Ethiopian International Journal of Multidisciplinary Research

pISSN:2349-5707 Volume:13,Issue 2, February -2026 eISSN:2349-5715

# SUSTAINABLE BIO-COMPOSITE INSULATION MATERIALS FOR SANDWICH PANELS PRODUCED FROM AGRICULTURAL WASTE

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**Abstract:** This paper presents a comprehensive theoretical and experimental study on the development of bio-based thermal insulation materials intended for use as core layers of sandwich panels in residential buildings. The composites were produced using locally available agricultural residues, including cotton stalks and cereal straw, combined with a polymeric binder. Particular attention was paid to microstructural design, porosity formation, and heat transfer mechanisms within the material. The developed insulation boards demonstrated thermal conductivity values in the range of $\lambda$ = 0.045–0.060 W/m·K at densities of 210–230 kg/m³, confirming their suitability for energy-efficient and environmentally sustainable housing construction.

**Keywords:** bio-based insulation; agricultural waste; sandwich panels; thermal conductivity; composite materials

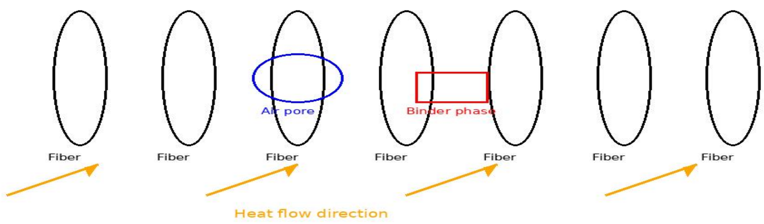
## 1. Introduction

The building sector is responsible for a significant share of global energy consumption, which has intensified research into advanced thermal insulation materials capable of reducing heat losses and greenhouse gas emissions [1,2]. Traditional insulation materials such as mineral wool and polymer foams provide good thermal performance; however, their production is associated with high embodied energy, limited recyclability, and environmental concerns.

Bio-based insulation materials derived from renewable lignocellulosic resources have gained increasing attention due to their lower environmental footprint and compatibility with circular economy principles [3]. Agricultural residues represent an abundant and inexpensive raw material base that remains largely underutilized.

In Uzbekistan, large quantities of cotton stalks and cereal straw are generated annually as by-products of agriculture. These residues are often burned or discarded, causing environmental pollution. Their conversion into value-added thermal insulation materials offers both ecological and socio-economic benefits [4,5].

Figure 1. Bio-based insulation composite microstructure and heat tran



pISSN:2349-5707 Volume:13,Issue 2, February -2026 eISSN:2349-5715

Figure 1. Schematic representation of bio-based insulation composite microstructure and heat transfer pathways.

## 2. Materials and Methods

Cotton stalks and cereal straw were used as lignocellulosic fillers for the production of bio-based thermal insulation composites. The raw materials were mechanically shredded and sieved to obtain fibrous particles with controlled size distribution. Prior to composite fabrication, the fibers were dried in a laboratory oven to a moisture content below 10 wt.% in order to improve bonding quality and processing stability.

A polymeric binder was applied to the dried fibers by spraying under mechanical mixing to ensure uniform distribution and sufficient inter-fiber adhesion. The treated fibers were then formed into mats and subjected to cold pre-pressing, followed by hot pressing using a hydraulic press to obtain consolidated insulation boards.

Thermal conductivity (λ) was measured using a steady-state heat flow meter apparatus in accordance with standard testing procedures. Density was determined from mass-to-volume ratio, and moisture content was evaluated gravimetrically. All measurements were performed on multiple specimens, and average values were reported.

Figure 2. 3D Sequential Technological Flow of Bio-Based Insulation Board Production

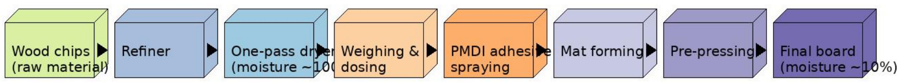



Figure 2. 3D sequential technological flow of bio-based insulation board production.

## 3. Results

The experimental investigation revealed a distinct and reproducible relationship between thermal conductivity and material density for the developed bio-based insulation composites. As the density of the boards increased, a gradual increase in thermal conductivity was observed. This trend is primarily associated with enhanced heat transfer through the solid lignocellulosic phase, which becomes more continuous at higher densities due to reduced pore volume and increased inter-fiber contact.

At lower densities, the composite structure contained a larger fraction of air-filled pores, where heat transfer is dominated by gas-phase conduction and radiative effects, resulting in lower overall thermal conductivity. As density increased, the reduction in porosity and the formation of continuous binder-assisted fiber networks facilitated more efficient conductive heat flow through the solid phase.

An optimal balance between thermal efficiency and structural integrity was achieved at a density of approximately 215 kg/m³, where the composite exhibited a thermal conductivity of $\lambda \approx 0.048$ W/m·K. This value satisfies the technical requirements for thermal insulation core layers in sandwich panel systems used in residential building envelopes. At this density, sufficient mechanical stability was obtained without a significant penalty in thermal performance.

The results indicate that careful control of density and microstructural parameters is crucial for optimizing the thermal behavior of bio-based insulation materials, enabling their effective integration into energy-efficient sandwich panel constructions.

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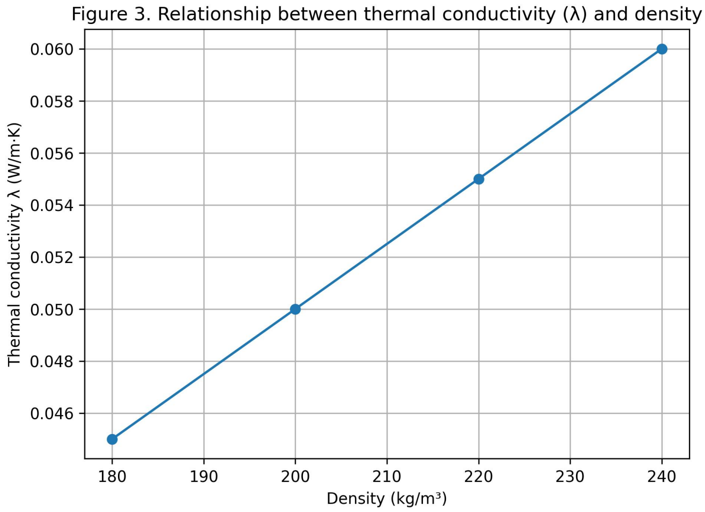


Figure 3. Relationship between thermal conductivity (λ) and density of bio-insulation boards.

## 4. Discussion

The observed increase in thermal conductivity with increasing material density can be attributed to several interconnected heat transfer mechanisms operating within the bio-based composite structure. At lower densities, the material contains a higher proportion of air-filled pores, where heat transfer is predominantly governed by gas-phase conduction and radiation, resulting in reduced overall thermal conductivity. As density increases, the porosity decreases and the continuity of the solid lignocellulosic framework becomes more pronounced, leading to enhanced heat transfer through the solid phase.

Furthermore, the increased amount of polymeric binder at higher densities promotes the formation of binder-induced thermal bridges between adjacent lignocellulosic fibers. These bridges create continuous heat transfer pathways that significantly increase conductive heat flow through the composite. Similar mechanisms have been widely reported in studies on wood-based and natural fiber insulation materials, particularly in research conducted in Belarus and other European countries, where the relationship between density, pore structure, and thermal performance has been extensively investigated [6,7].

When compared to conventional synthetic insulation materials such as expanded polystyrene and polyurethane foams, the developed bio-composite exhibits competitive thermal performance while offering substantial environmental advantages. The use of renewable agricultural residues reduces dependence on fossil-based raw materials, lowers embodied energy, and decreases greenhouse gas emissions associated with material production. In addition, the valorization of agricultural waste streams contributes to improved waste management and supports circular economy principles.

Overall, the results confirm that careful control of density and microstructural architecture is essential for optimizing the thermal efficiency of bio-based insulation composites, enabling their effective application in sandwich panel systems for energy-efficient buildings.

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Figure 4. 3D model of bio-composite insulation board with key parameters

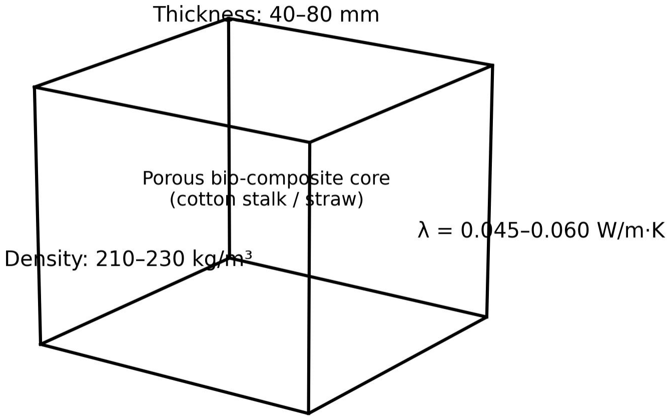


Figure 4. 3D model of bio-composite insulation board with key parameters.

### 5. Conclusions

In this study, a bio-based thermal insulation composite suitable for use as the core layer of sandwich panels was successfully developed using locally available agricultural residues, namely cotton stalks and cereal straw. The obtained results confirm that lignocellulosic waste materials can be effectively transformed into value-added insulation products with stable and reproducible thermal properties.

The developed bio-composites exhibited low thermal conductivity values in the range of $\lambda = 0.045–0.060$ W/m·K at moderate densities of 210–230 kg/m³, which meet the performance requirements for energy-efficient building envelopes. The experimental results demonstrated that thermal conductivity is strongly influenced by density and microstructural architecture, emphasizing the importance of controlled porosity and optimized binder content.

From an environmental perspective, the proposed material offers significant advantages over conventional synthetic insulation products. The use of renewable agricultural residues reduces reliance on fossil-based resources, lowers embodied energy, and contributes to the reduction of greenhouse gas emissions. Moreover, the utilization of agricultural waste supports sustainable waste management practices and aligns with circular economy strategies.

The proposed production technology is characterized by its simplicity, scalability, and adaptability. It can be implemented under laboratory conditions and readily transferred to small-scale industrial manufacturing without the need for complex or energy-intensive equipment. This makes the developed insulation material particularly suitable for regional production and application in developing and transition economies.

Overall, the findings of this study demonstrate the technical feasibility and environmental relevance of bio-based insulation composites for sandwich panel systems, providing a promising pathway toward sustainable and energy-efficient housing construction.

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