INDUSTRY ENVIRONMENT CO_2 EMISSIONS REDUCTIONS WITH BIO-BASED THERMAL INSULATION MATERIALS FROM HEMP AND FLAX

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Abstract
Beyond thermal efficiency, environmental assessment is crucial for evaluating insulation materials in industrial applications. Hemp and flax fiber bio composites offer renewable alternatives to energy-intensive mineral and synthetic insulators. Experimental evaluation confirmed adequate insulation properties, with thermal conductivity ranging from 0.045 to 0.060 W/(m·K) and reliable stability under humidity fluctuations and temperatures up to 200 °C. Life cycle assessment revealed primary energy demand of only 2–7 MJ/kg for bio-based composites, compared to 30–50 MJ/kg for glass fiber. Cradle-to-gate emissions were as low as 1.2–1.4 kg CO_2-eq/kg, while petrochemical composites exceeded 9 kg CO_2-eq/kg. This demonstrates a potential reduction of more than 75% in production-related emissions. Results confirm that hemp and flax composites combine functional insulation performance with significant environmental benefits, supporting industrial decarbonization and the transition towards circular economy solutions.

Keywords: *hemp-flax fiber, life cycle assessment, emissions reduction, industrial insulation*

INTRODUCTION

The industrial and construction sectors are recognized as major contributors to greenhouse gas emissions due to their intensive use of energy and reliance on conventional synthetic materials. Improving insulation practices is one of the most effective ways to enhance energy efficiency and reduce environmental impact. However, traditional insulators such as mineral wool, polystyrene, and polyurethane are linked with high production energy demands and significant carbon footprints *(Asdrubali et al., 2013)*. These drawbacks emphasize the need for sustainable alternatives that can balance performance with ecological responsibility.

Bio-based insulation materials derived from hemp (Cannabis sativa L.) and flax (Linum usitatissimum L.) fibres have emerged as promising options. Their renewable origin, rapid growth cycle, and ability to capture atmospheric carbon during cultivation provide clear environmental advantages *(Maiti et al., 2022; Różańska et al., 2023)*. Research has demonstrated that hemp and flax can be effectively incorporated into composites with properties suitable for industrial and construction insulation *(Collet & Prétot, 2014; Grohe, 2004)*. Advances in fibre processing and biocomposite technology further strengthen their potential for application *(Atmakuri et al., 2022; Stochioiu et al., 2024)*.

The aim of this study is to evaluate the potential of hemp and flax fibre biocomposites as bio-based thermal insulation materials, with particular emphasis on their contribution to reducing CO_2 emissions and supporting sustainable industrial development.

MATERIALS AND METHODS

The evaluation of hemp (Cannabis sativa L.) and flax (Linum usitatissimum L.) fibres for thermal insulation applications was based on findings reported in recent peer-reviewed studies, focusing on both material performance and environmental impact assessments *(Asdrubali et al., 2013; Collet & Prétot, 2014; Grohe, 2004; Mansor et al., 2015; Piekarski et al., 2020)*.

Raw materials considered in the form of fibres obtained through water- and dew-retting, processes that strongly influence fibre quality and insulation capacity *(Różańska et al., 2023; Stochioiu et al., 2024)*.

Composite formulations reinforced with hemp or flax analysed in combination with bio-based and synthetic binders to assess structural and thermal suitability *(Atmakuri et al., 2022)*.

Thermal conductivity testing in the reviewed studies followed internationally recognized standards. Measurements commonly carried by using the hot plate method (ISO 8302), the heat flow meter method (ASTM C518 / ISO 8301), or the guarded hot box method (ISO 8990).

These procedures enabled the determination of steady-state heat transfer characteristics under controlled temperature and humidity conditions, ensuring comparability with conventional insulation materials *(Collet & Prétot, 2014; Grohe, 2004)*. Complementary tests also examined hygrothermal behaviour and stability under elevated temperatures to simulate industrial operating conditions.

For environmental evaluation, life cycle assessment (LCA) data reviewed from studies applying standardized ISO 14040/14044 frameworks. These assessments considered cradle-to-gate system boundaries and quantified primary energy demand and greenhouse gas emissions, enabling direct comparison with mineral wool, polystyrene, and polyurethane insulation *(Mansor et al., 2015; Piekarski et al., 2020)*.

This combined methodological approach integrates standardized thermal testing with environmental performance analysis, offering a comprehensive basis for evaluating hemp and flax composites as sustainable insulation solutions.

RESULTS AND DISCUSSION

CO_2 emission reductions (LCA results). The environmental benefits of hemp and flax insulation materials are most clearly expressed through life cycle assessment (LCA). Hemp and flax fibres capture carbon during growth, resulting in a negative cradle-phase footprint. Recent LCAs demonstrate that hemp-based insulation achieves emissions as low as 1.2–1.4 kg CO_2-eq/kg, compared to more than 9 kg CO_2-eq/kg for polyurethane foam and 6–7 kg CO_2-eq/kg for mineral wool *(Mansor et al., 2015; Piekarski et al., 2020; Benfratello et al., 2013)*. A recent review highlights that bio-based insulators can reduce total embodied emissions in buildings by up to 75% when replacing synthetic alternatives. Moreover, large-scale adoption could contribute significantly to EU climate neutrality targets by lowering demand for petrochemical feedstocks *(Bourbia et al., 2023)*.

Evaluate the extent to which hemp and flax insulation materials contribute to reducing carbon emissions compared to conventional insulation products. The sequestration effect of hemp and flax during cultivation is particularly important. Studies estimate that one tonne of dry hemp fibre can fix up to 1.6–2.0 tonnes of atmospheric CO_2, offsetting a substantial share of production-related emissions *(Maiti et al., 2022; Arrigoni et al., 2017)*. This net balance makes them unique compared to mineral-based materials, which only add to atmospheric CO_2.

Engineering and Material Advances. Engineering properties of hemp and flax composites have advanced significantly. The ai mis to analyse recent technological improvements that enhance the performance, durability, and industrial applicability of hemp and flax composites. Modern processing technologies allow the integration of natural fibres into polymer matrices, improving their mechanical strength, water resistance, and durability. Hybrid composites reinforced with hemp or flax and combined with biopolymers such as polylactic acid (PLA) have demonstrated mechanical performance comparable to glass fibre composites while reducing CO_2 emissions by more than 80% *(Palumbo et al., 2018)*.

Processing innovations such as enzymatic retting and mechanical refining have improved fibre quality and consistency *(Różańska et al., 2023)*. Additionally, new flame-retardant bio-based coatings have been developed, addressing one of the primary barriers to industrial adoption *(Brischke & Meyer-Veltrup, 2021)*. These advances enable hemp and flax composites to move beyond niche use and enter more demanding applications such as pipeline insulation and industrial thermal barriers.

Thermal Insulation Efficiency. Most important is to compare the results of thermal performance of hemp and flax composites with widely used synthetic and mineral insulation materials. Thermal conductivity is a critical factor in insulation performance. Hemp and flax composites consistently achieve values in the range of 0.040–0.060 W/(m·K), directly comparable to mineral wool (0.035–0.045 W/(m·K)) and expanded polystyrene (0.033–0.040 W/(m·K)) *(Collet & Prétot, 2014; Asdrubali et al., 2013; Dämmgen et al., 2019)*.

While mineral-based insulators slightly outperform in terms of conductivity, natural fibres provide superior hygrothermal regulation. They buffer indoor humidity and stabilize microclimates, reducing the risk of condensation *(Palumbo et al., 2016)*. Industrial tests confirm that hemp and flax insulation remain stable under temperatures up to 200 °C, making them viable for pipeline and equipment insulation *(Grohe, 2004; Latapie et al., 2023)*.

Performance can be optimized through densification and binder selection. For instance, hemp shiv–lime composites have been shown to maintain conductivity around 0.050 W/(m·K) while providing additional fire resistance *(Benfratello et al., 2013)*. Thus, while synthetic foams provide lower conductivity, the overall performance profile of hemp and flax materials remains competitive when sustainability and moisture regulation are considered.

Sustainability and Circular Economy. One of the main advantages of hemp and flax insulation is their alignment with circular economic principles. This is the way to highlight the role of hemp and flax insulation materials in supporting circular economic strategies and sustainable industrial practices. These fibres are renewable, biodegradable, and often locally sourced, reducing transportation emissions *(Maiti et al., 2022)*. At end of life, hemp and flax composites can be composted or recycled into new insulation panels, unlike petrochemical foams which typically end up in landfills *(Papadopoulos, 2005)*. The integration of hemp and flax into industrial applications also supports rural economies and agricultural diversification, providing additional socio-economic benefits *(Bourbia et al., 2023)*. Moreover, using agricultural residues for insulation production further reduces waste and maximizes resource efficiency *(Deng et al., 2022)*.

Tab. 1 Comparison of Hemp/Flax Insulation with Conventional Materials

Material type	Thermal conductivity (W/m·K)	Primary energy demand (MJ/kg)	CO_2 emissions (kg CO_2-eq/kg)
Hemp fibre composite	0.045-0.060	2-7	1.2-1.4
Flax fibre composite	0.045-0.060	3-6	1.3-1.6
Mineral wool	0.035-0.045	30-50	6-7
Expanded polystyrene	0.033-0.040	70-85	9-10
Polyurethane foam	0.030-0.035	80-95	>9

Hemp and flax composites show thermal conductivity values between 0.045–0.060 W/m·K, which are slightly higher than synthetic foams such as polyurethane (0.030–0.035 W/m·K) and expanded polystyrene (0.033–0.040 W/m·K), but comparable to mineral wool (0.035–0.045 W/m·K) . This demonstrates that bio-based insulation achieves similar thermal efficiency for most industrial and construction applications *(Collet & Prétot, 2014; Asdrubali et al., 2013; Dämmgen et al., 2019)*.

In terms of environmental performance, hemp and flax are far superior. Their primary energy demand (2–7 MJ/kg) is substantially lower than that of mineral wool (30–50 MJ/kg) or synthetic foams (>70 MJ/kg). Moreover, their CO_2 emissions (1.2–1.6 kg CO_2-eq/kg) are up to seven times lower than mineral wool and almost ten times lower than polyurethane *(Mansor et al., 2015; Piekarski et al., 2020; Benfratello et al., 2013)*. Importantly, hemp and flax additionally sequester carbon during growth, which is not reflected in these figures, further improving their net climate impact.

From a functional perspective, hemp and flax insulation offers moisture regulation, recyclability, and biodegradability, while conventional materials are less sustainable, often requiring energy-intensive processing, furthermore synthetic foams slightly outperform bio-based materials in conductivity, hemp and flax composites provide a more balanced profile when considering thermal performance, environmental sustainability, and circular economy potential.

CONCLUSIONS

Hemp and flax fibre biocomposites demonstrate strong potential as sustainable thermal insulation materials. They provide comparable thermal performance to conventional insulators while offering clear advantages in reducing embodied energy and CO_2 emissions. Advances in fibre processing and composite reinforcement further enhance their technical reliability, enabling wider industrial application. While challenges such as fire resistance and long-term durability remain, these materials support both climate change mitigation and circular economy goals. Overall, hemp and flax composites represent a viable pathway toward more sustainable industrial insulation practices.

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