Bulgarian Chemical Communications, Volume 57, Special Issue B (pp. 260-273) 2025 DOI: 10.34049/bcc.57.B.A0033

Development of cashew nutshell-based composite material and heat-absorber panel: a comprehensive review

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Revised: April 07, 2025

This research focuses on developing a cashew nutshell (CNS) biochar-based composite panel to serve as a cost-effective and eco-friendly thermal energy storage alternative. Cashew nutshells, one of the most prevalent kinds of agricultural waste, can be subjected to controlled pyrolysis to obtain biochar. It is rich in thermal resilience, carbon content, and porosity, which are essentials for efficient heat absorption and retention. The purpose of the study is to compare the thermal efficiency of CNS-based panels with that of more conventional materials like metal and wood, to examine their construction, characterization, and performance assessment.

The proposed panel promotes sustainability and energy conservation *via* diverse applications, including industrial waste heat recovery, building thermal insulation, and solar thermal energy utilization. Construction and build processes have major impacts on ground, air, and water pollution. This research aims to combine waste reduction with clean energy development by providing a high-performance, inexpensive, and renewable thermal storage system. Additionally, this reearch will also explore phase change material integration to further enhance energy retention.

Keywords: Cashew nutshell (CNS), CNSL extraction, composite material, heat absorbing panel.

INTRODUCTION

The global demand for sustainable heat solutions has increased along with the increased interest in bio-based materials for heat absorption and retention. While traditional materials like metal and concrete provide high thermal conductivity, they can also pose environmental challenges, have high production costs, and lack of sustainability. In order to address these problems, this study explores the feasibility of cashew nutshell (CNS) biochar-derived composites as novel, sustainable alternatives in heat-absorbing panels. cashew nutshells (CNS) is a common and high lignocellulosic content agronomic waste product. Due to high phenolic resins in their structure, cashew nutshells have the potential to be used as materials for carbon-based thermal energy storage. Through regulated pyrolysis, CNS can be transformed into biochar with a high carbon content, high thermal stability, and improved porosity all essential characteristics for effective heat absorption and retention [1-3]. This project aims to investigate a systematic approach for developing a lightweight, long-lasting heat-absorbing panel for thermal energy storage and distribution for a variety of applications by incorporating CNS biochar into composite binders and composite reinforcement materials.

Although their hard shells need to be removed before processing, cashew nut seeds are high in fiber, healthy fats, and proteins [4]. 11,900 hectares of cashew farms were spread in Uttaradit, Chonburi, and Ubon Ratchathani in Thailand in 2019. The shell, which makes up 67–80% of the nut's weight, produces a substantial amount of biomass waste. Roasting produces shells that are semi-carbonized. Other processing techniques include frying, roasting, or mechanical cutting [5]. Applications in both industry and medicine can be found for cashew nutshell liquid (CNSL), a dark brown oil that is high in phenolic chemicals such as cardanol and anacardic acid. It is a natural substitute for manufactured phenols and makes up 30–35% of the shell's weight. Acetone has the highest CNSL output among extraction techniques, which also include solvent, heat, and mechanical procedures.

CASHEW NUTSHELL-BASED MATERIALS

Cement-based composites

Materials like cement composites are essential to the construction sector. However, the manufacture of cement uses a lot of energy and contributes significantly to CO_2 emissions. Researchers have

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studied CNS-derived supplemental cementitious materials (SCMs) handled at various temperatures, such as CNS ash (CNSA), uncalcined CNS, and CNS powder (CNSP), in an effort to address these problems.

For instance, Sakthivel and Suthaviji (2024) [6] have investigated the use of CNSA as a partial substitute for ordinary portland cement (OPC) and discovered that its pozzolanic activity improved long-term strength at an ideal CNSA concentration of 10 -30 %. Lima and Rossignolo (2010) [7] have investigated the physical and chemical characteristic of CNSA for application in cement suggesting that it has pozzolanic potential. Additionally, a critical assessment by Thirumurugan *et al.* (2018) [8] noted that, because of its oxide composition, CNSA shows promise as pozzolanic material and a possible SCM, enabling partial cement replacement in mortar and concrete applications. In mortar and concrete applications, CNSA shows promise as a pozzolanic material to partially replace cement.[9]. While a 20% substitution is appropriate for non-load-bearing applications and results in denser and stronger concrete, a 15% substitution is thought to be ideal for structural use. According to additional studies, up to 25% CNSA substitution improves overall strength, pore minimization, curing, and water absorption. On the other hand, because of its poor mechanical properties, uncalcined CNS cannot be used as a substitute for cement [10]. The effectiveness of CNS biomass is increased by calcining it, which permits a larger substitution ratio.

Generally, it is very crucial to achieve a high bearing capacity for soil stabilization. According to research, CNSA and lime together increase the strength of extremely expansive soils. For example, compressive strength rose dramatically when 5.5% of lime was substituted for 0.5% of CNSA. Only slight benefits were seen in lateritic soil when CNSA and glass industrial waste were added, according to another study. CNSA decreased the maximum dry density of the soil while increasing soil cohesiveness and decreasing the friction angle. The ideal CNSA % for soil stabilization, as well as its long-term impacts and cost-effectiveness in comparison to alternative stabilizers, require further investigation [9].

Biopolymers

Researchers are creating plant-based biopolymers to solve the environmental problems caused by non-biodegradable petrochemical polymers. Biodegradable plastics can be made using polyesters, proteins, lipids, and polysaccharides from renewable agricultural sources. Both cellulose and starch are important in this study, with starch showing promise as a non-toxic, biodegradable, and renewable substitute in the polymer sector. CNSc starch had double the solubility of maize starch, high crystallinity, and resin agglomeration, but it showed less swelling than polymeric resins despite having a high amylopectin concentration. Although its thermal processing should not go over 174°C, these properties make it a promising renewable material for the synthesis of polymers [10].

Along with starch, CNSc has been used to extract pure cellulose using a modified acid hydrolysis process that is followed by bleaching and alkali treatment. The application of CNSc in the synthesis of phenolic resin is another encouraging advancement. In the presence of particular catalysts, liquefaction of high-lignin biomass enables the partial replacement of formaldehyde with biomass, resulting in phenolic resins that are more ecologically friendly [11]. Due to its high lignocellulosic content, CNSc is a great feedstock for chemical transformation and liquefaction. A 2:1 phenol-to-CNSc ratio produced the most resin during the liquefaction process, which comprised heating ground CNSc and phenol with sulfuric acid. The oligomeric nature of the resin was confirmed by gel permeation chromatography, and the functional groups and chemical structure typical of phenolic compounds were validated by FTIR and NMR investigations. Although more study is required for thorough characterization, this breakthrough shows promise for CNS-derived resins. In conclusion, lignin, cellulose, and starch, all are crucial building blocks of biopolymer. With their biodegradability and lower environmental effect, starch-based biopolymers provide environmentally benign substitutes for petroleum-based plastics in products including packaging, cutlery, bags, and films [12].

Polymer matrix composites

Different types of CNS have been used as matrix ingredients, fillers, and reinforcements in composites for packaging, coatings, and structural materials [13]. As an illustration, consider the production of bio-thermoplastic films containing CNSc starch, walnut shell cellulose for reinforcing, and antioxidants from pomegranates for clever packaging uses. While decreasing moisture retention, higher CNSc starch concentration improved mechanical characteristics and oxygen transfer rates. The cellulose-reinforced film with pomegranate peel extract that performed the best showed promising properties for packaging. Composites have also been made using CNSP in polymeric matrices [14]. The characteristics of the composite were impacted by varying CNS concentrations when it was mixed with a recycled high-density polyethylene (rrHDPE) matrix. As the CNSP level rose, thermal examination revealed two stages of degradation with decreased crystallinity. The composite showed improved fluidity as a result of residual CNSL, although FTIR measurement revealed interface degradation. After processing, SEM pictures indicated voids, while mechanical testing demonstrated increased elongation at fracture and decreased elastic modulus [15].

Some researchers have investigated CNSA-based solutions to offset the detrimental effects of residual CNSL. In one investigation, an epoxy resin composite reinforced with sawdust, rice husk, and CNSA in different ratios was created. In addition to wood residues, ground CNSc has been added to particle boards. Because of the irregular particle geometry and residual CNSL caused by CNSc, strength and dimensional stability were adversely affected by the adhesive type and CNS/wood ratio [16]. But compared to pure wood boards, these boards showed less flammability, burning more slowly and extinguishing themselves more quickly. All things considered, CNS shows great promise as an economical and renewable component in composite materials, improving mechanical, physical, and chemical qualities while lowering prices for particular uses.

Supercapacitors

CNSAC's huge surface area, exceptional porosity, outstanding chemical stability, and improved electrical conductivity have all led to its use in electrochemical double-layer capacitors (EDLCs). It has been effectively created by carbonization in an inert atmosphere after chemical activation with different KOH ratios. A 3D honeycomb-like porous structure was discovered by SEM examination, which is very advantageous for ion transport and electrolyte storage. CNSAC is a preferred electrode material for supercapacitors because of its large surface area, which offers several interfaces for charge storage. Higher KOH activation ratios were shown to enhance pore size; however, this effect waned at an activation ratio of 1:2. As a potential substitute for supercapacitor applications, the CNSAC sample with a 2:1 activating agent ratio demonstrated greater capacitance (214 F/g), quicker charge transfer, and 98% capacitance retention after 1000 cycles [11].

Because of its large porosity and surface area, CNSAC exhibits good features for electrochemical applications overall. Strong promise for long-term performance in actual energy storage devices is indicated by its capacity to maintain high capacitance even after 1000 cycles. Nonetheless, a thorough assessment of supercapacitors that use CNSAC is required, with an emphasis on factors including cycle efficiency, energy density, power density, and long-term stability.

The findings of this study will offer fresh perspectives on high-performance, low-cost, and renewable thermal energy storage materials, enabling a more thorough use of agricultural waste in green energy applications. Future advancements, such as the use of phase change materials (PCMs) to boost energy retention capacities, will be based on the findings.

LITERATURE REVIEW

Throughout the world, the bushy, evergreen cashew tree (*Anacardium occidentale*) is found in tropical climates. The cashew's edible nut is its primary and most valuable product, even if cashew farming can yield a pseudo-fruit (cashew apple) that is used in the food industry. A beneficial product for a range of industrial uses that are garnering attention is cashew nutshell liquid, or CNSL, a phenolic liquid found inside cashew nuts that are encased in a shell with an internal honeycomb structure [17]. Large cashew producers in West Africa and Southeast Asia account for 90% of global cashew production. In any event, raw cashew nut production figures have increased gradually over time, from 1.6 million tons in 2003 to 2.13 in 2006-07 and 3.30 in 2015, as a result of growing demand for this item [18-20]. These figures, however, are usually thought to represent an underestimation of the true production. Consequently, the cashew industry generates an increasing amount of shell waste that needs to be properly valued. Burkina Faso accounts for around 2.3% of global production (75,000 metric tons) and has a planted surface area of 4 MHa, according to the African Cashew Initiative [21]. The bulk of production is meant for exports because smallholder farmers usually lack the specialized tools or equipment required for cashew nutshell processing or the recovery of CNSL as a valuable product [22]. Cashew nutshells are frequently disposed of (or temporarily stored for fire) at the field margins due to their toxicity [23]. If any of the CNSL is released and subsequently builds up or is absorbed into soil or water channels, this poses a serious environmental risk [24, 25]. In contrry, empty nutshells and CNSL may be valuable feedstocks for a variety of applications [26].

The high-energy byproduct of processing cashew nuts is their shell. It could replace fuelwood for thermal uses in a plant. As part of this approach, an effort has been undertaken to convert cashew nutshells into energy by gasification [27]. The physical attributes of the raw cashew nut were evaluated in connection with its moisture content. The average measurements of the three main axes (length, width, and thickness), mass ratio, equivalent diameter, and sphericity were measured at a moisture content of 46% d.b. Measurements were made of the 100 nut mass, porosity, bulk density, actual density, and coefficient of friction for moisture concentrations ranging from 15 to 05% d.b. It was found that raw cashew nuts' real density and 100 nut mass increased in tandem with their moisture content. The porosity and bulk density decreased linearly with increasing moisture content [28]. The successful synthesis of premium activated carbon from cashew nutshells, a frequently available agricultural waste product, represents a significant advancement in sustainable and eco-friendly material science. According to this study, it may have practical use in areas like gas storage and air purification, as well as perhaps in resolving environmental problems like greenhouse gas capture [29]. The physico-chemical properties of cashew nutshells show that they are suitable as raw materials for thermochemical energy recovery processes. However, their direct usage in these heat processes has detrimental effects on human health and the environment [30]. For the creation of many materials, including cellulose, lignin, and starch, CNS shows great promise. These factors make CNS a versatile and renewable resource that can be utilized in a variety of products, including activated carbon, adhesives, coatings, biopolymers, composites, cementitious materials, and rubber additives. This article reviews other applications for CNS. The potential uses are divided into three categories: material development, energy production, and substance absorption. The materials section discusses a number of applications where CNS is utilized as a raw material to produce cementitious materials, biopolymers, and other composites [31]. Various forms of CNS have been used as reinforcements, fillers, and matrix components in composites for structural materials, coatings, and packaging. For example, Harini *et al.* (2018) [32] synthesized a composite employing CNSc starch to make bio-thermoplastic sheets. Pomegranate antioxidants and antibacterial ingredients were mixed with walnut shell cellulose, which served as reinforcement, to create ingenious packaging. Better oxygen transfer rates and improved mechanical properties were the outcomes of increased CNSc starch concentrations in the composite, both of which are crucial packing qualities. The solubility of CNS starch films ranged from 40% to 48%, and higher concentrations of CNSc starch led to decreased moisture retention. Different CNS concentrations were investigated, and the composite properties were evaluated. The findings of tensile tests revealed a lower elastic modulus and greater elongation at fracture. The poor performance could have been caused by partial CNSL extraction, low resin absorption by the fiber, inadequate control of CNSP particle size, or void formation during processing. The author suggested that CNS-reinforced polymer composites might be suitable for less demanding applications, even if complete CNSL extraction is required for structural use [33]. Another example of CNS composites was provided by Mari and Villena (2016) [34], who combined pulverized CNSc with wood waste to create particle boards. The type of glue and the CNS/wood ratio had an impact on strength and dimensional stability. These two characteristics are adversely affected by CNSc replacement due to the uneven particle shape and residual CNSL. While boards lit more slowly and extinguished more rapidly than pure wood, they were less combustible and caused less damage to the wood board area. The results show that CNSc has budgetary benefits and is suitable for less demanding applications.

CNS has shown promise in several applications as an affordable and renewable component for composite materials, offering opportunities to reduce costs while enhancing mechanical, physical, and chemical properties [31]. Researchers have used epoxy polymer composites with sisal fiber mat and stainless-steel wire mesh (SSWM) as reinforcements together with cashew nutshell liquid (CNSL) to generate a special type of hybrid polymer matrix. The composite materials were made using compression molding, and their performance was assessed by looking at their mechanical and thermal properties. When it comes to flexural strength, plain epoxy polymer composites (EP) outperform hybrid polymer composites (HP) [35].

The CNSL waste is packed tightly in an airtight container and heated to 500° C for one h in a stir casting furnace. This CNSL biochar is used to strengthen unsaturated polyester resin for making composites. The composites were prepared using the solution dispersion method at different weight percentages of 5, 10, and 15. The prepared specimens were subjected to tensile, flexural, and impact strength testing. With improvement percentages of 21, 41, and 37, respectively, the maximum tensile, flexural, impact, and hardness strength of a 10% biochar-filled composite surpasses that of an unfilled composite [36].

Table 1 presents a literature survey that provides valuable insights into the utilization of cashew nutshell-derived materials for developing efficient heat-absorbing panels and related thermal applications.

Table 1. Utilization of cashew nutshell-derived materials for developing efficient heat-absorbing panels.

Methodology	Materials used	Potential applications in heat-absorbing panels	Key findings	Ref.
Thermal oxidative stability testing was performed by TG/DTG and DSC analysis and PMMA films were doped with 1 % CNSL derived phenolic lipids.	CNSL derivatives (cardanol and cardol) and PMMA.	CNSL based additives can be used in composite materials for heat absorbing panels to improve thermal stability and resistance to oxidation.	CNSL derived phenolic lipids (cardanol and cardol) remarkably improv the thermal -oxidative stability of PMMA films. TG/DTG and DSC characterizations confirmed 37enhanced thermal resistance.	[37]
CNSL based resin composites was fabricated with coconut Fibers, followed by mechanical and thermal analysis.	Coconut fibers and CNSL based resin	CNSL based resins can be treated as sustainable binders in heat absorbing panels, enhancing mechanical integrity and reducing environmental impact.	Bio-composites prepared from CNSL resin and natural fibers show improved mechanical and thermal properties. Also enhanced biodegradability and sustainability.	[38]
Soxhlet extraction technique was adopted by using polar and non-polar solvents followed by HPLC characterizations.	CNSL, Various solvents	Extraction of CNSL improves thermal efficiency and modifying it into heat absorbing panel material.	CNSL contains cardanol, cardol and anarcardic acid showing excellent thermal stability. Different extraction techniques influence material efficiency.	[39]
Bio-based Mannich polyols was synthesized by oxazolidine route, followed by characterization through FTIR, NMR and mechanical testing.	CNSL-based Mannich polyols, polyurethane foam.	CNSL derived polyurethane foams can improve the insulation properties of heat absorbing panels, also making them energy efficient and fire resistant.	CNSL based polyols were used for developing rigid polyurethane foams with enhanced insulation properties and low thermal conductivity.	[40]
CNSL based coating was developed, followed by thermal efficiency testing on solar collectors.	CNSL copper plates, B_2O_3/Bi_2O_3 flux.	CNSL based coating can improve the efficiency of solar thermal collectors and heat absorbing panels.	By using CNSL based coating for solar thermal collectors, 42.86 % efficiency was achieved and showed a high absorptivity and low reflectance properties.	[41]
Alkylation was carried out for the modification of cardanol into antioxidants, followed by oxidative stabilization of gasoline.	CNSL derived hydrogenated cardanol, tert-butyl chloride.	CNSL derived hydrogenated cardanol can enhance the longevity and stability of heat-absorbing panels by preventing oxidative degradation due to its antioxidant properties.	Hydrogenated cardanol modified into antioxidants by alkylation with tert-butyl chloride exhibited superior stabilization compared to commercial gasoline additives.	[42]
Mannich polyols were synthesized using oxazolidine, followed by NMR, FTIR and mechanical testing.	CNSL-derived Mannich polyols, polyurethane foam	CNSL based polyurethane foams could be improved fire resistance and insulation in heat absorbing panels.	CNSL based Mannich polyols can be a good alternative to petrochemical based polyols. The resulting polyurethane foams showed high mechanical strength and low thermal conductivity.	[43]
Thiophosphorylated CNSL derivatives was synthesized, followed	CNSL phosphorus derived compounds	CNSL phosphorus derived compounds could improve the heat resistance of materials	A new thiophosphorylated CNSL derivative was synthesized, showed a significant enhancement in	[44]

by oxidative stability and thermal testing.	and mineral oils.	and durability in heat absorbing panels due to its antioxidant properties.	oxidative stability when tested in mineral oils.	
The larvicidal activity testing was performed against Aedes aegypti, followed by evaluation of cardol's effectiveness and toxicity.	CNSL-based cardol.	CNSL could contribute to develop antimicrobial coating for heat absorbing panels due to its biocidal properties.	CNSL based cardol exhibited strong larvicidal activity against Aedes aegypti, exhibited its and ability to penetrate cell membranes due to its liposolubility.	[45]
CNSL based bio-composite was fabricated with bamboo fibers, followed by thermal and mechanical testing and TGA analysis.	CNSL derived resin, bamboo fibers.	CNSL derived bio-composites could be developed lightweight, thermally stable and durable heat absorbing panel.	CNSL based bio-composites fabricated with bamboo fibers showed increased tensile strength, modulus and improved thermal stability.	[46]

Few researchers in India have studied cashew nutshells as a waste treatment and composite material. To the best of the authors' knowledge, no relevant research has been done on heat absorption panels that use cashew nutshells. The purpose of this study is to develop biochar-based heat panels using cashew nutshell (CNS) charcoal. Before being pulverized into a fine powder, CNS is dried, crushed, and pyrolyzed at 400–600°C. After combining 60–70% of biochar with 30–40% of resin binder, the mixture is reinforced with fiberglass or natural fibers, molded, compressed, and left to dry at room temperature or 80°C.

A black thermal coating enhances heat absorption. When tested for solar heating, heat retention, and industrial heat recovery, panels show better heat absorption, longer retention, and structural stability than conventional materials. Testing for waste heat recovery can be done at "Thermax Ltd.,pune" following panel development. Companies that manufacture solar panels can also conduct testing.

MATERIALS AND METHODS

To understand the methodology for development of heat absorbing panel, by using composite material obtained from cashew nutshell and epoxy resin in an easier way, a flowchart has been prepared as shown in Fig. 1. In the primary material processing step, collect cashew nutshells and extract CNSL for its heat-resistant properties. Thereafter, pyrolyze the remaining shell biomass in an environment with low oxygen levels to prepare biochar. Combine the prepared biochar with a binding material (like epoxy resin or biodegradable polymer) to create a heat-absorbing composite [25-31]. Secondly, compress the biochar-binder mixture into compact flat panels during the panel fabrication stage. To improve the efficiency of heat absorption, use a black coating. Next, undertake thermal performance testing, such as heat retention, solar heating, and industrial waste heat recovery, during the testing & evaluation stage. Examine the effectiveness of CNS biochar panels in comparison to more conventional materials like wood and metal. Test the panels in a variety of applications, including industrial heat recovery, building insulation, and solar water heating, at the final stage, application and validation. Examine how phase change materials (PCMs) might be incorporated to improve the effectiveness of heat storage.

RAW MATERIAL COLLECTION & PREPROCESSING

Cashew nutshells (CNS) must go through several crucial preprocessing and raw material collection processes in order to be ready for additional processing. The main raw material is cashew nutshells, an agricultural waste. In order to maintain structural integrity in the finished product and retain processed CNS particles together, binding elements are necessary. Epoxy resin is appropriate for long-lasting applications because of its excellent adherence and durability. Natural resins, which come from plants, provide a good bonding option that is also environmentally benign. By using fewer synthetic materials while retaining adequate strength and flexibility, biodegradable binders—such as adhesives based on lignin or starch—improve sustainability. The intended use and environmental factors influence the binder selection [9]. We have listed out some selected raw materials used for the development of heat absorbing panel, as shown in Table 2.

DESCRIPTION OF METHODS AND EQUIPMENT

Equipment for carbonization: a pyrolysis chamber or kiln

An essential step in turning CNS into a substance with a high carbon content is carbonization. In order to prevent combustion, the shells are heated in a regulated atmosphere with a restricted oxygen supply in a kiln or pyrolysis chamber. While pyrolysis chambers provide more sophisticated, effective thermal processing with better temperature control, kilns are still utilized for carbonizing biomass. Because of its high porosity and energy density, the resultant carbonized material can be used in composite panel production, filtration, and insulation [24, 26].

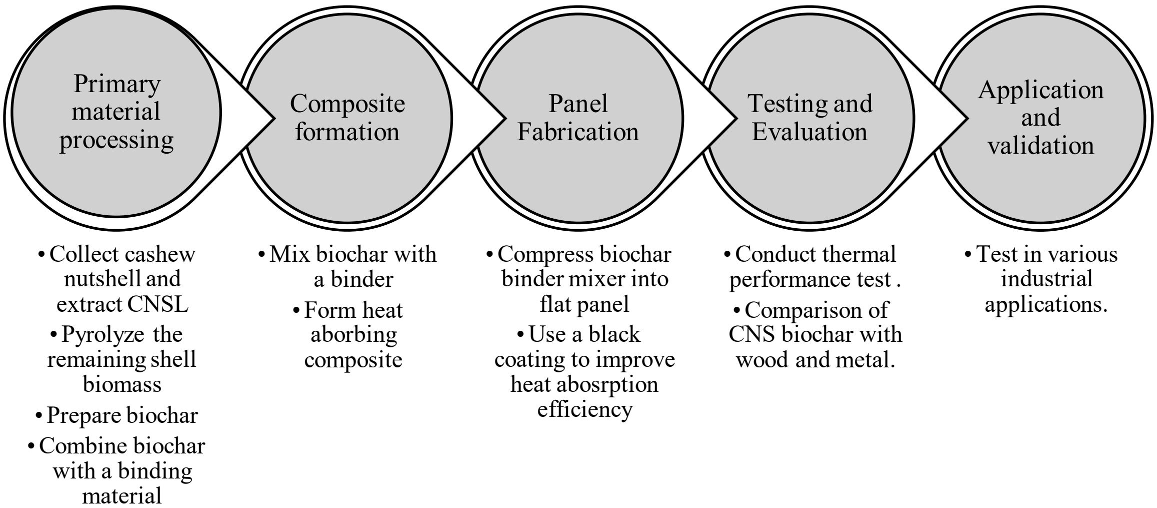

Fig. 1. Flowchart of the methodology for development of heat absorbing panel**.**

Table 2. Different raw materials used for the development of heat absorbing panel.

Raw material	Layer	Purpose	Ref.
Composite of Cashew Nutshell (CNS), Biochar (60-70) % and Resin (30–40%).	Heat-absorbing layer, or core layer	High carbon content and thermal stability make it the primary medium for absorbing and storing heat.	[47]
Natural fiber (such as jute or coconut fiber) or fiberglass mesh.	Layer of Reinforcement	Resists breaking under heat expansion and offers structural strength.	[48]
Thermal Black Paint or Nano-Carbon Mist.	Coating the Surface (outer layer)	Maximizes energy intake by improving absorption of solar and infrared heat.	[49]
Metal or silicone frame	(Optional) Edge Reinforcement	Improves durability and maintains the shape of the component. Also protects edges from damages due to pressure or external forces.	[50]

Panel mold: steel or wooden structures to form the panel

In order to transform processed CNS material into usable goods, panel molds are employed to compress and shape the mixture into homogeneous panels. Steel molds' remarkable longevity, precise shape, and resistance to heat and pressure make them ideal for industrial manufacture. Despite their lesser durability, wooden molds are affordable and suitable for experimental or small-scale applications. The molds ensure that the mixture solidifies into consistent panel dimensions, which facilitates its use in a range of applications such as insulating boards, construction materials, and solar heat absorbers [16].

Material for surface coating: black heat-absorbing paint or thermal coating

A surface coating is applied to enhance the panel's thermal properties and longevity. Black heat-absorbing paint is commonly used to improve heat retention and boost the efficiency of solar panels. Improved resistance to UV radiation, moisture, and mechanical damage are further benefits of thermal coatings. Because these coatings ensure longevity and efficacy, the final product is suitable for applications like solar cookers, insulation panels, and energy-efficient building materials.

METHODOLOGY DESCRIPTION

Preprocessing procedures

Preprocessing is a crucial step in preparing cashew nutshells for further thermal and industrial use. The process begins with the careful collection of raw cashew nutshells, which are then sun-dried to eliminate any residual moisture. Proper drying is essential because moisture content may reduce the efficiency of subsequent processing steps, leading to uneven thermal decomposition or incomplete combustion [9]. Additionally, drying prevents mold growth and microbiological deterioration, keeping the shells in the best possible condition for further treatment. When the shells have sufficiently dried, they are crushed into small bits. Size reduction is the term for this process. This step is crucial for boosting pyrolysis efficiency because breaking the shells into uniform pieces enhances heat transfer and allows for more controlled carbonization. The greater surface area allows for better conversion of the shells into activated carbon or biochar and faster breakdown. Furthermore, for applications such as thermal insulation panels, bio-composite materials, and energy-efficient industrial products, consistent end product from the homogenous particle size is essential. By carefully completing these preprocessing steps, cashew nutshells can be transformed into useful, sustainable materials that will help cut waste and advance eco-friendly concepts.

Production of biochar (thermal treatment)

A very efficient thermal breakdown method called pyrolysis is used to turn cashew nutshells into activated carbon or biochar, which has better heat retention qualities. In this procedure, the crushed cashew nutshells are heated to regulated temperatures between 400 and 600°C in a low-oxygen atmosphere [51]. A slow breakdown of organic materials while maintaining the carbon content is ensured by the absence of oxygen, which inhibits full combustion. Cashew nutshell liquid (CNSL) and other volatile chemicals are released during the gas removal process that occurs during this phase. The important phenolic chemicals found in CNSL can be extracted and used separately for commercial uses such adhesives, coatings, and bio-based resins. The pyrolysis process is a sustainable way to turn agricultural waste into a useful, carbon-rich substance with a variety of industrial uses. It has been observed in the literature that around 400–600°C is the optimal temperature range for pyrolysis to optimize the thermal efficiency of biochar [52]. This range minimizes full combustion while optimizing carbon retention. In order to assure a slow breakdown of organic matter while maintaining the carbon content, the heating rate should be slow to moderate, usually between 5 and 10°C per minute. Depending on the desired qualities of the biochar, the ideal time for the pyrolysis process is around 3 to 4 hours, as shorter pyrolysis time (less than 3 hrs) may lead incomplete carbonization and longer pyrolysis time may result to excessive carbon loss due to secondary reaction and hence resulting in reduced yield and thermal efficiency [53, 54]. A more stable, carbon-rich biochar with improved heat retention qualities results from a longer residence time, which permits more thorough volatile release. The process of recycling cashew nutshells through regulated pyrolysis and activation helps to reduce waste, promote environmental sustainability, and create environmentally suitable substitutes for synthetic products.

CNSL extraction: A waste product of agriculture, of cashew manufacturing, cashew nutshells (CNS) are frequently thrown away as garbage [26]. They can, however, be recycled for environmentally friendly uses and contain useful components. Carbonized CNS can be utilized in composite materials when treated appropriately, lowering agricultural waste and encouraging environmentally beneficial alternatives. They are perfect for thermal applications like bio-based panels and energy-efficient goods because of their high carbon content [29]. In order to extract CNSL through cold processing, the raw shell was then crushed into smaller pieces using a compressed screw mincer powered by a 5 HP engine, as shown in Fig. 2.

Cold-pressed hydraulic extraction

A 2 HP three-phase motor that rotates at 1430 rpm and a pump that can produce high-pressure output of up to 16 MPa at 15.8 cm3/rev are both part of the hydraulic system utilized in the extraction.

Fig. 2. Using a mincer, grind the cashew nutshells into tiny bits [51]

A 3-inch diameter, 18 mm thick steel cylinder with 2 mm holes drilled in the bottom was used to build the compression cylinder. Using the supported core, a hydraulic cylinder was used to push the compression cylinder higher, compressing the cashew nutshells inside. The compression compelled the CNSL to flow into an oil tray from the hole at the bottom of the compression cylinder after a certain amount of time [10]. The several parts of the specially constructed extraction machine are shown in Fig. 3.

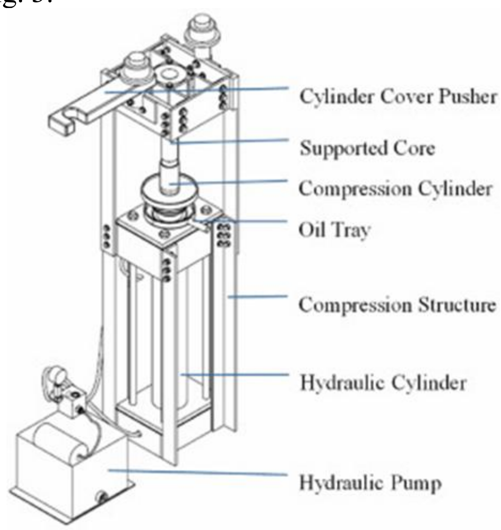

Fig. 3. Cold-pressed hydraulic extraction [10]

Heat in a low oxygen environment: The crushed shells are then subjected to thermal decomposition in a controlled low-oxygen environment to prevent complete combustion. The shells are heated for one to two hours at temperatures between 400 and 600°C in a metal drum, kiln, or pyrolysis chamber. Only volatile substances, including cashew nutshell liquid (CNSL), are released due to the lack of oxygen, leaving behind carbon-rich biochar. The temperature and duration of heating play a crucial role in determining the final properties of the biochar, including its thermal stability and adsorption capacity [22, 23].

Cooling & grinding

To avoid structural damage from abrupt temperature changes, the biochar must be cooled gradually after the pyrolysis process is finished. To prevent oxidation, cooling is typically carried out in a controlled or inert atmosphere. To guarantee consistent particle size and increase its usefulness in processes like soil improvement, energy storage, and water filtration, the biochar is ground into a fine powder after cooling. Fine grinding enhances surface reactivity and allows for better binding in composite materials.

Activation process

To further enhance the porosity and adsorption properties of the biochar, an activation process can be carried out. This entails processing the charcoal with chemical agents like potassium hydroxide (KOH) or phosphoric acid (H_3PO_4). Because of its superior ability to trap impurities and enhance chemical reactions, activated carbon is widely used in energy storage (supercapacitors), water purification, air filtration, and industrial catalysis. The activation process dramatically increases surface area and pore volume, turning the biochar into activated carbon with improved adsorption capacity [29].

Panel fabrication

Achieving a homogenous consistency is essential to maintaining structural integrity and improving heat retention properties for solar energy applications. To begin the fabrication process, a biochar-resin mixture is prepared by combining 60–70% biochar with 30–40% epoxy resin. This composition guarantees a robust, long-lasting panel with improved thermal and mechanical properties. The mixture is thoroughly stirred until it forms a thick, uniform paste, ensuring proper binding between the biochar particles and the resin.

Mold the panel: Once the mixture is ready, it is poured into a flat mold of predefined dimensions (e.g., 30 cm × 30 cm × 1 cm for experimental testing). The mold helps shape the panel into a uniform structure suitable for practical applications. After pouring, the material is compressed evenly to eliminate air pockets, ensuring a dense and compact panel with enhanced durability and thermal efficiency. Proper compression prevents defects such as voids or weak spots, which could reduce the panel's performance.

Curing process: The molded panel must undergo a curing process to harden and acquire its final strength. Basically, there are two approaches to curing: Room temperature curing and Heat assisted curing. Room temperature curing allows the panel to set naturally for 24–48 hours, which promotes gradual hardening and solid bonding between biochar and glue. While heat assisted curing speed up resin polymerization, placing the panel in an oven set between 60 and 80°C shortens the fabrication time. When a quicker turnaround is needed for large-scale production, this approach is especially helpful.

Surface coating for maximum heat absorption

A heat-absorbing surface coating is applied to the panel to improve its thermal efficiency. Black paint or a carbon-based coating, which both enhance absorption of solar light, can be used to accomplish this. For uses including solar thermal energy systems, heat insulation panels, and renewable energy sources, a properly placed coating optimizes the panel's capacity to trap and hold heat.

Thermal properties measurement test of heat absorbing panel

Thermal conductivity test: A TD 1002 Heat Conduction Base Unit was used to perform the thermal conductivity (TC) test for cashew nutshell biochar-epoxy resin composites in accordance with BS EN 12664 requirements. Before testing, cylindrical samples (30 mm in diameter by 20 mm in height) were oven-dried for 24 h at 105°C to eliminate moisture. Temperature observations were taken during ten min of a constant 9.9 W heat flow. Fourier's Law was used to calculate thermal conductivity as:

$$k = \frac{\Phi . \mathrm{t}}{A . \Delta \mathrm{T}}$$

where Φ is heat flow, t is specimen thickness, A is surface area, ΔT is temperature difference, and k is thermal conductivity. The test results indicate that the increasing the biochar content, thermal conductivity decreases, resulting in enhanced insulation properties. On comparison with conventional epoxy resin and concrete, the biochar-based epoxy exhibited lower thermal conductivity making it promising material for thermal insulation applications [55].

Specific heat capacity (SHC) test: Using the electro-calorimetry method, the cashew nutshell biochar-epoxy composite's specific heat capacity (SHC) was ascertained. Cubic specimens of 50 × 50 × 50 mm³ were constructed, and holes were drilled at two thirds of the depth for a thermometer and an immersion heater (2000 W, 220–250 V). Samples were placed in a calorimeter on the twenty-eighth day of curing, and temperature, current, and voltage readings were taken while power was provided. Since thermal expansion was minimal, the formula for the calculation of specific heat capacity can be given as:

$$C_p = \frac{Q_2 - Q_1}{\big((m_2 - m_1)\big)(t_2 - t_1)}$$

where C_p is the specific heat capacity, Q_2 and Q_1 are final and initial heat energy respectively, m_2 and m_1 are final and initial mass of material and t_2 and t_1 are final and initial temperature. This method effectively determines the thermal storage capacity of the cashew nutshell biochar-epoxy composite, which is crucial for its potential applications in thermal insulation and energy-efficient materials. It has been investigated that biochar epoxy resin has a higher specific heat capacity than other conventional epoxy resin and concrete [56].

Experiment with solar heating: In order to assess the solar energy absorption efficiency of the manufactured heat-absorbing panel, it is exposed to direct sunshine from 9 AM to 3 PM. Thermocouples or infrared thermometers are used to record the temperature every 30 min. The panel's capacity to retain heat is evaluated by contrasting it with more traditional materials like metal and wood panels. This comparison aids in determining whether the panel made from cashew nutshells has better thermal absorption and retention capabilities. The chosen heat source is applied to the panel for a predetermined amount of time, usually 30 to 60 min. The heating conditions and the panel material's thermal conductivity are taken into consideration while determining the exposure duration. This stage guarantees that the panel will have enough time to effectively absorb and store heat. Thermal sensors or infrared thermometers are used to take temperature readings every five minutes in order to track heat absorption. The recorded data aids in the analysis of the panel's long-term heat absorption efficiency. Good thermal absorption is confirmed by a gradual rise in temperature, whereas effective heat retention is indicated by a quick rise followed by stabilization. The results are later compared with conventional materials to assess the panel's overall performance.

Test of heat retention: The panel is exposed to an infrared lamp for two hours to replicate a controlled heating environment to assess its capacity to store and retain heat. The cooling rate is tracked over time once the heat source is switched off.

Table 3. Quantitative comparison with existing commercial materials: [9,10, 14,18,25,40,54]

Property	CNS biochar-epoxy composite	Standard epoxy resin	CNS biochar-cement composite	Conventional concrete	Polyurethane foam
Thermal Conductivity (W/mK)	0.10–0.25	0.3–0.4	0.5–0.7	1.4–2.0	0.02–0.03
Heat Retention Efficiency	19% higher than standard epoxy	Not more	15–20% higher	Less than CNS Biochar- cement composite	Very high
Insulation rating (R-value per inch)	6.5–7.5	4–5	2–3	Less than CNS biochar- cement composite	5–6
Flexural strength	12–23% higher	Not more	10–15% higher	Less than CNS biochar- cement composite	Low
Compressive strength	10–20% higher	Not more	5–10% higher	Less than CNS biochar- cement composite	Low

Comparing the panel's ability to sustain temperature to more conventional heat-absorbing materials is the goal. Better heat retention is shown by a slower cooling rate, which makes the panel more appropriate for thermal storage applications. A quantitative comparison of thermal properties of cashew nutshell biochar-epoxy composite with other materials is depicted in Table 3. It can be observed from the table that cashew nutshell epoxy composite has lower conductivity than standard epoxy resin, concrete and cement composite making it a better insulator. It has highest compressive and flexural strength making it a structurally viable alternative. *Test of industrial heat recovery:* To test the panel's capacity to capture and reuse waste heat, it is placed close to boiler exhaust pipes in an industrial environment. To track the panel's heat absorption and retention properties, the temperature is tracked for six hours. By analyzing the data, researchers can determine if the panel effectively recycles waste heat, making it useful for energy conservation in manufacturing plants and other industrial applications.

EXPERIMENTAL SETUP

The manufacture of biochar, panel construction, and controlled performance testing are all steps in the experimental setting used to assess the cashew nutshell (CNS)-based heat-absorbing panel's performance. In order to produce carbon-rich biochar, 10–15 kg of dry and crushed CNS must be heated in a low-oxygen kiln at 400–600°C for two to three hours. This process is known as pyrolysis. To improve porosity and thermal performance, the biochar is finely ground after cooling and, in certain situations, activated with chemical agents like KOH or H_3PO_4. 60–70% of biochar and 30–40% of resin binders are combined at the panel construction stage, and for structural stability, fiberglass mesh or natural fibers are added for reinforcement. After being poured into 50 cm × 50 cm × 2 cm steel or wooden molds, the mixture is compacted to achieve a homogeneous density. It is then allowed to cure for 48–72 hours at ambient temperature or for 5–6 hours in an oven set to 80°C. After that, a black thermal coating is put on to improve the absorption of solar heat. The experimental set up is shown in Fig. 4 [51]. The experimental setting includes industrial heat recovery, heat retention, and sun heating tests for performance evaluation. Using infrared thermometers, thermocouples, and data loggers, the panel is exposed to direct sunshine from 9 AM to 3 PM. Temperature readings are taken every 30 minutes during this experiment, and the outcomes are compared to those of control panels made of metal and wood.

In order to test for heat retention, the panel is exposed to an infrared heat source for two hours. After that, the heat is turned off, and the cooling rate is tracked over time. In order to assess the panel's viability for waste heat recovery applications, the industrial heat recovery test entails positioning the panel next to boiler exhaust pipes and monitoring the temperature rise and retention over a 6-hour period. These tests offer vital information about the panel's thermal stability, heat absorption efficiency, and potential for practical uses in energy storage, insulation, and solar thermal systems.

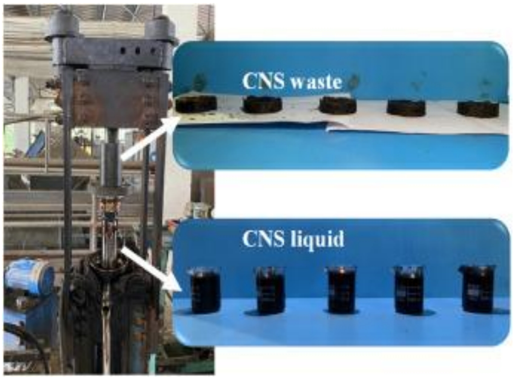

Fig. 4. Experimental setup [51]

A combination of thermal cycling tests and mechanical load evaluations can be used to evaluate the structural integrity of the cashew nutshell (CNS)-based composite panel under various load situations and thermal cycles. To evaluate the panel's thermal stability and replicate real-world temperature fluctuations, it should undergo repeated heating and cooling cycles in accordance with ASTM D3045 and other standards. To assess strength retention and durability, mechanical testing, such as tensile (ASTM D638), compressive, and flexural tests (ASTM D790), should be carried out both before and after thermal exposure. Using methods like scanning electron microscopy (SEM) or dynamic mechanical analysis (DMA), important factors including flexural strength, tensile properties, dimensional stability, and the existence of defects like delamination or cracks should be examined. The outcomes will establish the composite's ability to withstand mechanical loads and heat-induced stress, offering information on its viability for structural uses [57]. Costa *et al*. [58] have been investigated the thermal stability and mechanical properties of cashew nut shell liquid. They have examined tensile and flexural strength, proposing valuable data on the materials performance under thermal cycling and mechanical load.

RESULTS AND DISCUSSION

When compared to more conventional materials like metal and wood, the cashew nutshell-based panel exhibits greater heat absorption. Its black surface covering and carbon-rich composition allow it to absorb solar or infrared radiation more efficiently, which speeds up heating.

Because of this, it is a material that shows promise for solar heating and thermal energy storage applications [59].

The panel's capacity to hold heat for a long time is one of its main benefits. Compared to traditional materials, the biochar-based construction is more efficient since it releases stored heat gradually. This feature is quite advantageous.

Long-term durability is ensured by the panel's ability to retain its integrity even after numerous heating and cooling cycles. The mix of the biochar and resin offers exceptional thermal stability, in contrast to certain materials that stretch, shatter, or deteriorate at high temperatures. Because of this, it can be used for energy-efficient heating systems, environmentally friendly building insulation, and industrial applications that need reliable performance in a range of temperatures.

Cashew nutshell-based heat absorbing panel are having various important alternative applications as shown in Fig. 5 [10]. The cashew nutshell-based heat-absorbing panel can be integrated into solar thermal systems for water and air heating applications. Its high heat absorption and retention capabilities allow for efficient energy capture from sunlight, making it a cost-effective and eco-friendly alternative to conventional solar heating materials. These panels can be used in solar water heaters, drying systems, and space heating solutions to improve energy efficiency. The panel's excellent thermal retention properties make it ideal for insulating homes, offices, and industrial buildings. When used in walls, ceilings, or floors, it reduces heat loss, enhancing energy efficiency and lowering heating or cooling costs. Additionally, its sustainable composition provides an environmentally friendly alternative to synthetic insulation materials, promoting green building initiatives. A lot of waste heat produced by industries is frequently wasted. To capture and repurpose thermal energy, these heat-absorbing panels can be placed next to boilers, exhaust pipes, or heat-emitting equipment. This application increases overall production unit efficiency, lowers fuel consumption, and promotes energy conservation. By combining cashew nutshell-based panels with phase change materials (PCMs), energy storage efficiency can be increased. PCMs enhance the panel's capacity for thermal management by storing excess heat and releasing it gradually. Some specific types of PCMs are paraffin wax, stearic acid, and polyethylene glycol (PEG), which can counter the biochar due to their high latent heat storage capacity and compatibility [60].

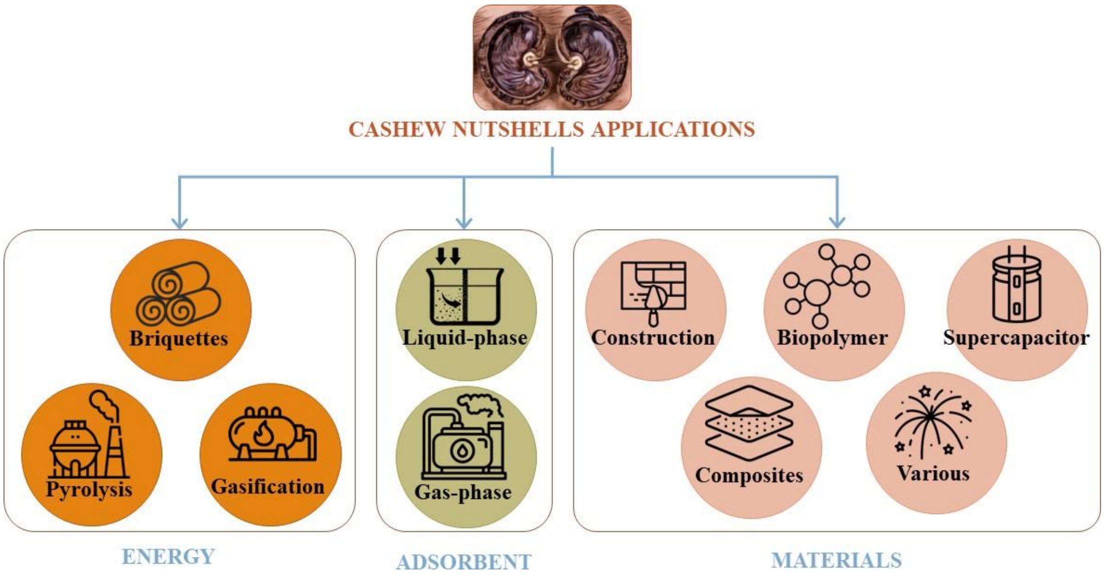

Fig. 5. Main cashew nutshell alternative applications [10]

The integration of paraffin PCM into CNS biochar not only improve the thermal conductivity but also enhance their long-term stability, hence, offers long-lasting and sustainable energy storage choices that can be applied to off-grid heating systems, smart grids, and renewable energy systems.

CONCLUSIONS

This work reviews the current research on the systematic approach to develop a cashew nutshell-based heat absorbing panel**.** By turning cashew nutshell (CNS) trash into biochar-based heat panels, this study promotes environmental sustainability and provides a number of advantages. It provides a cost-effective alternative to traditional thermal materials like concrete and metal, while also enhancing heat absorption and retention for greater energy efficiency. In order to reduce dependency on non-renewable energy sources and the carbon footprint, the sturdy and lightweight panels can be utilized for a number of applications, such as solar water heating, building insulation, and industrial waste heat recovery. Furthermore, heat storage capacity might be further increased by future advancements that use phase change materials (PCMs). Overall, this study encourages green energy initiatives, energy efficiency, and the development of sustainable materials for both residential and commercial use.

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