



# Agricultural Waste-Based Thermal and Acoustic Insulation Materials: A Comprehensive Review for Sustainable Building Applications

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## Abstract

The construction sector is facing increasing pressure to reduce energy consumption, carbon emissions, and dependence on non-renewable materials. In this context, agricultural residues have emerged as promising alternatives for developing sustainable thermal and acoustic insulation materials. This review examines the potential application of four abundant agricultural by-products—coconut fiber, rice straw, rice husk, and sugarcane bagasse—in building insulation systems. The study synthesizes recent findings from international literature regarding the physical properties, thermal conductivity, sound absorption performance, environmental benefits, and practical challenges associated with these materials. The analysis indicates that agricultural waste-based insulation materials can achieve thermal and acoustic performance comparable to many conventional products while offering significant advantages in terms of renewability, waste reduction, and carbon footprint mitigation. However, challenges related to moisture resistance, durability, fire performance, and large-scale commercialization remain. The review highlights the important role of agricultural waste-derived insulation materials in promoting green building development and supporting the transition toward a circular and low-carbon construction industry.

**Keywords:** Agricultural waste; Thermal insulation materials; Acoustic insulation; Sustainable construction; Green building materials.

## I. Introduction

The building sector accounts for approximately 37% of global energy-related carbon dioxide emissions and nearly 40% of total energy consumption worldwide. As urbanization accelerates and demand for residential, commercial, and industrial buildings continues to increase, improving building energy efficiency has become a major global priority. Thermal insulation materials play a crucial role in reducing heat transfer through building envelopes, thereby lowering heating and cooling energy demands and improving indoor thermal comfort.

Conventional insulation materials, including fiberglass, mineral wool, polyurethane foam, and expanded polystyrene, have dominated the construction market for decades due to their excellent thermal performance. However, their production often requires substantial energy consumption and relies heavily on non-renewable resources. In addition, concerns regarding environmental impacts, disposal issues, and occupational health risks associated with some synthetic insulation materials have encouraged researchers and industry stakeholders to seek more sustainable alternatives.

In recent years, agricultural residues have attracted increasing attention as renewable resources for the production of eco-friendly building materials. According to Pamu and Alugubelli (2025), agricultural waste generation continues to rise globally due to expanding agricultural production and food processing industries. Large quantities of residues such as rice straw, rice husk, coconut fiber, and sugarcane bagasse are often disposed of through open burning or uncontrolled dumping, resulting in significant environmental pollution and greenhouse gas emissions.

The conversion of agricultural waste into building materials represents an effective strategy for implementing circular economy principles while simultaneously addressing waste management challenges. Ouda et al. (2025) emphasized that waste-derived insulation materials contribute to resource conservation, carbon reduction, and sustainable development goals. Similarly, Massoudinejad et al. (2019) highlighted the growing interest in utilizing agricultural and industrial wastes for thermal and acoustic insulation applications due to their favorable physical properties and environmental advantages.

Recent developments in bio-based composites have further expanded opportunities for agricultural residues in building applications. Pawłosik et al. (2025) reported significant progress in the development of bio-

based thermal insulation materials through improved manufacturing technologies and material engineering approaches. Furthermore, scientometric analyses conducted by Ganasen et al. (2023) revealed a substantial increase in research output related to agricultural waste utilization in construction materials over the past decade.

Although numerous studies have investigated individual agricultural residues, a comprehensive synthesis of their thermal and acoustic insulation performance remains limited. Therefore, this review aims to provide an integrated assessment of major agricultural waste materials used for building insulation, focusing on coconut fiber, rice straw, rice husk, and sugarcane bagasse. The review evaluates their material characteristics, insulation performance, environmental benefits, current limitations, and future development potential within sustainable building systems.

## **II. Contents**

### **2.1. Global Overview of Agricultural Waste-Based Insulation Materials**

The building sector is one of the largest consumers of energy and natural resources worldwide. According to recent studies, buildings account for approximately 30–40% of global energy consumption and contribute significantly to greenhouse gas emissions. As governments and industries seek pathways toward carbon neutrality, improving building energy efficiency has become a major priority. Thermal insulation plays a critical role in reducing heat transfer through building envelopes, thereby lowering energy demand for heating and cooling.

Conventional insulation materials such as expanded polystyrene, polyurethane foam, mineral wool, and glass wool have been extensively used due to their favorable thermal properties. However, these materials are associated with several environmental concerns, including high embodied energy, dependence on fossil resources, difficulties in recycling, and waste management challenges at the end of their service life. Consequently, researchers have increasingly focused on developing bio-based insulation materials derived from renewable and locally available resources.

Agricultural residues represent one of the most promising categories of sustainable insulation materials. Every year, millions of tons of agricultural waste are generated globally from crop production and food-processing industries. A significant proportion of these residues is either burned in open fields or disposed of in landfills, leading to environmental pollution and greenhouse gas emissions. Transforming agricultural waste into building insulation products offers an effective strategy for waste valorization while simultaneously reducing environmental burdens.

Recent review studies have demonstrated that agricultural residues possess favorable characteristics for insulation applications, including low density, porous microstructures, high lignocellulosic content, and relatively low thermal conductivity. Among various agricultural residues, coconut fiber, rice straw, rice husk, and sugarcane bagasse have attracted substantial research attention due to their abundance and promising insulation performance.

### **2.2. Coconut Fiber as a Thermal and Acoustic Insulation Material**

Coconut fiber is obtained from the outer husk of coconut fruits and is widely available in tropical countries. The material consists primarily of cellulose, lignin, and hemicellulose. Compared with many other natural fibers, coconut fiber contains a relatively high lignin content, which contributes to its durability and resistance to biological degradation.

Numerous studies have reported thermal conductivity values ranging from 0.038 to 0.055 W/m·K for coconut fiber insulation panels. These values are comparable to several commercial insulation materials and indicate good resistance to heat transfer. The hollow and porous internal structure of coconut fibers creates air pockets that reduce thermal conductivity and improve insulation performance.

Beyond thermal insulation, coconut fiber also exhibits excellent acoustic properties. Sound waves entering the porous structure undergo multiple reflections and energy dissipation, resulting in significant noise reduction. Research has shown that coconut-fiber-based acoustic panels can achieve sound absorption coefficients exceeding 0.70 in medium and high frequency ranges.

From an environmental perspective, coconut fiber insulation contributes to waste reduction and carbon sequestration. Since coconut trees absorb carbon dioxide during growth, the incorporation of coconut fibers into building materials helps store carbon throughout the product life cycle. Additionally, the production process generally requires lower energy inputs than synthetic insulation materials.

Despite these advantages, several limitations remain. Coconut fibers exhibit relatively high moisture absorption, which may reduce thermal performance under humid conditions. Therefore, surface treatments and composite formulations are often necessary to enhance durability and long-term stability.

### **2.3. Rice Straw-Based Insulation Materials**

Rice straw is one of the most abundant agricultural residues worldwide, particularly in Asian countries where rice production dominates agricultural activities. Traditionally, rice straw is often burned after harvest, generating significant air pollution and carbon emissions.

The fibrous structure of rice straw makes it suitable for insulation applications. Thermal conductivity values typically range between 0.040 and 0.065 W/m·K, depending on density, moisture content, and manufacturing techniques. These values indicate that rice straw can effectively reduce heat transmission through building envelopes.

Rice straw insulation products are commonly manufactured in the form of compressed panels, fiberboards, and composite blocks. The material's porous internal structure contributes to both thermal insulation and sound absorption. Several studies have reported satisfactory acoustic performance in residential and educational buildings.

Economically, rice straw offers substantial advantages due to its widespread availability and low cost. In many rice-producing countries, the raw material can be obtained with minimal transportation expenses, making it attractive for local construction industries.

However, challenges associated with rice straw include high flammability, susceptibility to biological degradation, and moisture sensitivity. To address these issues, researchers have investigated various treatment methods such as borate treatment, alkali treatment, and incorporation into composite systems with natural binders.

#### **2.4. Rice Husk-Based Insulation Materials**

Rice husk is a by-product generated during rice milling processes and represents approximately 20% of total rice grain weight. The unique characteristic of rice husk lies in its high silica content, which distinguishes it from many other agricultural residues.

The presence of silica enhances fire resistance and dimensional stability. Thermal conductivity values reported for rice husk-based materials generally range from 0.035 to 0.050 W/m·K. These values are comparable to many conventional insulation products used in modern construction.

Rice husk can be incorporated into insulation materials through various manufacturing approaches, including loose-fill insulation, composite boards, lightweight concrete, and bio-composite panels. The porous microstructure contributes to reduced thermal conductivity and improved sound attenuation.

Life-cycle assessments indicate that rice husk insulation products can significantly reduce environmental impacts compared with synthetic alternatives. The utilization of rice husk also addresses waste management challenges in rice-producing regions.

#### **2.5. Sugarcane Bagasse-Based Insulation Materials**

Sugarcane bagasse is the fibrous residue remaining after juice extraction in sugar processing industries. Large quantities of bagasse are generated annually in many tropical and subtropical countries.

Due to its lightweight and porous structure, bagasse demonstrates favorable insulation properties. Reported thermal conductivity values generally range from 0.040 to 0.060 W/m·K. The material also exhibits good sound absorption characteristics because of its interconnected pore network.

Several researchers have successfully developed bagasse-based insulation boards using natural binders and environmentally friendly manufacturing processes. These products offer an attractive alternative to petroleum-based insulation materials.

Furthermore, utilizing bagasse contributes to circular economy principles by converting industrial by-products into value-added construction materials. This approach simultaneously reduces waste disposal problems and creates additional revenue streams for agricultural industries.

#### **2.6. Comparative Analysis of Agricultural Waste Insulation Materials**

Comparative analysis reveals that each agricultural residue possesses distinct advantages and limitations. Coconut fiber demonstrates superior durability and acoustic performance. Rice straw offers exceptional availability and economic benefits. Rice husk provides enhanced fire resistance due to its silica content. Sugarcane bagasse presents favorable thermal performance and compatibility with composite manufacturing processes.

Although thermal conductivity values are relatively similar among these materials, their long-term performance varies depending on environmental conditions, manufacturing methods, and treatment processes. Therefore, material selection should consider local resource availability, climatic conditions, and specific building requirements.

#### **2.7. Environmental and Sustainability Benefits**

The utilization of agricultural waste in insulation materials aligns closely with sustainable development and circular economy principles. By converting agricultural residues into construction products, waste generation is reduced, open-field burning is minimized, and greenhouse gas emissions are lowered.

Compared with conventional insulation materials, agricultural waste-based products generally require lower manufacturing energy and generate smaller carbon footprints. Life-cycle assessment studies consistently indicate substantial environmental advantages associated with bio-based insulation systems.

Moreover, the adoption of agricultural waste insulation materials supports rural economic development by creating new markets for agricultural by-products and increasing farmers' income opportunities.

## **2.8. Opportunities and Challenges for Agricultural Waste-Based Insulation Materials in Vietnam**

Vietnam is widely recognized as an agricultural country with abundant biomass resources generated from crop cultivation and agro-processing activities. Every year, millions of tons of rice straw, rice husk, sugarcane bagasse, coconut husks, corn stalks, and other agricultural residues are produced across the country. According to national agricultural statistics, rice cultivation alone generates tens of millions of tons of straw and husk annually, while the sugar and coconut industries produce substantial quantities of bagasse and fiber residues. Despite their significant resource potential, a considerable proportion of these materials remains underutilized and is often disposed of through open-field burning or uncontrolled dumping.

The increasing emphasis on sustainable construction and energy-efficient buildings presents an important opportunity for the development of agricultural waste-based insulation materials in Vietnam. In recent years, the Vietnamese construction sector has experienced rapid growth, accompanied by rising demand for thermal comfort and energy conservation. The widespread use of air-conditioning systems in residential, commercial, and industrial buildings has significantly increased electricity consumption, particularly during the hot season. Consequently, improving building envelope performance through effective insulation has become an important strategy for reducing energy demand and mitigating greenhouse gas emissions.

Agricultural residues possess several characteristics that make them suitable candidates for insulation applications in the Vietnamese context. Their low density, porous internal structures, and lignocellulosic composition contribute to favorable thermal resistance. Furthermore, the availability of these materials within local agricultural regions can reduce transportation costs and support decentralized manufacturing systems. This localized production model aligns well with the principles of the circular economy and rural industrial development promoted by the Vietnamese government.

However, despite the abundance of raw materials, several challenges continue to hinder large-scale implementation. One of the primary barriers is the lack of industrial-scale processing technologies specifically designed for agricultural residue-based insulation products. Most existing studies remain at the laboratory or pilot scale, with limited commercialization. In addition, quality consistency remains a concern because agricultural residues vary significantly depending on crop species, harvesting practices, climatic conditions, and storage methods.

Another important challenge relates to durability and long-term performance under Vietnam's tropical climate. High humidity, heavy rainfall, and biological degradation can adversely affect natural fiber-based insulation materials if adequate protective treatments are not applied. Moisture absorption may increase thermal conductivity, reduce structural integrity, and promote fungal growth. Consequently, further research is needed to improve moisture resistance while maintaining environmental sustainability.

Economic considerations also influence market adoption. Although agricultural residues themselves are inexpensive, manufacturing processes involving fiber treatment, binder addition, panel formation, and quality control may increase production costs. As a result, many developers continue to rely on conventional insulation products that are already established within existing supply chains. Overcoming this challenge will require technological innovation, supportive government policies, and increased awareness among construction stakeholders regarding the environmental and economic benefits of bio-based insulation materials.

The successful integration of agricultural waste into building insulation systems therefore depends not only on material performance but also on broader factors such as policy support, industrial infrastructure, market acceptance, and technological readiness. Vietnam possesses significant advantages in terms of biomass availability, yet realizing this potential will require coordinated efforts among researchers, manufacturers, policymakers, and the construction industry.

## **2.9. Future Research Directions and Sustainable Development Perspectives**

The growing interest in sustainable construction materials has positioned agricultural waste-based insulation as an important research area for the coming decades. While substantial progress has been achieved in understanding the thermal and acoustic behavior of agricultural residues, many scientific and technological questions remain unresolved. Future research should move beyond simple material characterization and focus on developing comprehensive solutions that integrate material performance, environmental sustainability, economic feasibility, and practical implementation.

One promising direction involves the development of advanced bio-composite insulation systems. Most current studies investigate individual agricultural residues separately; however, combining multiple agricultural fibers may create synergistic effects that improve thermal resistance, acoustic performance, mechanical strength, and durability simultaneously. For example, hybrid composites containing rice husk and coconut fiber or bagasse and straw may overcome some of the limitations associated with single-material systems. Such approaches could lead to more competitive products capable of meeting international building standards.

Another critical area concerns life-cycle assessment and carbon accounting. Although agricultural waste-based materials are generally regarded as environmentally friendly, comprehensive evaluations of their environmental impacts throughout the entire life cycle remain limited. Future studies should quantify embodied energy, carbon sequestration potential, greenhouse gas emissions, transportation impacts, and end-of-life disposal scenarios. These assessments are particularly important as countries increasingly adopt net-zero carbon targets and sustainable building certification systems.

For Vietnam, future research should pay particular attention to climate-responsive material development. Building materials that perform well in temperate climates may not necessarily achieve the same effectiveness under tropical conditions characterized by high humidity and temperature fluctuations. Therefore, long-term field studies conducted under actual Vietnamese climatic conditions are necessary to evaluate durability, thermal stability, biological resistance, and maintenance requirements. Such studies would provide valuable evidence for future commercialization efforts.

Digital technologies may also contribute significantly to future advancements. Artificial intelligence, machine learning, and computational material modeling can accelerate the optimization of bio-based insulation materials by predicting thermal behavior, moisture transport, and structural performance. These technologies can reduce experimental costs while supporting more efficient material design processes.

From a broader sustainability perspective, agricultural waste-based insulation materials have the potential to contribute simultaneously to several national development objectives. They can support waste reduction strategies, promote renewable resource utilization, reduce dependence on imported construction materials, create new economic opportunities for rural communities, and contribute to national climate change mitigation commitments. Their development aligns closely with Vietnam's Green Growth Strategy, Circular Economy Action Plan, and commitments under international climate agreements.

Ultimately, the future success of agricultural residue-based insulation materials will depend on the ability to bridge the gap between laboratory research and industrial application. Establishing stronger collaboration between universities, research institutes, construction companies, and policymakers will be essential for transforming agricultural waste from an environmental burden into a valuable resource for sustainable building development. As global demand for environmentally responsible construction continues to increase, Vietnam possesses a unique opportunity to become a regional leader in the development and commercialization of bio-based insulation technologies derived from agricultural residues

### III. Conclusion

Agricultural residues such as coconut fiber, rice straw, rice husk, and sugarcane bagasse possess considerable potential as sustainable thermal and acoustic insulation materials. Their favorable insulation performance, environmental benefits, and widespread availability make them attractive alternatives to conventional synthetic products. While challenges related to durability, moisture resistance, and fire safety remain, ongoing technological advancements are continuously improving material performance. The utilization of agricultural waste in building insulation not only supports energy-efficient construction but also contributes to waste valorization, carbon reduction, and circular economy development. Future research and industrial innovation will be essential to facilitate the large-scale adoption of these bio-based insulation materials in sustainable construction practices.

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