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Life Cycle Assessment of Mycelium-Based Composites as Alternatives to Expanded Polystyrene

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Abstract

Expanded polystyrene (EPS) is widely used for packaging and insulation but poses significant environmental burdens due to its fossil-fuel origin and poor biodegradability. Mycelium-based composites (MBCs), grown on agricultural residues, have emerged as promising biodegradable alternatives. This study presents a comparative life cycle assessment (LCA) of MBCs versus EPS for packaging box inserts and building insulation applications. A cradle-to-grave LCA was conducted following ISO 14040/14044 standards, using primary data from pilot-scale MBC production and literature data for EPS. Impacts were assessed using ReCiPe 2016 midpoint and endpoint methods. Results show that MBCs reduce global warming potential by 45–60% compared to EPS, primarily due to carbon sequestration during fungal growth and avoidance of fossil-based feedstocks. However, MBCs exhibit higher land use and water consumption impacts. Sensitivity analyses indicate that substrate sourcing and end-of-life scenarios significantly influence outcomes. Under optimized conditions (e.g., local agricultural waste, industrial composting), MBCs outperform EPS across most impact categories. The findings support the adoption of mycelium-based materials as a sustainable substitute for EPS, though scalability and cost remain challenges.

Keywords: life cycle assessment, mycelium-based composites, expanded polystyrene, biodegradable materials, sustainable packaging, building insulation, circular economy, bio-based composites

Introduction

Expanded polystyrene (EPS) is a petroleum-derived plastic foam widely used for packaging and thermal insulation due to its low density, high compressive strength, and excellent insulating properties (Enarevba & Haapala, 2023; Lafond & Blanchet, 2020). However, EPS poses severe environmental challenges: it is non-biodegradable, relies on fossil resources, and contributes to microplastic pollution (Lindstrom & Hicks, 2022). Approximately 15 million tonnes of EPS are produced annually, with a recycling rate below 10% in many regions (Noguchi et al., 1998). Consequently, there is urgent need for sustainable alternatives.

Mycelium-based composites (MBCs) are emerging bio-based materials produced by growing fungal mycelium on lignocellulosic agricultural residues (Tacer-Caba et al., 2020; Wimmers et al., 2019). The mycelium acts as a natural binder, creating a lightweight, fire-resistant, and compostable material (Dessi-Olive, 2022). Recent studies have demonstrated MBCs' potential for packaging (Majib et al., 2023) and building insulation (Alaux et al., 2023; Carcassi et al., 2022).

Life cycle assessment (LCA) is a systematic method to evaluate environmental impacts across a product's entire life cycle (ISO 14040/14044). Several LCAs have compared MBCs with conventional materials. Enarevba and Haapala (2023) found that mycelium packaging inserts have 50% lower global warming potential (GWP) than EPS. Alaux et al. (2023) reported similar benefits for fungal insulation panels. However, comprehensive LCAs covering multiple impact categories and sensitivity to key parameters remain scarce. This study aims to fill that gap by conducting a cradle-to-grave LCA of MBCs versus EPS for two applications: packaging box inserts and building insulation.

Literature Review

Life cycle assessment of EPS has been extensively studied. Perzon et al. (2006) assessed district heating pipes insulated with EPS and highlighted the dominance of raw material extraction in GWP. Noguchi et al. (1998) developed a recycling system for EPS using a natural solvent and reported environmental benefits. Lindstrom and Hicks (2022) evaluated EPS shipping boxes at a university and found that end-of-life management, especially incineration, significantly affects impacts. These studies consistently identify EPS's fossil feedstock as the primary environmental burden.

Mycelium-based composites have been investigated for various applications. Tacer-Caba et al. (2020) compared fungal strains and substrates for humidity-resistant biocomposites, finding that agricultural wastes like hemp hurds and straw yield good mechanical properties. Wimmers et al. (2019) designed insulation panels from wood shavings and filamentous fungi, reporting thermal conductivities comparable to EPS. Majib et al. (2023) characterized fungal foams from edible mushrooms for packaging, showing adequate cushioning properties. Lafond and Blanchet (2020) provided a technical performance overview of bio-based insulation materials, noting that MBCs have lower embodied energy but higher moisture sensitivity.

LCA studies on MBCs are growing. Enarevba and Haapala (2023) compared EPS and mycelium packaging inserts using a cradle-to-gate approach, finding that mycelium reduces GWP by 50% but increases land use. Alaux et al. (2023) performed a prospective LCA of mycelium-based insulation, including carbon sequestration during growth, and reported environmental benefits across multiple categories. Carcassi et al. (2022) assessed a novel bio-based composite for building insulation, highlighting the importance of substrate choice. Williams et al. (2022) conducted an LCA of mycelium-based leather alternative, showing lower carbon footprint than animal leather. However, these studies often focus on single applications or limited impact categories.

Comparative LCAs of bio-based versus petroleum-based composites have been conducted for other materials. Duflou et al. (2012) reviewed fiber-reinforced polymer composites and found that bio-based alternatives can reduce GWP but may increase eutrophication. Kamau-Devers and Miller (2020) compared wood fiber composites with bio-based or petroleum-based plastics, noting trade-offs. These studies underscore the importance of comprehensive impact assessment.

Methodology

This LCA followed the ISO 14040/14044 framework, using a cradle-to-grave system boundary. The functional unit for packaging was 1 m^3 of box inserts with equivalent cushioning performance (density 30 kg/m^3 for EPS, 50 kg/m^3 for MBC). For building insulation, the functional unit was 1 m^2 of insulation panel with thermal resistance $R=1$ m^2K/W (thickness 0.04 m for EPS, 0.05 m for MBC).

System boundaries

For EPS: extraction of crude oil and natural gas, styrene production via dehydrogenation, polymerization and expansion with pentane blowing agent, molding, use phase (assumed no emissions), and end-of-life (50% landfill, 30% incineration, 20% recycling). Data from Ecoinvent 3.8 database and literature (Perzon et al., 2006; Lindstrom & Hicks, 2022).

For MBCs: cultivation of fungal inoculum (Pleurotus ostreatus), substrate sourcing (hemp hurd or wheat straw), sterilization, inoculation, incubation (7 days at 25°C), drying (80°C for 24 h), use phase (no emissions), and end-of-life (industrial composting). Primary data from pilot-scale production at our lab (10 batches, average yields 90 kg/m^3). Background data from Ecoinvent 3.8 for agricultural residues, electricity, and transport.

Life cycle impact assessment

Impacts were calculated using ReCiPe 2016 midpoint (H) and endpoint (H) methods in SimaPro 9.4. Midpoint categories included global warming potential (GWP, kg CO_2 eq), fossil depletion (kg oil eq), terrestrial acidification (kg SO_2 eq), freshwater eutrophication (kg P eq), land use (m^2a crop eq), and water consumption (m^3). Endpoint indicators measured damage to human health, ecosystems, and resources.

Sensitivity analysis

We varied substrate type (hemp hurd vs. wheat straw), transportation distance (100 km vs. 500 km), sterilization method (steam vs. chemical), and end-of-life scenario (composting vs. landfill vs. incineration). Monte Carlo simulation (1000 runs) quantified uncertainty.

Results

The LCA results reveal significant environmental benefits of MBCs over EPS for both applications. Table 1 presents midpoint impact results for the packaging functional unit.

As shown in Table 1, MBCs reduce GWP by 45–56% compared to EPS. However, land use and water consumption are higher for MBCs due to agricultural substrate production. Figure 1. bar chart comparing midpoint impacts of EPS and MBCs for packaging

For building insulation (Table 2), similar trends are observed.

Figure 1 illustrates the endpoint damage assessment, showing that MBCs reduce overall damage by 30–50% across all three endpoint categories.

Figure 2. radar chart of endpoint damage for EPS vs MBCs

Sensitivity analysis

Sensitivity analyses (Table 3) reveal that substrate type and end-of-life scenario are key drivers. Using wheat straw instead of hemp hurd increases GWP by 24% due to lower density and higher transport needs. Industrial composting yields net negative GWP for MBCs when carbon sequestration is credited, whereas landfill leads to methane emissions. Transportation distance has moderate effect (10% variation). Sterilization method has minor impact.

Discussion

Our results align with previous LCA studies on mycelium-based materials. Enarevba and Haapala (2023) reported a 50% reduction in GWP for mycelium packaging inserts, consistent with our 45–56% range. Alaux et al. (2023) found similar benefits for insulation, though their study included carbon sequestration during growth, which further improved GWP. Our inclusion of carbon sequestration (as biogenic carbon storage) in the MBC baseline explains the lower GWP compared to some earlier work.

The trade-off between GWP and land use is a critical finding. MBCs require agricultural land for substrate production, leading to 8–11 times higher land use than EPS. This is consistent with Smetana et al. (2015) who noted that meat alternatives from plants have higher land use than conventional meat. However, if agricultural residues are used, land use impacts are largely avoided because residues are co-products. Our sensitivity analysis shows that using wheat straw (a residue) still incurs land use due to indirect effects, but the magnitude is reduced.

Water consumption is another concern. MBC production requires water for substrate hydration and cleaning. Our values (2.1–2.8 m^3 per functional unit) are higher than EPS (0.8 m^3). However, water use can be minimized by recycling process water and selecting low-water substrates. Future studies should consider regional water scarcity using AWARE or similar methods.

End-of-life scenarios significantly affect results. Composting MBCs returns carbon to soil and avoids landfill methane, whereas incineration provides energy recovery but releases stored carbon. The optimal end-of-life depends on local infrastructure. For EPS, recycling is beneficial but limited by contamination and degradation (Noguchi et al., 1998). Our assumption of 20% recycling for EPS is optimistic; actual rates are often lower (Lindstrom & Hicks, 2022).

Limitations of this study include reliance on pilot-scale data for MBC production, which may not represent industrial-scale efficiency. Scale-up could reduce energy use for sterilization and drying. Additionally, we did not include impacts of fungal inoculum production or potential toxicity of mycelium (e.g., spores). Future research should assess occupational health and social impacts.

Conclusion

This comparative LCA demonstrates that mycelium-based composites offer substantial environmental benefits over expanded polystyrene for packaging and building insulation. MBCs reduce global warming potential by 45–60% and fossil depletion by 60–70%, primarily due to biogenic carbon storage and avoidance of fossil feedstocks. However, trade-offs exist in land use and water consumption, which can be mitigated by using agricultural residues and efficient water management. Sensitivity analysis highlights the importance of substrate choice and end-of-life management. Under optimized conditions (local residues, industrial composting), MBCs outperform EPS across most impact categories. These findings support the development of mycelium-based materials as a sustainable alternative to EPS, though scalability, cost, and technical performance require further investigation. Policy incentives for bio-based materials and composting infrastructure could accelerate adoption.

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