thermal energy storage systems, supporting the goals of the circular economy and environmental sustainability [34]. The approximate composition of coconut coir and water hyacinth is presented in **Table 1**. The eco-friendly composites are synthesized, when blended coconut coir and water hyacinth together with hydroxyl/carbonyl (cellulose/lignin) groups to improve their bonding, absorbency and lightness in the composites.

The cellulose in the composite provided structural strength and a high surface area once processed in the presence of linear, semi-crystalline polysaccharide polymer. The presence of lingocellulosic biomass in the composite improves the permeable structure needed for energy storage capacity. Hemicellulose on the other hand consists of monosaccharides (xylose, mannose, glucose, etc.) is amorphous, removed by pretreatment processes to increase the cellulose's accessibility and material's crystallinity. A complex, aromatic biopolymer acts as a binding agent, providing resistance and rigidity to microbial degradation that makes it a pioneer for carbon materials.

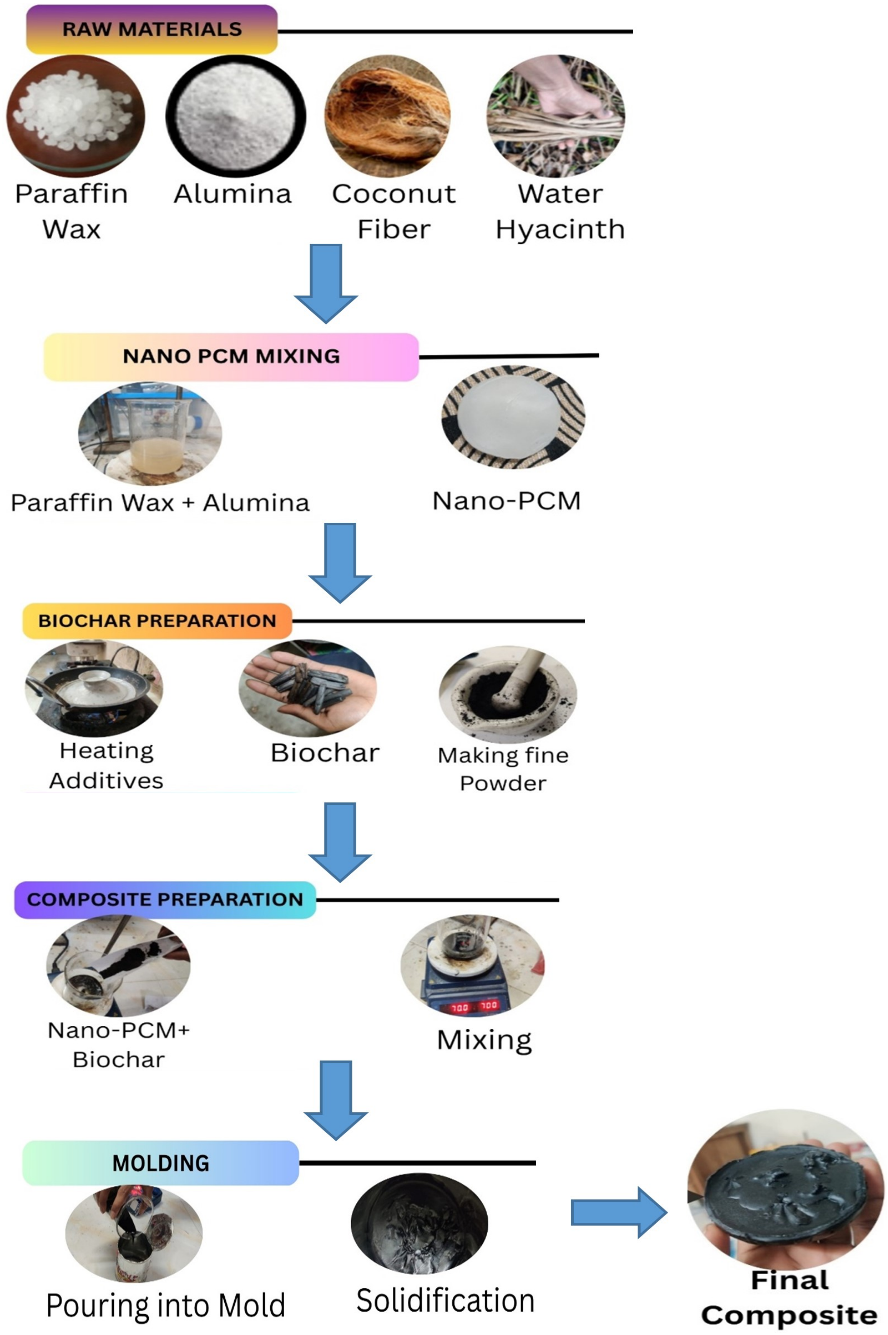


Figure 1. Steps of nanocomposite PCM bio-composite preparation.

Table 1. The approximate composition of coconut coir (CC) and water hyacinth (WH).

	Coconut Coir (Mesocarp)	Water Hyacinth (Stems & Leaves)
Main components	Cellulose (27% - 45%), Hemicellulose (15% - 20%), Lignin (40% - 50%), Ash/Moisture (1.3%)	Cellulose (~19.5% - 50%), Hemicellulose (~19.5% - 33.4%), Lignin (~2.25% - 10%), Ash/Moisture (up to 24.2%)
Key features	Hardness, durability, rigidity and smooth, water resistance to composites	Large pores, light weight, rough surface, high water absorption capacity

In raw form of coir and hyacinth are not used unless they are converted into activated carbon through processes involving carbonization and chemical activation. The organic components like cellulose, hemicellulose, lignin act as the carbon precursor. The treatment processes here remove the non-carbon elements to ensure its porosity with a large specific surface area. The high surface area and porous structure of activated carbon are necessary for the adsorption/desorption of ions in the electrolyte that is also very essential for energy storage systems. To enhance the material's surface chemistry as well as electrochemical performance, chemical treatments are performed. The chemical treatment was performed to extract cellulose from water hyacinth, as it has low lignin and high holocellulose content. Coconut coir, conversely, has very high lignin content, requiring specific treatments to make it suitable for energy storage applications.

2.2. Synthesis of PCM

As such, a composite phase change material (PCM) was developed by utilizing paraffin wax as the primary base material, and its performance was enhanced through the addition of aluminum oxide (Al_2O_3) nanoparticles and biochar derived from two different biomass sources, coconut fiber and water hyacinth. The steps involved in the preparation of nano-PCM bio-composite are shown in **Figure 1**. The paraffin wax was selected here due to its excellent properties, including high latent heat of fusion, chemical inertness, thermal reliability, non-toxicity, and economic affordability. However, despite these benefits, paraffin wax suffers from a major drawback: its intrinsically low thermal conductivity (0.2 W/m·K) that restricts the rate of absorption and release of thermal energy [35] [36]. This limitation reduces its overall efficiency in applications; it requires rapid heat exchange or cyclic thermal charging and discharging characteristics.

To address this issue, aluminum oxide (Al_2O_3) nanoparticles were selected as a thermal conductivity enhancer due to their high intrinsic conductivity, chemical stability, and compatibility with organic matrices. A concentration of 1 wt% Al_2O_3 was introduced into molten paraffin wax, and the resulting mixture was subjected to a controlled magnetic stirring process. This was conducted at a temperature of 70˚C and a speed of 700 rpm for a two-hour duration. The aim of this step was to achieve homogeneous dispersion of the nanoparticles throughout the parafene wax matrix without the formation of agglomeration that affects negatively on the uniformity and enhancement of thermal conductivity. To further improve the structural integrity of the composite PCM and to mitigate the leakage commonly observed during the melting phase, biochar was incorporated as a porous stabilizing scaffold. Biochar, a carbon-rich material with high porosity, was derived from the biomass through the pyrolysis process is known for its ability to absorb and retain molten materials. Pyrolysis (heating without oxygen) process was performed at temperatures ranging from 400˚C to 800˚C to maintain the properties, surface area, carbon content and porosity for specific applications. As such two different bio-waste materials, coconut fiber and water hyacinth were selected as feed stocks for biochar production, aligning the goals of waste management and its sustainability. The raw biomass was first thoroughly cleaned to eliminate any surface contaminants or residues, and then left to sun-dry for 48 hours to remove moisture. After drying completely, the biomass was chopped into smaller pieces to increase its surface area and made ready for the pyrolysis process that was conducted in sealed traditional clay cooking pots. This pot was heated on a gas stove to simulate an oxygen-limited environment that facilitated carbonization of the biomass toward achieving structurally porous, carbon-rich structure.

Biochar was produced separately from coconut fiber and water hyacinth through slow pyrolysis under oxygen-limited conditions. Prior to pyrolysis, both biomass feedstocks were thoroughly washed to remove adhering impurities and sun-dried for 48 h. The dried materials were subsequently chopped into small pieces to facilitate relatively uniform thermal decomposition. For each feedstock, a measured quantity of dry biomass was placed in a lidded clay pyrolysis vessel and heated using a gas-fired heating source. The temperature was increased from ambient temperature to a target pyrolysis temperature of 500˚C at an average heating rate of approximately 10˚C min^{-1}, followed by a 60 min residence period at 500˚C. The vessels remained tightly covered throughout carbonization, with only a small outlet provided for the release of volatile pyrolysis gases. Consequently, external air ingress was minimized and an oxygen-deficient atmosphere was maintained without the use of externally supplied nitrogen. After completion of pyrolysis, the heat source was removed and the vessels were kept closed until they cooled naturally to room temperature to prevent oxidation of the hot char.

Once it was pyrolyzed, the resulting biochar was manually crushed using a mortar and pestle into fine powder until it became suitable for mixing with the paraffin matrix. This manual grinding approach was selected to avoid nanoparticle contamination and maintain the natural porous structure of the biochar. The previously prepared Al_2O_3 was then added to 10 wt% of biochar and magnetic stirring process at 70˚C and 700 rpm was conducted for the preparation of composite PCM. This process resulted in two distinct biochar-reinforced nanocomposite PCM variants—one containing coconut fiber biochar and the other containing water hyacinth biochar. Finally, the hot nanocomposite mixtures were carefully poured into pre-cleaned aluminum molds and allowed it to cool and solidify under ambient room temperature (25˚C). This natural cooling process helped to ensure the samples are solidified without introducing thermal shock, deformation, or structural imperfections, thereby preserving the physical integrity and homogeneity of the final composite PCM blocks. Biochar, particularly from biomass waste such as coconut fiber and water hyacinth, has shown promise in improving thermal performance and structural stability of PCM composites. Although a combined system of paraffin, Al_2O_3, coconut or hyacinth biochar has not been directly reported, the components have each been individually validated in the literature as effective PCM enhancers. Thus, three samples are selected here as

Paraffin + 1 wt% of Al_2O_3 [37], Paraffin + 1 wt% of Al_2O_3 + 10 wt% of Water Hyacinth Biochar, and Paraffin + 1 wt% of Al_2O_3 + 10 wt% of Coconut Fiber Biochar to analyse the thermal performance.

Prior to composite preparation, the coconut-fiber and water-hyacinth biochars were ground and sieved to obtain a uniform particle-size fraction of <150 μm. The sieved biochar powders were subsequently oven-dried at 105˚C for 24 h to remove residual moisture and then stored in airtight containers until use. The Al_2O_3 nanoparticles, with a nominal particle size of approximately 20 - 50 nm, were dried at 80˚C for 12 h before incorporation into the paraffin matrix to minimize moisture-induced agglomeration. These controlled particle-size and drying procedures were adopted to improve additive dispersion and reproducibility and to minimize variations in composite porosity and thermal conductivity. A pure-paraffin sample was included as the control and tested under identical experimental conditions. Its thermal conductivity was used as the baseline for comparison with the Al_2O_3-containing and biochar-containing PCM composites, enabling the individual contributions of Al_2O_3, coconut-fiber biochar, and water-hyacinth biochar to the enhancement of thermal conductivity to be quantified.

3. Results and Analysis

3.1. FTIR Analysis

A powerful, non-destructive technique, FTIR (Fourier Transform Infrared) was used for the qualitative and quantitative chemical analysis to identify and verify composition, and to analyze complex mixtures of the sample. The FTIR spectra of Nano-PCM samples are shown in **Figure 2**. This analysis aimed to determine whether these additives introduced any new chemical bonds that altered the molecular structure of the base PCM. The FTIR spectra were collected across a wavenumber range of 4000 - 500 cm^{-1} for the three samples: i) Paraffin + 1 wt% of Al_2O_3 (Nano-PCM) [37], ii) Paraffin + 1 wt% of Al_2O_3 + 10 wt% of Water Hyacinth Biochar, and iii) Paraffin + 1 wt% of Al_2O_3 + 10 wt% of Coconut Fiber Biochar are presented in **Figure 2**. This FTIR spectroscopy shows the chemical structure, functional group, integrity and interaction behavior of paraffin wax that was modified with aluminum oxide (Al_2O_3) nanoparticles and two biochars, coconut fiber and water hyacinth. In all samples, strong absorption peaks were observed in the wavenumber 2880 - 2892 cm^{-1}, corresponding to C–H stretching vibrations in $-CH_2$ and $-CH_3$ groups. These peaks are the characteristic of aliphatic hydrocarbons that confirm the presence of base paraffin structure. Specifically, the Nano-PCM sample showed a peak at 2892 cm^{-1}, while the composites with coconut coir and water hyacinth biochar exhibited slight shifts to 2888 cm^{-1} and 2880 cm^{-1}, respectively. These minor shifts are attributed to weak physical interactions such as van der Waals forces or mild hydrogen bonding between paraffin chains and the added nanoparticles or porous carbon structures. Importantly, no new peaks were detected in any of the samples, indicating that no chemical reaction or covalent bonding occurred between paraffin and the additives.

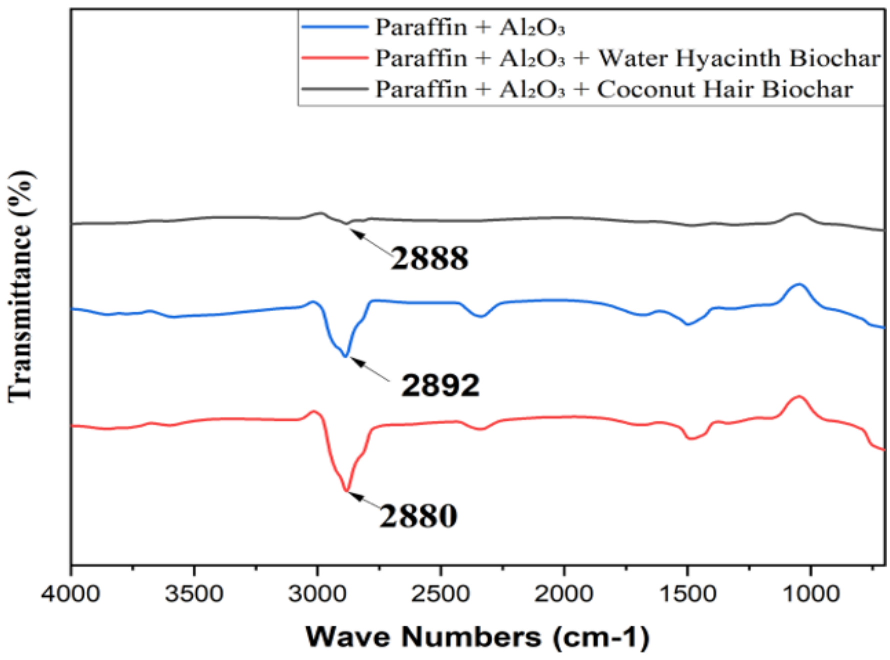
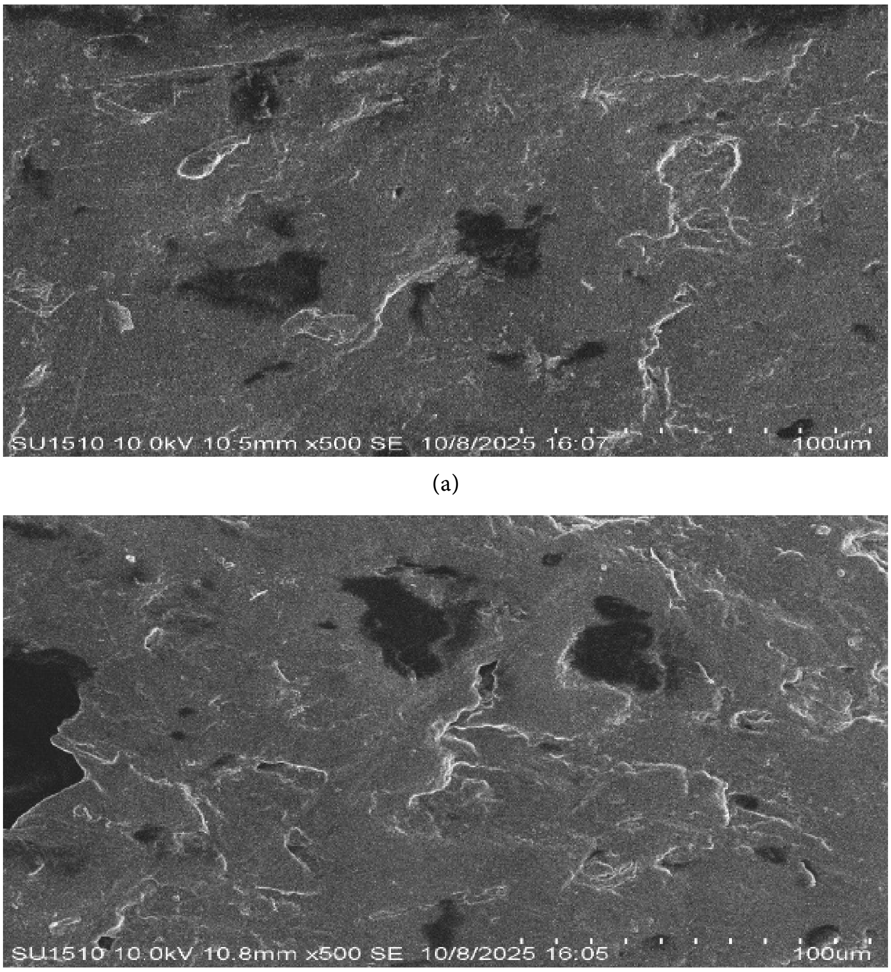


Figure 2. FTIR spectra of Nano-PCM samples.

These findings are consistent with previous research studies of [21] [24] demonstrated the persistence of C–H stretching peaks in FTIR spectra and confirmed the chemical inertness and compatibility of paraffin with additives like Al_2O_3 and biochar. Additionally, the presence of small bands between 1000 - 1200 cm^{-1} allocated to C–O or C=C stretching vibrations originates from oxygenated surface groups in the biochar and supports paraffin encapsulation shaped stability during melting cycles [30] [31]. Thus, these FTIR results confirm the structural integrity of paraffin and ensure no undesirable chemical interactions occurred. This validates the safe integration of Al_2O_3 nanoparticles and biochar into paraffin for the enhancement of thermal energy storage capacity without compromising the chemical stability that is suitable for long-term thermal cycling applications.

3.2. SEM Analysis

The surface topography and composition of the samples are observed in scanning electron microscope (SEM) analysis. This provides high-resolution, magnified images by scanning the materials at higher magnification and in larger depth. The SEM was employed to investigate the surface geomorphology and microstructural supply of aluminum oxide (Al_2O_3) nanoparticles and biochar within the paraffin matrix. This analysis was conducted to determine whether the additives were unvaryingly dispersed and to identify any morphological features, such as voids, particle agglomeration, or porosity, that could influence the thermal performance and structural integrity of the composite PCMs. The SEM images at 500× magnification of paraffin-based Nano-PCM with coconut fiber biochar and with water hyacinth biochar are presented in **Figure 3(a)** and **Figure 3(b)**, respectively.



(a)

(b)

Figure 3. (a) SEM image of Nano-PCM with coconut coir biochar (CC); (b) SEM image of Nano-PCM with water hyacinth biochar (WH).

The SEM image of the paraffin-based Nano-PCM coconut fiber and water hyacinth biochars reveals a relatively rough and non-uniform surface texture, featuring a number of irregular dark regions. The dark areas in the SEM image confirm the presence of a carbon-rich structure in the biochar. The particle sizes of the sample are found within the range of 500 to 700 nm. Similar SEM images were observed in the previous study [22]. The specific surface areas of biochar are also obtained in the range from 100s to 1000s m^2/g and the specific volume of empty space (pores) of pore volume, 0.1 - 1.5 cm^3/g. As seen from the SEM images, the biochar particle has lots of pores on its surface that are filled with Nano-PCM, and thus increase the surface area. A similar observation in the SEM images was noted for agricultural biomass, where migration and sintering of inorganic elements in biochar were taking place [38]. The presence of visible pores in the biochar suggests that the porous construction of the coconut fiber biochar was largely retained after composite formation, in **Figure 3(a)**. Such porosity is beneficial, as it enables the melted paraffin to be engrossed and held within the matrix, thus enhancing shape stability and reducing leakage during phase transitions. Furthermore, no significant particle deposit was observed in the images, indicating the well-dispersing of Al_2O_3 nanoparticles and biochar within the matrix. The SEM image in **Figure 3(b)**, water hyacinth biochar surface morphology is marked rougher and more splintered. This dispersion of biochar appeared more uneven compared to the coconut fiber biochar. This variation may be due to the difference in cellular structures and pyrolysis behavior of water hyacinth biomass that yields the presence of loosely packed and irregular pores in the biochar [30]. As could be seen in the image, some microvoids and surface fractures were interspersed with lighter zones, paraffin and Al_2O_3 that could locally disrupt as the thermal conductivity pathways. Despite these textural differences, both SEM micrographs confirm the successful integration of Al_2O_3 nanoparticles and biochar into the paraffin matrix. The biochar appears to provide a steadying porous scaffold, while the Al_2O_3 nanoparticles are evenly dispersed without notable agglomeration. Such morphological integrity is essential for safeguarding consistent thermal behavior, minimal leakage, and structural stability during repeated melting-solidification cycles; this analysis also supported by previous investigations on PCM composite structures [26].

3.3. Thermal Conductivity Analysis

Thermal conductivity is a key thermophysical property governing the heat-transfer efficiency, charging/discharging rate, and overall thermal response of phase change materials (PCMs). It is particularly important in applications requiring rapid thermal energy exchange, including solar thermal systems, building-envelope thermal management, and electronic cooling systems. Although paraffin wax is widely used as a PCM because of its high latent heat, chemical stability, and reliability, its inherently low thermal conductivity limits the rate of heat absorption and release during repeated thermal cycles [36].

In the present study, the thermal conductivity of paraffin-based composites was modified through the incorporation of Al_2O_3 nanoparticles and biochar derived from coconut fiber and water hyacinth. As shown in **Figure 4**, the paraffin/Al_2O_3 nanocomposite (Nano PCM) exhibited a thermal conductivity of 0.17 W/m·K, whereas the addition of coconut-fiber biochar (Nano PCM+CO) increased the thermal conductivity to 0.24 W/m·K. Similarly, the water-hyacinth-biochar composite (Nano PCM+WH) exhibited a thermal conductivity of 0.23 W/m·K. Thus, the biochar-containing composites showed higher thermal conductivity than the paraffin/Al_2O_3 nanocomposite, with the coconut-fiber-biochar composite providing the highest value among the investigated samples.

The experimentally obtained thermal-conductivity values were compared with previously reported data [23] [24] [31] [35], as summarized in **Table 2**. The values obtained in the present study ranged from 0.17 to 0.24 W/m·K, while literature values for comparable paraffin-based composites ranged approximately from 0.12 to 0.39 W/m·K. Differences among the reported values may result from variations in filler concentration, particle size, porosity, interfacial thermal resistance, sample preparation, and the degree of nanoparticle or biochar dispersion within the paraffin matrix. Agglomeration of Al_2O_3 nanoparticles or non-uniform distribution of biochar can interrupt continuous heat-conduction pathways and consequently reduce the expected enhancement in thermal conductivity. The incorporation of Al_2O_3 nanoparticles can improve heat transfer within paraffin because the inorganic particles provide relatively conductive pathways through the PCM matrix. The simultaneous presence of biochar may further influence the effective thermal-conduction network through its porous carbonaceous structure and interaction with the nanoparticles. However, the addition of solid fillers can reduce the mass fraction of paraffin and therefore may decrease the overall latent heat of the composite. Consequently, enhancement of thermal conductivity must be balanced against possible reductions in latent-heat-storage capacity.

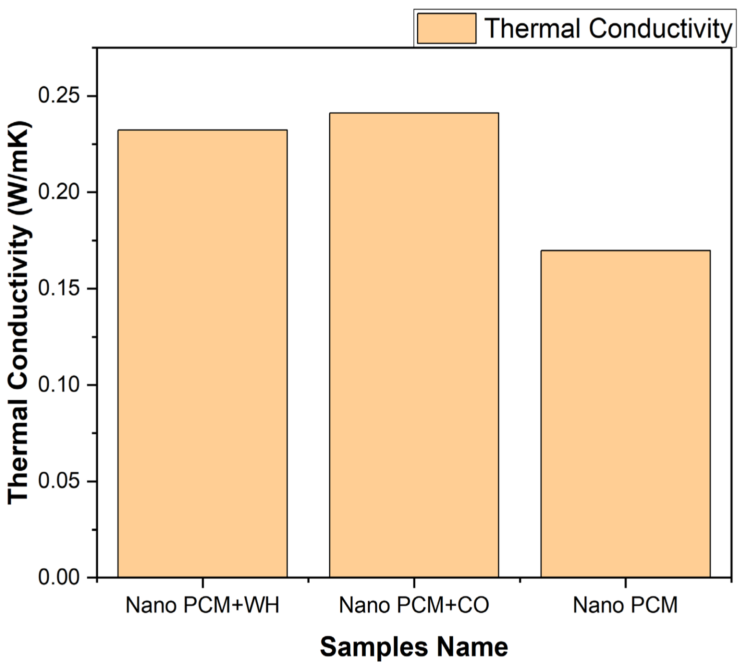


Figure 4. Thermal conductivity analysis.

Table 2. Comparison of thermal conductivity with literature studies.

Literature	Materials	Thermal Conductivity W/mK	
		Literature	Present Study
Samara *et al.* (2024) [23]	Paraffin wax and Al_2O_3	0.307	0.17
Hamdani *et al.* (2014) [35]		0.12 - 0.21	
Rajamony *et al.* (2024) [31]	PCM & coconut coir biochar	0.39	PCM & Coconut Fiber: 0.24 PCM & Water Hyacinth: 0.23
	Base PCM	0.22	
Mohtasim & Das (2024) [24]	PCM & water hyacinth biochar	0.27	

During phase change, heat transfer is governed by different mechanisms. In the melting process, both conduction and natural convection within the liquid PCM may contribute to heat transfer, whereas solidification is predominantly controlled by conduction. Therefore, the presence of thermally conductive Al_2O_3 nanoparticles and biochar can have a particularly noticeable influence during solidification by facilitating heat removal through the composite matrix. The combined incorporation of Al_2O_3 and biochar therefore provides a potential strategy for improving the thermal response of paraffin-based PCMs, although optimization of filler loading and dispersion is necessary to achieve an appropriate balance between thermal conductivity and latent-heat-storage capacity.

3.4. Moisture Absorption Analysis

The effectiveness of encapsulation in composite phase change materials significantly influences their performance and feasibility in practical applications. A moisture absorption test measures how much water a material can absorb, usually by weighing a dry sample, soaking it, and then re-weighing it to find the increase in weight, indicating its suitability for specific applications. To assess the moisture resistance of the PCM composite, the weight of the sample was selected here as 1 g, and it was submerged in water for 12 hours at room temperature, as shown in **Figure 5**. The final weight was measured, and the increased weight was observed as 1.001 g, indicating negligible moisture absorption. This analysis depicts that the incorporation of biochar into the Alumina-paraffin matrix enhances water repellency. The porous carbon structure of biochar likely helps encapsulate the paraffin more effectively, thereby minimizing water penetration. Furthermore, paraffin itself is hydrophobic that ultimately complements the role of biochar in enhancing leakage and moisture resistance.

The biochar of water hyacinth and coconut coir used here as reinforce materials with alumina and paraffin wax to produce carbon-rich porous material derived from biomass waste. Coir fiber and water hyacinth have the advantage related to their renewable nature and their high output in local sourcing. Also, the effect of reinforcing the composite matrix causes a more flexible behavior that can be an advantage to absorb or release energy in lightweight structures. The improved performance is attributed to the porous and carbon-rich structure of biochar, which facilitates enhanced thermal bridging between paraffin domains. SEM imaging confirmed these insights: the coconut coir biochar demonstrated a more uniform, fibrous, and interconnected matrix compared to the less compact structure of water hyacinth biochar that likely contributed to its superior conductivity. These findings collectively demonstrated that dual reinforcement with Al_2O_3 nanoparticles and biochar not only enhances thermal conductivity but also promotes waste valorization, positioning this approach as both a technical and ecological solution for PCM-based thermal energy storage systems.

Figure 5. Water absorption test.

4. Conclusions

Alumina-paraffin-based phase change material (PCM) composites reinforced with sustainable, carbon-rich biochar derived from coconut fiber and water hyacinth were successfully prepared and characterized. FTIR analysis indicated that the incorporation of Al_2O_3 nanoparticles and biochar did not introduce significant chemical changes in the paraffin matrix, while SEM observations demonstrated the incorporation and distribution of the additives within the composite structure. The main contribution of this study is the utilization of agricultural and aquatic biomass wastes as low-cost functional additives for developing more sustainable PCM composites.

The incorporation of biochar improved the thermal conductivity of the alumina-paraffin PCM. Among the investigated samples, the coconut-fiber-biochar composite exhibited the highest thermal conductivity of 0.24 W/m·K, compared with 0.23 W/m·K for the water-hyacinth-biochar composite and 0.17 W/m·K for the Al_2O_3-paraffin composite. The moisture-absorption results further provided information on the interaction of the composites with moisture under the investigated conditions. Overall, the findings demonstrate the potential of waste-derived biochar for enhancing the thermal transport characteristics of paraffin-based thermal energy storage materials while contributing to biomass-waste valorization and sustainable material development.

However, latent heat capacity, melting and solidification behavior, leakage resistance, quantitative shape stability, and long-term thermal reliability were not evaluated in the present study. Therefore, these properties cannot be concluded from the current results. Future work should include differential scanning calorimetry (DSC), leakage and shape-stability testing, and repeated thermal cycling to determine latent heat retention, phase-transition stability, leakage resistance, and long-term durability before the composites are considered for practical applications such as building thermal management, electronics cooling, and solar thermal energy storage.

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Author Contributions

Himangshu Bhowmik: Conceptualization, methodology, supervision, project administration, investigation, data interpretation, writing, review and editing. Mahadi Hasan Mahim: Experimental investigation, materials preparation, data collection, characterization, data analysis, and writing original draft. Mandira Bhowmik: Literature review, validation, review and editing. Shaon Talukdar: Methodology, validation, technical analysis, interpretation of results, review. All authors reviewed and approved the final version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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