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Evaluating net-GWP benefits of mycelium-based composites in traditional timber frame construction systems

D Sáez[1], D Márföldi[2] and M Trautz[1]

[1] Chair for structures and structural design, RWTH Aachen University, Germany

[2] Marcell Breuer Doctoral School of Architecture, University of Pécs, Hungary

E-mail: saez@trako.arch.rwth-aachen.de

Abstract. One of the main environmental challenges the construction industry faces nowadays is the massive outsourcing of resources for material production. In this realm, mycelium-based composites (MBC) emerge as a promising solution, offering a renewable and biodegradable option for construction materials. MBCs are produced by cultivating filamentous fungal strains on lignocellulosic substrates, which enables the utilization of local agricultural or industrial waste. Moreover, MBCs exhibit a rapid growth cycle, allowing for faster biomass production than conventional renewable materials such as timber, which require years to mature. This unique characteristic of MBCs positions them as an innovative and scalable alternative for sustainable construction. This study conducts a cradle-to-gate life cycle assessment (LCA) of MBC, supplemented by partial analysis of end-of-life phases (C2-C4) and recycling potential (D), for their application in sandwich panels within timber frame construction systems. The LCA assesses the environmental impact of producing 1 m^3 of MBC using a waste-sourced spruce wood substrate, focusing on Global Warming Potential (GWP), conducted per DIN EN ISO 14044:2021-02 and EN 15804 standards. Different end-of-life (EoL) scenarios were considered: recycling MBCs into new production cycles and down cycling as soil amendments. Using a waste-derived substrate that acts as a biogenic carbon sink alongside these EoL scenarios positively impacts the net-GWP values of MBC. The results of the LCA are compared against two conventional sandwich panel core materials based on information included in Environmental Product Declarations (EPD). The benchmarking compares GWP and reference service life (RSL), showing that MBC generally achieves a lower net GWP across most life cycle stages. However, further investigation is needed to understand the feasibility of industrial-scale MBC production.

1 Introduction

1.1 Mycelium-based composites as carbon sink solutions

The construction industry is one of the most significant contributors to global greenhouse gas emissions, mainly due to the extensive outsourcing of raw materials and energy-intensive production processes.

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The urgent need to reduce embodied carbon in construction has led to a growing interest in alternative materials with lower embodied emissions, which can significantly reduce the sector's overall carbon footprint.

Bio-based materials of plant origin, such as timber, hemp, straw, or bamboo, capture CO_2 from the atmosphere during their growth phase, acting as carbon sinks [1]. Through photosynthesis, these materials store atmospheric carbon in their biomass, delaying its release until the end of their life cycle. This unique characteristic makes them a promising alternative to conventional construction materials.

Carbon sink materials, or climate-negative materials, sequester more carbon than they emit. MBCs, cultivated from filamentous fungi on lignocellulosic substrates, often sourced from agricultural or industrial waste, are a promising sustainable construction alternative. This approach reduces reliance on non-renewable resources and enhances carbon sequestration, as MBCs store atmospheric carbon from their feedstock. Their rapid growth cycle sets them apart from conventional biomass, like timber, which takes decades to mature for construction purposes.

1.2 Assessing MBC beyond insulation

Most existing LCA studies on MBCs focus on insulation, evaluating their GWP in building envelopes. However, MBCs also offer load-bearing potential in constructive systems. This study fills a research gap by examining MBC use in a traditional timber frame. It focuses on a sandwich-like structural panel, where the MBC core is bonded to side plates through the so-called bio-welding, a unique material property of mycelium. Also, the binding property of MBC on the CLT-Plates has a bracing effect on the system's surface[2]. The MBC core is cultivated using *Ganoderma lucidum* fungal strains on lignocellulosic substrates of wood chips sourced from a local sawmill (spruce and Douglas fir). This research quantifies the net-GWP benefits of MBC when applied as a structural component rather than an insulation material, further exploring its potential as a substitute for conventional sandwich panels.

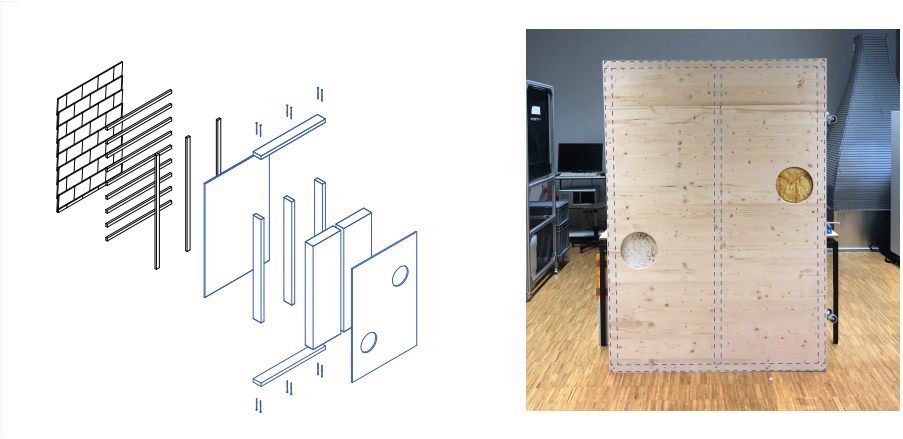

Figure 1: MBC implementation in traditional timber frame system. Left: exploded axonometric drawing of the assembly with the assessed elements in blue; right: photo of a 1:1 scale demonstrator, on the left side with MBC core and on the right glass wool (GW) core.

1.3 Biogenic carbon modeling

The calculation of biogenic carbon in LCA is particularly challenging due to the need to consider both the mycelium growth phase and the growth period of its lignocellulosic substrate. Traditional static carbon accounting methods assume carbon neutrality, where the CO_2 absorbed during biomass growth is fully released at the EoL. However, dynamic LCA models introduce a more nuanced approach by factoring in carbon sequestration timing, material lifespan, and delayed emissions from reuse or recycling scenarios.

For MBCs, this complexity is heightened as the biogenic carbon footprint must account not only for the rapid regrowth of mycelium but also for the more extended regrowth period of the lignocellulosic substrate, in our case, spruce, and Douglas fir. While hemp or straw substrates can regenerate in one year, making them attractive for fast carbon sequestration cycles, this study intentionally uses wood chips sourced from the timber industry as a waste-derived substrate.

Germany produces approximately 21 million cubic meters of sawn timber and 14.5 million cubic meters of engineered wood products annually, highlighting the availability of post-industrial wood leftovers

[3]. The rotation period of different tree species varies significantly, with poplar requiring 30–50 years, birch 60–80 years, and Douglas fir 60–100 years. While Douglas fir, from a biogenic carbon modeling perspective, offers a higher CO_2 sequestration potential, spruce is more widely produced in Germany, making it a more practical and readily available substrate for industrial applications.

This study uses a dynamic LCA (dLCA) approach to model temporal carbon fluxes accurately. It assesses carbon uptake pre- and post-harvest, offering a precise net-GWP representation of MBC in timber frame construction. By integrating the substrate's long-term carbon cycle and mycelium's short-term regrowth, this method comprehensively assesses biogenic carbon storage and emissions over the material's life cycle.

1.4 End-of-life and module D considerations in LCA

This paper evaluates the net-GWP of MBC in timber frame construction through a cradle-to-gate LCA, including partial EoL analysis (C2-C4) and benefits beyond the system boundary (Module D)**.** Many LCA studies on MBC only assess cradle-to-gate, neglecting carbon savings or emissions from material disposal and recovery. Environmental impacts extend beyond production, requiring the assessment of EoL scenarios for long-term sustainability. In LCA, Module C covers deconstruction, transport, disposal, and waste treatment (C1-C4). At the same time, Module D addresses benefits beyond system boundaries. This study considers only C2- C4 phases, including energy recovery incineration (D_hr), particle board production (D_pp), recycling for MBC production (D_MBCp), and recovery as soil amendments (D_sa).

Moreover, by benchmarking the MBC-based timber system against conventional sandwich panel materials using EPDs, this research aims to provide insights into the feasibility of MBC as a scalable, low-carbon alternative in construction. Unlike conventional sandwich panel core materials (see Table 1), which often rely on synthetic foams or high-energy processing, MBC is bio-based and can be repurposed or reintegrated into biological cycles, potentially reducing long-term carbon emissions.

2 Methods

2.1 LCA framework

The LCA was conducted according to DIN EN 14044:2021 [4]. The examination included the scope definition and data collection for the life cycle inventory analysis (LCI) covering selected environmental impact categories. It also encompassed the evaluation of the life cycle impact assessment (LCIA) and the elaboration of EoL scenarios, highlighting the benefits beyond the system boundaries, namely the possible recycling and recovery potentials of the material after its functional use. The environmental impacts of the collected data were calculated in the OpenLCA 2.2.0 software. The LCIA evaluated the environmental impacts of the examined life-cycle stages based on the Ecoinvent 3.10 dataset [5]. Since some flow categories were not incorporated in the Ecoinvent database, it was supplemented by the Agribalyse 3.1.1 [6] database.

2.2 Scope of the LCA

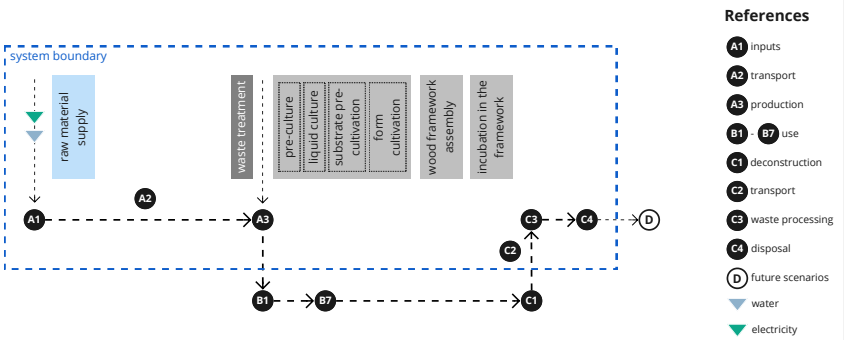

Figure 2: System boundaries and beyond

The LCA evaluates the environmental impacts of MBC material derived from spruce waste from a local sawmill. In this case, MBC is applied as a core to a spruce timber frame construction system (TFCMBC). Due to its unique binding property, MBC binds itself to the plates usually nailed to the timber frame

structure, forming an even bonding between the core and the plate, resulting in a bracing effect [7][2]. The analysis focuses on the material's net-GWP impact, including GWP-fossil (GWP_{fossil}), GWP-biogenic (GWP_{bio}), and GWP land use and land-use change (GWP_{luluc}) emissions. To facilitate comparability of the MBC with conventional core insulation materials, the functional unit was defined as 1 m^3 produced at a laboratory scale, while for TFCMBC, a functional unit of 1 m^2 was established.

The system boundaries[Fig. 2], based on DIN EN 14044:2021, follow a cradle-to-gate approach (A1-3) and include an evaluation of EoL phases. Module D was also analyzed. While we found LCA studies on MBC that addressed the use phase (B) and acknowledged the significance of functional energy in LCA [8], we chose to exclude this phase due to the assumptions it requires about building applications, which could add uncertainty. The boundaries cover the entire production system, from material cultivation in the lab to denaturation, material transportation, waste management, and laboratory waste inactivation. Resource use, including water and energy consumption, was examined. The electricity within the boundaries was treated as renewable. The energy assessment considers only embodied energy, excluding operational energy since phase B is outside this investigation.

2.3 Life-cycle inventory analysis

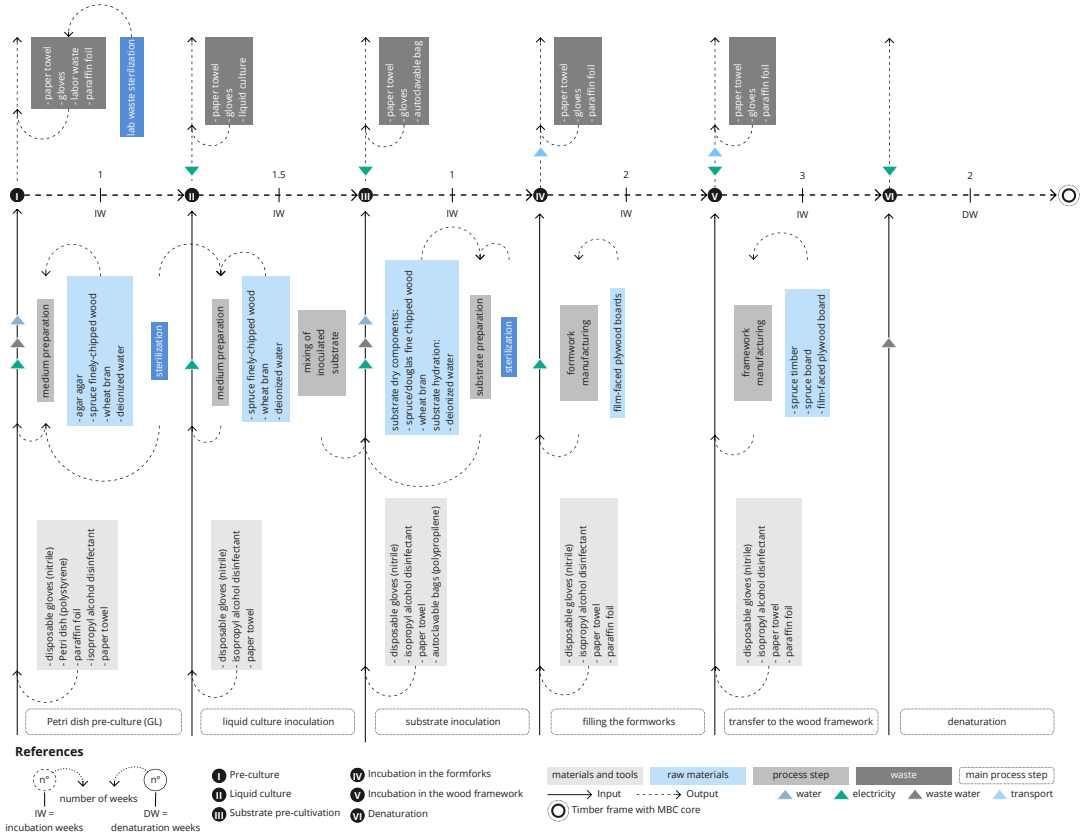

Figure 3: A1-A3 product stage process flow diagram of a timber frame system with MBC-core

LCI data was gathered from laboratory experiments for raw materials in MBC production. Following growth protocols from earlier research, 0.168 m^3 of inoculated woody substrate was prepared for a timber frame using MBC. Laboratory measurements defined the raw materials and tools, upscaled to 1 m^3. Physical allocation was used for data collection, with materials reported in kg or m^3, based on the Ecoinvent dataset. Collected data was categorized into life-cycle stages within specified boundaries, including raw materials from the Petri dish culture, liquid medium, wood substrate, and additional materials like polystyrene or plywood, along with disinfection protocols in the A3 phase. Outputs included waste materials and treatment methods: packaging waste, disposable tools, excess pre-culture, and liquid medium, with 5% liquid medium classified as waste, measured and upscaled for the LCA functional

unit. Transportation was split into two parts: delivering raw materials for the woody substrate and delivering timber structure. We calculated transport from the sawmill to the lab and substrate bags to the cultivation site, including plywood from the manufacturer. No transport was calculated for culture media components in the basic inventory**.** Secondary data included electricity and water usage during production based on equipment user manuals. Electricity was calculated from equipment power ratings and usage duration defined by lab protocols. Water use for sterilization was derived from autoclave manuals, while processing activities and associated electricity in EoL stages and module D were also considered.

2.4 Dynamic carbon storage assessment

The MBC material's carbon storage was calculated according to the time-dependent dLCA, considering the dynamic growth of the biomass. The dynamic regrowth after harvest approach was used for this purpose, which considers not only the CO_2 removals and biogenic CO_2 emissions of the harvested biomass used for the material production but also the CO_2 removal of the re-planted tree. This model estimates a regrowth of the biomass from the harvest, where the harvested trees' CO_2 emission, and CO_2 sequestration of the re-planted biomass are overlapped. CO_2 uptake was modeled with the Cabrine growth model [9] using the following equation:

$$l_t = C_P * \frac{NPP_T}{(1+100)^{(\frac{T}{2}-t)/\frac{T}{2}}}$$

Where l_t is the amount of biomass grown in a year, C_P is the biogenic CO_2 factor for the plant type, calculated according to Carcassi et al. [10], NPP_T is the amount of wood required for the declared unit of the research, T is the rotation period of the biomass, and t is the time for which the CO_2 storage is calculated. The time-dependent CO_2 storage of the MBC was assessed with the DYNCO2 tool [11] according to the material's reference service life (60 years), and the rotation period of the spruce wood (80 years).

2.5 End-of-life scenarios

Recent LCAs on MBCs examine various EoL scenarios, mainly highlighting incineration as the standard method, recovering energy from combustion [12] [10][8]. Other pathways include aerobic digestion with biomass storage in landfills and anaerobic digestion that captures methane for biosynthetic gas. Another option involves recycling MBC as a substrate[12], where 70% of MBC is reused, and 30% is incinerated for heat recovery. Our research identifies four EoL strategies for TFCMBC based on Germany's standard wood waste treatments**:** D_hr, capturing heat from timber combustion; D_pp, reusing timber and MBC to produce particle board; D_MBCp, using ground MBC and timber as substrates in MBC production; and D_sa, employing ground MBC as a soil amendment to enhance soil health, supported by chitin's benefits [13]. The heat from combusted framework materials is harnessed as energy. The LCI for EoL scenarios was derived from secondary data, encompassing raw material assumptions and energy and water use throughout manufacturing processes.

2.6 Life cycle impact assessment and data quality assessment

The LCIA was conducted using the Open LCA 2.2 software. The environmental impacts were calculated using the Ecoinvent v3.10, and the Agribalyse 1.1.0 dataset based on the collected LCI data. The elementary flows and processes of the divided life-cycle stages were added and calculated separately. We used the EN 15804 + A2 impact assessment method for the calculations. The allocation method was defined in the process since each material and supplementary tool involved was measured and up-scaled to the functional unit based on the laboratory protocol. To assess the system's uncertainties relating to the calculated data, all input and output quality entries were estimated according to the Pedigree matrix. We analyzed the uncertainty using the software's built-in Monte Carlo simulation calculation tool. Ten thousand runs were carried out for the total uncertainty distribution and variance. The data quality assessment results are shown in the Supplementary Informations (SI) [14]

2.7 Benchmarking

The benchmarking aimed to compare ecological factors, including net GWP, GWP_{bio}, and the RSL of the MBC, with the data of eight conventional core insulation materials, along with the outcomes of the TFCMBC compared to two sandwich panels available on the market. This research segment sought to identify leading competitors and potential substitutes for the materials examined. Secondary data

were gathered according to predefined system boundaries, encompassing information on the comparative materials' A1-3, C2-4, and Module D phases. Because the data sources utilized different functional units, we standardized the net-GWP and GWP_{bio} results according to the research's functional units. The collected data were illustrated in graphs, including the LCA result for the MBC and TFCMBC. We calculated the net values from the evaluated products. The target value for the benchmark was established between the minimum and average values.

Table 1: Benchmarking: insulation materials and sandwich panels

Category	Material	acronym	Thickness [m]	U value [W/m*K]
conventional insulation products	glasswool	GW	0.03	1.17
	rockwool	SW	0.03	1.37
	polystyrene particle foam	EPS	0.03	1.34
	polystyrene extruded foam	XPS	0.1	0.26
natural insulation products	hemp	H	0.1	0.40
	hemp lime	HL	0.03	2.53
	wood fiber	WF	0.03	1.23
	wood wool	WW	0.01	3.4
sandwich panels	Kingspan TEK	KS	0.142	0.17
	Kingspan AWPflex	AWP	0.12	0.16

3 Results and Discussion

3.1 Life-cycle impact assessment

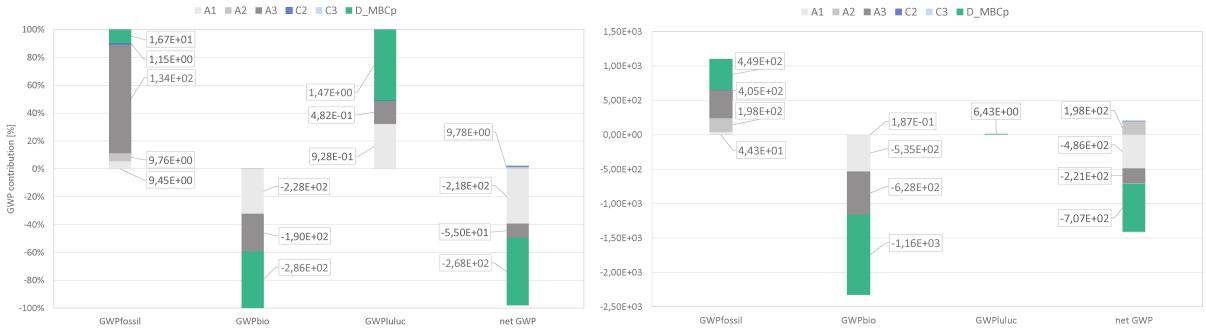

Figure 4: GWP for $1m^2$ of TFCMBC (left) and $1m^3$ of MBC (right)

Figure 4 (right) illustrates the GWP for $1m^3$ of MBC and (left) $1m^2$ of TFCMBC, revealing key differences in environmental performance. The results consider different life cycle impact categories, including GWP_{fossil}, GWP_{bio}, GWP_{luluc}, and net-GWP, with contributions from A1-A3 phases, EoL processes, and Module D. A notable difference between the two systems is the higher GWP_{fossil} in MBC than in TFCMBC. The results indicate that $1m^3$ of MBC generates approximately 449 kg CO_2-eq of fossil-based emissions, whereas $1m^2$ of TFCMBC accounts for 247 kg CO_2-eq. This disparity can be attributed to the higher material volume in the $1m^3$ functional unit, which amplifies the emissions from the production and processing stages. The main contributors to these emissions are the A3 phase, similar to other reviewed literature [12][8] [10], and the allocation of end-of-life benefits in module D (for more details, see subsection 3.2). In contrast, TFCMBC benefits from a reduced absolute volume of MBC per square meter, lowering its overall fossil-related impact. The GWP_{bio} of MBC is significantly higher than that of TFCMBC, which is expected given the larger volume of material assessed in the $1m^3$ functional unit. The

data indicates that MBC stores approximately -1160 kg CO_2-eq, while TFCMBC sequesters around -858 kg CO_2-eq. This highlights MBC's ability to act as a carbon sink, balancing out its higher fossil-based emissions. Despite its energy-intensive production phase, the strong negative GWP_{bio} values suggest that MBC remains highly advantageous in long-term carbon storage. Module D scenarios further influence this carbon sequestration effect, where recycling and reuse strategies extend the carbon storage period beyond the product's primary life cycle.

The GWP_{bio} of MBC is significantly higher than that of TFCMBC, which is expected given the larger volume of material assessed in the $1m^3$ functional unit. The data indicates that MBC stores approximately -1160 kg CO_2-eq, while TFCMBC sequesters around -858 kg CO_2-eq. This highlights MBC's ability to act as a carbon sink, balancing out its higher fossil-based emissions. Despite its energy-intensive production phase, the strong negative GWP_{bio} values suggest that MBC remains highly advantageous in long-term carbon storage. Module D scenarios further influence this carbon sequestration effect, where recycling and reuse strategies extend the carbon storage period beyond the product's primary life cycle.

The impact of GWP_{luluc} is relatively minor in both cases, though slightly higher in TFCMBC due to the inclusion of timber frame components, which require additional forestry resources. However, this difference is not as pronounced as in fossil and biogenic emissions, indicating that land-use impact is less critical in determining the overall environmental performance of the two systems.

When considering the net-GWP values, the results reinforce the role of MBC as a carbon-negative material. The data shows that $1m^3$ of MBC achieves net sequestration of approximately -1209 kg CO_2-eq, while $1m^2$ of TFCMBC reaches around -607 kg CO_2-eq. The more significant negative value for MBC directly results from the greater volume assessed and the potential for extended sequestration through reuse and recycling pathways. Although TFCMBC maintains a negative net-GWP, its impact is less pronounced due to the lower material volume per unit area. However, TFCMBC provides a balanced solution that integrates structural advantages with sustainability benefits.

3.2 Module D

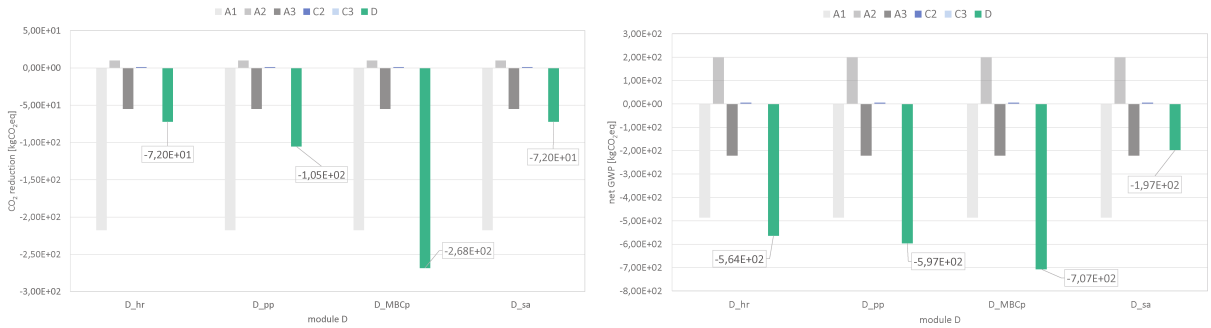

Figure 5: Module D comparing four different scenarios for TFCMBC (left) and MBC (right)

The analysis of module D scenarios provides valuable insights into the potential carbon savings and emission reductions associated with different EoL strategies for TFCMBC and MBC. The four scenarios under consideration, D_hr, D_pp, D_MBCp, and D_sa, already mentioned in subsection 1.4, represent different approaches to extending the material's service life and carbon sequestration potential, ultimately influencing the system's net-GWP.

Figure 5, TFCMBC, and MBC exhibit negative CO_2-equivalent values across all scenarios, confirming their role in carbon mitigation beyond the system boundary. However, differences in impact magnitude emerge between the two materials. D_hr leads to a CO_2 reduction of -218 kg CO_2-eq in both cases, demonstrating that energy recovery provides fossil fuel substitution benefits. However, incineration rapidly releases stored biogenic carbon, making it a less effective strategy for long-term sequestration.

D_pp exhibits a less significant reduction in CO_2 emissions compared to the other scenarios. Since repurposing TFCMBC and MBC as a secondary material in engineered wood products delays but also releases carbon during its manufacturing.

Among all scenarios, D_MBCp results in the most substantial CO_2 reduction, reaching -707 kg CO_2-eq. This approach extends the carbon storage potential of MBC, where the sequestration effect is significantly amplified compared to TFCMBC.

The D_sa scenario also contributes to substantial CO_2 reductions, as MBC's organic content integrates into soil ecosystems, effectively acting as a long-term carbon sink. The impact is more pronounced for MBC than TFCMBC, which could be turned into, e.g., mulch, suggesting that mycelium-based materials offer more significant carbon sequestration benefits when applied as soil amendments. This pathway also avoids emissions from synthetic fertilizers, reinforcing its environmental benefits.

MBC shows significantly more significant CO_2 reduction than TFCMBC in all scenarios due to its higher biogenic carbon content and easier post-processing. MBC retains nearly three times more carbon than TFCMBC, demonstrating material reuse's potential to lower net-GWP by circulating biogenic carbon instead of releasing it. D_MBCp is the most effective strategy for maintaining negative CO_2 emissions, followed by D_sa, which promotes long-term biological retention cycles.

3.3 Results considering biogenic GWP

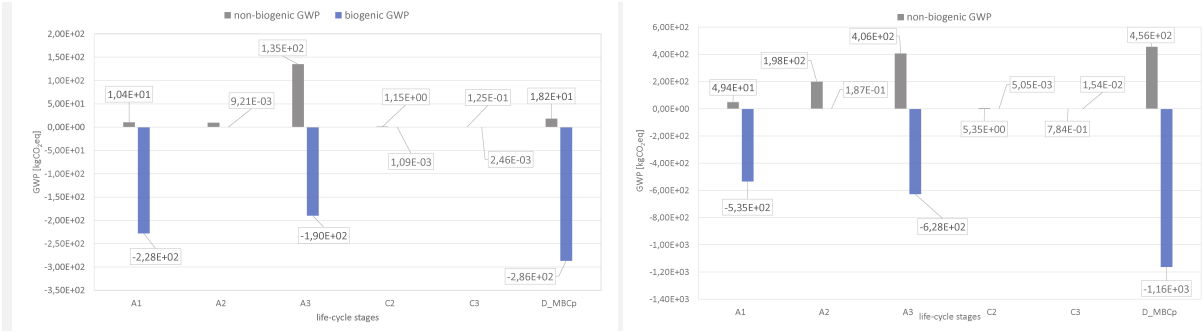

Figure 6: Non-biogenic GWP and biogenic GWP comparison for TFCMBC (left) and MBC (right)

Figure 6 shows a key distinction in carbon sequestration between the two materials, particularly in GWP_{bio} values. The A1 stage shows negative GWP_{bio}, indicating carbon sequestration from biomass growth, with a more pronounced effect in MBC, reaching values over -535 kg CO_2-eq, compared to -228 kg CO_2-eq in TFCMBC. This suggests MBC, with its higher organic content, is a better carbon sink than composite timber. The difference stems from TFCMBC's lower biogenic carbon per functional unit due to timber elements.

In contrast, the A3 stage contributes the highest non-biogenic emissions in both materials. TFCMBC shows a GWP increase of about 135 kg CO-eq, while MBC has a much higher emission at 406 kg CO-eq, indicating greater energy needs for MBC production. However, MBC's GWP_{bio} savings far exceed its production emissions, highlighting its strong long-term carbon storage potential.

EoL phases (C2-C3) show minimal impact, with low transport and disposal contributions. However, Module D (D_ MBCp) reveals significant carbon savings from material reuse. GWP_{bio} in this phase is notably negative: -1160 kg CO_2-eq for MBC and -441 kg CO_2-eq for TFCMBC.

3.4 Results of the benchmarking

Figure 7 shows the analysis of GWP_{bio} and highlights the superior carbon sequestration potential of MBC and TFCMBC compared to market alternatives. The MBC system exhibits a significantly lower GWP_{bio} (-2325 kgCO_2eq), surpassing all conventional and natural insulation materials. TFCMBC also achieves substantial biogenic carbon storage, reaching -703 kgCO_2-eq, significantly outperforming commercial sandwich panels.

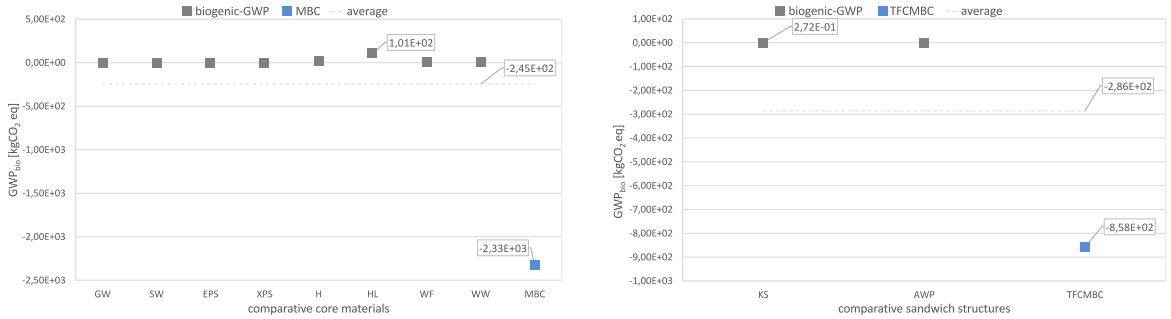

Figure 7: GWP biogenic benchmarking of construction products: MBC (left) and TFCMBC (right)

All conventional insulation materials show near-zero biogenic GWP due to reliance on synthetic sources. Some natural materials, like hemp-lime (HL) and wood wool (WW), have moderate biogenic carbon storage, but none reach MBC's negative emissions level**.**

Kingspan TEK and AWPflex show near-zero biogenic GWP for sandwich panels, lacking significant biogenic carbon storage. In contrast, TFCMBC demonstrates substantial sequestration at -858 kgCO2-eq, well below the market average**,** confirming its sustainability against standard sandwich panels.

The GWPbio difference between MBC and TFCMBC is due to TFCMBC's lower mycelium-based material proportion, diluting its biogenic carbon storage. Nevertheless, both systems maintain a negative biogenic GWP, emphasizing their carbon sequestration contribution in construction.

The RSL of MBC and TFCMBC, benchmarked against conventional insulation and sandwich panel materials, is estimated at 60 years, aligning with durable materials like wood wool and timber. In favorable scenarios, MBC and TFCMBC demonstrate competitive longevity, positioning them as viable long-term solutions for sustainable construction; however, further research is needed. See SI [14]for a comparative RSL chart.

4 Conclusion

This study demonstrates the environmental benefits of MBC in timber frame construction. A comprehensive dLCA highlights TFCMBC as a sustainable alternative to conventional sandwich panels, particularly in net-GWP. MBC sequesters carbon effectively, acting as a carbon-negative material throughout its life cycle. Its superior biogenic carbon storage stems from using waste-derived lignocellulosic substrates, which serve as an additional carbon sink. However, the biogenic GWP values in product EPDs may not have been assessed using a dynamic methodology.

Module D analysis shows that recycling MBC or repurposing it as a soil amendment maximizes carbon sequestration and reduces environmental impact. While incineration provides energy recovery, it is less effective for long-term carbon storage. Dynamic carbon modeling further supports MBC's role in delaying emissions and promoting a circular material economy.

Challenges remain for large-scale adoption, including industrial production feasibility, material durability, and structural performance. Enhancing manufacturing efficiency and reducing fossil-based emissions will be critical. Integrating MBC into timber systems can help transition construction toward regenerative materials that reduce non-renewable reliance and sequester carbon. Future research should focus on scaling production, improving resilience, and optimizing EoL strategies to maximize MBC's potential as a mainstream building material.

5 Acknowledgments

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