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Thermophysical-Mechanical Characterization of Date Palm Trunk Bark Powder Composites for Sustainable Insulation Applications: Bibliometric Analysis and Experimental Evaluation in Support of the Sustainable Development Goals (SDGs)

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ABSTRACT

Agricultural waste can provide sustainable alternatives to building insulation while supporting the Sustainable Development Goals (SDGs). This study combines bibliometric analysis with experimental evaluation to investigate epoxy-bonded date palm trunk bark powder composites for insulation applications. Bibliometric data were used to identify trends and position the study within agricultural-waste-based insulation research. Composite panels with different filler loadings were fabricated and assessed through density, thermal conductivity, heat flux, water uptake, compressive strength, and scanning electron microscopy. The results showed a non-linear performance trend because porosity, particle packing, matrix continuity, and interfacial structure governed heat transfer and mechanical response. The optimum formulation achieved a combination of insulation efficiency, structural adequacy, and moisture resistance, demonstrating the potential of date palm waste for sustainable building applications.

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1. INTRODUCTION

The building sector requires effective thermal insulation to reduce heat transfer through building envelopes and lower energy demand for indoor cooling and heating. Conventional insulation materials such as expanded polystyrene, extruded polystyrene, polyurethane, and mineral wool provide good thermal performance, but their dependence on non-renewable resources and their environmental impacts during production and disposal have encouraged the development of more sustainable alternatives (Kumar *et al.*, 2023; Hernando Castro *et al.*, 2025).

Agricultural residues are promising raw materials for sustainable insulation because they are generally lightweight, porous, renewable, and capable of disrupting heat-transfer pathways (Ali *et al.*, 2022; Tahar *et al.*, 2024). Their use also provides a practical route for converting agricultural waste into value-added construction materials and reducing reliance on synthetic insulation products (Dovjak *et al.*, 2017). Date palm biomass is particularly relevant in regions where large amounts of leaves, fibers, pits, trunk residues, and bark waste are generated. Previous studies have shown that date palm-derived materials can be incorporated into polymeric matrices to produce composites with useful thermal and mechanical properties (Masri *et al.*, 2018; Ghazi and Jaddan, 2021; Raza *et al.*, 2022). However, the performance of natural-filler composites is governed by more than filler content alone. Density, porosity, particle dispersion, matrix continuity, interfacial bonding, and moisture uptake jointly influence thermal conductivity and mechanical behavior (Mawardi *et al.*, 2021; Nagaraj *et al.*, 2020). Resin-rich composites may provide better structural continuity, whereas higher filler contents may improve thermal resistance by increasing porosity. Excessive filler loading, however, can promote particle agglomeration, weak interfacial bonding, moisture sensitivity, and reduced compressive performance (Benchouia *et al.*, 2023; Doddamani, 2025). Therefore, an optimum composition is needed to balance insulation efficiency, structural stability, and durability.

Previous studies have mainly focused on date palm fibers, leaflets, pits, and other lignocellulosic residues, while finely ground date palm trunk bark remains insufficiently investigated as an epoxy-bonded insulation filler (Masri *et al.*, 2018; Mlhem *et al.*, 2024; Dhakal *et al.*, 2024). In addition, only limited studies have simultaneously examined thermal conductivity, density, heat flux, water absorption, compressive behavior, and microstructure within one integrated optimization framework. This gap limits understanding of the relationships between filler loading, microstructural development, and overall insulation performance.

This study aims to characterize epoxy-bonded date palm trunk bark powder composites for sustainable insulation applications through bibliometric analysis and experimental evaluation. Composite specimens with different filler loadings were assessed using density measurement, thermal conductivity and heat-flux analysis, water-uptake testing, compressive-strength testing, and scanning electron microscopy. The novelty of this study lies in combining bibliometric positioning with a microstructure-guided evaluation of thermophysical and mechanical performance to identify an optimum formulation and clarify its relevance to sustainable construction and the Sustainable Development Goals (SDGs).

2. LITERATURE REVIEW

Sustainable thermal insulation research has increasingly focused on replacing petroleum-based products with renewable materials derived from natural fibers and agricultural residues. Natural insulation products can reduce dependence on synthetic materials and provide an additional pathway for agricultural-waste utilization, although their environmental and technical performance depends on raw-material processing, binder selection, and service conditions (Dovjak *et al.*, 2017). Agricultural residues are particularly attractive because their low density and porous lignocellulosic structure can restrict solid-phase heat transfer and retain air within the composite structure (Ali *et al.*, 2022; Tahar *et al.*, 2024).

Date palm residues have been investigated in several forms, including surface fibers, leaflets, pits, and particulate waste. Date palm surface fibers have demonstrated potential as green thermal-insulation materials because of their lightweight structure and natural porosity (Raza *et al.*, 2022). Composites prepared from date palm leaflets and expanded polystyrene waste have also shown that agricultural residues can be combined with polymeric binders to produce insulation materials with useful physical and thermal characteristics (Masri *et al.*, 2018). Date pits incorporated into bio-polyester matrices further demonstrate that different date palm residues can be valorized as fillers for sustainable insulation systems (Mlhem *et al.*, 2024).

Polymeric matrices play an important role in stabilizing lignocellulosic fillers and transferring mechanical loads within natural-filler composites. Epoxy resin is suitable for this purpose because it provides adhesion, dimensional stability, and continuous matrix formation. Epoxy-based composites containing date palm waste particles have shown that filler incorporation can significantly influence thermal conductivity because the filler distribution changes the continuity of heat-transfer pathways within the matrix (Ghazi and Jaddan, 2021). However, increasing cellulosic filler loading does not necessarily result in a linear improvement in thermal or mechanical performance because higher loading can introduce poor wetting, voids, agglomeration, and weak interfacial regions (Nagaraj *et al.*, 2020).

The relationship between density and thermal conductivity in bio-based insulation composites is complex. Lower density is often associated with greater porosity and more trapped air, which can improve thermal resistance. Nevertheless, particle size, pore connectivity, filler packing, and matrix continuity may be more influential than bulk density alone (Mawardi *et al.*, 2021). Consequently, composites with similar densities may exhibit different thermal conductivities when their internal structures and interfacial characteristics differ. This condition makes morphological analysis necessary for explaining the measured thermophysical response.

Moisture behavior is another important consideration because date palm fibers contain hydrophilic lignocellulosic components. Water absorption may cause dimensional changes, interfacial weakening, and deterioration of mechanical properties during prolonged exposure. The use of date palm fibers in composite materials therefore requires a balance between the porosity needed for thermal resistance and the matrix coverage needed to limit moisture penetration (Dhakal *et al.*, 2024). Mechanical stability must also be maintained because excessive filler loading and weak filler-matrix bonding can reduce the capacity of the composite to transfer compressive loads (Doddamani, 2025).

The main findings and research limitations of relevant studies are summarized in **Table 1**. The comparison indicates that previous research has established the potential of date palm residues and other agricultural wastes as insulation materials. However, most studies focused on fibers, leaflets, pits, or general date palm particles. Limited attention has been given to finely ground date palm trunk bark powder and to the simultaneous evaluation of thermal conductivity, heat flux, density, water uptake, compressive performance, and microstructure within one experimental framework.

Table 1. Comparison of previous studies related to agricultural-waste and date-palm-based insulation materials.

STUDY	MATERIAL SYSTEM	MAIN FOCUS	RELEVANCE TO THE PRESENT STUDY	REMAINING LIMITATION
Dovjak *et al.* (2017)	Natural and synthetic insulation materials	Environmental comparison	Establishes the sustainability rationale for natural insulation	Does not experimentally optimize date palm composites
Masri *et al.* (2018)	Date palm leaflets and expanded polystyrene waste	Composite characterization	Demonstrates the applicability of date palm residues in insulation composites	Uses leaflets rather than trunk bark powder
Nagaraj *et al.* (2020)	Date palm seed filler and vinyl ester	Effect of filler loading on thermal and mechanical properties	Shows that filler loading controls composite performance	Uses seed-derived filler and a different polymer matrix
Ghazi and Jaddan (2021)	Epoxy and date palm waste particles	Thermal conductivity	Supports the use of epoxy-bonded date palm particles	Limited integrated assessment of moisture, strength, and microstructure
Mawardi *et al.* (2021)	Oil palm wood-based bio-insulation	Particle size and thermal properties	Highlights the roles of structure, density, and particle characteristics	Uses oil palm rather than date palm trunk bark
Raza *et al.* (2022)	Date palm surface fibers	Green thermal insulation	Confirms the insulation potential of date palm biomass	Focuses on surface fibers rather than powdered bark
Ali *et al.* (2022)	Date palm leaves and wheat straw fibers	Thermal insulation and sound absorption	Demonstrates the value of hybrid agricultural residues	Does not evaluate epoxy-bonded trunk bark powder
Benchouia *et al.* (2023)	Date palm fibers and polystyrene	Thermal insulation performance	Provides evidence for date-palm-based building insulation	Uses fibrous reinforcement and synthetic foam matrix
Mlhem *et al.* (2024)	Date pits and bio-polyester	Sustainable thermal insulation	Broadens the use of date palm waste in bio-composites	Uses date pits rather than trunk bark
Dhakal *et al.* (2024)	Date palm fibers	Review of properties and applications	Identifies key interfacial, moisture, and performance considerations	Review-based and not specific to trunk bark powder
Doddamani (2025)	Date palm fiber polymer composites	Mechanical and thermal properties	Demonstrates the need to balance insulation and strength	Focuses on fiber composites rather than fine bark particles

Based on this literature, a clear research opportunity exists to examine date palm trunk bark in finely powdered form as an epoxy-bonded insulation filler. The present study addresses this gap by relating filler loading to thermal conductivity, heat flux, density, compressive strength, water uptake, and scanning electron microscopy. This integrated approach is needed to determine whether an optimum composition can provide low heat transfer while retaining adequate physical and mechanical stability for non-load-bearing insulation applications.

2. METHODOLOGY

This study employed a quantitative experimental approach combined with bibliometric analysis to evaluate the thermophysical and mechanical performance of epoxy-bonded date palm trunk bark powder composites for sustainable insulation applications. The research framework consisted of bibliometric analysis, raw material preparation, composite fabrication, thermophysical characterization, mechanical testing, water absorption evaluation, and microstructural analysis.

Date palm trunk bark waste was collected from the Janabiyah region, Bahrain. The bark was washed with distilled water, cleaned using hot water to remove surface impurities, oven-dried to constant weight, mechanically ground, and sieved to obtain a uniform powder with an average particle size of approximately 0.1 mm. The epoxy matrix consisted of Araldite® LY-556 resin and HY-951 hardener mixed according to the manufacturer's recommended ratio. Composite specimens containing different filler loadings (15, 45, 50, 55, and 70 wt%) were fabricated using a cold-compaction technique followed by room-temperature curing. The specimen preparation procedure, fabrication process, and composite compositions are presented in **Figures 1-3** and **Table 2**.

Table 2. Composition and specifications of epoxy/date palm trunk bark powder composites.

SAMPLE	EPOXY RESIN (WT%)	DATE PALM TRUNK BARK POWDER (WT%)	PARTICLE SIZE (MM)	FABRICATION METHOD	CURING CONDITION	INTENDED EVALUATION
S1	85	15	0.1	Cold compaction	24 h at room temperature	Baseline composition
S2	55	45	0.1	Cold compaction	24 h at room temperature	Intermediate filler loading
S3	50	50	0.1	Cold compaction	24 h at room temperature	Balanced composition
S4	45	55	0.1	Cold compaction	24 h at room temperature	Optimum composition evaluation
S5	30	70	0.1	Cold compaction	24 h at room temperature	High filler loading evaluation

Note: The epoxy system consisted of Araldite® LY-556 resin and HY-951 hardener mixed at a resin-to-hardener ratio of 10:1 by weight.

Figure 1. Preparation of date palm trunk bark powder for composite fabrication.

Figure 2. Flowchart of the fabrication process for epoxy-bonded date palm trunk bark powder composites.

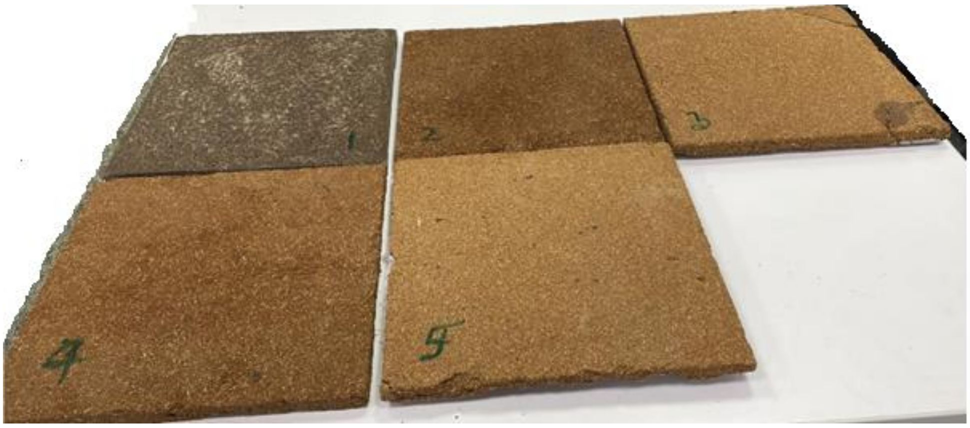


Figure 3. Fabricated epoxy/date palm trunk bark powder composite specimens with different filler loadings.

The density of the fabricated composites was determined from the measured mass-to-volume ratio following ASTM C134. Thermal conductivity and heat flux were evaluated under steady-state one-dimensional heat-transfer conditions using a FOX800 Heat Flow Meter. Water absorption was determined following ASTM D570 to evaluate the moisture resistance of the developed composites. Compressive strength was measured using a universal testing machine according to ASTM C165. The fractured surfaces and filler-matrix interactions were further characterized using scanning electron microscopy (SEM) to explain the relationship between microstructure and thermophysical-mechanical performance.

The experimental results were analyzed by comparing the influence of filler loading on density, thermal conductivity, heat flux, compressive strength, water absorption, and microstructural characteristics. Correlation analyses between density and thermal conductivity, as well as density and compressive strength, were performed to identify the optimum composite formulation for sustainable building-insulation applications.

3. RESULTS AND DISCUSSION

3.1. Bibliometric Analysis of Agricultural Waste-based Thermal Insulation Research

A bibliometric analysis was conducted to identify recent research trends in agricultural-waste-based thermal insulation materials and to position the present study within the existing scientific landscape. The retrieved dataset contained 80 publications indexed in the Scopus database using keywords related to agricultural waste, thermal performance, and insulation materials. The annual publication trend is presented in **Figure 4**.

Research activity remained relatively limited during the early years, indicating that agricultural residues were initially considered alternative rather than mainstream resources for thermal insulation. However, publication output gradually increased after 2015 and accelerated considerably during the last decade. The highest publication output was observed in the most recent years, demonstrating increasing scientific interest in developing environmentally friendly insulation materials from renewable biomass resources.

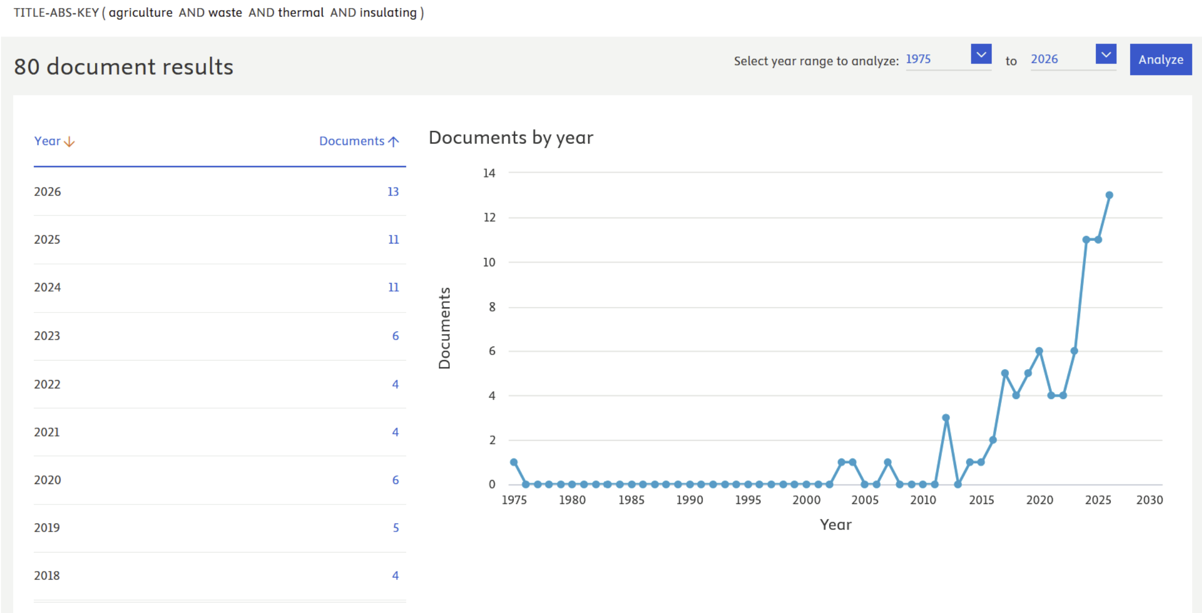


Figure 4. Annual publication trend of agricultural-waste-based thermal insulation research.

The increasing publication trend reflects the growing global demand for sustainable building materials capable of improving energy efficiency while simultaneously reducing agricultural waste disposal. Buildings account for a considerable proportion of global energy consumption, making thermal insulation one of the most effective approaches for reducing cooling and heating loads. Consequently, researchers have increasingly explored renewable raw materials that can replace petroleum-based insulation products without significantly compromising thermal performance. Similar developments have been reported for natural fibers, agricultural residues, and lignocellulosic composites used in sustainable building applications (Ali *et al.*, 2022; Tahar *et al.*, 2024).

Another important observation from the bibliometric analysis is the diversification of biomass resources investigated for insulation applications. Earlier studies primarily focused on conventional natural fibers, whereas recent investigations have expanded toward agricultural by-products such as wheat straw, rice husk, coconut fibers, oil palm residues, sunflower stalks, and date palm biomass. This diversification demonstrates that agricultural residues are increasingly recognized not merely as waste materials but as valuable engineering resources capable of supporting circular-economy strategies and sustainable construction practices (Dovjak *et al.*, 2017).

The bibliometric findings also indicate that thermal insulation research has evolved from simple material characterization toward integrated performance evaluation. Recent studies increasingly combine thermal conductivity with density, moisture resistance, mechanical properties, and microstructural analysis to better understand the mechanisms governing insulation performance. This evolution suggests that thermal conductivity alone is insufficient for evaluating insulation materials because practical applications require balanced thermophysical and mechanical properties.

Despite the increasing number of publications, studies specifically investigating date palm trunk bark powder remain limited. Most published works have examined date palm fibers, leaflets, pits, or general biomass particles instead of finely ground trunk bark incorporated into an epoxy matrix (Masri *et al.*, 2018; Mlhem *et al.*, 2024; Dhakal *et al.*, 2024). Furthermore, relatively few studies have integrated bibliometric analysis with comprehensive experimental characterization to explain how filler loading influences thermal conductivity, density, moisture behavior, mechanical properties, and microstructure simultaneously. Therefore, the present study addresses this research gap by combining bibliometric analysis with experimental investigation to establish a more comprehensive understanding of sustainable insulation composites derived from date palm trunk bark powder.

Beyond identifying research trends, the increasing publication activity also highlights the contribution of agricultural-waste-based insulation materials to several SDGs. The development of renewable insulation materials supports energy-efficient buildings through reduced thermal losses, promotes the utilization of agricultural residues as value-added products, and contributes to more sustainable construction systems. Consequently, the present study aligns with global efforts to improve building sustainability while encouraging the utilization of locally available agricultural waste resources.

3.2. Density Evolution of the Developed Composites

The density of the fabricated composites is presented in **Figure 5**. Density is one of the most fundamental physical properties governing both thermal and mechanical behavior because it reflects the combined influence of filler loading, matrix content, particle packing, and internal porosity. The density decreased markedly as the filler content increased from 15 to 50 wt%. This reduction is mainly attributed to the gradual replacement of the epoxy matrix by the lower-density lignocellulosic filler. In addition, increasing filler content promoted the formation of internal pores and reduced the continuity of the resin phase, thereby lowering the overall bulk density. Similar observations have been reported for natural-fiber composites in which increasing biomass content generally decreases density because lignocellulosic materials possess lower intrinsic density than polymer matrices (Mawardi *et al.*, 2021).

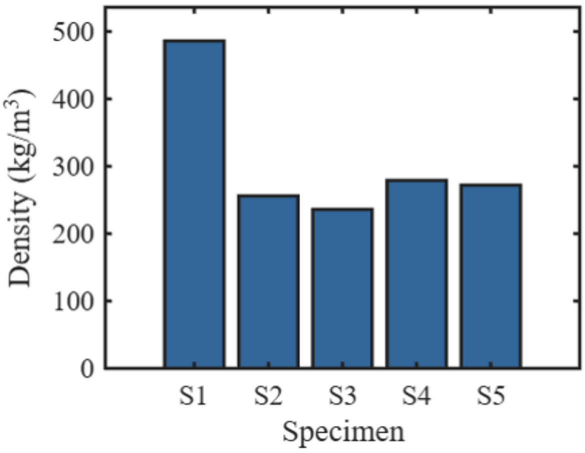


Figure 5. Variation in composite density as a function of date palm trunk bark powder loading.

Interestingly, further increasing the filler loading beyond 50 wt% resulted in a slight increase in density instead of a continuous decrease. This behavior indicates that density evolution cannot be explained solely by the proportion of filler and resin. At higher filler concentrations, closer particle packing and compaction during specimen fabrication may reduce part of the internal void volume, leading to a moderate increase in bulk density. The result suggests that the final density depends on the interaction among particle arrangement, pore distribution, and matrix continuity rather than filler loading alone.

The observed density trend provides important information for interpreting subsequent thermophysical behavior. In many porous insulation materials, lower density is generally associated with lower thermal conductivity because increased pore volume and trapped air reduce conductive heat transfer. Nevertheless, this relationship is often non-linear because excessive porosity may also reduce structural integrity or alter particle connectivity. Therefore, density should be considered together with thermal conductivity, heat flux, compressive strength, and microstructural characteristics to obtain a comprehensive understanding of insulation performance.

The density evolution observed in this study also suggests that optimizing insulation materials requires balancing lightweight characteristics with structural stability. Excessively dense composites may increase solid-phase heat conduction, whereas extremely low-density composites may suffer from poor mechanical performance. Consequently, density alone cannot be considered the primary criterion for selecting the optimum formulation. Instead, it serves as one of several interrelated parameters that collectively determine the suitability of the developed composites for sustainable building insulation. The subsequent sections examine how these density variations influence thermal conductivity, heat-transfer mechanisms, and overall thermophysical-mechanical performance.

3.3. Thermal Conductivity and Heat-transfer Mechanisms

The thermal conductivity values of the developed composites are presented in **Figure 6**. Thermal conductivity is the primary parameter for evaluating insulation materials because it quantifies the ability of heat to be transferred through the material. Lower thermal conductivity indicates greater resistance to heat flow and consequently better insulation performance. The measured thermal conductivity values of all composite formulations remained below the commonly accepted insulation threshold of 0.1 W m^{-1} K^{-1}, demonstrating that the developed composites have potential for sustainable building insulation applications. Thermal conductivity exhibited a non-linear response to increasing filler loading. The conductivity initially increased as the filler content increased from 15 to 45 wt%, subsequently decreased to its minimum value at 55 wt%, and finally increased slightly at 70 wt%. This behavior indicates that thermal transport in the developed composites is governed by multiple competing mechanisms rather than by filler concentration alone.

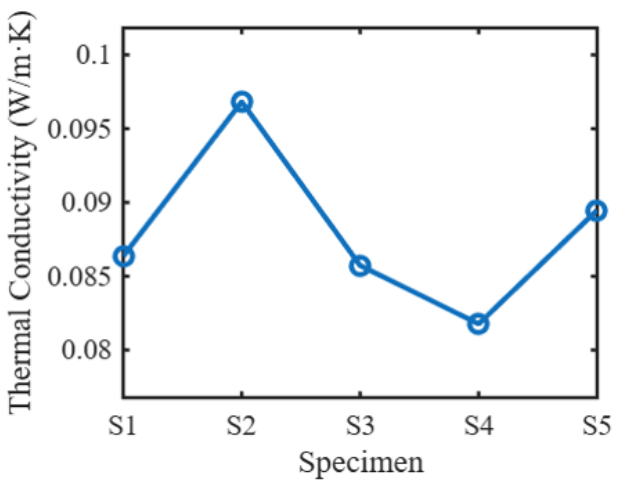


Figure 6. Thermal conductivity of epoxy/date palm trunk bark powder composites with different filler loadings.

At relatively low filler loading, the epoxy matrix remained continuous and effectively surrounded the bark particles. The intimate contact between filler particles and the surrounding resin promoted the formation of continuous solid conduction pathways, allowing heat to be transferred more efficiently through the composite. Although lignocellulosic fillers possess relatively low thermal conductivity, the continuous resin network facilitated heat propagation across the composite, explaining the increase in thermal conductivity observed at intermediate filler loading. Similar behavior has been reported in natural-fiber polymer composites where enhanced filler-matrix contact increases effective heat transfer through the solid phase (Ghazi and Jaddan, 2021).

Further increasing the filler content produced a different thermal response. At approximately 55 wt% filler loading, thermal conductivity reached its minimum value. This result indicates the existence of an optimum filler composition at which internal porosity, discontinuous resin pathways, and dispersed lignocellulosic particles collectively maximize thermal resistance. The increasing number of microscopic voids introduces stagnant air pockets, while discontinuities in the epoxy phase interrupt continuous heat-conduction pathways. Because air possesses significantly lower thermal conductivity than solid materials, these pores act as thermal barriers that suppress conductive heat transfer. Consequently, the composite exhibits superior insulation performance despite containing a larger fraction of solid filler.

The reduction in thermal conductivity cannot be explained solely by decreasing density. Instead, the results suggest that the internal microstructure governs heat transfer more strongly than bulk density. Changes in pore distribution, particle arrangement, matrix continuity, and filler dispersion modify the effective conduction pathway throughout the composite. Therefore, two specimens with comparable density may exhibit different thermal conductivities if their internal structures differ. Similar observations have been reported for bio-based insulation materials, where porosity and interfacial characteristics dominate thermal transport mechanisms rather than density alone (Mawardi *et al.*, 2021).

When the filler loading increased further to 70 wt%, thermal conductivity increased slightly. This phenomenon is attributed to particle agglomeration and closer contact among neighboring bark particles. Excessive filler concentration reduces the amount of epoxy available to separate adjacent particles, thereby promoting localized solid-phase connectivity. As particle contact becomes more frequent, additional conductive pathways are formed, partially offsetting the thermal resistance generated by internal pores. Consequently, the insulation performance deteriorates slightly despite the high biomass content. Similar trends have been reported in highly filled lignocellulosic composites, where excessive filler loading leads to agglomeration and reduced overall thermal efficiency (Nagaraj *et al.*, 2020).

Figure 7 demonstrates that density and thermal conductivity do not exhibit a simple linear relationship. Although density generally decreased with increasing filler content up to 50 wt%, thermal conductivity followed a different trend by initially increasing before decreasing at higher filler loading. This discrepancy confirms that density alone cannot explain the thermophysical behavior of the developed composites.

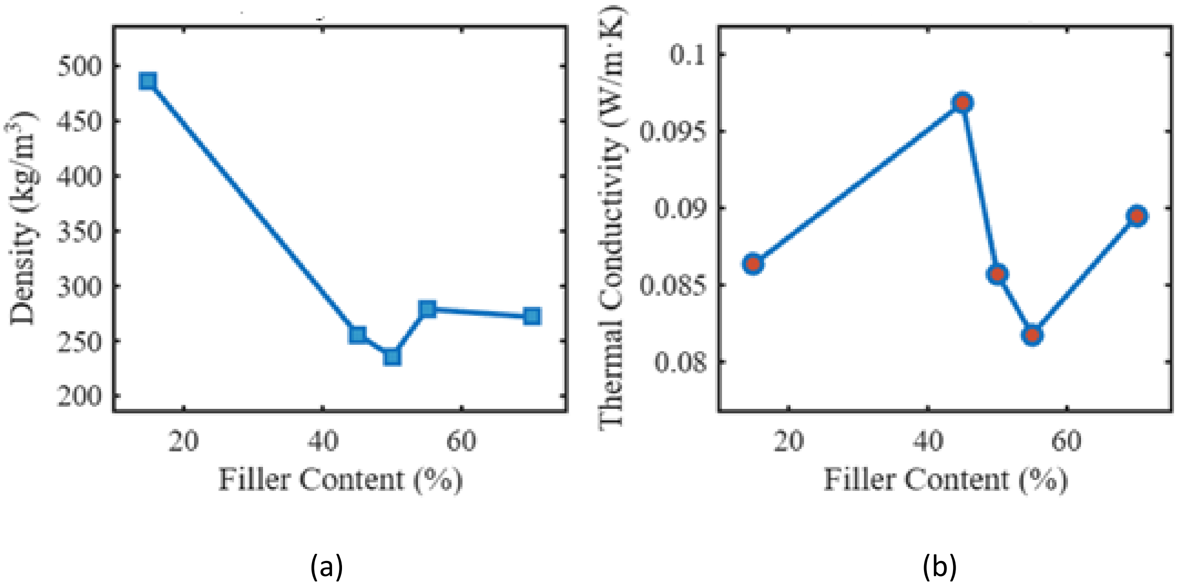


Figure 7. Relationship between composite density (a) and thermal conductivity (b) as a function of filler loading.

The absence of a direct correlation indicates that thermal transport depends on several interacting microstructural factors. Internal pore size, pore connectivity, filler orientation, particle packing, and the continuity of the epoxy phase all influence the effective conduction pathway. A reduction in density caused by increased porosity may improve thermal insulation only when the pores remain well distributed and the solid conduction network is effectively interrupted. Conversely, localized particle agglomeration may restore conductive pathways even if the composite remains relatively lightweight. Therefore, optimization of bio-based insulation materials requires simultaneous consideration of density, microstructure, and filler distribution rather than relying on density as the sole design parameter.

The observed thermophysical behavior demonstrates that the optimum composite formulation results from balancing two competing mechanisms. Increasing filler loading promotes porosity and increases thermal resistance, whereas excessive filler concentration enhances particle connectivity and facilitates solid-phase heat conduction. The optimum composition is therefore obtained when porosity is sufficiently high to interrupt heat-transfer pathways without causing excessive particle agglomeration. This balance explains why the composite containing 55 wt% date palm trunk bark powder exhibited the best thermal-insulation performance among all formulations investigated.

3.4. Heat-transfer Characteristics and Thermal Resistance

The steady-state temperature distribution and corresponding heat flux of the developed composites are presented in **Figure 8**. The temperature profiles exhibit nearly linear distributions across the specimen thickness, indicating one-dimensional steady-state heat conduction under the experimental conditions. The absence of significant curvature in the temperature profiles suggests that internal heat generation was negligible and that heat transfer was dominated by conductive mechanisms.

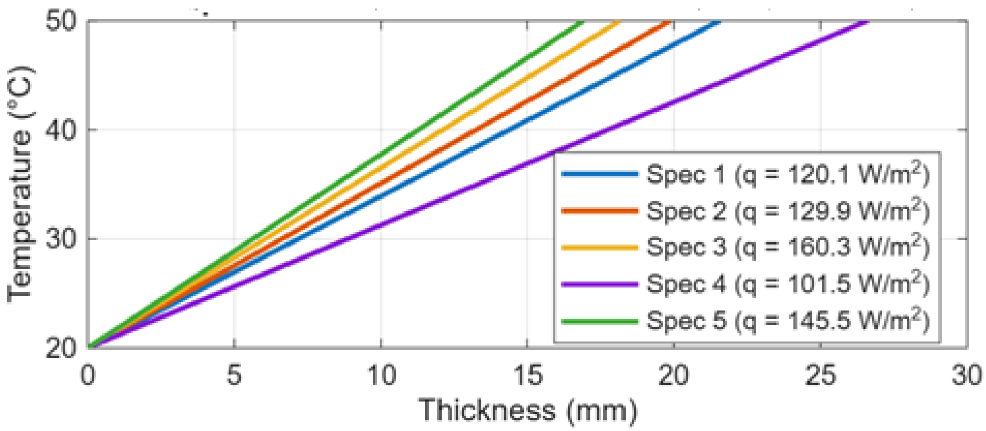


Figure 8. Steady-state temperature distribution and corresponding heat flux of the developed composites.

The linear temperature profiles are consistent with Fourier's law of heat conduction, indicating that heat transfer through the composite depends primarily on the thermal conductivity of the material and the temperature gradient across the specimen. Under identical boundary temperatures, composites possessing lower thermal conductivity provide greater resistance to heat flow, resulting in reduced heat flux and improved insulation performance. Consequently, differences in the measured heat flux among the developed composites directly reflect variations in their internal thermal resistance.

The results demonstrate that heat flux decreased as the composite structure became more resistant to heat conduction. The S4 composite, which exhibited the lowest thermal conductivity, also showed the lowest heat flux, confirming that the 55 wt% filler loading provided the most effective resistance to conductive heat transfer. The reduction in heat flux is attributed to the combined effects of discontinuous resin pathways, increased pore volume, and air entrapment within the composite structure. These features interrupt continuous solid conduction pathways and force heat to travel through a more tortuous route, thereby increasing the overall thermal resistance.

In contrast, composites containing either excessive resin or excessive filler exhibited relatively higher heat-transfer rates. At low filler loading, the continuous epoxy matrix provided uninterrupted conductive pathways that facilitated heat propagation through the material. At very high filler loading, closer particle contact and localized agglomeration partially restored solid-phase connectivity, allowing heat to bypass part of the insulating pore structure. These observations further support the existence of an optimum filler loading rather than a continuously improving thermal response with increasing biomass content.

Figure 9 confirms that thermal conductivity strongly influences the heat-transfer capability of the developed composites. Nevertheless, the relationship is not perfectly proportional because heat transfer is simultaneously affected by specimen geometry and internal structure. Besides thermal conductivity, parameters such as specimen thickness, pore distribution, particle dispersion, and matrix continuity collectively determine the effective thermal resistance. Therefore, materials exhibiting similar thermal conductivity values may still produce different heat-transfer rates if their internal architectures differ.

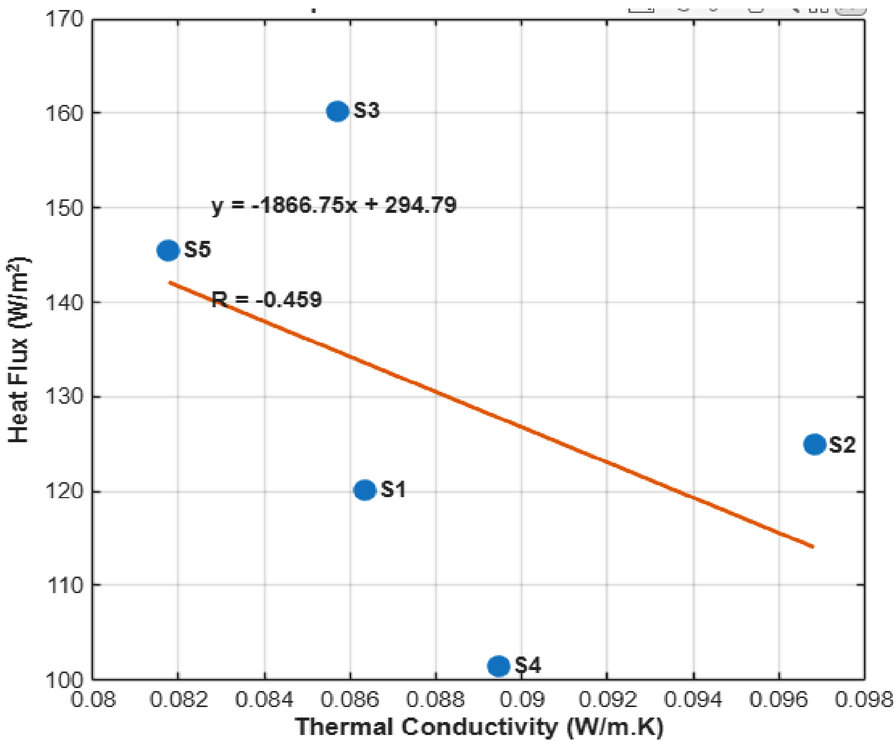


Figure 9. Influence of thermal conductivity on heat-transfer behavior of the developed composites.

The developed composites behave as heterogeneous porous materials rather than homogeneous solids. Heat is transferred through both the continuous solid phase and the stagnant air trapped within the pore network. Because the thermal conductivity of air is considerably lower than that of the solid constituents, increasing the volume of uniformly distributed closed pores effectively reduces the overall thermal conductivity. However, this beneficial effect is achieved only when pore formation does not excessively reduce structural integrity or create preferential conduction pathways through particle agglomeration.

Thermal performance is governed by the interaction between composition and microstructure. Increasing the amount of date palm trunk bark powder modifies particle distribution, resin continuity, and internal porosity, which together determine the effective heat-transfer pathway. Consequently, optimization of insulation materials should not rely solely on reducing density or maximizing biomass content but should instead consider the balance between conductive pathways and pore-induced thermal resistance. This finding explains why the S4 formulation containing 55 wt% date palm trunk bark powder produced the most favorable thermal insulation performance. And, it provides an important basis for interpreting the subsequent microstructural and mechanical analyses.

3.5. Integrated Thermophysical Performance and Microstructure-property Relationship

The comparative thermophysical performance of the developed composites is presented in **Figure 10**, while the corresponding microstructural characteristics are shown in **Figure 11**. The combined interpretation of these results explains how filler loading affects density, thermal conductivity, thermal resistance, and heat-transfer behavior through changes in the internal composite structure. Each formulation exhibited a different balance of thermophysical properties. No single specimen achieved the best value for every parameter, confirming that insulation-material optimization cannot be based on one property alone.

Among the tested formulations, the composite containing 55 wt% date palm trunk bark powder showed the most favorable overall balance because it combined low thermal conductivity, high thermal resistance, moderate density, and reduced heat-transfer capability.

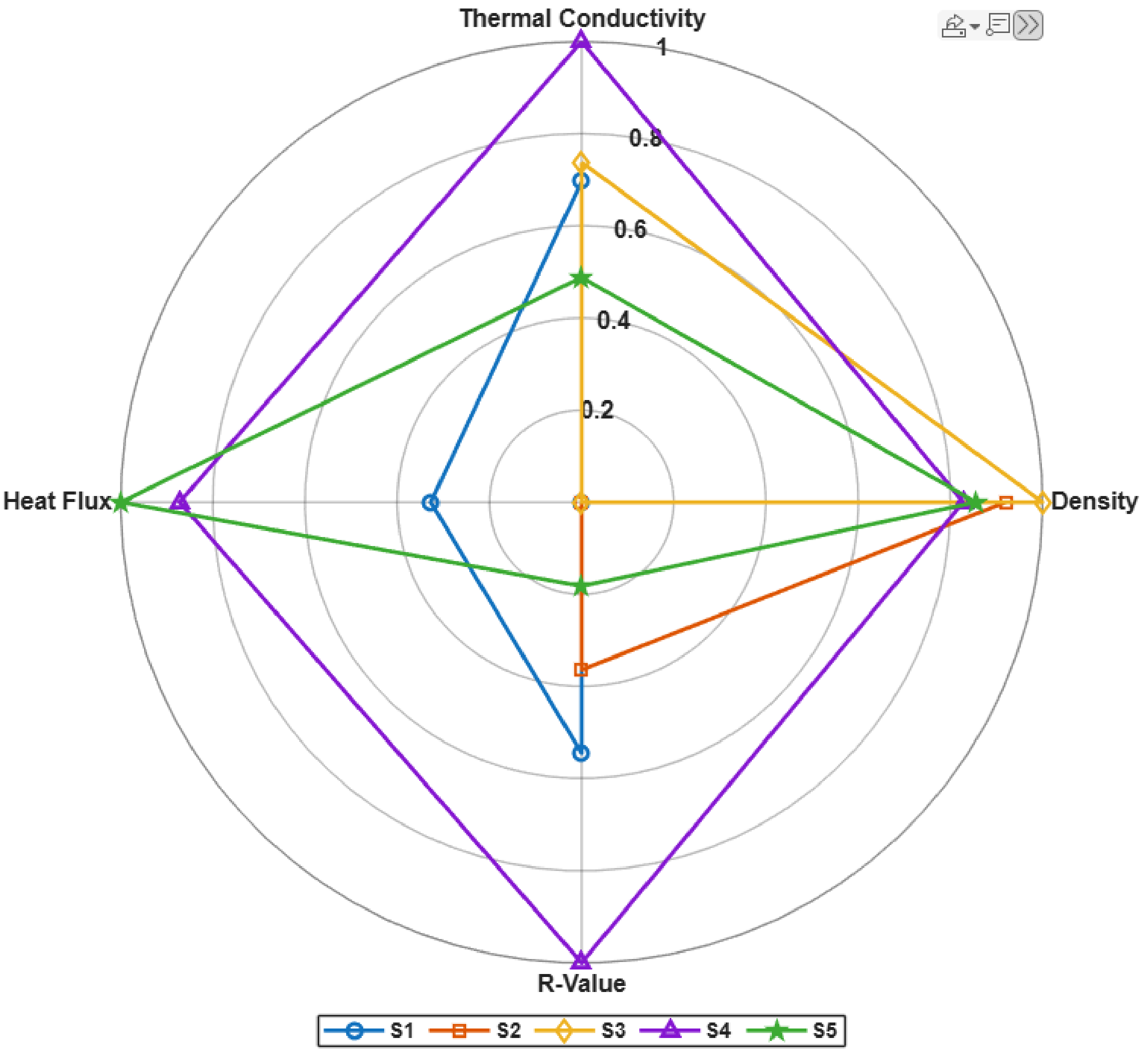
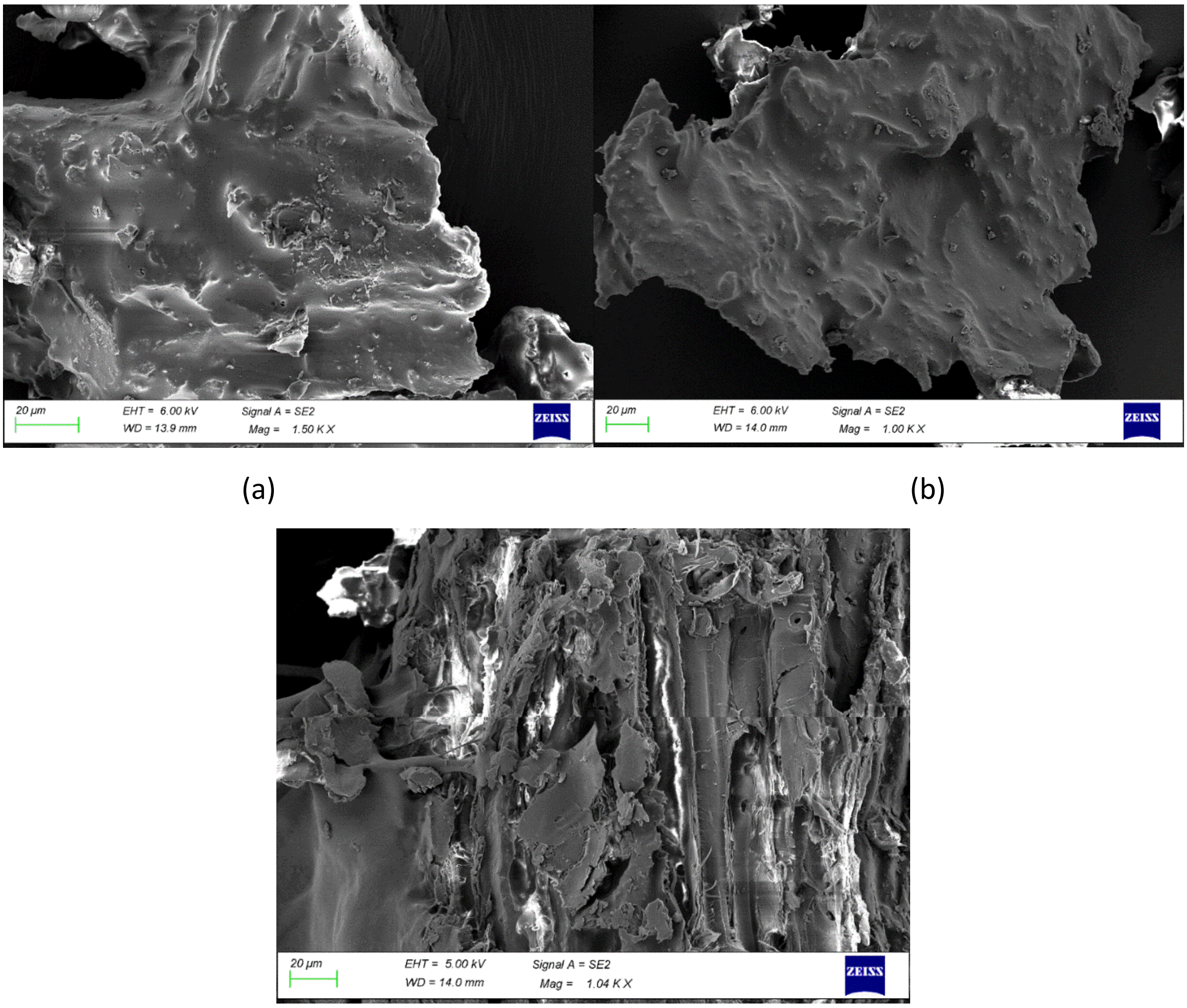


Figure 10. Comparative thermophysical performance of the developed composite specimens.

The microstructural characteristics responsible for these differences are shown in **Figure 11**. At lower filler loading, the epoxy matrix remained relatively continuous and surrounded the bark particles more effectively. This structure supported good particle-matrix contact but also created continuous solid pathways that facilitated heat conduction. As the filler loading increased, the resin phase became less continuous and more microvoids and interfacial gaps developed. These features trapped air and interrupted conductive pathways, thereby increasing thermal resistance.

The specimen containing 55 wt% filler exhibited the most favorable microstructure for thermal insulation. Its dispersed pores, discontinuous resin pathways, and reduced solid-phase connectivity limited heat transfer without creating excessive agglomeration. At the highest filler loading, particle contacts became more frequent and localized agglomeration occurred. These connected particles partially restored solid conduction pathways and contributed to the slight increase in thermal conductivity.

The thermal performance of the composites was governed primarily by microstructural development rather than by bulk density alone. Particle dispersion, pore distribution, matrix continuity, and interfacial structure jointly determined the effective heat-transfer pathways. Similar relationships between filler loading, porosity, interfacial defects, and thermal behavior have been reported in date-palm- and lignocellulosic-filler composites (Ghazi and Jaddan, 2021; Mawardi *et al.*, 2021; Nagaraj *et al.*, 2020).



(c)

Figure 11. SEM micrographs of epoxy/date palm trunk bark powder composites with different filler loadings: (a) 45; (b) 50; and (c) 55%.

To position these findings within the existing literature, **Table 3** compares the material systems, characterization scopes, and main contributions of previous bio-based insulation studies with those of the present work. Previous studies have established the potential of date palm fibers, leaflets, pits, and particulate waste for thermal-insulation applications. However, the present study extends this body of work by examining finely ground date palm trunk bark powder and simultaneously evaluating its thermal, physical, mechanical, moisture, and microstructural behavior. This integrated approach enables the optimum formulation to be identified and its performance to be explained through changes in porosity, particle packing, matrix continuity, and interfacial structure.

Table 3. Comparison of the present study with previous investigations on bio-based insulation composites.

STUDY	MATERIAL SYSTEM	MATRIX OR BINDER	EVALUATED PROPERTIES	MAIN CONTRIBUTION	DISTINCTION FROM THE PRESENT STUDY
Masri *et al.* (2018)	Date palm leaflets	Expanded polystyrene waste	Physical and thermal properties	Demonstrated the feasibility of date palm residues for insulation composites	Used leaflets rather than finely ground trunk bark powder
Nagaraj *et al.* (2020)	Date palm seed-derived cellulosic filler	Vinyl ester	Thermal and mechanical properties	Evaluated the effect of filler loading on composite performance	Used seed-derived filler and a different polymer matrix
Ghazi and Jaddan (2021)	Date palm waste particles	Epoxy	Thermal conductivity	Confirmed the thermal-insulation potential of epoxy/date palm waste composites	Did not integrate moisture, compressive, and detailed microstructural evaluation
Mawardi *et al.* (2021)	Oil palm wood particles	Biopolymer-based system	Density, particle-size effects, and thermal properties	Highlighted the roles of particle structure and density	Investigated oil palm rather than date palm trunk bark
Raza *et al.* (2022)	Date palm surface fibers	Fiber-based insulation system	Thermal properties	Established date palm surface fibers as green insulation materials	Focused on fibers rather than powdered bark composites
Ali *et al.* (2022)	Date palm leaves and wheat straw fibers	Fibrous insulation system	Thermal and acoustic properties	Demonstrated the potential of hybrid agricultural residues	Did not examine epoxy-bonded trunk bark powder
Benchouia *et al.* (2023)	Date palm fibers	Polystyrene	Thermal and physical properties	Developed an eco-friendly date-palm-based insulation material	Used fibrous reinforcement and a polystyrene matrix
Mlhem *et al.* (2024)	Date pits	Bio-polyester	Thermal and physical properties	Expanded the use of date palm residues in sustainable insulation	Used pits rather than trunk bark powder
Dhakal *et al.* (2024)	Date palm fibers	Various matrices	Review of thermal, mechanical, and interfacial properties	Summarized the potential and limitations of date palm fibers	Review-based and not specific to trunk bark powder
Doddamani (2025)	Date palm fibers	Polymer matrix	Mechanical and thermal properties	Demonstrated the trade-off between insulation and mechanical strength	Focused on fiber composites rather than finely ground bark particles
Present study	Date palm trunk bark powder	Epoxy	Bibliometric trend, density, thermal conductivity, heat flux, water absorption, compressive performance, and SEM	Provides an integrated microstructure-guided optimization of thermophysical and mechanical performance	Combines bibliometric positioning, experimental characterization, and SDG relevance

3.6. Mechanical Performance of the Developed Composites

The compressive performance of the developed composites is presented in **Figure 12**, while the relationship between density and compressive strength is illustrated in **Figure 13**. Mechanical performance is an important consideration for insulation materials because building insulation panels should maintain adequate structural integrity during handling, installation, and service, even though they are generally intended for non-load-bearing applications.

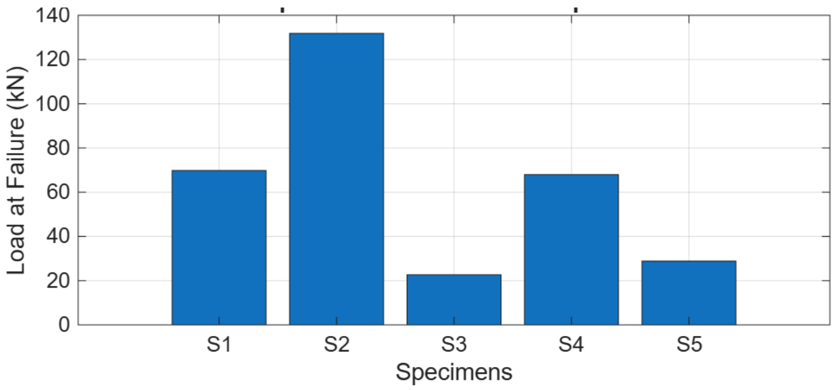


Figure 12. Epoxy/date palm trunk bark powder composites with different filler loadings.

As shown in **Figure 12**, compressive strength generally decreased as the proportion of date palm trunk bark powder increased. Composites containing higher epoxy content exhibited greater resistance to compressive loading because the continuous polymer matrix efficiently transferred applied stresses throughout the specimen. The epoxy matrix also enhanced particle encapsulation and reduced stress concentration around individual filler particles, thereby improving overall structural continuity. Increasing the bark powder content gradually reduced compressive strength because the resin phase became increasingly discontinuous. The reduction in matrix continuity limited stress transfer between neighboring particles and promoted localized deformation during compression. Furthermore, increasing filler loading introduced additional pores and interfacial defects that acted as stress-concentration sites, accelerating crack initiation and propagation under compressive loading. Similar behavior has been reported for natural-fiber polymer composites, where excessive filler loading decreases mechanical performance because of poor interfacial adhesion and insufficient matrix coverage (Doddamani, 2025). Although mechanical strength decreased with increasing filler loading, the optimum insulation formulation retained sufficient structural integrity for non-load-bearing applications. The composite containing approximately 55 wt% filler provided an acceptable balance between thermal insulation and mechanical stability. The optimum composition should not be selected solely according to thermal conductivity but should simultaneously satisfy practical mechanical requirements.

The relationship between density and compressive strength is further examined in **Figure 13**. The correlation analysis demonstrates that density alone does not adequately explain the compressive behavior of the developed composites. Although denser materials are generally expected to exhibit greater mechanical strength, the experimental results reveal noticeable deviations from this trend. Some specimens possessing relatively low density exhibited higher compressive strength than denser formulations, indicating that internal structural characteristics exert a stronger influence than bulk density alone.

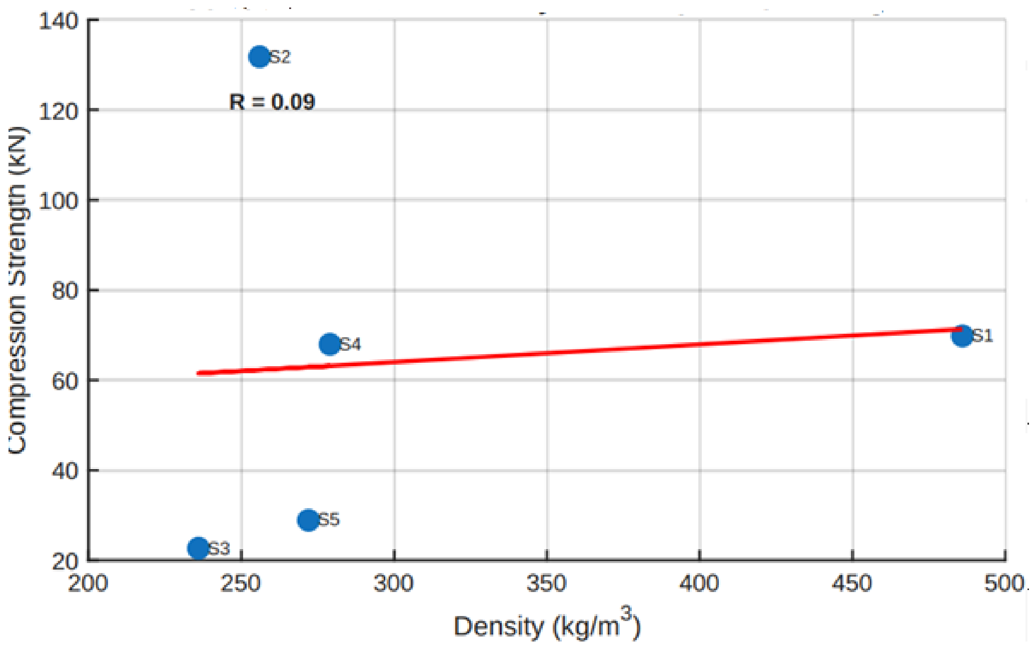


Figure 13. Relationship between composite density and compressive strength.

The observed behavior can be attributed to differences in particle packing, pore distribution, and filler-matrix interaction. Uniform particle dispersion allows external loads to be transferred more effectively throughout the composite, whereas localized agglomeration and irregular pore formation produce weak regions that initiate premature failure. Consequently, mechanical performance depends primarily on microstructural integrity rather than on density itself. These findings are consistent with the SEM observations presented previously, which showed that filler dispersion and matrix continuity govern both thermal transport and mechanical behavior.

3.7. Water Absorption Characteristics

The water absorption behavior of the developed composites is presented in **Figure 14**. Moisture resistance is an important consideration for bio-based insulation materials because water penetration can increase thermal conductivity, cause dimensional changes, weaken filler-matrix interfaces, and reduce long-term mechanical stability. As shown in **Figure 14**, water absorption generally increased with increasing date palm trunk bark powder content. This behavior is associated with the lignocellulosic structure of the bark particles, which contains hydrophilic hydroxyl groups capable of interacting with water molecules. Increasing the filler content therefore increased the number of moisture-attracting sites within the composite. Similar moisture sensitivity has been identified as an important limitation of date-palm-fiber composites (Dhakal *et al.*, 2024).

The increase in water absorption was also influenced by the development of pores and interfacial gaps. At low filler loading, the relatively continuous epoxy matrix encapsulated the bark particles and limited water penetration. As the filler proportion increased, the amount of resin available to cover the particles decreased, while the number of pores and discontinuous interfaces increased. These structural features provided additional pathways for water to enter the composite.

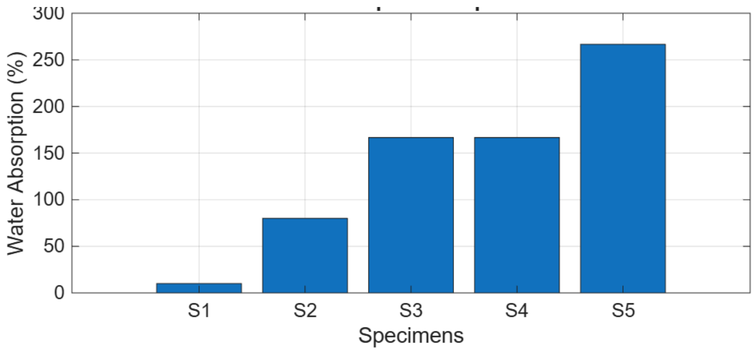


Figure 14. Water absorption of epoxy/date palm trunk bark powder composites after immersion testing.

The composite containing 55 wt% filler exhibited moderate water absorption. Its moisture uptake was higher than that of the resin-rich formulations but lower than that of the composite containing 70 wt% filler. This result indicates that the 55 wt% formulation developed sufficient porosity to improve thermal resistance without producing the excessive open-pore structure observed at the highest filler loading.

Excessive moisture uptake at high filler loading may negatively affect long-term durability, particularly in humid environments. Water absorbed by the lignocellulosic particles may cause swelling, interfacial weakening, and gradual deterioration of mechanical properties. Therefore, increasing the biomass fraction does not necessarily improve the overall suitability of the composite. The filler content must instead be optimized to balance thermal insulation, moisture resistance, and structural stability.

The combined performance of the five formulations is summarized in **Table 4**. The assessment considers density, thermal conductivity, water absorption, and compressive performance because these properties collectively determine the suitability of a material for non-load-bearing insulation applications. As summarized in **Table 4**, each formulation provided a different combination of advantages and limitations. S2 exhibited the strongest compressive performance, whereas S3 had the lowest density. However, neither formulation provided the best overall combination of thermal and physical properties. S5 contained the largest proportion of agricultural waste, but its high-water absorption and reduced mechanical stability limited its suitability for practical insulation applications.

S4, containing 55 wt% date palm trunk bark powder, provided the most balanced performance. This formulation achieved the lowest thermal conductivity while maintaining moderate density, manageable water absorption, and adequate compressive stability for non-load-bearing applications. Its favorable performance resulted from a microstructure containing sufficient porosity to interrupt heat-transfer pathways without producing excessive particle agglomeration or severe matrix discontinuity.

Table 4. Overall performance assessment of the developed composite formulations.

SAMPLE	DATE PALM TRUNK BARK POWDER	DENSITY CHARACTERISTIC	THERMAL CONDUCTIVITY CHARACTERISTIC	WATER ABSORPTION CHARACTERISTIC	COMPRESSIVE PERFORMANCE	OVERALL ASSESSMENT
S1	15 wt%	Highest density	Low thermal conductivity, but dominated by continuous epoxy pathways	Lowest moisture uptake	Good matrix continuity	Resin-rich reference composite
S2	45 wt%	Lower than S1	Highest thermal conductivity	Low-to-moderate moisture uptake	Highest compressive performance	Mechanically favorable but thermally less effective
S3	50 wt%	Lowest density	Reduced thermal conductivity	Moderate moisture uptake	Moderate mechanical stability	Lightweight composite with favorable insulation performance
S4	55 wt%	Moderate density	Lowest thermal conductivity	Moderate moisture uptake	Adequate for non-load-bearing use	Optimum balanced formulation
S5	70 wt%	Slightly higher than the minimum density	Slightly higher thermal conductivity than S4	Highest moisture uptake	Lowest mechanical stability	High biomass content but limited by moisture sensitivity and structural weakness

Accordingly, the optimum formulation was identified through a multi-property assessment rather than through thermal conductivity alone. The results demonstrate that successful bio-based insulation design requires an appropriate balance among thermal resistance, moisture response, density, and mechanical integrity. Further improvement may be achieved through particle-surface treatment or enhanced interfacial bonding to reduce moisture uptake while preserving the advantageous porous structure of the 55 wt% formulation.

3.8. Integrated Optimization of Thermophysical and Mechanical Properties

To further quantify the relationship between bulk density and thermal conductivity, **Figure 15** presents a correlation analysis together with the corresponding coefficient of determination. Unlike Figure 7, which compares the variation of both properties with filler loading, Figure 15 evaluates whether density can statistically explain the observed changes in thermal conductivity. The integrated variation of density, thermal conductivity, and heat flux is subsequently visualized in **Figure 16**.

The correlation analysis in **Figure 15** indicates a weak relationship between bulk density and thermal conductivity. The low coefficient of determination shows that variations in density alone cannot adequately explain the thermal performance of the developed composites. Instead, filler dispersion, pore morphology, interfacial bonding, particle packing, and matrix continuity collectively determine the effective heat-transfer pathways. Thus, **Figure 15** complements **Figure 7** by quantitatively confirming that thermal conductivity is controlled by microstructural characteristics rather than by density alone.

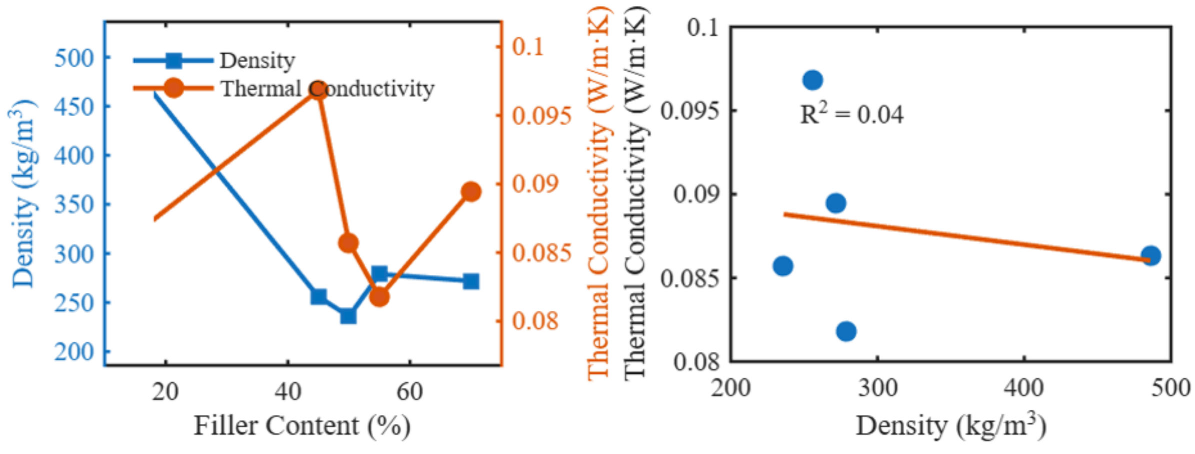
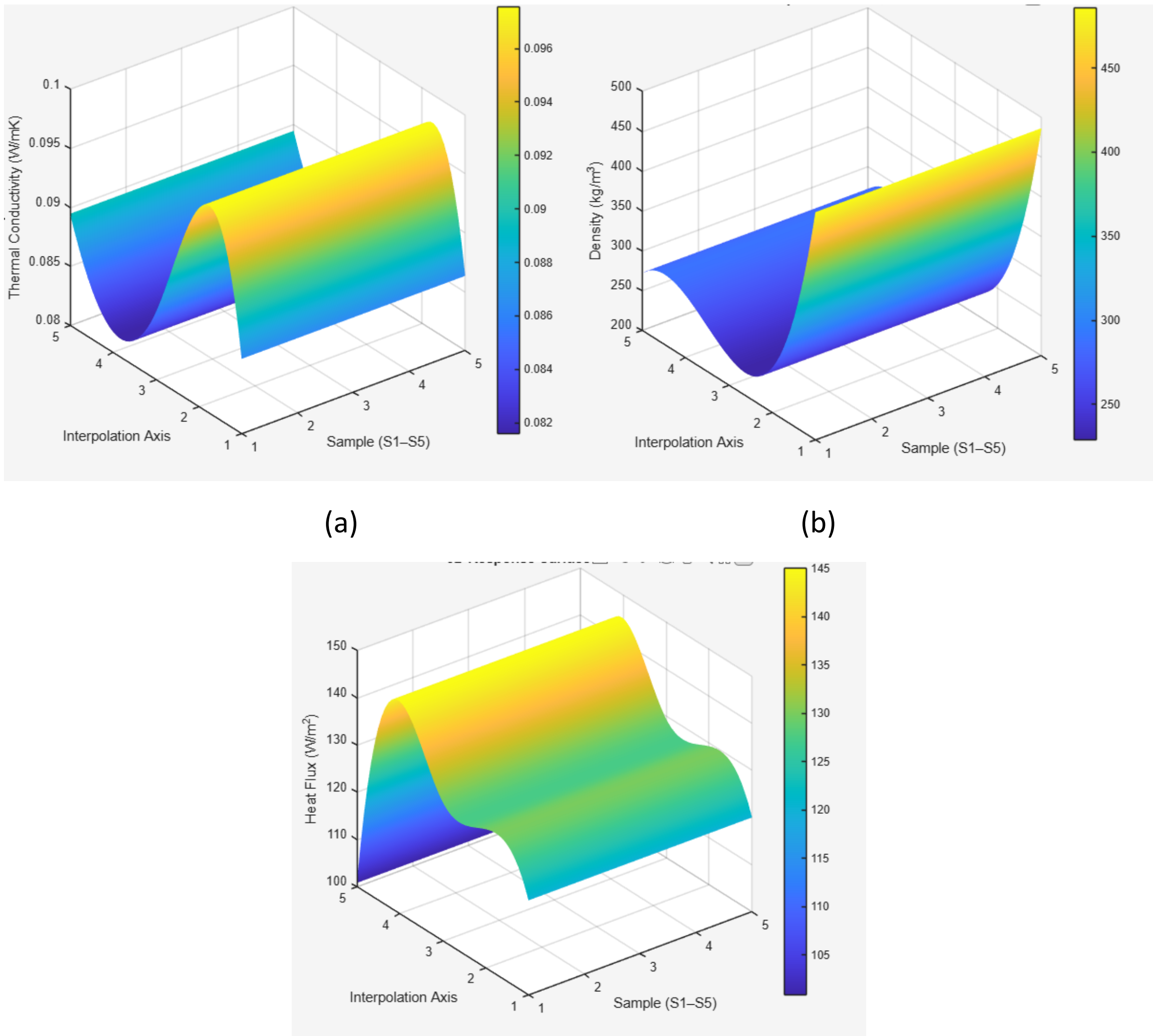


Figure 15. Relationship between density (a) and thermal conductivity (b) of the developed composites, including the coefficient of determination.

The combined effects of the investigated variables are further illustrated through the response surface presented in **Figure 16**. The response surface provides an integrated visualization of the interactions among density, thermal conductivity, and heat flux. The three-dimensional representation clearly demonstrates that the developed composites exhibit non-linear thermophysical behavior across the investigated filler compositions. Instead of changing proportionally with filler loading, the measured properties evolve through complex interactions involving particle distribution, pore development, and resin continuity.

Among the investigated formulations, the intermediate filler composition consistently occupied the most favorable region of the response surface because it combined relatively low thermal conductivity with moderate density and reduced heat-transfer rate. This behavior demonstrates that the optimum insulation performance results from balancing several competing mechanisms rather than maximizing one individual property. Increasing filler loading improves thermal resistance by increasing internal porosity, whereas excessive filler loading promotes particle agglomeration that partially restores conductive pathways. Likewise, increasing resin content enhances structural continuity but simultaneously increases heat conduction through the continuous polymer phase.

The integrated analysis also demonstrates that thermophysical performance should always be evaluated together with mechanical stability and moisture resistance. The optimum formulation was not necessarily the lightest specimen or the specimen containing the highest biomass fraction. Instead, it was the formulation capable of maintaining low thermal conductivity while preserving acceptable compressive performance and moderate water absorption. Such balanced behavior is particularly important for practical insulation materials because thermal efficiency alone cannot guarantee satisfactory long-term service performance.



(a) (b)

(c)

Figure 16. Three-dimensional response surface illustrating the thermophysical characteristics of the developed composites: (a) thermal conductivity, (b) density, and (c) heat flux.

The integrated optimization confirms that approximately 55 wt% date palm trunk bark powder provides the most appropriate balance between thermal insulation, structural integrity, and moisture resistance among the investigated formulations. This finding establishes an effective design guideline for developing sustainable bio-based insulation composites based on agricultural waste.

3.9. Practical Implications for Sustainable Building Insulation

The practical application of the developed composites is illustrated in **Figures 17-21**, which demonstrate their potential implementation as insulation layers in building-envelope systems. These conceptual illustrations translate the experimental findings into practical engineering applications by showing how reduced thermal conductivity contributes to improved building energy performance.

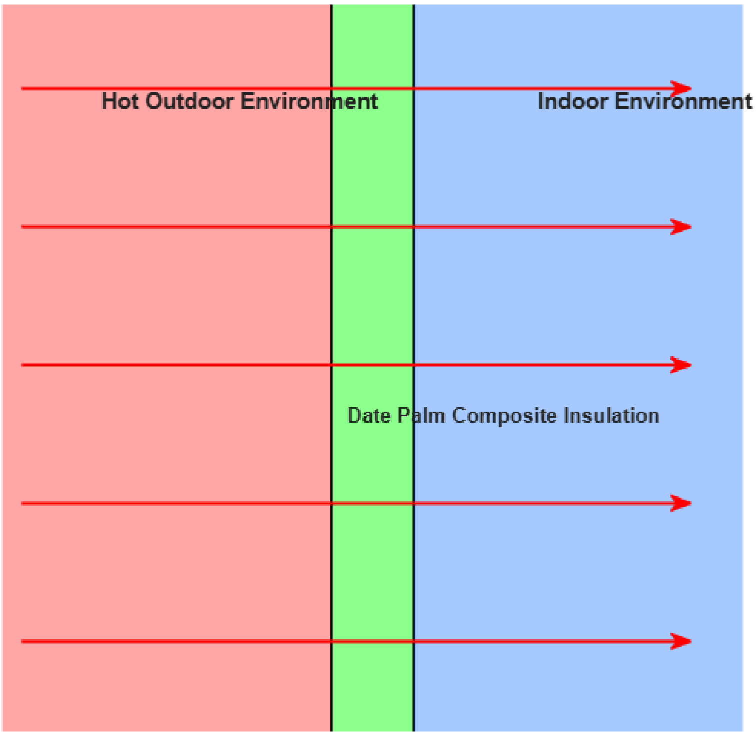


Figure 17. Conceptual application of the developed composite in a building envelope.

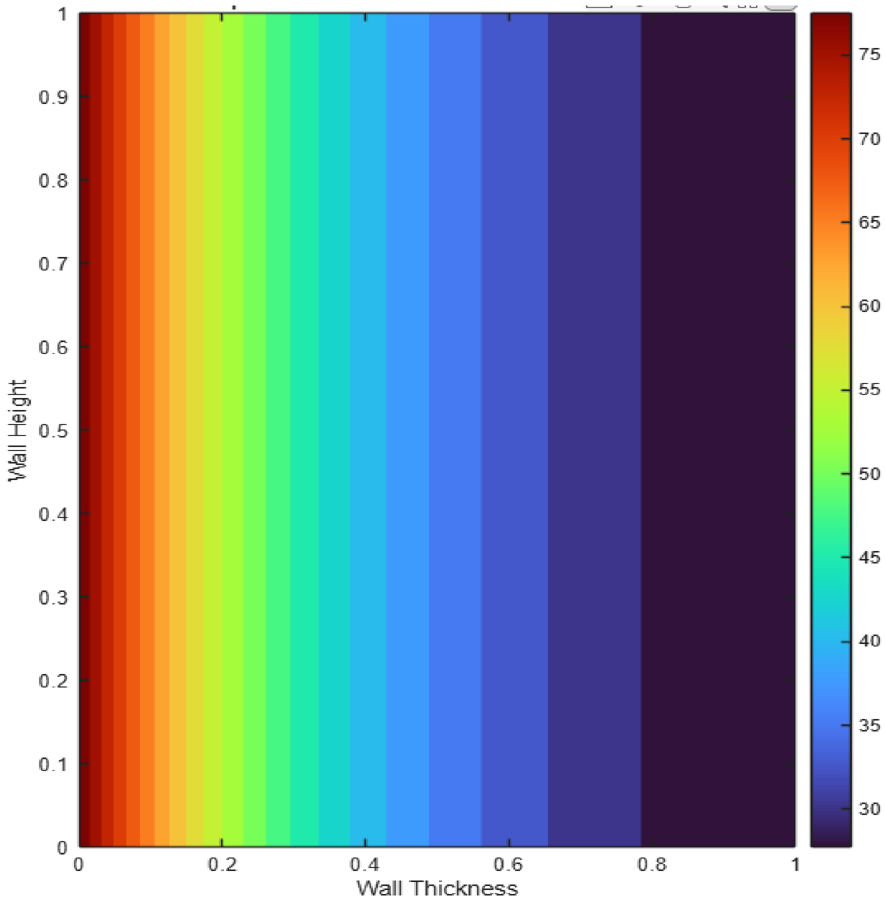
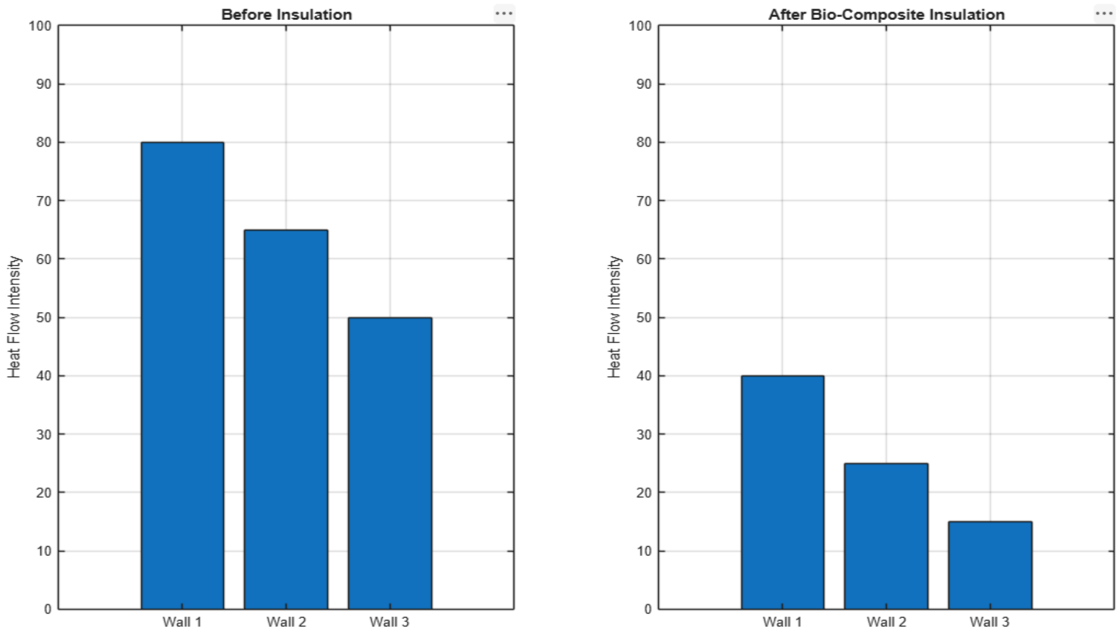


Figure 18. Temperature gradient across an insulated wall incorporating the developed composite.



(a) (b)

Figure 19. Comparison of heat transfer before (a) and after (b) insulation.

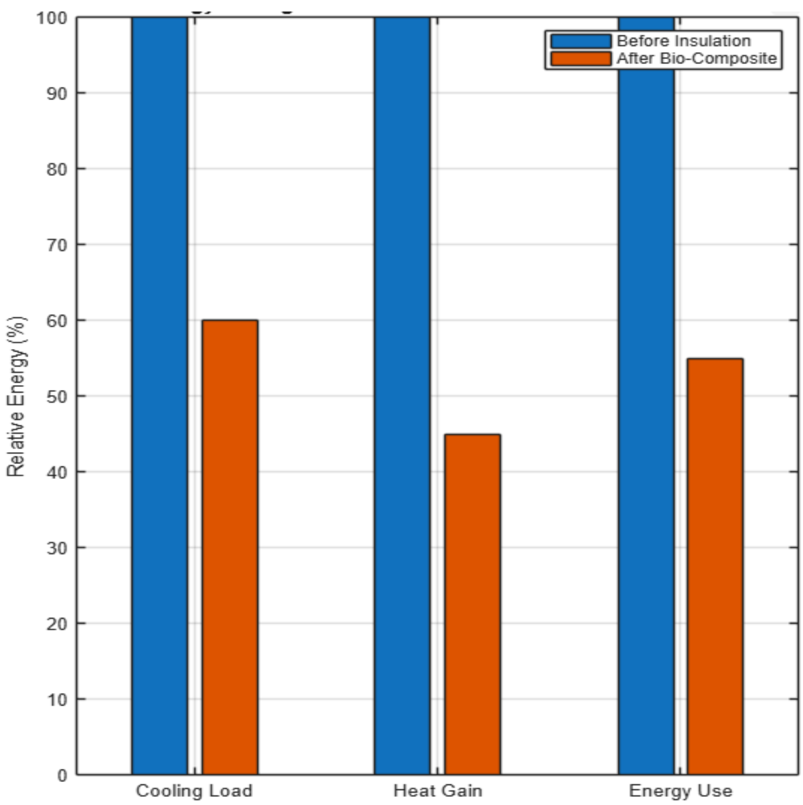


Figure 20. Potential reduction in building energy consumption through improved thermal insulation.

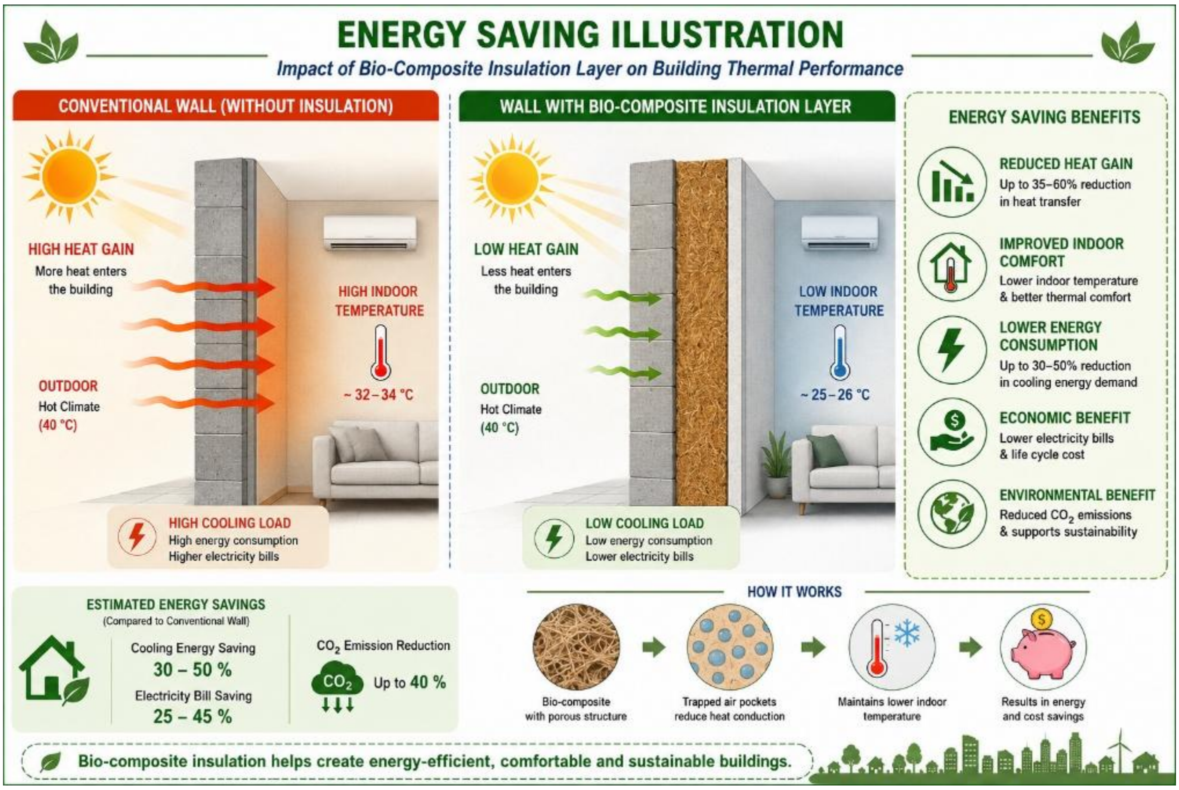


Figure 21. Practical application of the developed composite in sustainable buildings.

The building-envelope model presented in **Figure 17** demonstrates that the developed composite functions as a thermal barrier between the external environment and conditioned indoor space. The experimental results indicate that lower thermal conductivity reduces conductive heat transfer through the wall assembly, thereby minimizing heat gain from the surrounding environment. Such behavior is particularly beneficial for buildings located in hot-climate regions, where cooling energy constitutes a significant portion of total building energy consumption.

The temperature distribution illustrated in **Figure 18** further explains the insulation mechanism. A larger temperature drop across the insulation layer indicates greater thermal resistance and reduced heat transmission through the building envelope. This behavior is consistent with the experimentally measured thermal conductivity and heat-flux results, confirming that the optimized composite effectively suppresses conductive heat transfer. Consequently, the insulation layer helps maintain more stable indoor thermal conditions while reducing the demand for mechanical cooling systems.

The comparison presented in **Figure 19** illustrates the influence of insulation on heat-transfer intensity. Without insulation, heat is transferred more rapidly through the building envelope because continuous conductive pathways facilitate energy transmission from the outdoor environment to indoor spaces. Incorporation of the developed composite interrupts these pathways and increases thermal resistance, thereby reducing the amount of heat entering the building. This improvement contributes directly to lower cooling loads during building operation.

The energy-saving concept shown in **Figure 20** demonstrates the broader significance of the developed material. By reducing conductive heat gain, insulation materials decrease cooling energy demand and improve overall building energy efficiency. Although the present study did not perform whole-building energy simulations, the measured reduction in thermal conductivity indicates that the developed composites possess favorable characteristics for improving thermal performance in building-envelope applications. Future studies may combine experimental material characterization with numerical building-energy analysis to quantify potential reductions in annual energy consumption.

Figure 21 summarizes the practical role of the developed bio-based composite within sustainable construction systems. Beyond improving thermal performance, the use of date palm trunk bark powder provides an effective strategy for converting agricultural waste into value-added engineering materials. This approach supports resource efficiency, promotes waste valorization, and reduces dependence on petroleum-derived insulation products. Consequently, the developed composite contributes not only to improved building energy performance but also to broader sustainability objectives associated with renewable-material utilization and circular-economy practices.

4. CONCLUSION

This study combined bibliometric analysis and experimental evaluation to investigate the thermophysical and mechanical performance of epoxy-bonded date palm trunk bark powder composites for sustainable insulation applications. The results demonstrated that filler loading significantly influenced density, thermal conductivity, heat transfer, compressive strength, water absorption, and microstructural characteristics. The optimum formulation was achieved at an intermediate filler loading because it provided the best balance between thermal insulation, mechanical stability, and moisture resistance. The findings confirm that microstructure plays a more important role than bulk density in governing thermal performance. Therefore, date palm trunk bark powder has strong potential as a renewable insulation material for sustainable building applications and supports the SDGs through agricultural-waste valorization and improved building energy efficiency.

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7. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the paper was free of plagiarism.

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