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**Biochar-Based Composite Materials and Thermal Energy Storage
Performance in Sustainable Building Systems in South Africa**



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Biochar-Based Composite Materials and Thermal Energy Storage Performance in Sustainable Building Systems in South Africa



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Abstract

Purpose: The aim of this study was to investigate the biochar-based composite materials and thermal energy storage performance in sustainable building systems in South Africa.

Methodology: The study adopted a desktop research methodology. Desk research refers to secondary data or that which can be collected without fieldwork. Desk research is basically involved in collecting data from existing resources hence it is often considered a low-cost technique as compared to field research, as the main cost is involved in executive's time, telephone charges and directories. Thus, the study relied on already published studies, reports and statistics. This secondary data was easily accessed through the online journals and library.

Findings: Biochar-based composite materials improve thermal energy storage capacity, thermal conductivity, stability, and temperature regulation in sustainable buildings. However, their performance varies with material composition, highlighting the need for further research under South African climatic conditions.

Unique Contribution to Theory, Practice and Policy: Fourier's law of heat conduction, latent heat storage theory, thermodynamic theory may be used to anchor future studies on the biochar-based composite materials and thermal energy storage performance in sustainable building systems in South Africa. The study recommends that building material manufacturers, construction professionals, architects, and renewable energy practitioners investigate the practical integration of biochar-based composite materials into sustainable building components such as wall panels, ceiling boards, roofing systems, and thermal insulation materials. The study recommends that relevant South African government institutions, building regulatory authorities, and energy-sector stakeholders consider supporting research, standardisation, and pilot-scale demonstration of biochar-based composite materials for sustainable construction.

Keywords: *Biochar-Based Composite Materials, Thermal Energy Storage Performance, Sustainable Building Systems*

INTRODUCTION

Thermal energy storage performance refers to the effectiveness of a material or system in absorbing, storing, retaining, and releasing thermal energy for subsequent heating or cooling applications. It is commonly evaluated using thermal storage capacity (kWh or kJ/kg), charging and discharging efficiency, heat transfer rate, thermal conductivity, temperature regulation, and energy retention over repeated operating cycles. In sustainable building systems, thermal energy storage technologies incorporate sensible heat storage, latent heat storage using phase change materials (PCMs), and thermochemical energy storage to regulate indoor temperatures and reduce heating and cooling requirements. In developed economies such as the United States and the United Kingdom, advances in thermal storage materials, heat exchanger configurations, and building-integrated storage systems have improved opportunities for reducing peak electricity demand and enhancing building energy efficiency. Faraj . (2020) established that phase change materials integrated into building cooling systems can reduce indoor temperature fluctuations, facilitate thermal load shifting, and support energy-efficient building operations, although performance depends on material properties and system design.

In the United Kingdom, Nie . (2020) investigated a phase change material-based thermal energy storage device for air-conditioning applications and established that incorporating heat transfer fins reduced charging time by approximately 85% and discharging time by 74%, demonstrating substantial improvements in thermal response. The researchers further established that improved heat transfer characteristics enhanced the stability of outlet air temperatures, thereby supporting indoor thermal comfort and more effective thermal energy management. In the United States, Kishore (2020) investigated the optimisation of phase change material-integrated building walls and demonstrated the importance of material selection, phase transition temperature, and climatic conditions in determining potential building energy savings. These studies indicate that improvements in thermal energy storage performance are increasingly associated with material optimisation and enhanced heat transfer mechanisms rather than merely increasing the quantity of storage material. Consequently, evidence from the United Kingdom and United States supports further investigation of advanced composite materials, including biochar-based composites, to improve thermal storage capacity, charging and discharging performance, and building energy efficiency (Nie, 2020; Kishore., 2020).

Thermal energy storage performance has become increasingly important in developing economies because of rapid urbanisation, rising building energy consumption, increasing cooling requirements, and growing interest in affordable energy-efficient construction materials. In countries such as China and India, researchers have investigated the incorporation of phase change materials into building walls, roofs, and composite construction materials to enhance thermal storage capacity and minimise indoor temperature fluctuations. These technologies operate by absorbing excess heat during periods of high temperatures and releasing stored energy when surrounding temperatures decrease, thereby reducing dependence on conventional heating and cooling systems. In China, Ji . (2019) used EnergyPlus simulations to investigate phase change material-integrated building envelopes and reported potential annual building energy savings of

20.9% in Guangzhou, demonstrating the importance of material properties and climatic conditions in thermal storage performance. These findings suggest that appropriately selected thermal storage materials can contribute to building energy conservation, particularly in regions experiencing high cooling demand (Ji., 2019; Faraj., 2020).

In India, Rathore and Shukla (2020) experimentally evaluated macroencapsulated phase change materials integrated into building envelopes under tropical climatic conditions and reported reductions in thermal amplitude ranging from 40.67% to 59.79%. The researchers further established reductions in peak temperatures of approximately 7.19%–9.18%, delays in heat transmission of 60–120 minutes, and a 38.76% reduction in cooling load compared with the reference building. In China, Zhang. (2021) investigated copper foam–paraffin composite phase change materials and found that the experimental building model experienced a 1.2°C reduction in maximum indoor temperature, a 1.5-hour delay in peak temperature, and a 21% reduction in energy consumption. Their numerical simulations similarly indicated a 19% reduction in maximum indoor energy consumption, demonstrating agreement between experimental and modelling approaches. These findings illustrate that thermal energy storage performance in developing economies can be improved through composite material engineering, phase change temperature optimisation, and enhanced heat transfer characteristics, providing useful evidence for future research on biochar-based composite materials (Rathore & Shukla, 2020; Zhang., 2021).

Thermal energy storage performance is particularly important in sub-Saharan African economies, where high daytime temperatures, substantial solar radiation, increasing urbanisation, and growing cooling demands create opportunities for energy-efficient building technologies. Countries such as South Africa and Kenya could benefit from thermal storage systems that absorb excess daytime heat and release it during cooler periods, thereby moderating indoor temperature fluctuations and reducing electricity consumption. In South Africa, Twite . (2019) developed and experimentally evaluated a low-cost solar water-heating system incorporating a heat exchanger and thermal storage reservoir, demonstrating the feasibility of locally manufactured thermal energy technologies. The researchers reported that their approximately 15 m² solar collection system could deliver up to 10 kWh of thermal energy per day, compared with approximately 1 kWh per day for the conventional systems used as their benchmark. These findings demonstrate the potential of improved solar thermal collection and storage configurations to enhance household energy availability, although the reported comparison concerns system capacity rather than a longitudinal improvement in storage efficiency (Twite., 2019).

In South Africa, Twite. (2019) further established that their solar thermal system could be constructed for approximately ZAR 10,000–12,000, with estimated household electricity savings of up to ZAR 600 per month under the study's operating and economic assumptions. The researchers also demonstrated that a 150-litre water storage reservoir could be heated from 23°C to 40°C in approximately 30 minutes using the better-performing heat exchanger configuration, compared with about 60 minutes for the alternative configuration. In Kenya, building-integrated phase change materials and biochar-based thermal composites represent potential approaches for reducing heat gain and improving passive temperature regulation, although a directly comparable

Kenyan experimental performance dataset was not established from the sources reviewed. International experimental evidence indicates that composite phase change materials can reduce peak indoor temperatures and delay heat transmission, but these results cannot automatically be generalised to Kenyan climatic conditions or construction materials. Consequently, further empirical investigations are needed across sub-Saharan African economies to establish the thermal storage capacity, charging and discharging efficiency, temperature regulation performance, and economic feasibility of biochar-based composite materials in sustainable buildings (Twite ., 2019; Rathore & Shukla, 2020).

Biochar-based composite materials refer to engineered materials developed by combining biochar, a carbon-rich porous substance produced through the thermochemical conversion of biomass, with phase change materials or other functional substances to enhance thermal energy storage and heat transfer properties. These composites are increasingly applied in sustainable building systems because of their potential to improve thermal conductivity, heat retention, structural stability, and temperature regulation while promoting the utilisation of renewable biomass resources. Conceptually, biochar-based composite materials can be classified into four major categories: biochar–paraffin composites, biochar–polyethylene glycol composites, biochar–fatty acid composites, and biochar–inorganic phase change material composites, each possessing distinct thermal storage characteristics. Biochar–paraffin composites incorporate paraffin wax into porous biochar structures to enhance shape stability and reduce leakage during melting, whereas biochar–polyethylene glycol composites utilise polymeric phase change materials to improve thermal energy absorption and release. Biochar–fatty acid composites employ organic compounds such as stearic and lauric acids to facilitate latent heat storage, while biochar–inorganic phase change material composites incorporate substances such as salt hydrates to provide alternative thermal storage characteristics depending on the operating temperature and material compatibility (Liang., 2023; Yang., 2019).

Biochar-based composite materials influence thermal energy storage performance through their effects on thermal conductivity, latent heat capacity, charging and discharging rates, and thermal cycling stability. Biochar–paraffin composites can improve thermal responsiveness and reduce leakage through the porous supporting structure, while biochar–polyethylene glycol composites can facilitate reversible heat absorption and release during solid–liquid phase transitions. Biochar–fatty acid composites provide opportunities for temperature regulation in building envelopes because their phase transition temperatures can be selected to correspond with desired indoor thermal conditions, although performance depends on the fatty acid composition and biochar loading ratio. Biochar–inorganic phase change material composites may offer relatively high volumetric heat storage capacity, but their effectiveness can be limited by phase separation, supercooling, corrosion, and compatibility challenges that require additional material engineering (Yang ., 2019; Liang ., 2023). Therefore, these four composite material categories provide a conceptual framework for investigating how biochar-based composite materials influence thermal energy storage performance in sustainable building systems, particularly through heat storage capacity, thermal conductivity, temperature regulation, and long-term thermal stability

Problem Statement

The increasing demand for energy-efficient and environmentally sustainable buildings has intensified the need for innovative thermal energy storage technologies capable of regulating indoor temperatures and reducing dependence on conventional heating and cooling systems. In South Africa, the need to improve building energy efficiency is particularly important because buildings experience varying thermal conditions across climatic regions, creating demand for affordable and effective temperature regulation solutions. Conventional building materials generally possess limited latent heat storage capacity, while commonly used phase change materials (PCMs) face challenges associated with low thermal conductivity, leakage during melting, and reduced performance under repeated thermal cycling. Liang (2023) established that incorporating biochar into phase change materials offers opportunities to improve shape stability, heat transfer, and thermal energy storage through the porous structure and functional properties of biomass-derived carbon. Nevertheless, translating these material-level improvements into reliable and economically viable thermal energy storage systems for sustainable buildings remains a significant challenge, particularly where locally available biomass resources and construction practices must be considered (Liang, 2023; Mohtasim & Das, 2024).

Although recent studies have demonstrated promising thermal properties of biochar-based composite materials, their performance varies considerably according to biochar feedstock, composite formulation, phase change material type, and processing conditions. For example, Rajamony . (2024) established that incorporating coconut-shell biochar into an organic phase change material increased thermal conductivity from 0.22 W/m·K to 0.39 W/m·K, representing an improvement of approximately 77%. Similarly, Katish. (2024) reported that a biochar–octadecane composite achieved a phase change material loading of 62.21%, a latent heat storage capacity of approximately 116.7 J/g, and thermal stability over 300 heating and cooling cycles. However, the same study identified a 45.50% reduction in the 28-day compressive strength of mortar when PCM–biochar composites replaced 40% of the sand, illustrating the trade-offs between thermal storage performance and structural integrity. These findings indicate that improving thermal conductivity or storage capacity does not necessarily guarantee satisfactory overall building performance, highlighting the need to investigate thermal storage efficiency, material stability, heat transfer characteristics, and construction compatibility simultaneously (Rajamony ., 2024; Katish ., 2024).

Despite these advances, an important research gap remains concerning the comparative performance of different biochar-based composite formulations under South African building conditions. Existing studies demonstrate the potential of biochar-based phase change materials, but the evidence reviewed does not establish how biochar–paraffin, biochar–polyethylene glycol, biochar–fatty acid, and biochar–inorganic phase change material composites compare when evaluated using consistent thermal performance indicators and building operating conditions. Furthermore, variations in feedstock characteristics, biochar porosity, phase change temperatures, and composite loading ratios make it difficult to generalise laboratory findings to practical building applications. Mohtasim and Das (2024) emphasised that bio-derived composite phase change

materials require further optimisation and investigation of their technical, economic, and environmental performance before widespread implementation. Consequently, there is a need for context-specific empirical research examining how different biochar-based composite materials influence thermal energy storage capacity, thermal conductivity, charging and discharging efficiency, and thermal cycling stability in sustainable building systems in South Africa (Liang ., 2023; Mohtasim & Das, 2024). The central problem addressed by the proposed study is the insufficient comparative, context-specific evidence on the extent to which different biochar-based composite materials can enhance thermal energy storage performance in sustainable building systems in South Africa. Without such evidence, building material developers, construction professionals, and energy-efficiency practitioners may face difficulties identifying composite formulations that provide effective heat storage, reliable temperature regulation, acceptable mechanical properties, and long-term thermal stability. The proposed study therefore seeks to establish the influence of biochar-based composite materials on thermal energy storage performance, focusing on storage capacity, thermal conductivity, charging and discharging characteristics, and thermal cycling stability. The findings are expected to contribute to the development of locally appropriate, resource-efficient building materials and provide empirical evidence for advancing sustainable construction and thermal energy management in South Africa.

Theoretical Framework

Fourier's Law of Heat Conduction

Fourier's law of heat conduction was developed by French mathematician and physicist Joseph Fourier in 1822. The theory explains that heat flows from regions of higher temperature to lower temperature, with the heat transfer rate determined by thermal conductivity and the temperature gradient. It underpins this study by explaining how biochar incorporation influences heat transfer within composite materials. In South African sustainable buildings, it will guide the assessment of thermal conductivity and charging and discharging rates across different biochar-based composites. Kant. (2021) emphasised the importance of improving thermal conductivity to enhance phase change material performance.

Latent Heat Storage Theory

Latent heat storage theory originates from the pioneering work of Joseph Black in the eighteenth century, particularly his investigations of latent heat during phase transitions. The theory explains how materials absorb or release thermal energy during changes of physical state without substantial temperature variation. It is relevant because biochar-based composites incorporating paraffin, polyethylene glycol, fatty acids, or salt hydrates can store and release heat through phase transitions. This theory will guide the evaluation of latent heat capacity, phase transition temperature, and thermal storage efficiency. Aftab. (2021) demonstrated the importance of phase change materials in enhancing thermal energy storage and sustainable energy systems.

Thermodynamic Theory

Thermodynamic theory developed through the contributions of Rudolf Clausius and William Thomson (Lord Kelvin) during the nineteenth century. Its first and second laws explain energy conservation, heat transfer, energy conversion, and the limitations of thermal processes. The theory is relevant for assessing energy retention, thermal losses, charging and discharging efficiency, and cycling stability of biochar-based composites. It also provides a basis for determining whether stored thermal energy can effectively regulate indoor temperatures under South African climatic conditions. Liang (2023) highlighted the importance of composite structure and thermophysical properties in improving biochar-based thermal storage systems.

Empirical Review

Jeon (2019) investigated the feasibility of using biochar-based phase change material composites as environmentally sustainable building materials for latent heat storage. The researchers adopted an experimental and numerical modelling approach, preparing composite materials through vacuum impregnation of fatty acid-based phase change materials into porous biochar structures. Thermal conductivity, thermal stability, chemical compatibility, and leakage resistance were experimentally evaluated, while numerical simulations examined potential building energy savings. The findings indicated that the composite achieved a thermal conductivity of $0.1727 \text{ W/m}\cdot\text{K}$ and exhibited favourable leakage resistance and thermal stability, while the building simulations indicated a reduction in maximum annual energy consumption of approximately 531.31 kWh for the reference building model. The study demonstrated that biochar-based composites could contribute to improved building energy performance through latent heat storage and passive thermal regulation. The findings support further evaluation of composite formulations under different climatic conditions and building configurations, particularly to determine their applicability to sustainable building systems in South Africa.

Wan (2019) investigated the development of a form-stable phase change material using pinecone-derived biochar as a supporting matrix for palmitic acid to improve thermal energy storage performance. The study employed an experimental materials-characterisation methodology involving scanning electron microscopy, X-ray diffraction, Fourier-transform infrared spectroscopy, differential scanning calorimetry, thermogravimetric analysis, and thermal conductivity testing. The findings revealed that the optimised composite exhibited melting and solidification temperatures of 59.25°C and 59.13°C , respectively, with corresponding latent heat capacities of 84.74 kJ/kg and 83.81 kJ/kg . Furthermore, its thermal conductivity reached $0.3926 \text{ W/m}\cdot\text{K}$, representing an improvement of 43.76% compared with pure palmitic acid, while maintaining favourable thermal stability. The study demonstrated the potential of agricultural and forestry residues as low-cost supporting materials for thermal energy storage composites. The findings support further investigation of locally available biomass-derived biochar and the selection of phase change temperatures appropriate for South African building applications.

Jeon (2019) investigated the potential of coconut oil-impregnated biochar composites as latent heat storage insulation materials for sustainable building applications. The researchers produced

biochar from pinecones, pine sawdust, and paper mill sludge and incorporated coconut oil through vacuum impregnation. The experimental methodology involved Fourier-transform infrared spectroscopy, differential scanning calorimetry, thermal conductivity measurements, and thermogravimetric analysis. The findings revealed a maximum latent heat storage capacity of 74.6 J/g, thermal conductivity as low as 0.030 W/m·K, and maximum specific heat capacity of 1.69 J/g·K, demonstrating promising insulation and thermal storage properties. The study established that biochar-supported coconut oil composites could provide thermal insulation alongside heat storage. The findings support further investigation of locally available biomass feedstocks and their suitability for passive temperature regulation in South African buildings.

Das (2020) investigated the development of a low-cost, form-stable phase change composite using water hyacinth-derived biochar as a supporting material for solar thermal energy storage. The researchers adopted an experimental approach involving biomass pyrolysis, composite preparation, thermal characterisation, and conductivity testing. The findings indicated that the composite achieved a latent heat of fusion of 179.4 J/g, while water hyacinth biochar enhanced thermal conductivity by up to 13.82 times compared with the original phase change material. The addition of aluminium powder further increased thermal conductivity to approximately 17.27 times that of the original material. The study demonstrated the potential of converting invasive aquatic biomass into functional thermal energy storage materials. The findings support further evaluation of water hyacinth-derived biochar and other locally available biomass resources for affordable thermal storage applications in South African buildings.

Atinafu (2021) investigated the potential of engineering biochar with multiwalled carbon nanotubes to enhance phase change material encapsulation and thermal energy storage performance. The researchers adopted an experimental methodology using bamboo-derived biochar and carbon nanotubes to develop hybrid supporting matrices through a one-step hydrothermal process, followed by impregnation with n-dodecane. The findings established phase change material loading capacities of 51.3%, 70.6%, and 83.2% for biochar, biochar-carbon nanotube hybrids, and carbon nanotubes, respectively. Corresponding latent heat storage capacities were 93.4 ± 1.1 J/g, 127.3 ± 1.1 J/g, and 152.3 ± 1.3 J/g, demonstrating improved thermal storage performance through carbon nanotube incorporation. The researchers further observed favourable shape stability, thermal stability, and chemical compatibility. The findings support evaluating engineered biochar composites alongside unmodified biochar materials to determine whether improved thermal storage capacity justifies additional production costs in South African sustainable buildings.

Atinafu (2021) investigated the comparative effectiveness of biochar, activated carbon, expanded graphite, and multiwalled carbon nanotubes as supporting matrices for phase change materials. The researchers employed a comparative experimental methodology involving heptadecane impregnation into different carbon-based supporting materials, followed by thermal and structural characterisation. The previously identified study reported a latent heat storage capacity of 195.9 J/g for an expanded graphite-supported composite, indicating the importance of matrix selection in determining energy storage capacity. Its findings suggested that pore structure, surface

chemistry, and phase change material loading influence thermal performance and composite stability. The study highlighted the need to evaluate biochar against alternative carbon-based matrices rather than assuming that biochar always offers superior thermal performance. Its implications for South Africa include the need for comparative assessments of thermal performance, material availability, environmental sustainability, and cost-effectiveness. However, the author attribution and reported numerical result for this particular article require verification against its original publication before use in a dissertation.

Hekimoğlu (2021) investigated the development of porous biochar–heptadecane composites using carbonised lemon peel as a supporting matrix for improving latent heat storage capacity, thermal conductivity, and leakage resistance. The researchers adopted an experimental materials-development methodology involving composite preparation, thermal characterisation, conductivity measurements, and thermal cycling tests. The findings indicated that the composite exhibited a melting temperature of 19.79°C and a latent heat storage capacity of 141.8 J/g, suggesting its suitability for low-temperature thermal storage applications. The researchers further reported thermal conductivity approximately 1.8 times that of pure heptadecane, alongside favorable leakage resistance and cycling stability. The study demonstrated that agricultural waste-derived biochar could provide an effective supporting structure for phase change materials. The findings support further investigation of fruit-processing residues and other locally available biomass resources for thermal regulation in South African sustainable buildings.

METHODOLOGY

This study adopted a desk methodology. A desk study research design is commonly known as secondary data collection. This is basically collecting data from existing resources preferably because of its low-cost advantage as compared to field research. Our current study looked into already published studies and reports as the data was easily accessed through online journals and libraries.

FINDINGS

The results were analyzed into various research gap categories that is conceptual, contextual and methodological gaps

Conceptual Research Gap

The conceptual research gap arises from the limited integration of different biochar-based composite material characteristics into a comprehensive framework for explaining thermal energy storage performance. Jeon (2019) examined thermal conductivity, thermal stability, leakage resistance, and energy-saving potential, while Wan (2019) focused on pinecone biochar–palmitic acid composites and their latent heat storage characteristics. Similarly, Das (2020) investigated water hyacinth biochar composites, whereas Atinafu (2021) emphasised carbon nanotube-enhanced biochar and phase change material loading capacities. Although these studies demonstrated improvements in individual thermal properties, the reviewed evidence provides limited systematic comparison of biochar–paraffin, biochar–polyethylene glycol, biochar–fatty

acid, and biochar–inorganic phase change material composites using consistent performance indicators. Furthermore, the relationships between composite composition, thermal conductivity, latent heat capacity, charging and discharging efficiency, and thermal cycling stability have not been comprehensively examined within a single comparative framework in the studies reviewed. Therefore, the proposed research seeks to address this conceptual gap by developing an integrated assessment of how different biochar-based composite materials influence thermal energy storage performance in sustainable building systems in South Africa.

Contextual Research Gap

The contextual research gap concerns the limited translation of laboratory-based thermal energy storage findings into practical sustainable building applications under realistic operating conditions. Wan. (2019), Das (2020), and Hekimoğlu (2021) primarily employed laboratory experiments to evaluate the thermophysical properties of biochar-based composites, including latent heat capacity, thermal conductivity, and leakage resistance. Although Jeon . (2019) incorporated numerical simulations to estimate building energy savings, the reviewed studies provide limited evidence concerning the performance of these materials when integrated into actual building components and exposed to fluctuating indoor and outdoor temperatures. In addition, the effects of building design, ventilation, humidity, seasonal temperature variations, and repeated thermal cycling on long-term storage efficiency remain insufficiently addressed in the supplied evidence. The economic feasibility of using locally available biomass feedstocks and the compatibility of biochar-based composites with conventional construction materials also require further investigation. Consequently, the proposed study seeks to address this contextual gap by evaluating thermal energy storage performance under conditions representative of sustainable building systems, including temperature regulation, charging and discharging behaviour, operational stability, and practical material suitability.

Geographical Research Gap

The geographical research gap relates to the limited South Africa-specific empirical evidence within the seven reviewed studies on the performance of biochar-based composite materials in sustainable building systems. Jeon (2019), Wan (2019), Das. (2020), Atinafu (2021), and Hekimoğlu. (2021) investigated different biochar-based thermal storage materials, but the evidence presented does not establish their performance under South African climatic, environmental, and construction conditions. South Africa experiences diverse climatic conditions, including hot and dry inland environments, humid coastal regions, and areas characterised by substantial seasonal temperature variations, which may influence the effectiveness of phase change materials and their thermal storage performance. Furthermore, locally available biomass resources, such as agricultural residues, forestry waste, and invasive plant biomass, may possess different physical and chemical properties from the feedstocks examined in the reviewed studies. Consequently, findings obtained from other geographical settings cannot automatically be generalised to South African sustainable buildings without context-specific validation. The proposed study therefore seeks to address this geographical gap by investigating biochar-based

composite materials using locally relevant biomass resources and evaluating their thermal energy storage performance under climatic and building conditions representative of South Africa.

CONCLUSION AND RECOMMENDATIONS

Conclusions

Biochar-based composite materials present considerable potential for enhancing thermal energy storage performance in sustainable building systems in South Africa. The reviewed empirical literature demonstrates that incorporating biochar into phase change materials can improve thermal conductivity, latent heat storage capacity, thermal stability, leakage resistance, and heat transfer characteristics. Biochar–paraffin, biochar–polyethylene glycol, biochar–fatty acid, and biochar–inorganic phase change material composites offer different thermal storage characteristics that may contribute to improved indoor temperature regulation and reduced heating and cooling energy requirements. Studies by Jeon (2019), Wan . (2019), Das . (2020), Atinafu . (2021), and Hekimoğlu . (2021) demonstrate the potential of biomass-derived carbon materials to support phase change materials and improve their thermal performance. However, the effectiveness of these composites depends on factors such as biomass feedstock, biochar porosity, phase change material composition, thermal conductivity, phase transition temperature, and composite loading ratio.

Despite these advances, significant conceptual, contextual, and geographical research gaps remain concerning the comparative performance of biochar-based composite materials in sustainable building applications. Existing studies have predominantly focused on laboratory characterisation of individual composite formulations, with limited integrated assessment of their thermal energy storage performance under realistic building operating conditions. Furthermore, the evidence reviewed provides insufficient information on how these materials perform under South Africa's diverse climatic conditions and construction practices. The suitability of locally available biomass resources, long-term thermal cycling stability, economic feasibility, and compatibility with conventional building materials also require further investigation. Addressing these gaps is essential for identifying biochar-based composite formulations that combine effective thermal energy storage with environmental sustainability and practical applicability.

The proposed study on Biochar-Based Composite Materials and Thermal Energy Storage Performance in Sustainable Building Systems in South Africa is therefore expected to contribute valuable empirical evidence on the relationships between composite material characteristics and thermal energy storage performance. By examining thermal storage capacity, thermal conductivity, charging and discharging efficiency, and thermal cycling stability, the study will provide a basis for evaluating the effectiveness of different biochar-based composite formulations. The findings may support the development of affordable, locally appropriate, and environmentally sustainable building materials that improve passive thermal regulation and reduce reliance on conventional heating and cooling technologies. Ultimately, the research has the potential to advance sustainable construction practices, promote the productive utilisation of biomass waste, and contribute to energy-efficient building development in South Africa.

Recommendations

Theory

The study recommends the development of an integrated theoretical framework combining Fourier's Law of Heat Conduction, Latent Heat Storage Theory, and Thermodynamic Theory to explain the relationship between biochar-based composite materials and thermal energy storage performance. Existing studies have largely examined individual thermophysical characteristics, including thermal conductivity, latent heat capacity, phase transition temperature, and thermal stability, without consistently integrating these properties into a unified analytical framework (Jeon ., 2019; Wan ., 2019). The proposed research should therefore examine how biochar feedstock characteristics, pore structure, phase change material composition, and composite loading ratios interact to influence thermal conductivity, energy storage capacity, charging and discharging efficiency, and thermal cycling stability. Particular attention should be given to comparing biochar–paraffin, biochar–polyethylene glycol, biochar–fatty acid, and biochar–inorganic phase change material composites under standardised experimental conditions.

The study is expected to contribute an integrated conceptual framework explaining how the physical and chemical properties of different biochar-based composite formulations influence multiple dimensions of thermal energy storage performance. By combining heat conduction, latent heat storage, and thermodynamic principles, the research may clarify the relationships and trade-offs between thermal conductivity, latent heat capacity, and long-term material stability. The framework could also explain how phase transition temperatures and composite loading ratios influence the suitability of thermal storage materials for different building environments. This contribution would extend the application of established thermal energy theories to biochar-based composite materials under South African building conditions, providing a foundation for further research on sustainable thermal storage technologies.

Practice

The study recommends that building material manufacturers, construction professionals, architects, and renewable energy practitioners investigate the practical integration of biochar-based composite materials into sustainable building components such as wall panels, ceiling boards, roofing systems, and thermal insulation materials. Experimental evaluations should assess thermal storage capacity, thermal conductivity, charging and discharging rates, leakage resistance, mechanical compatibility, and performance under repeated heating and cooling cycles. Researchers should prioritise locally available biomass resources, including agricultural residues, forestry waste, and suitable invasive plant biomass, to determine their feasibility as affordable raw materials for biochar production. Furthermore, pilot-scale building experiments should be conducted across representative South African climatic regions to establish the effects of biochar-based composites on indoor temperature regulation, thermal comfort, and building energy consumption. Material selection should also consider manufacturing costs, durability, fire safety, environmental impacts, and compatibility with existing construction technologies before commercial implementation.

The study is expected to provide comparative experimental evidence that can guide the selection, formulation, and application of biochar-based composite materials in sustainable building systems. Its findings may help identify combinations of biochar feedstocks and phase change materials that offer an appropriate balance between thermal storage capacity, heat transfer efficiency, durability, and affordability. The research could also inform practical guidelines for incorporating biochar-based composites into building envelopes and developing prototypes suitable for South African climatic conditions. By investigating the utilisation of locally available biomass waste, the study may support resource-efficient material production, waste valorisation, and the development of locally appropriate thermal energy storage solutions. These contributions could assist construction professionals and material manufacturers in making evidence-based decisions about adopting biochar-based thermal storage technologies.

Policy

The study recommends that relevant South African government institutions, building regulatory authorities, and energy-sector stakeholders consider supporting research, standardisation, and pilot-scale demonstration of biochar-based composite materials for sustainable construction. The Department of Electricity and Energy, the Department of Public Works and Infrastructure, the Department of Forestry, Fisheries and the Environment, and the South African Bureau of Standards could play complementary roles in supporting research, environmental assessment, material testing, and the development of appropriate technical guidance within their respective mandates. Policymakers should encourage collaboration among universities, research institutions, biomass producers, construction companies, and renewable energy organisations to evaluate the feasibility of integrating biochar-based thermal storage materials into energy-efficient buildings. Policy initiatives should also promote the responsible utilisation of agricultural and forestry residues while ensuring that biochar production and composite manufacturing comply with applicable environmental, health, and safety requirements. Furthermore, financial incentives, research grants, and demonstration programmes could be considered to support the development and validation of promising composite technologies before their wider adoption. The study is expected to generate empirical evidence that could inform future technical standards, sustainable building guidelines, and policy discussions concerning biochar-based thermal energy storage materials in South Africa. By identifying measurable performance indicators such as latent heat capacity, thermal conductivity, thermal cycling stability, and building energy-saving potential, the research may provide a scientific basis for evaluating the suitability of these materials for construction applications. The findings could also inform policy discussions on biomass waste utilisation, circular economy practices, low-carbon building materials, and energy-efficient construction. In addition, evidence on the performance and economic feasibility of locally sourced biochar composites may help policymakers assess opportunities for supporting domestic sustainable material industries. These contributions would strengthen the evidence available for aligning innovative building materials with South Africa's broader objectives for energy efficiency, resource sustainability, and environmentally responsible construction.

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