



REVIEW ARTICLE

BIODEGRADABLE ALTERNATIVES AND SUSTAINABLE INSULATION: A REVIEW OF LIGNOCELLULOSIC BIOMASS FOR ENERGY-EFFICIENT MATERIALS

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ABSTRACT

This review's objective is to comprehensively gather knowledge and understanding of the production of insulating components for constructions that employ lignocellulose waste. Currently, the construction sector is responsible for over 40% of global energy use. Lignocellulose waste products are abundantly available around the world, and obtaining positive environmental impacts requires their effective repurposing. With a few easy modifications and binders, waste lignocellulosic material may be used right away as a thermal insulator. The requirement for effective thermal insulation, thermal conductivities $< 0.1 \text{ W/m.K}$, is routinely met by these materials. To improve the physicochemical properties of thermoplastics and thermosets and make them appropriate as thermal insulators, lignocellulosic waste can be used as a filler or reinforcement ingredient. This strategy is in line with sustainability standards and allows for the substitution of renewable materials for 30–50% of the polymer content. These investigations also provide thermal conductivity values below 0.1 W/m.K . Furthermore, considering the interest in integrating lignin-based residues into the modification of polymers that break down to create heat-insulating materials, treated lignocellulose, cellulose, and related substances (such as nanocellulose whenever microcrystalline cellulose) may be used as affordable materials for producing biodegradable insulators. This review offers a comprehensive examination and comparison of various strategies, giving researchers ideas for developing new research techniques and filling current knowledge gaps.

KEYWORDS

lignocellulose waste, thermal insulator, microcrystalline cellulose

1. INTRODUCTION

Consumption of power and environmental degradation are two of the 21st century's most pressing issues. A large portion of this issue is related to buildings, which have a detrimental impact on the environment due to their high energy consumption and major contribution to emissions of greenhouse gases (GHG) (Meng et al., 2023). As a result, it is critical to take vital action to resolve this problem.

Because building design has a big influence on the building's overall performance, it needs specific attention, particularly for the early phases (Abolore et al., 2023). The International Energy Agency (IEA, 2019) estimates that buildings account for 28% of related to energy CO₂ emissions and around 30% of worldwide final energy consumption (Prasad et al., 2023). Reducing building energy use is essential to achieving the Goals of Sustainable Development Goal 7, which is the provision of everyone with modern, affordable, reliable, and sustainable energy to everyone. Furthermore, this field of study is crucial to accomplishing Goal 11, which is to promote Sustainable cities and towns improve the quality of life for their residents and reduce their adverse environmental

consequences (Roy and Chundawat, 2023). Thermal insulation materials are essential for lowering energy losses and maintaining the optimal interior temperature in buildings (Güleç et al., 2023). These benefits are quite important as fossil fuels provide the bulk of the world's energy (Mujtaba et al., 2023).

Consequently, insulating materials contribute to lower energy use, which lowers CO₂ emissions and promotes environmental sustainability (Gallego-García et al., 2023). Beyond lowering energy losses, installing insulation has a number of other benefits. It raises the property's value and results in considerable savings on heating and cooling costs (Areeya et al., 2023). By maintaining a consistent temperature and serving as a sound barrier to lessen noise, insulation enhances the indoor atmosphere (Kumar et al., 2023). Additionally, it aids in humidity regulation, which inhibits the growth of mould and improves the longevity of construction materials (Reis et al., 2023).

The switch from conventional insulation materials based on petroleum to biobased alternatives is crucial for making the installation of insulation genuinely green and protecting the environment. There are significant

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environmental benefits to this change, particularly in terms of lower emissions and less garbage going to landfills (Kumar et al., 2023). Bio-based substances, which are often biodegradable, are emerging as sustainable options in insulation, according to recent advancements in the field (Ji et al., 2023). Building insulation requires low heat conductivity, and bio-based insulating materials have performed on par with those derived from petroleum (Rodrigues Reis et al., 2023).

Expanded polystyrene (EPS) as well as extrusions of polystyrene (XPS) are now the most common materials used in insulation, although there are sustainability concerns with their production and disposal (Amesho et al., 2023). Although the foaming processes degrade the ozone layer, polystyrene production generates harmful byproducts and consumes non-renewable resources (Sharma et al., 2023). Due to logistical challenges and limitations on recycling, disposal is often done in landfills. Nonetheless, worldwide recycling initiatives, including EPS recycling, are making headway (Pang et al., 2023).

Bio-based substitutes show promise since they provide similar results with less of an impact on the environment, helping to create a brighter tomorrow (Harrison et al., 2023). In their assessment of agricultural and industrial debris as building insulation materials came to the conclusion that these materials have a number of benefits, such as minimal environmental impact, renewability, recyclability, and biodegradability (Dongare and Pawar, 2023). They concluded that these materials are low-density, low-cost, non-abrasive, and offer good insulation, healthy indoor conditions, and passive indoor environmental management.

To make these sorts of materials comparable to traditional insulators, they recommended that the following areas be addressed: increasing durability, addressing swelling as well as dimensional stability, decreasing moisture absorption, improving water resistance, improving thermal stability, and developing remedies to prevent biological vulnerability to fire, insect species, and mould. Using a comparative life cycle analysis (LCA) and life cycle costing (LCC) study, compared two conventional insulations, EPS and stone wool, with four bio-based insulation materials: wood fibre, hemp fibre, flax, and miscanthus (Rasid et al., 2021). Their study found that wood fibre and miscanthus were the most environmentally friendly bio-based insulations. When it came to expenses, miscanthus and EPS were the most economical choices. Nevertheless, miscanthus's market integration is still somewhat restricted.

In 11 of the 18 environmental effect categories, bio-based insulations fared better than EPS and stone wool, demonstrating their potential to lessen buildings' environmental impact (Mankar et al., 2021). Used xerogels derived from sunflower straw to create low-cost, low-energy, and ecologically friendly thermal insulating materials. Because 3-Aminopropyltriethoxysilane with SiO₂ nanoparticles is added, the xerogels exhibit remarkable mechanical strength, amazing fire resistance, exceptional superhydrophobicity, and a water contact angle of 153.2°. They also have superb thermal insulation (0.0469 W/m.K).

These enhanced characteristics make xerogels made from sunflower straw ideal for a variety of thermal insulation applications, solving the issues with bio-based insulators (Nasar et al., 2022). Developed the substance galactomannan (KGM), the aerogel using a simple freeze-drying technique, producing an environmentally friendly and sustainable biopolymer framework. The bio-based KGM-SiO₂ aerogel material is now a feasible option for green thermal insulation in buildings due to these advancements (Soomro and Ahmad, 2021). They used ammonium polyphosphate, boric acid, and alumina hydroxide as fire retardants and lactic acid, acetic acid, and montan wax as fungicides and water repellents.

Their results showed that adding boric acid greatly enhanced fire performance by reducing the rate at which combustion spread. In spite of extreme circumstances, none of the additions totally stopped the growth of mould, but boric acid successfully reduced it and presented a novel technique for creating eco-friendly, superelastic biomass aerogels without cross-linkers, hence reducing the risk of fire (Sankaran et al., 2020). This procedure involved covering the aerogel surface with a nonflammable siloxane and creating highly oriented wave-shaped layer microstructures. The resulting aerogel demonstrated a wide range of beneficial properties, including low density, hydrophobicity, anisotropic super-elasticity, and strong flame retardancy (Vieira et al., 2020).

Additionally, the aerogel demonstrated outstanding recyclability and amazing oil absorption characteristics, absorbing oil with an efficiency of up to 117 times its weight. For insulation materials to serve their purposes in construction applications, they must possess a variety of desired qualities (Prasad et al., 2023). Minimising energy or gaining it requires extraordinary thermal resistance, particularly as demonstrated by high R-

values along with low U-values. In terms of thermal insulation, the R-value and U-value are essential metrics for evaluating a material's insulating properties. The R-value, which measures thermal resistance, indicates increased insulation simply because it more effectively stops heat movement. Conversely, the U-value measures electrical transmission; a lower U-value indicates better insulation since it allows for less heat transfer. Low U-values and high R-values are ideal for optimal energy efficiency (Lobato-Peralta et al., 2021). In order to maintain its insulating properties and prevent the formation of mould, insulation must also be able to tolerate moisture (Siddique et al., 2021).

However, when utilising insulating materials based on organic elements, mould development might be substantial. This can be lessened by treating organic insulating materials with fungicidal or mould inhibitors to stop the formation of mould. Mould spore proliferation is inhibited by the protective barrier these treatments create (Ehite, 2023). Fire resistance enhances building safety by halting the spread of flames and providing inhabitants with time to leave in the event of a fire (Rajendran et al., 2018). Mechanical properties such as compressive strength and elongation at break are crucial for flexibility and the ability to withstand pressure and deformation (Rahmati et al., 2020).

Additionally, by lowering noise pollution, sound absorption qualities help create acoustically pleasing interior spaces (Kram et al., 2023). Last but not least, eco-friendly features like recyclable properties, non-toxicity, and the use of sustainable or natural resources are increasingly valued in order to encourage environmentally conscious construction methods (Zhang et al., 2021). For the production of insulation, lignocellulosic waste from forestry byproducts and agricultural leftovers provides an affordable option (Guiao et al., 2022). Waste disposal may be minimised, and the environmental effect can be greatly reduced by turning lignocellulosic wastes into insulating materials (Mujtaba et al., 2023).

Interestingly, lignocellulosic wastes are ecologically friendly because they balance the carbon cycle by absorbing CO₂ during photosynthesis (Zhang et al., 2023). Using lignocellulosic biomass also reduces the need for landfilling and prevents harmful activities like burning fields, which release harmful chemicals (Dhara et al., 2023). Another important factor is that when lignocellulosic biomass is used in thermal reactions like combustion, pyrolysis, or gasification for energy purposes, it can release emissions such as carbon monoxide (CO) and carbon dioxide (CO₂), nitrogen oxides (NO_x), particulate matter (PM), organic chemicals (VOCs), and sulphur oxides (SO_x) (Esquivel-Hernández et al., 2022).

Due to the use of regulated chemical compounds that do not produce hazardous gases, low-temperature procedures, and the absence of combustion, the production of insulation using lignocellulosic biomass usually avoids emissions of toxic gases (Pham et al., 2023). The methods also frequently use closed systems, encase the biomass fibres in a binder material, and use air purification techniques to collect any possible emissions (Yoo et al., 2020). Additionally, the fibres are sometimes mixed with polymeric compounds before degradation, which also restricts emissions (Chen et al., 2023). According to studies, this conversion process can improve resource efficiency and lower greenhouse gas emissions by using resources that would otherwise be thrown away, which helps create a more sustainable circular economy (Thi et al., 2016).

Before being employed, lignocellulosic biomass fibres are frequently modified by fibre processing techniques, such as silane and alkaline treatments. For example, date palm fibres were treated with NaOH to strengthen the phenolic resin (Nahak et al., 2022). The findings demonstrated that treated fibre composites had higher flexural and tensile strengths, and that the tensile modulus was markedly enhanced by the treatment.

The influence of silane and peroxide from hydrogen treatments on the fibres of oil palm as well as sugarcane bagasse was examined (Wang et al., 2021). They discovered that the lignocellulosic qualities of thermal insulation materials were improved by silane and hydrogen peroxide treatments. In particular, silane-treated fibres enhanced thermal insulation boards' mechanical performance and interfacial bonding, enhancing their structural integrity.

By analysing two primary strategies that have the chance to completely transform the insulation business, this review article represents a noteworthy advancement in the field of environmentally-friendly insulating materials (Raud et al., 2019). The first strategy investigates the direct application of lignocellulosic waste in conjunction with binders, offering a creative way to recycle trash and turn it into useful insulating materials. In order to recycle waste and create valuable insulating materials, the first technique looks at the direct use of lignocellulosic

material in combination with binders (Fatma et al., 2018). This study goes far beyond by highlighting significant research gaps in addition to providing a comprehensive summary of the most recent advances in this field. In doing so, it serves as a lighthouse for further studies that seek to achieve a number of Sustainable Development Goals (SDGs), including Goal 9 (Industry, Development, Innovation, and Infrastructure) and Goal 12 (Responsible Consumption and Production) (Ullah et al., 2015).

2. LIGNOCELLULOSE AS A SUSTAINABLE FEEDSTOCK

A plentiful and renewable resource, lignocellulose is easily accessible as waste from a variety of sources, including forest biomass, agricultural wastes, and crops grown specifically for energy (Hoang et al., 2021). The International Food and Agriculture Organisation (2021) estimates that there are around 606 gigatons of live plant matter and 59 gigatons of decaying material in the world's forests (Sharma et al., 2019). Around 1.3 billion tonnes of lignocellulosic biomass are produced annually worldwide. Between 370 and 520 million tonnes are produced each year from rice straw, a by-product of rice cultivation. Another important source of lignocellulosic biomass is bagasse, which is produced from sugarcane cultivation in amounts of around 279 million metric tonnes (Rahardjo and Azmi, 2021).

With an annual production of over 739.3 million metric tonnes, Brazil leads the world in production, followed by Pakistan, India and the US (Prasad and Sotenko, 2016). Around 1 billion tonnes of corn stover are produced worldwide each year, and because of its high carbohydrate content, it is a valuable feedstock for a variety of uses (Ab Rasid et al., 2021). This sustainable and promising feedstock has become a competitive alternative for the manufacturing of fuels and value-added goods. Cellulose, a substance called hemicellulose, are the three important biopolymers that make up lignocellulose. While lignin is a complex phenolic polymer that gives plants strength and protective qualities, cellulose, a linear glucose polymer, gives plants structural integrity (Mahmood, Hamayoun, 2019).

The overall structural integrity of plant cell walls is influenced by the heterogeneous polymer hemicellulose (Bharadwaj et al., 2023). Understanding the complex makeup and properties of these biopolymers will help scientists and businesses create effective processes for turning cellulose-based biomass into a variety of environmentally friendly products, chemicals, and alternative energy substitutes, laying the groundwork for a shift to a more resource-efficient and environmentally friendly economy (Malik et al., 2022). Understanding the complex structure and innate resilience of lignocellulosic biomass requires a basic understanding of its constituent parts (Wang and Lee, 2021).

Irrespective of the biomass source, lignocellulosic biomass usually contains all three of these substances in different amounts. As Table 1 illustrates, there are notable differences in the relative proportions of these components (Yang et al., 2023). The majority of lignocellulosic biomass materials are composed mostly of the cellulose fraction. Because of its fibrous structure as well as intermolecular hydrogen bonding, cellulose has an exceptional tensile strength, which makes it excellent for enhancing the mechanical qualities of a variety of goods (Farid and Andou, 2022).

Lignocellulose	Cellulose	Hemicellulose	Lignin	Ref
Rice husk	34	34	25	34
Oil palm waste	60	11	24	34
Cotton stalk	36	20	20	35
Corn cobs	39	40	39	36

3. LIGNOCELLULOSIC INSULATION MATERIALS

Compressing and gluing lignocellulosic fibres to create fibreboards or panels is a popular technique that produces fibreboards with desired sound-absorbing and thermal insulation qualities. To create lightweight, eco-friendly foams with high thermal insulation performance, another strategy is to create foam-like insulating materials utilising lignocellulosic sources, utilising techniques such as chemical modification, biochemical treatment, or blowing agents (Srivastava et al., 2023). Additionally, while maintaining the mechanical strength of polymer composites, adding lignocellulosic elements improves their insulating qualities. Sustainability issues arise when lignocellulosic fibres or particles are mixed with polymers like polyurethane or polystyrene (Periyasamy et al., 2023). In

order to comply with environmental objectives, they also evaluate environmental effects such as carbon footprint, recyclable qualities, and end-of-life concerns. Furthermore, these assessments identify research gaps and offer future possibilities for improving material qualities and resolving present issues (Roy et al., 2021). This thorough knowledge facilitates well-informed policy, investment, and technological development decisions, leading to the advancement of more sustainable and efficient industrial applications and construction practices. Beyond the research mentioned in this section, there are many more on this subject (Pascoli et al., 2022).

The authors have made an effort to incorporate extremely pertinent research, directly related to the approach under discussion, and empirically sound. Recent or highly referenced studies that describe mechanical qualities, density values, and thermal conductivity values were given precedence. This review did not include studies on composites constructed from biodegradable polymers and lignocellulosic fibres that did not report insulating qualities. Furthermore, research was done (Stanley et al., 2022).

Biomass Material	Proximate Analysis (% wt, dry basis)	Ultimate Analysis (% wt, dry basis)
	Moisture	Volatile matter
Wheat husk	4-10	55-60
Sugarcane Bagasse	5-8	65-67
Wood (Softwood)	4-9	65-67
Rice straw	6-9	55-57



Figure 1: DPSF/PVA-based insulators at varying densities (Siddique et al., 2024).

4. BIODEGRADABLE-BASED INSULATION MATERIALS

Natural, renewable resources like plant fibres (like hemp or flax) or recycled and recovered cellulose through biomass wastes are used to make biodegradable insulating materials. These materials are frequently utilised to create composites with biodegradable polymers or mixed with biodegradable binders. They provide a sustainable substitute for traditional insulating materials, lessen reliance on non-renewable resources, and have a minimal lifetime environmental effect (Karamat et al., 2024). Because they support green construction practices and environmental friendliness, these solutions are becoming more and more regarded. A substance is said to be biodegradable if it can naturally break down in the environment, typically as a result of microbial activity. As a result of this breakdown, the material is transformed into simpler, innocuous compounds, including carbon dioxide, water, and biomass (Nasar et al., 2022).

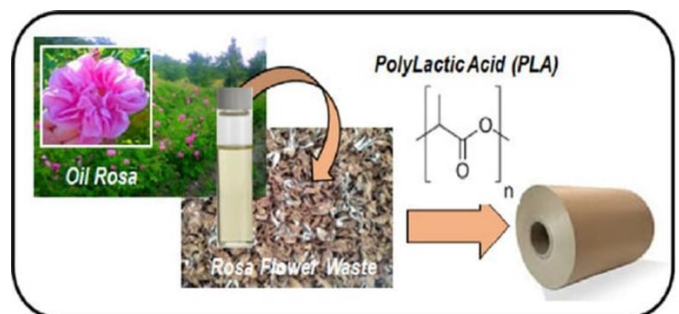


Figure 2: Cylindrical samples consisted of salinised date waste and polylactic acid (Jatoi et al., 2016).

5. CONCLUSION

This study provides a comprehensive analysis of lignocellulosic waste-based thermal insulating materials for buildings. Finding effective energy-saving solutions is essential as the building industry uses over 40% of the world's energy. One possible strategy to solve this issue with beneficial environmental effects is to use readily accessible lignocellulosic waste materials. One technique that does not require complex equipment or major alteration is the combination of lignocellulosic waste with binding agents. But these elements' excessive water absorption and poor mechanical strength frequently restrict their practical uses, necessitating further study in this field. To improve thermoplastic materials' physicochemical qualities as thermal insulators, lignocellulosic waste can also be used as a reinforcing agent or filler. Using renewable alternatives to replace 30–50% of the polymer structure improves practical performance while adhering to sustainability standards. The thermal conductivity of these composites typically ranges from 0.03 to 1.18 W/m.K., and they also offer the benefit of greater mechanical strength.

To address this, scientists are investigating how to improve the characteristics of biodegradable polymers by using lignocellulosic waste. Future research may concentrate on altering lignocellulosic materials to increase their hydrophobicity and enhance their compatibility with thermoplastics and biodegradable materials. Because of their robust mechanical qualities, unsaturated polyester resins (UPR) are frequently utilised in the thermostat industry for thermal insulation in buildings. Enhancing robustness and water resistance through chemical changes and new binding agents should be the top priorities of future research in lignocellulosic-based insulating materials. Developing scalable manufacturing techniques and conducting a thorough assessment of economic viability are necessary for moving from laboratory-scale to industrial-scale production. Widespread adoption requires the establishment of industry standards and certification procedures, which guarantee compliance with performance requirements and building rules by working with regulatory agencies. Additionally, the investigation of new green solvents like Deep Eutectic Solvents (DESs) represents a significant need in the literature at the moment. Natural fibres may be successfully modified by these solvents, increasing their hydrophobicity and strengthening interfacial interactions in insulating composites.

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