Proceedings of ICEGEE 2026 Symposuim: AI-Based Medicine and Biological Data Analysis
DOI: 10.54254/2753-8818/2026.AU33070

Performance-Application Oriented Analysis of Research Progress on Organic Waste Composite Building Thermal Insulation Materials

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Abstract. With the growing demand for low energy consumption and carbon reduction, the application of organic waste composite thermal insulation materials in building energy efficiency has become more practically significant. Therefore, this paper investigates the multiapplication caused by performance differences of various composite materials, and classifies organic waste composite thermal insulation materials into three types: super-insulation, intrinsic flame-retardant insulation, and non-load-bearing structural insulation. These three types take super thermal insulation, intrinsic flame retardancy, and mechanical load-bearing capacity as the core capability, and apply in different scenarios respectively. Future research should focus on the intrinsic flame retardancy of organic wastes, development of green flame retardants, hydrophobic modification strategies, and the establishment of application-oriented systematic evaluation systems. These research measures will enable organic waste composite materials to maintain relatively excellent thermal insulation performance while enhancing their sustainability, flame retardancy, and other properties, so as to adapt to various construction projects and replace most traditional insulation materials.

Keywords: building thermal insulation materials, organic waste, application orientation, sustainability

1. Introduction

As one of the important industries in various countries, the traditional construction industry involves the processing and production of building materials that bring enormous energy consumption and carbon emissions, also cause serious environmental pollution and safety hazards. Especially in the processing and production of high-performance building thermal insulation materials such as polystyrene and so on. Although these materials have good thermal insulation performance, their production process relies on petroleum as a raw , so the process results in a lot of disadvantages such high energy consumption, high carbon emissions, non-fire resistance and flammability. Meanwhile, traditional disposal methods of organic wastes, such as agricultural straw and rice husks, kitchen waste residues, etc, also exacerbate regional pollution and carbon emissions. To solve the pollution and high carbon emission problems caused by the production of high-performance building

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DOI: 10.54254/2753-8818/2026.AU33070

insulation materials, the core breakt hrough lies in finding sustainable processing materials. The emergence of organic wastes provide new ideas and possibilities for changing production raw materials,which not only have strategic significance in addressing energy consumption and low-carbon emission reduction but also realize the reuse of waste resources.

Recent studies have shown that some organic wastes can be compounded with other materials through new processing technologies and methods. According to inherent properties, organic waste will apply in the production and processing of green building insulation materials as fillers, biological substrates, etc. For example, Viel, M. et al., in their preliminary research, first determined the process and material ratio to ensure the bonding effect, then selected three types of hemp-straw composites materials. They compared and analyzed hemp-polysaccharide composites materials from chemical and physical perspectives using scanning electron microscopy (SEM), proving that composites materials have higher mechanical properties than traditional building insulation materials. And the thermal conductivity of composites materials as low as 67.9-69.0 mW/(m·K). This kind of materials reduce energy consumption in construction projects, while their excellent mechanical properties enable them to be used as rigid insulation materials in projects [1]. Pavelek, M. et al. compounded a type of agricultural waste (Brassica napus), with wood chips to form a thermal insulation material. This waste has thermal insulation properties similar to mineral wool, ensuring certain thermal insulation performance, while the easy installation of materials provides designers with design freedom [2]. Sarkar, A. et al. used wheat straw to synthesize a nanocomposite material with low thermal conductivity and used sodium bicarbonate as a flame retardant to enhance its flame retardancy. The excellent hydrophobicity of the nanocomposite enables a material recycling rate up to 90%, providing prospects for bio-insulation materials [3]. However, existing research mostly on the performance improvement brought by technical strategies, rarely consider the changes in application scenarios resulting from the enhancement of different properties. In summary, using organic wastes as raw materials for compounding building insulation materials not only solves the disposal and recycling problems of these organic wastes but also replaces part of the current traditional insulation material processing and production, greatly reducing the energy consumption in the production process. Moreover, due to differences in composite material production technologies, the comprehensive properties of the materials will change.

Based on the above, this paper classifies building thermal insulation composite materials synthesized from organic wastes according to performance-oriented application scenario differences, and divides them into three types: super-insulating, intrinsically flame-retardant, and non-load-bearing structural insulation. It explores how building themal insulation materials compounded from different organic wastes, due to differences in synthesis mechanisms or production technologies, undergo make differences in mechanical properties, flame retardancy, and other aspects, finally leading to different application forms.

2. Analysis of advantages and disadvantages of traditional building thermal insulation materials and international standards

As an important material, thermal insulation materials are used in various fields such as construction, industry, pipelines, and equipment. The core evaluation basis is thermal conductivity and thermal resistance, but different application fields have different standards. This paper discusses themal insulation materials specifically for the construction industry. Currently, compared to other types of insulation materials, building insulation materials, in addition to requirements for thermal insulation performance, focus on energy efficiency and fire safety (personnel safety) or need to meet mechanical performance requirements as needed. According to the International Organization for

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Standardization, in terms of thermal insulation performance, different materials have different thermal conductivity requirements. For example, polyurethane foam has detailed requirements for thermal conductivity according to classification. In terms of mechanical properties, different requirements for compressive strength, closed-cell content, water absorption, etc., exist for different usage scenarios. Even specific requirements exist for certain special materials, such as specific specifications for cellulose foam insulation materials. In terms of thermal insulation performance, they are classified into Class I, Class II, and Class III (30 kg/m^3). For building insulation materials with certain load requirements, compressive modulus, flexural modulus, etc., are also specified.

Before the rise of the circular economy, various building insulation materials were also used. These traditional building insulation materials are suitable for building construction sites in terms of resistance to external stress and flexibility. But, these insulation materials also have problems such as excessively high thermal conductivity, average thermal insulation performance, or poor physical properties, and their production and disposal are prone to causing environmental pollution. For example, the thermal conductivity of mineral wool changes with factors such as temperature and moisture content, leading to increased thermal conductivity [4]; although PUR exhibits relatively excellent thermal insulation performance, the toxic gases released when it burns in a fire pose a great hazard to health [4].

3. Characteristics and applications of organic wastes

Organic wastes generally refer to solid wastes, mainly composed of hydrocarbons and biodegradable materials, generated in agriculture, forestry, industry, and urban life, such as rice husks, straw, sawdust, urban kitchen waste, etc. The chemical composition of such wastes is mainly cellulose, hemicellulose, and lignin. When treating and reusing organic wastes, alkali treatment is usually chosen to extract lignin and cellulose. These two substances extracted from organic wastes will determine the thermal stability, physical properties, mechanical properties, self-adhesion, etc., of the final composite material [5-7].

Lignin is a natural binder within the cell wall, enhancing cell rigidity and the ability to cope with environmental stress. At the same time, its abundant functional groups give it characteristics such as thermal stability, flame retardancy, high hydrophobicity and so on [8]. Many studies on composite materials have shown that a higher lignin content can increase the rigidity of composite materials to use in building load-bearing frameworks, or synthesize composite materials with lower thermal conductivity, providing prospects for thermal insulation materials [9]. As for cellulose, the abundant hydrogen bonds it contains form hydrogen bond networks within and between molecules [8]. Together with van der Waals forces（VDW）, the interaction between polymer chains promotes parallel stacking, forming nanofibers. Pure cellulose is then extracted by mechanical or chemical methods, and nanocellulose aerogels are prepared using sol-gel technology [10]. The addition of cellulose significantly improves the mechanical properties and hydrophobic of aerogels, making aerogels suitable for adsorption or separation materials in pollution treatment. In terms of thermal insulation, although it affects the thermal conductivity of aerogels, they still exhibit excellent thermal insulation performance among a range of materials and can be used as insulation materials in some fields [10,11].

4. Application status of organic waste composite insulation materials

Based on the above studies, organic wastes can be used in the production of building insulation materials. However, the different types and functions of organic wastes lead to differences in

DOI: 10.54254/2753-8818/2026.AU33070

composite material synthesis technologies, resulting in differentiated performance changes, which allow for the division into different application scenarios or fields. According to the changes in application scenarios brought about by performance differences of various composite materials, they are divided into three types: super-insulating, flame-retardant safe, and structural insulation. Based on this classification, this paper will discuss the relevance of performance and application.

4.1. Abbreviations and acronyms

The core performance indicator of the super-insulating type focuses on the thermal insulation performance of the material. Merillas, B. et al. mentioned that taking the thermal conductivity of air as the boundary, when the thermal conductivity of a material is lower than thermal conductivity of air (0.026 W/m·K), it can be regarded as a super-insulating material. Therefore, thermal conductivity is used as the classification standard, and materials with thermal conductivity less than 0.026 W/m·K are classified under the super-insulating type [12]. Among existing organic waste composite building insulation materials, nanocellulose aerogels best meet this standard.

Yueqi Wu et al., in their review on nanocellulose aerogels, indicated that the preparation of nanocellulose aerogels first requires purification of cellulose from biomass raw materials with chemical methods, then nanocellulose treatment through mechanical processing, and finally freeze-drying to prepare aerogels. The thermal conductivity of nanocellulose aerogels can reach 0.018-0.024 W/m·K, exhibiting excellent thermal insulation among various insulation materials, but they show a high tendency to be flammable [13].

Based on the characteristics of nanocellulose aerogels mentioned above, when such materials are to be used as building insulation materials, their flame retardancy and other properties are usually modified. Bhardwaj, S. et al. introduced methyltrimethoxysilane (MTMS) and water-soluble ammonium polyphosphate (APP) to improve crosslinking hydrophobicity and flame retardancy [14]. Poulose, A. et al. mechanically mixed egg shell powder (ESP) with nanocellulose aerogels to prepare ESP-modified cellulose nanofiber aerogels (ESP-CNFA). In vertical flame test, the limiting oxygen index (LOI) of the material reached 32, showing extremely excellent flame retardancy [15].

Currently, super-insulating materials are significantly superior to other types in terms of thermal insulation, but they still require inorganic materials to enhance their flame retardancy. They are suitable for building energy efficiency retrofitting projects or near-zero energy building projects. However, compared to the other two types, super-insulating materials have poorer flame retardancy and mechanical properties, making them unsuitable for volumetric public buildings, civil buildings, and other scenarios.

4.2. Intrinsically flame-retardant type

The intrinsically flame-retardant type mainly refers to utilizing the chemical components in organic wastes to exert flame retardancy. The core classification standard is that without adding additional flame retardants, the material still meets relevant international standards for flame retardancy, such as self-extinguishing time <10 s, LOI ≥30%, and combustion class B1 (difficult to ignite) (ISO 11925-2, ISO 4589-2).

Mitchell Jones et al., in their study, used Trametes versicolor mycelium as a binder and synthesized composite materials with rice husks, fine glass powder, wheat and so on as substrates. They found that for the mycelium composite material with rice husks as the substrate, due to the presence of silica dioxide in rice husks, a silicate barrier layer formed at high temperatures, enhancing the thermal shielding effect, resulting in a peak heat release rate (PHRR) of 133 kW/m²,

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which was 33.5% lower than PHRR of extruded polystyrene foam board (XPS). It exhibited excellent thermal insulation and flame retardancy, while the carbon monoxide emission volume(0.02g) during combustion was the smallest when using rice husks as the substrate [16]. It is suitable for scenarios where fire safety is required but thermal insulation performance requirements are relatively low. Baojuan Deng et al. used vanillic acid to treat eucalyptus fiber as a lignin source, changed the hemicellulose content, and prepared flame-retardant foams by freeze-drying. Utilizing the surface-exposed uncondensed structures of lignin that melt and carbonize in situ at high temperatures, the limiting oxygen index (LOI) of the material reached as high as 51%, and the peak heat release rate (pHRR) was only 24.01 kW/m². Moreover, the material could continuously insulate heat at 220°C for 2 hours, showing good thermal insulation performance [17].

Intrinsically flame-retardant materials have good thermal conductivity performance, and in terms of flame retardancy, they do not require additional inorganic materials as flame retardants. They can be used in scenarios with high flame-retardant requirements, such as fire barrier zones in high-rise buildings. However, some materials under the intrinsically flame-retardant type also possess intrinsic hydrophilicity, and water absorption can seriously affect their durability.

4.3. Non-load-bearing structural insulation type

The core of the non-load-bearing structural insulation type lies in the need for organic wastes to act as a reinforcing phase or skeleton in the composite material, so that the material needs to have high mechanical properties while possessing certain thermal insulation performance, thereby meeting the requirements for non-load-bearing or semi-load-bearing structures. According to international standards, building insulation materials that need to bear certain loads should meet mechanical property requirements such as compressive strength ≥0.5 MPa and flexural strength ≥5 MPa.

Guoqiang Shao et al. used intergenerational cultivation, with Ganoderma lucidum as the raw material and sterilized straw, corn, and wheat as substrates to cultivate mycelium, which was then hot-pressed and air-dried to prepare mycelium composite boards (MBs). After testing, it was found that the thermal conductivity of MBs was 0.13-0.20 W/m·K, much lower than that of polystyrene boards of the same density. In terms of mechanical properties, the compressive strength of MBs was 8.91 MPa, and the elastic modulus was 920 MPa, both higher than international standards, and their mechanical properties were similar to those of gypsum boards [18]. They can be used as internal partition walls or in combination with other high-efficiency insulation materials (aerogels) as composite wall partitions between households. Zhangxin Yu et al. used coniferous virgin pulp paper fibers as reinforcement material, mixed with about 5% wollastonite microcrystalline cellulose, and prepared non-asbestos fiber-reinforced cement boards by autoclave curing. The saturated water flexural strength of this material reached 17.4 MPa, and the thermal conductivity was 0.29 W/m·K. Its mechanical properties are superior to traditional asbestos fiber-reinforced cement boards, with medium thermal insulation performance, suitable for non-load-bearing external wall structures [19].

The thermal insulation performance of non-load-bearing structural insulation materials is not as excellent as that of the other two types, but this type of material has a certain load-bearing capacity, making the structure more complete. It is suitable for prefabricated building interior walls or indoor partitions, ensuring space division while providing certain thermal comfort. However, due to the high thermal conductivity of non-structural insulation types, they cannot meet the efficient insulation requirements of some building projects.

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5. Conclusion

This review paper, based on the "core performance-application" orientation supplemented by "multifunctional properties," classifies building insulation materials synthesized from organic wastes into three types: super-insulating, intrinsically flame-retardant, and non-load-bearing structural insulation. Represented by nanocellulose aerogels, super-insulating materials achieve super-insulating performance through nanotechnologies, and their flame retardancy is enhanced by adding flame retardants, making them suitable for low-energy building projects and other scenarios with extremely high energy efficiency requirements. Represented by rice husk mycelium composites, intrinsically flame-retardant materials utilize chemical components metal oin the raw materials for flame retardancy, achieving excellent flame retardancy, while maintaining good thermal insulation performance. Represented by hot-pressed mycelium boards, non-load-bearing structural insulation materials achieve densification through hot-pressing processes, resulting in giving the material a certain load-bearing capacity for use as internal partition walls to enhance thermal comfort.

The application of organic wastes in building insulation materials, while maintaining the thermal insulation performance required for insulation materials, enriches research on multiple properties of materials, especially in building energy efficiency. Although progress has been made in many aspects, challenges remain. In terms of flame retardancy requirements, improving flame retardancy leads to a certain degree of increase in thermal conductivity and a decrease in green benefits; the hydrophobicity of organic wastes affects the durability of materials.

Therefore, future research should focus on the following aspects: firstly, establishing an application-oriented evaluation system that considers the property changes of building insulation materials in different application scenarios; secondly, focusing on the intrinsic flame retardancy of materials or developing green flame retardants to address the flammability of some materials.

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