END REPORT

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Recipient:	RWTH Aachen, Lehrstuhl für Tragkonstruktionen
Subject (acronym):	MycoPor Porositätsbestimmung myzelbasierter Werkstoffe zur Beurteilung ihres Potenzials für den Einsatz als tragendes Baumaterial
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Reporting date as per notification:	
Reporting period:	29.03.2024-30.11.2024

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1. List of the most important scientific and technical results and other significant achievements

1.1 Work packages and milestones acc. work plan

The following tables are based on the work plan and schedule (Fig. 1).

work package (WP)	Working period	Actual state
WP 1 Method of determining porosity	01.10.2023-30.11.2023	The objectives of WP 1 have been fulfilled.
WP 2 Porosity determination of fungi-substrate combinations	01.12.2023-31.01.2024	The objectives of WP 2 have been fulfilled.
WP 3 Testing of mechanical properties of selected combinations	01.01.2024-30.04.2024	The objectives of WP 3 have been fulfilled.
WP 4 Production of prototypical building products	01.05.2024-30.09.2024	The objectives of WP 4 have been fulfilled.

Milestones (M)	Deadline	Actual state
M 1	31.01.2024	Milestone 1 has been achieved.
M 2	30.04.2024	Milestone 2 has been achieved.
M3	30.06.2024	Milestone 3 has been achieved.

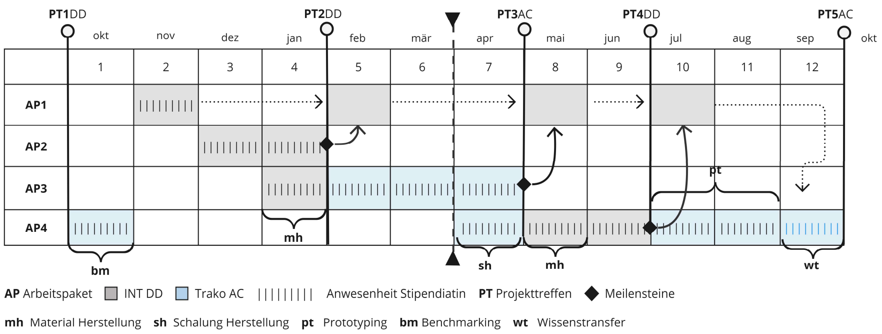

Figure 1. Schedule of the project.

1.2 Most important scientific and technical results and other achievements that could impact the project.

In the following, the most significant achievements of the project are described.

Work package 1

Objectives:

WP 1 focuses on the development of a reproducible methodology for the determination of density and porosity of lignocellulose-based mycelium-based composites (MBCs) designed for structural purposes. The main objective is to establish a robust and reproducible protocol for the measurement of these parameters, using gas pycnometry to ensure accuracy and consistency.

Methodology for density measurement and porosity calculation:

- **Test specimens:** Standard-sized cylindrical forms (h=70 mm, d=45 mm, according to DIN EN 826:2013) were cultivated with a standard combination of beech substrate and *Ganoderma lucidum*

(GL) fungal strain. The specimens have been grown under the same cultivation conditions and differed only in the incubation time of 3, 4, 5, 6, and 7 weeks. Due to the expected biological variation, ten specimens were produced for every incubation period.

- **Density measurements with an Anton Paar Ultrapyc 5000: t**he density of the samples was measured using the Anton Paar Ultrapyc 5000 gas pycnometer according to DIN 66137-2 (“DIN 66137-2,” n.d.). This method uses an inert gas, Nitrogen (N), which penetrates into the smallest pores without damaging the samples and offers higher accuracy than a method based on liquid displacement. Ultrapyc's variable chamber sizes allow accurate measurements by matching the chamber volume to the sample size. The procedure involves pressurizing the sample chamber, releasing gas into a reference chamber, and calculating the density of the specimen from the resulting pressure drop, providing accurate density analysis (Zauer et al., 2013).
- **Porosity calculation:** The gas pycnometer measures the specimens' pore-free volume and skeletal density. The Φ can be calculated from the ρ_{bulk}, and $\rho_{skeletal}$ with the following equation (1) (Baumgartinger, 2023; Gibson and Ashby, 1997):

$$\Phi = 1 - \left(\frac{\rho_{bulk}}{\rho_{skeletal}}\right) \quad (1)$$

Results and Analyzis:

The first measurement protocol had to be modified due to systematic errors caused by incorrect calibration. Initially, calibration was performed using only the largest calibration device (V = 56.5592 cm³), which incorrectly set the sample chamber volume to 158.41 cm³. In order to solve this problem, the calibration was revised with both the largest (V = 56 cm³) and the smallest (V = 7 cm³) calibration device (Fig. 2). This adjustment resulted in the correct sample chamber volume of 144.54 cm³, ensuring accurate density measurements.

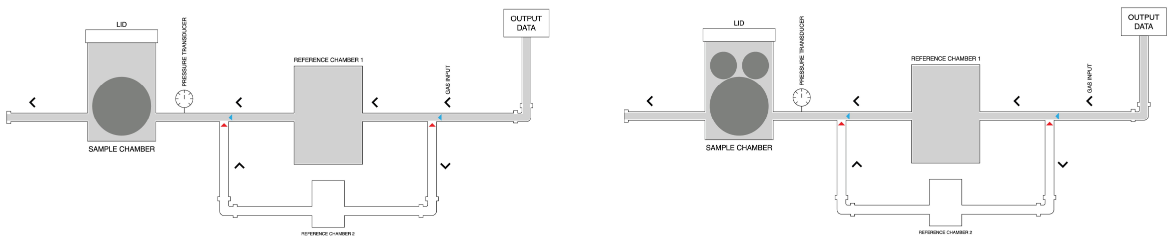

Figure 2. Outline of the false (left) and the correct (right) calibration process.

We repeated the measurements on two specimens from each incubation period to determine the correction factors, which allowed us to correct the previous results. The corrected outcomes represent the same tendency regarding all the measured properties (skeletal density, skeletal volume, and porosity). Figure 3 shows the comparison of the incorrect, and the correct data.

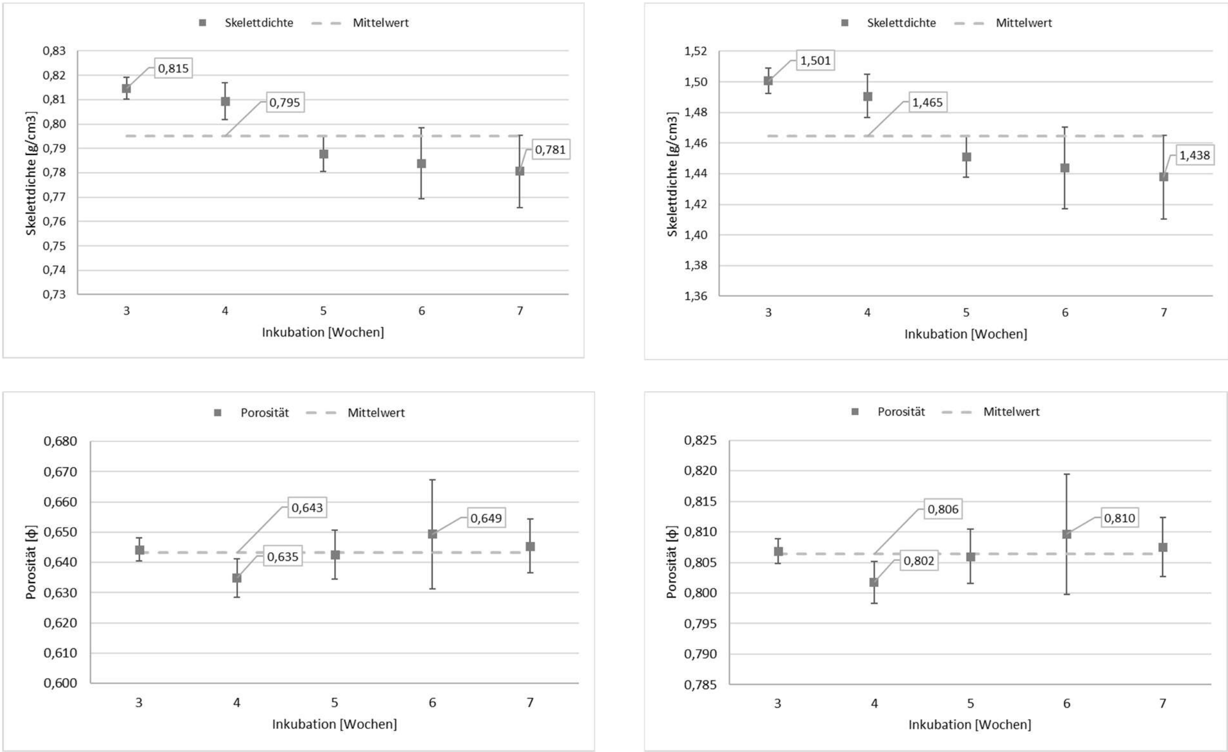

Figure 3. Comparison of measurement data. Left: incorrect data; right: corrected data. Top to down: skeletal density, porosity.

Work package 2

Objectives:

The aim of WP 2 is to determine the density and porosity of different fungal-substrate combinations based on the general protocol established in WP 1. As beech substrate is a high-quality hardwood and rarely found as a residue in the construction industry, it should be replaced by fast growing softwoods such as Douglas fir and spruce, which are produced in large quantities as waste. The aim of WP 2 is to investigate and optimise the growth conditions (Appels et al., 2019; Elsacker et al., 2020; Ghazvinian and Gürsoy, 2022; Haneef et al., 2017) of these softwood substrates and combinations of different fungal strains in order to improve the mechanical performance of the resulting samples. The Douglas fir (D), and spruce (S) woodchips, and sawdust for these investigations were provided by the project partner Gebr. Eigelshoven GmbH & Co. KG.

Methodology for the examination of growth conditions:

- **Investigation of the growth conditions:** The study followed the substrate preparation and cultivation protocol based on previous research by the team, combining Douglas fir, spruce, and poplar-based substrates with nine fungal strains: *Fomes fomentarius* (FF), *Fomitopsis pinicola* (FP), *Ganoderma applanatum* (GA), *Ganoderma lucidum* (GL), *Hericium erinaceus* (HE), *Marasmius ssp.* (MS), *Phanerochaete chrysosporium* (PC), *Pleurotus ostreatus* (PO), and *Trametes hirsuta* (TH). The reference of cultivation experiments was the standard GL-beech combination from previous research (Saez et al., 2021). Petri dishes were filled with sterilized wood substrate, centrally inoculated with liquid fungal pre-culture, and grown at 24°C for fifteen days. The reference GL-beech combination used a 10:1 ratio of wood to wheat bran. However, the growth conditions needed to be analyzed and optimized with different wood substrates and fungal strains. Hence, we conducted another agar growth test with different wood-wheat bran (WB) ratios (Apprich et al., 2014). Two different proportions (10:1 and 2:1) of ground chipped wood and WB were added to the mediums as nutrients instead of potato dextrose agar (PDA), and were mixed with deionized H_2O for the Petri-dish precultures. The growth tests with different fungal-substrate combinations were incubated at 24°C for fifteen days. By preparing the liquid pre-culture for cylindrical growth tests, potato dextrose broth (PDB) medium was replaced with finely ground wood and WB as nutrients in a 2:1 ratio and was mixed with deionized H_2O. The liquid cultures were cultivated in an incubation shaker at 24°C for twelve days.

- **Substrate preparation and form cultivation:** In the case of the substrates prepared for the specimen cultivation, the 2:1, and 10:1 ratio of finely chipped wood and WB mixtures were utilized, supplemented by a 5:2 proportion for the D-based substrate. The aim of utilizing the different ratios of wood substrate and WB was to examine the WB's influence on the substrate's cultivation period before the cultivation in the forms. The cylindrical forms were filled with 41-64 grams of substrate for specimen cultivation, varying depending on the wood-based substrate. The samples were incubated for four weeks at 24°C.
- **Density measurement and porosity calculation:** according to the established protocol of WP1 the measurements were performed using Nitrogen (N) and Helium (H) as inert gases to ensure the highest precision in determining the density and porosity values of the specimens.

Results and analysis:

1. **Petri-dish growth tests:** the growth behavior of the various fungal-substrate combinations was assessed through radial growth tests (the examples with two strains are shown in Fig. 4). The rigid network development was examined manually after drying. Among the nine fungal strains tested, GL, GA, FF, and TH demonstrated effective mycelium growth and strong connectivity with the B substrate. However, GL and FF strains exhibited weaker connectivity when combined with D and S substrates, despite performed sufficient growth. Further Petri-dish growth tests were conducted to optimize the growth conditions of softwood-based substrates combined with fungal strains. We used two ratios (10:1, 2:1) of D, P, and S substrate to wheat bran (WB) as nutrients. The Petri-dishes were inoculated with those four fungal strains (GL, GA, TH, PO), which showed the fastest growth during the radial growth tests.

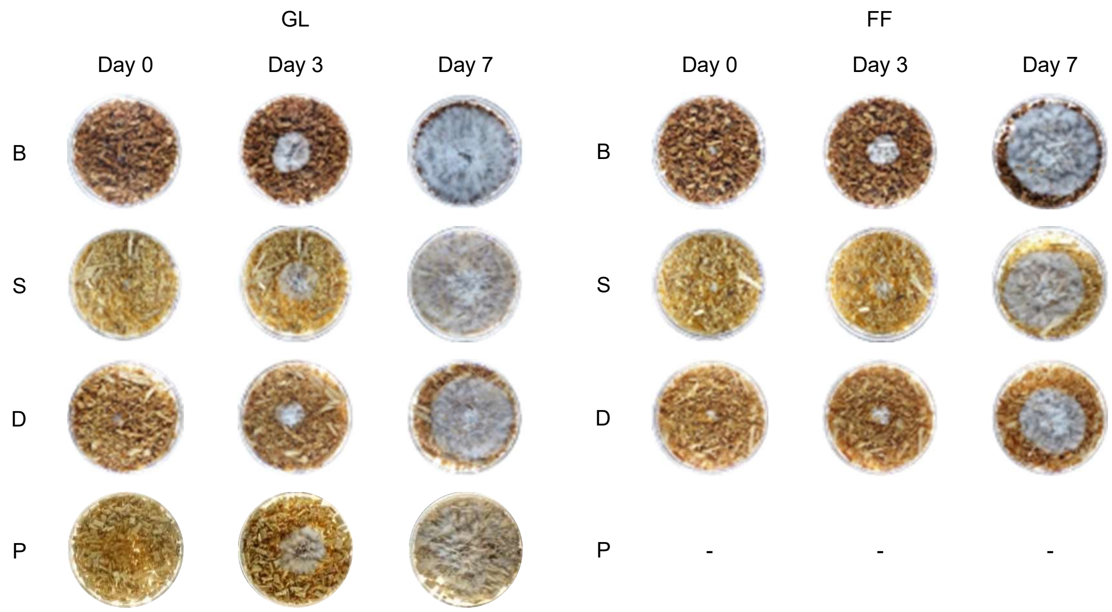

Figure 4. Examples for radial growth tests with two fungal strains.

2. **Substrate preparation, and cylindrical specimen cultivation**: the substrate mixtures were inoculated with GL, GA, and FF fungal strains based on the outcomes of the Petri-dish tests. The results of these tests represent that the higher WB content usually results in a shorter incubation period. The comparison of the the various fungal-substrate combinations' pre-cultivation periods is shown in Table 1. Six fungal-substrate combinations resulted in specimens suitable for compressive testing. None of the substrates inoculated with FF led to appropriate samples. The tests with GA yielded in sufficient mycelial growth when combining with a S substrate.

Table 1. Pre-cultivation periods of the examined fungi-substrate combinations.

	Substrate type	FF	FP	GA	GL
Beech	KGB	-	-	-	4 days
Douglas fir	D:WB 10:1	30 days	-	29 days	13 days
	D:WB 5:2	9 days	-	11 days	6 days
	D:WB 2:1	9 days	-	12 days	8 days
Poplar	P:WB 10:1	-	-	-	8 days
	P:WB 2:1	-	-	-	8 days
Spruce	KGB	-	-	-	7 days
	S:WB 10:1	10 days	-	14 days	-
	S:WB 2:1	10 days	15 days	14 days	7 days

3. **Density measurement, and porosity calculation:** the density and porosity fraction of the resulting specimens were measured. We used N and H as inert gases during the measurements. Since H has a smaller atomic size, we assumed its utilization would lead to more appropriate density measurements. To compare the accuracy of N, and H, we measured the density of seven S-GL specimens with both inert gases. The outcomes of this investigation show no significant differences in any of the measured values (Fig. 6**Fehler! Verweisquelle konnte nicht gefunden werden.**).

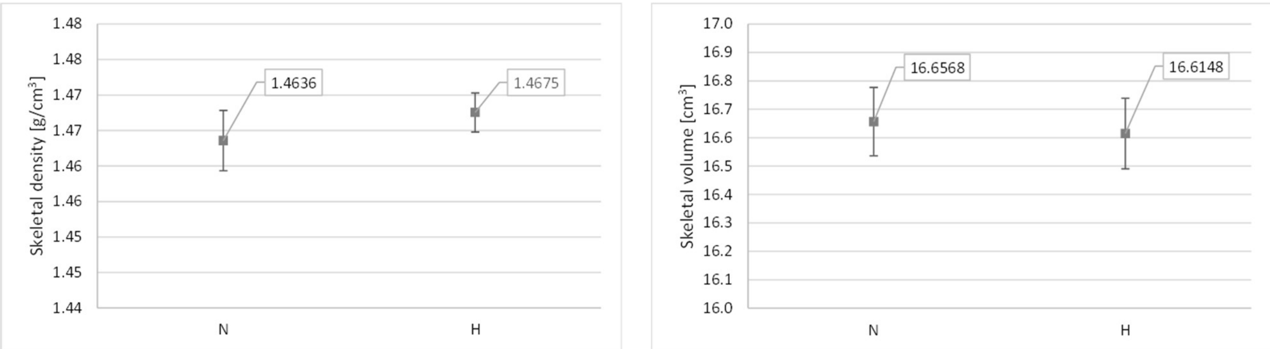

Figure 6. Comparison of skeletal density (left), and skeletal volume (right) measured with N, and H.

Figure 6 shows the outcomes of the density measurements, and the porosity calculation. The results of the different fungal-substrate combinations were averaged and plotted on graphs (Fig. 7 - 9).

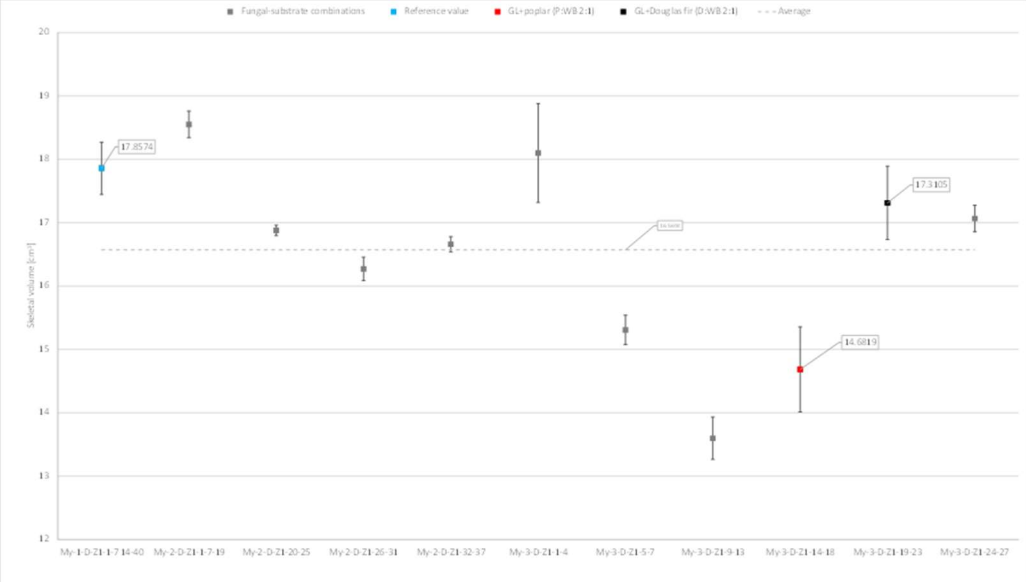

Figure 7. Skeletal volume results of the examined fungal-substrate combinations.

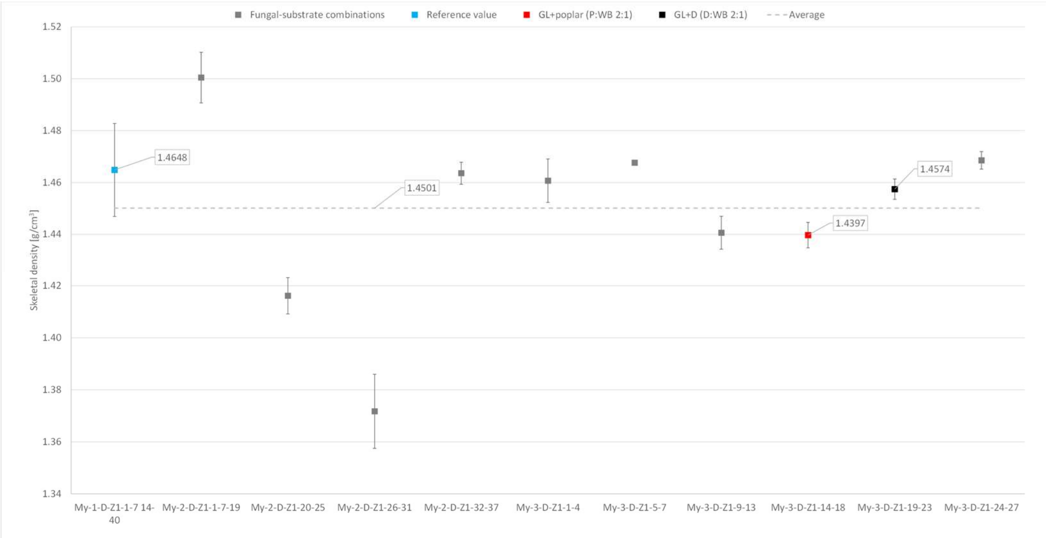

Figure 8. Skeletal density results of the examined fungal-substrate combinations.

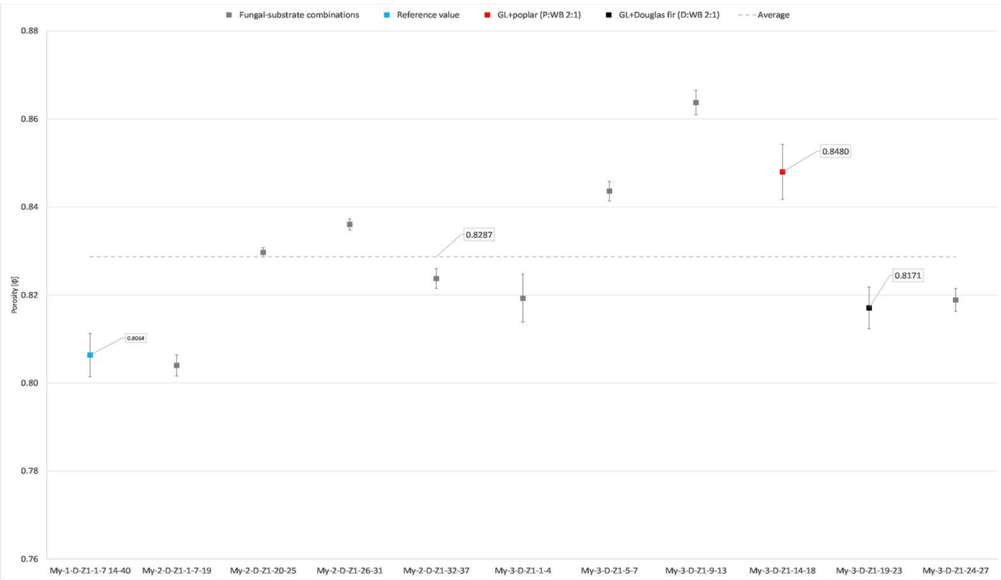

Figure 9. Porosity results of the examined fungal-substrate combinations.

Work package 3

Objectives:

The goal of this work package is to investigate the mechanical properties of mycelium-based composites (MBC), focusing on compressive strength and elasticity (Lelivelt et al., 2015), to establish correlations with porosity. This study builds on the outcomes of Work Packages 1 and 2, identifying combinations with optimal density and growth conditions for enhanced mechanical performance. The selected fungal-substrate combinations were tested using a standardized methodology to evaluate their compressive strength, elasticity, and porosity.

Mechanical testing methods:

- **Test specimens:** cylindrical specimens were cultivated using a variety of fungal-substrate combination showed in Table 2.
- **Compressive strength testing:** The mechanical strength of the specimens was tested using a universal testing machine (50 kN capacity) under uniaxial compression at a controlled displacement rate of 10 mm/min. Stress-strain curves were recorded for each specimen, focusing on stress at 10% strain to compare strength under consistent deformation. All tests were conducted in accordance with the DIN EN 826:2013 standard ("DIN EN 826," n.d.), which specifies methods for determining the behavior of thermal insulation materials under compressive load.

Table 2. Mycelial strain-substrate combinations in different testing phases My1, My2, My3

Test phase	Strain	Substrate	Geometry	Filling level	Incubation time	WB	Designation
My1	GL	Buche	chips	100%	3 weeks	-	My-1-D-Z1-1-7
	GL	Buche	chips	120%	3 weeks	-	My-1-D-Z1-8-13
	GL	Buche	chips	100%	4 weeks	-	My-1-D-Z1-14-20
	GL	Buche	chips	100%	5 weeks	-	My-1-D-Z1-21-27
	GL	Buche	chips	100%	6 weeks	-	My-1-D-Z1-28-34
	GL	Buche	chips	100%	7 weeks	-	My-1-D-Z1-35-40
My2	GL	Buche	chips	100%	2 weeks	-	My-2-D-Z1-1-7
	GL	Buche	chips	100%	3 weeks	-	My-2-D-Z1-8-13
	GL	Buche	chips	100%	4 weeks	-	My-2-D-Z1-14-18
	GL	Spruce	sawdust	100%	4 weeks	-	My-2-D-Z1-26-31
	GL	Spruce	chips	100%	4 weeks	-	My-2-D-Z1-20-25
	GL	Spruce	sawdust	100%	4 weeks	2:1	My-2-D-Z1-32-37
My3	GA	Spruce	sawdust	100%	4 weeks	2:1	My-3-D-Z1-1-4
	GA	Spruce	sawdust	100%	4 weeks	10:1	My-3-D-Z1-5-7
	GL	Poplar	sawdust	100%	4 weeks	10:1	My-3-D-Z1-9-13
	GL	Poplar	sawdust	100%	4 weeks	2:1	My-3-D-Z1-14-18
	GL	Douglas fir	sawdust	100%	4 weeks	2:1	My-3-D-Z1-19-23
	GL	Douglas fir	sawdust	100%	4 weeks	5:2	My-3-D-Z1-24-27

Results and analysis:

1. **Effect of substrate & incubation time:**

- Beech-based composites demonstrated the highest compressive strength (0.44 N/mm²) with a 4-week incubation period, confirming its reliability as a substrate for MBC. See Fig. 7 where the compressive strength value of the test specimens containing beech wood, represented in blue, as a substrate are contrasted to the rest of the substrate combinations.

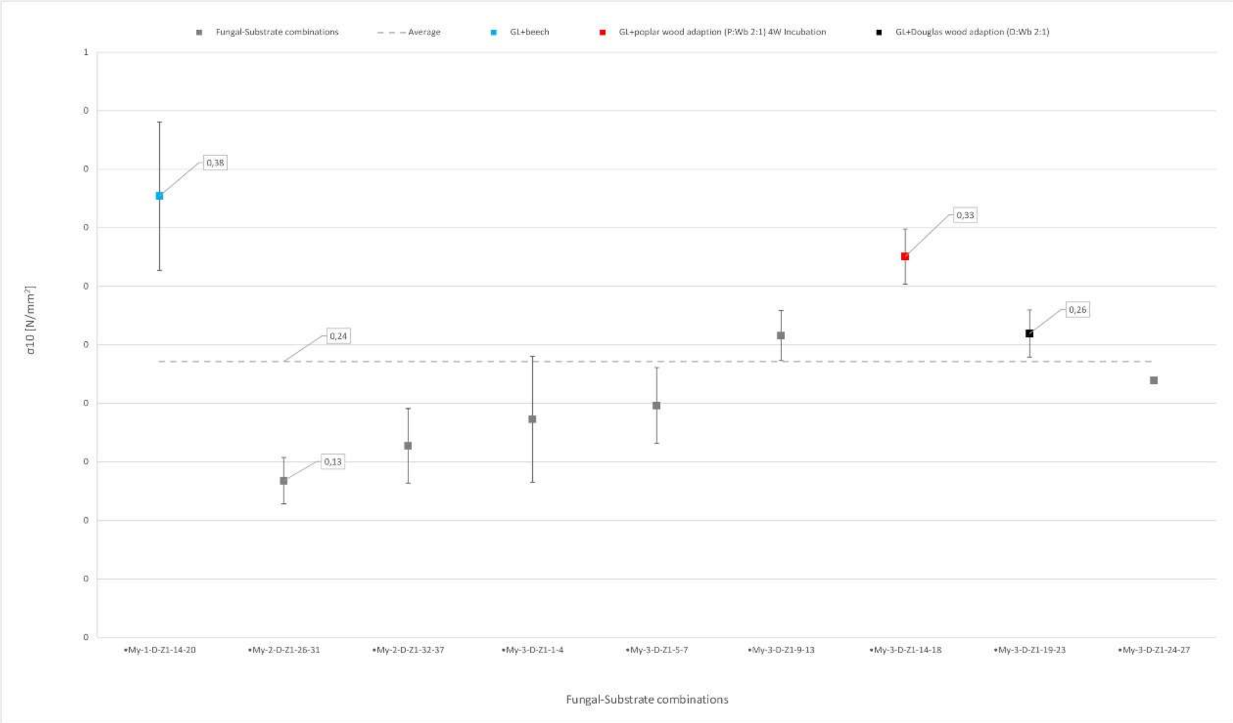

Figure 7. Compressive strength comparison among all fungi-substrate combinations.

- Softwoods such as spruce and Douglas fir, represented in black, exhibited lower strength than beech but showed potential for improvement when used with sawdust rather than wood chips.
- Poplar-based specimens, represented in red, exhibited an intriguing balance of high porosity (approximately 0.86) yet relatively strong compressive performance (0.33 N/mm²), attributed to a dense surface mycelial layer forming a quasi-jacket effect around the composite. Fig. 8 describes this effect on a schematic drawing.

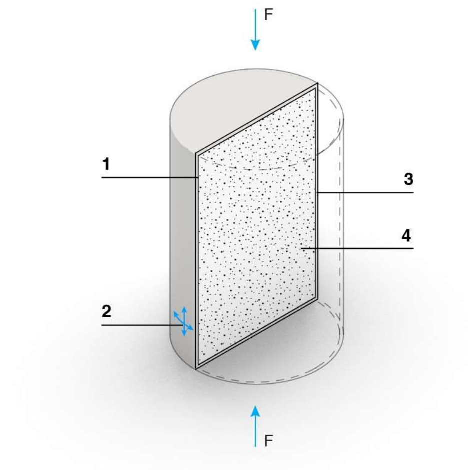

Figure 8. Illustration of the jacket effect of the quasi-pure mycelium surface on the poplar samples where [$\rho_1 > \rho_2$]. (1) Binding are between myco-jacket and MBC; (2) activation of the axial stresses alongside the myco-jacket surface (3); Φ_1, ρ_1; (4) Φ_2, ρ_2

2. **Porosity-Strength Correlation:**

- A general inverse relationship between porosity and compressive strength was observed, where denser materials (lower porosity) demonstrated greater resistance to compression. However, the poplar substrate emerged as an exception, achieving significant strength despite higher porosity, potentially due to unique substrate-mycelium interactions.

3. **Influence of WB Content:**

- Increased WB content in substrate mixtures (e.g., 2:1 ratio) generally resulted in denser composites, improving mechanical performance. This effect is clear to be seen on the different fracture behaviors in Fig.9.

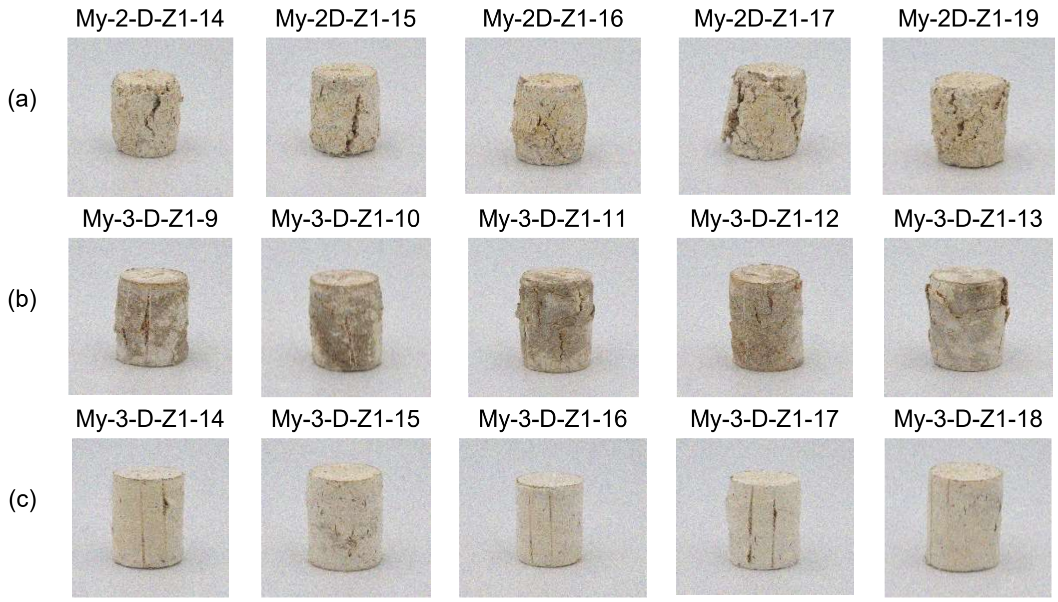

Figure 9. (a) Beech samples, (b) Poplar samples (with P:K 10:1), and (c) Poplar samples (with P:K 2:1). All pictures were taken after 20% strain.

4. **Mechanical Trends Across Strains and Substrates:**

- Specimens with sawdust substrates, such as spruce or poplar, generally outperformed their chipped wood counterparts, emphasizing the importance of particle geometry in enhancing the mycelium-substrate bond.

Work package 4

Demonstrator development – timber-frame wall with MBC core

Objective: The primary aim of this task was to design and construct a standard timber-frame wall demonstrator using a mycelium-based composite (MBC) as the core material. The demonstrator aimed to integrate findings from earlier work packages showcasing its potential for real-world construction applications.

The core was designed to serve dual purposes:

- **Insulation Material:** Providing thermal insulation and contributing to energy efficiency in the constructed wall.
- **Structural bonding agent:** Utilizing the natural binding properties of mycelium to adhere to the wooden frame, enhancing the overall connection between the core and the frame. This binding effect contributed to improved bracing and load distribution within the wall structure, supporting structural stability.

Methods:

1. **Preliminary stage: cultivation and denaturation trials:**

- To establish optimal conditions for cultivating and denaturing MBC within a timber-frame structure, two preliminary modules were constructed:
    - Module A: Dimensions of 0.25 m × 0.675 m × 0.16 m.
    - Module B: Dimensions of 0.50 m × 0.675 m × 0.16 m.
- Both modules were pre-cultivated in formwork molds for an initial two weeks to ensure uniform mycelial growth.
- After this initial cultivation, the partially grown MBC cores were transferred to timber-frame structures, where they completed an additional two weeks of growth. During this phase, the natural binding properties of the mycelium developed a strong adhesive connection with the timber-frame structure, enhancing the overall bonding and bracing effects.
- Following cultivation, a denaturation procedure was applied to both modules at a constant temperature of 70°C for three consecutive days, ensuring material stability and preventing further biological activity.

2. **Demonstrator development** [Fig. 10].**:**

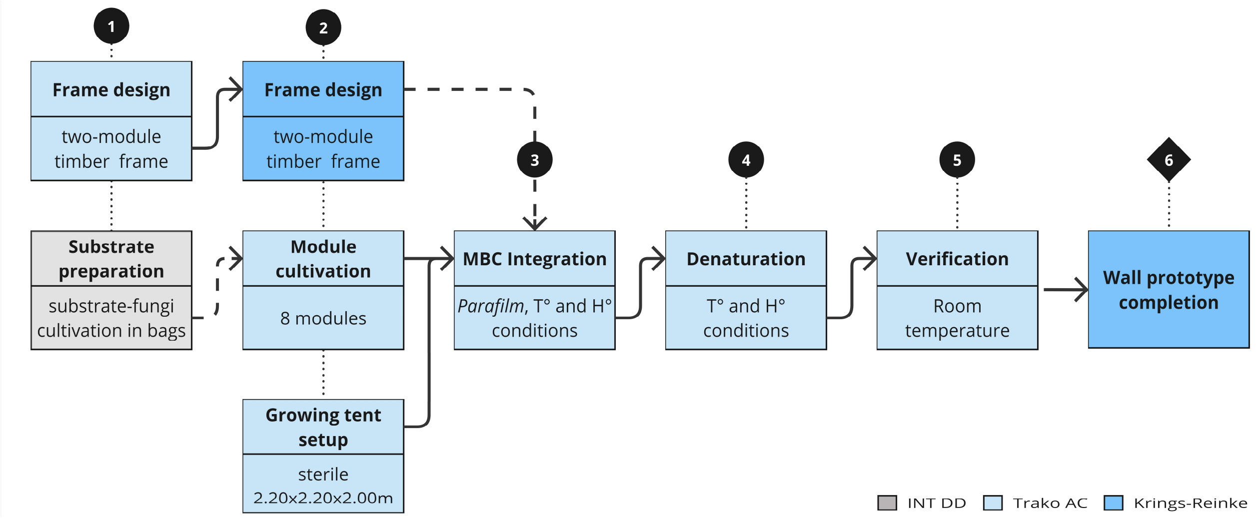

Figure 10. Workflow of the demonstrator development.

- **Design of the demonstrator:**
  The demonstrator comprised two timber frames:
    - One to be filled with MBC.
    - One to be filled with traditional insulation material, glass wool, for comparative purposes.
- **Fabrication and transport:**
  The timber frames for the demonstrator were fabricated by one of our project partners, the company Krings-Reinke, and transported to the lab at RWTH Aachen for further development [Fig. 11].
- **Module cultivation:**
    - 8 Modules A (as defined in 1. Preliminary stage) were cultivated in formworks for two weeks in an incubator under a temperature of approximately 24°C and an air humidity of 80–90%.
- **Scaling up growth conditions:**
  To accommodate the full demonstrator, an indoor growing tent (2.20 m × 2.20 m × 2.00 m) was set up [Fig. 11].
    - The environment was disinfected with ethanol.
    - A humidifier and a heating source with a sensor were installed to maintain constant conditions of 24°C temperature and 80–90% air humidity.
- **Installation of MBC into the frame** [Fig. 11].**:**

- The pre-cultivated Modules A were transferred into the timber frame.
- The modules were covered with Parafilm to prevent contamination and allowed to grow for another two weeks. To ensure complete bonding, the growth period was extended by an additional week.
- During the final week, the Parafilm was removed to enhance superficial mycelial growth.

- **Environmental monitoring** [Fig. 11]**:**
  The growing tent conditions, or scaled up incubator, were continuously monitored to maintain temperature and humidity stability throughout the cultivation process.
- **Denaturation process:**
  - After the three-week growth period, the denaturation process was initiated.
  - Environmental adjustments included:
    - Removing the humidifier and adding a dehumidifier.
    - Increasing heat sources to achieve a steady 40°C temperature and air humidity between 30–50% for 10 days.
  - To prevent cracking or separation between the MBC core and the timber frame—caused by their differing shrinkage coefficients—three clamps were used to stabilize the structure during the denaturation process.
  - Growth was verified as stopped by leaving the demonstrator at room temperature for an additional three weeks, during which no further mycelial growth was observed.

Figure 11. (a) wall prototype in scaled up incubator (indoor growing tent); (b) module A in formwork after two weeks of incubation; (c) installation of MBC into the frame; (c) cultivation monitoring after three weeks.

- **Completion of the wall prototype** [Fig. 12]**:**

- The project partner (Krings-Reinke) team finalized the wall prototype according to traditional construction standards.
- The wall was built with a ventilated façade and clad with European larch, a locally sourced material that does not require post-treatment for weather protection.
- Two controlling openings with circular shape were done on each frame, one to monitor the MBC and, the other, to monitor the glass wool.

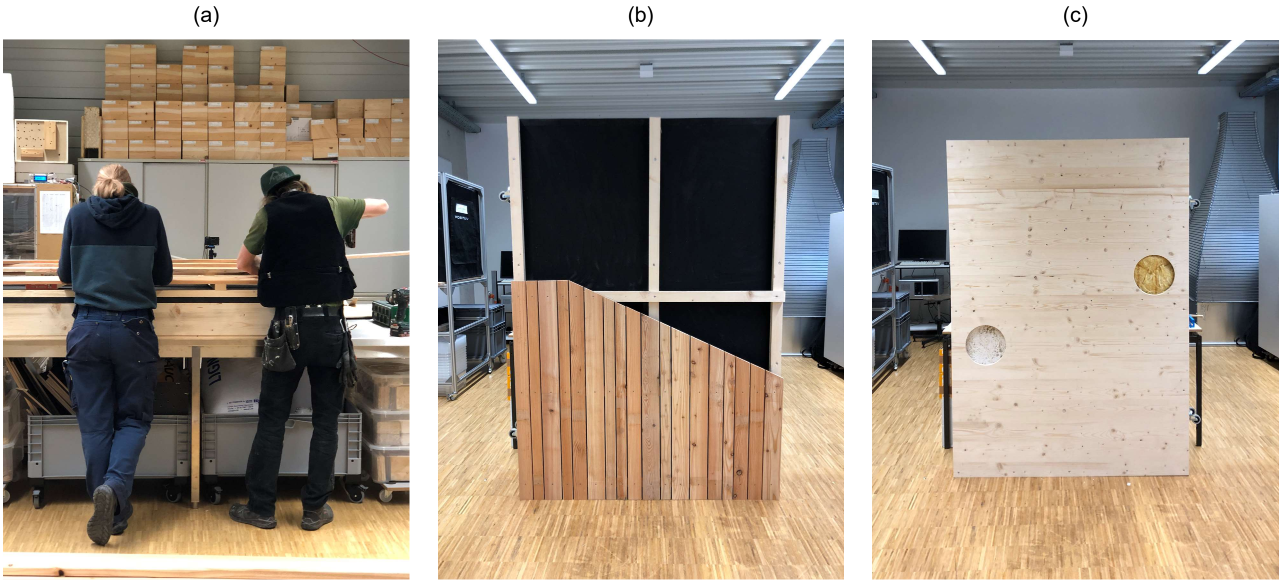

Figure 12. (a) project partner team finishing up the wall, (b) façade with larch cladding; (c) interior side of the wall with two controlling openings.

3. **Cabin model development:**
   To explore potential applications of the timber-frame wall demonstrator in real-world scenarios, a 1:20 scale model of a cabin design (approximately 40 m²) was developed. This model served to:

- Visualize how MBC-integrated timber-frame walls could be implemented in small-scale construction projects.
- Test assembly techniques and identify practical challenges associated with using MBC as both an insulation material and a structural bonding element.
- Provide insights into aesthetic and functional design considerations, such as the integration of MBC within a ventilated façade system.

Results and analysis:

1. **Fabrication and Transport**

- The timber frames were pre-fabricated by KR, following precise design specifications. This pre-fabrication process allowed for highly efficient use of materials and minimized waste, aligning with the sustainable goals of the project.
- Pre-fabrication enabled rationalization in resource allocation and labor, significantly reducing the need for on-site construction activities. By delivering complete, ready-to-assemble timber frames, the time and cost associated with on-site customization were greatly diminished.
- The pre-fabricated approach highlighted the scalability of the timber-frame system when integrated with MBC, showcasing its potential to lower costs and environmental impact for future implementations.

2. **Cultivation and Growth Conditions**

- **Challenges of Scaling Up:** Scaling up the cultivation process highlighted the difficulty of maintaining sterile conditions and environmental consistency on a larger scale. The growing tent approach required significant monitoring to sustain 24°C temperature and 80–90% humidity, while contamination risks posed an ongoing challenge despite precautions like Parafilm covers.
- **Future Scenarios for Scaling Up MBC Production:**
  - **On-Site Pop-Up Incubation Laboratory:**
    Temporary on-site setups, like the indoor growing tent, could enable direct integration of MBC into timber frames during construction. This approach minimizes transportation challenges but requires stringent environmental controls to avoid contamination.
  - **Centralized Off-Site Laboratory:**
    A dedicated facility could standardize the cultivation process as an intermediate step between timber frame pre-fabrication and construction. This scenario supports scalability, quality assurance, and streamlined delivery of ready-to-install systems, reducing on-site labor and complexity.

3. **Denaturation process**

- The whole process was described on methods, using clamps to address differential shrinkage between the MBC and timber prevented cracking or detachment, ensuring structural stability.

4. **Final wall prototype**

- The integration of the **ventilated façade** with locally sourced **larch wood cladding** completed the demonstrator providing a weather-resistant finish while maintaining the prototype's cradle-to-cradle objectives.
- The demonstrator highlighted the feasibility of utilizing MBC as a dual-purpose material: an insulation core and a structural bonding agent, supporting the timber frame and improving overall stability.

Benchmarking Process Based on Life-Cycle Assessment (LCA)

Objectives

- Conduct comprehensive life-cycle assessment of mycelium-based composite (MBC) material (Alaux et al., 2024)
- Compare environmental, economic, and social impacts with construction products
- Evaluate material performance across life-cycle stages

Methods

1. **LCA framework** [Fig. 13]

- The LCA was conducted following the DIN EN 14044:2006 ("DIN EN ISO 14044," n.d.) and EN 15804 ("DIN EN 15804," n.d.) standards.
- A cradle-to-gate approach was applied (Carcassi et al., 2022), supplemented by partly the end-of-life stages and recycling potential covering:
  - Product stage (A1-3): Material extraction and production.
  - End-of-life stages (C2-C4): Waste treatment, waste processing.
  - Recycling potential (D): Environmental benefits beyond the system boundaries.

- The process was modeled using Open LCA software and the EN 15804 +A2 Method for life-cycle impact assessment (LCIA).
- Two end-of-life scenarios were examined:
  1. Recycling as a soil regeneration additive (Hu et al., 2021; Pasche et al., 2024).
  2. Recycling as mulch.

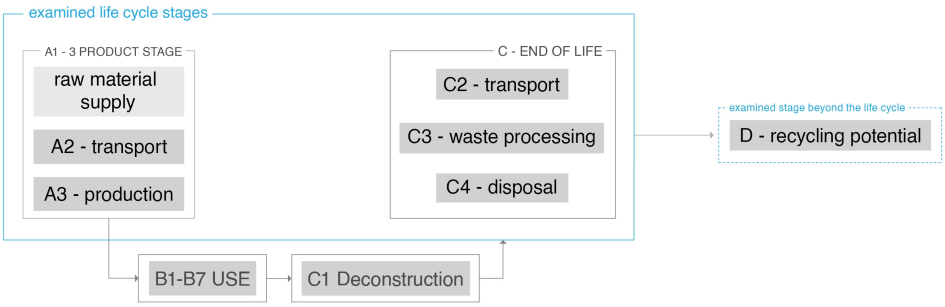

Figure 13. LCA system boundaries.

2. Benchmarking Process

- Environmental Product Declarations (EPD) of five comparative construction categories [Table 3] were standardized to ensure consistent units for evaluation.

Table 3. Construction products benchmarked and contrasted with MBC.

category	comparative material	abbreviation
conventional thermal insulation materials	Glasswool	GW
	Rockwool	RW
	Polystyrene particle foam	EPS
	Polystyrene extruded foam	XPS
natural thermal insulation materials	Hemp	H
	Hemplime	HL
	Holzfaser	WF
	Holzwolle	WW
sandwich panel	Kingspan TEK	KS
	Wandsystem Kingspan AWPflex®	AWP
bricks	BisoBims Hohlblöcke Classic	BB
	Silka Kleinformat	S
	Rigips Bauplatte RB 12,5	RB
	Hochlochziegel POROTON	HP
woodboards	Grobspanplatten	OSB
	Spannplatte	CHB
	Furnierschichtholz	LVL
	Brettsperrholz	CLT

- The declared unit was set at 1 m³, with results analyzed and plotted against benchmark target values, defined as the range between minimum and average values [Fig. 14].
- Benchmarking metrics included:
  - Environmental impact (e.g., GWP).
  - Economic factors (e.g., cost, service life) (BKI Baukosteninformationszentrum, 2023).
  - Social factors (e.g., work conditions, safety regulations).

Results and analysis

1. Environmental impact analysis

- The A1-3 phase had the largest impact on the life cycle, dominated by material extraction and production processes.
- The D stage demonstrated the least environmental impact, with potential benefits from recycling.
- In terms of natural thermal isolation materials, MBC's environmental impact resulted superior with a -5.04E+02 kgCO_2Eq.
- End-of-Life Scenarios:
    - Recycling processes involving mulch and soil regeneration additives offered favorable outcomes for MBC.
    - The closest competitors, LVL and CLT [Table 3], belong to the wood boards material category. However, due to its mechanical properties, such as compressive strength σ, MBC does not fully align with this category, even though it exhibits promising characteristics.

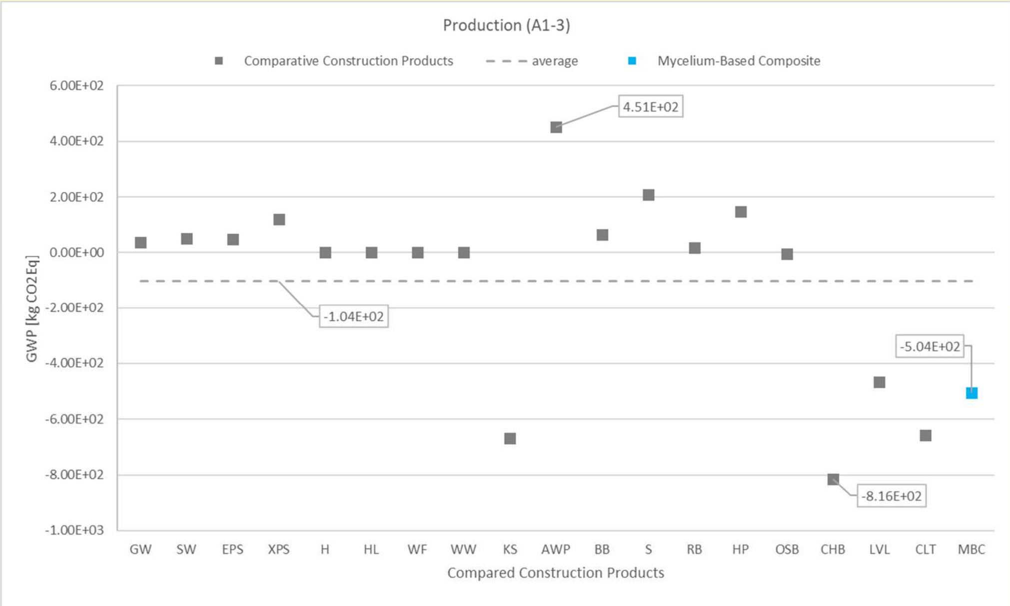

Figure 14. Comparison of GWP values of the product stage across five categories of conventional Construction Products and MBC.

2. **Economic factors**

- Service life ("Nutzungsdauern von Bauteilen für Lebenszyklusanalysen nach Bewertungssystem Nachhaltiges Bauen (BNB)," 2017) was assessed against benchmark targets, defined as the range between average and maximum values.
- MBC materials had competitive performance in terms of service life, closely rivaling hemp insulation and Laminated veneer timber.

3. **Social factors**

- All examined products adhered to European standards for workplace safety and occupational health, resulting in no significant differences among materials.

4. **Key Findings**

- Hemp insulation was identified as the overall closest competitor to MBC, with advantages in environmental metrics and end-of-life scenarios.

- MBC holds a significant advantage in terms of recycling potential and alignment with sustainability objectives, further emphasized by its negative GWP value during phases A1-3, reflecting its capacity to sequester carbon and reduce overall environmental impact in the production stages.

2. Comparison of the status of the project with the original work, time and resource planning.

Comparison of WP1 Status with Original Work, Time, and Resource Planning

The research activities for WP1, particularly the determination of material porosity using the gas pycnometer, were delayed due to unforeseen circumstances related to the project's funding timeline. The approval of the project did not coincide with the availability of financial resources, which necessitated the rental of the Anton Paar Ultrapyc 5000 pycnometer. This misalignment resulted in a postponement of all planned activities for WP1.

To ensure progress despite this delay, the focus shifted to WP4 (Benchmarking Process Based on Life-Cycle Assessment, LCA) while waiting for the necessary resources for WP1. Consequently, the initial timeline for WP1 was not adhered to as described in the project application, leading to a restructuring of the work sequence.

Criteria	Original plan	Completed work
Start date of WP1	Aligned with project approval	Delayed until after funding was made available
Focus of work	Determination of porosity and density (WP1)	Redirected Benchmarking Process using LCA (WP4)
Resource Use	Immediate access to pycnometer and materials	Delayed pycnometer rental; interim use of WP4 resources
Completion Status	Timely execution of all WP1 tasks	Completion delayed, requiring timeline adjustments

Comparison of WP2 Status with Original Work, Time, and Resource Planning

The delay in WP1 significantly impacted the schedule for WP2, requiring parallel execution of tasks related to the determination of porosity and the exploration of fungi-substrate combinations. This deviation from the planned sequential workflow increased complexity and workload. Despite this, the work package adapted by prioritizing key tasks, such as testing the radial growth of fungi on different wood geometries and optimizing combinations early on.

Criteria	Original plan	Completed work
Work sequence	Sequential (WP1 completion before WP2 initiation)	Overlapping work due to WP1 delays; parallel execution of tasks
Fungi-substrate screening	Predefined combinations tested for porosity	Extensive testing of new wood types, geometries, and wheat bran addition
Test specimen production	Early production based on predefined fungi-substrate combinations	Delayed until best combinations identified; then manufactured
Porosity measurement	Conducted post specimen production using established methodology	Methodology finalized during delay, allowing efficient measurement
Resource usage	Standard allocation based on predefined tasks	Increased resources for iterative testing and expanded material scope
Completion status	On schedule	Completed as planned, but with added effort and adaptive strategies

Comparison of WP3 Status with Original Work, Time, and Resource Planning

The need for extensive post-processing and analysis of the porosity data from WP1 and WP2 caused delays in the initiation of mechanical testing. This required prioritization and strategic adjustments to the testing plan. Compression testing was identified as the most relevant test for evaluating the influence of porosity on mechanical properties, leading to a focused approach that streamlined the process but deviated from the original comprehensive testing plan.

Criteria	Original plan	Completed work
Mechanical testing	Compression, shear, and bending tests on selected specimens	Only compression tests conducted on all 103 test specimens
Physical analysis	Lambda value and TGA test for best substrate-fungi combination	Excluded since beech wood + Ganoderma lucidum combination resulted on the best combination and we already have lambda value and TGA-Analysis
Specimen quantity	Limited to selected combinations	Tested all 103 produced cylinders
Focus of work	Comprehensive analysis of mechanical and physical properties	Targeted analysis of compression strength and its relation to porosity
Resource usage	Balanced across various tests	Concentrated on compression testing; omitted other physical analyses
Completion status	On schedule with all planned tests	Completed with focused scope; adjusted timeline and testing strategy

Comparison of WP4 Status with Original Work, Time, and Resource Planning

The manufacturing of the 1:1 prototype took longer than initially planned, extending the timeline by four weeks. This delay was primarily due to decisions made during the process to ensure the highest quality of the final product. Specifically, the cultivation period was extended by one additional week to optimize the material's properties, followed by three weeks of monitoring the material after denaturation to ensure its stability. These steps were essential to guarantee the success of the prototype construction, which was completed with the collaboration of the Krings-Reinke team during the final stages. While these adjustments caused a delay, they ultimately contributed to the reliability and quality of the results.

Criteria	Original plan	Completed work
Demonstrator manufacturing	Completed on schedule	Completed 4 weeks later; cultivation and monitoring extended
Benchmarking	Benchmarked with commercial products using relevant parameters	Completed using LCA-based GWP value for robust comparison
Dissemination	Planned publications at project end	Completed paper and abstract for publication during WP4
Resource usage	Standard allocation for prototype production and benchmarking	Additional resources for extended cultivation and monitoring
Completion status	On schedule with all planned tasks	Achieved goals with minor delays in prototype completion

3. Changes to the prospects of achieving the project objectives within the specified budget period, which may require an adjustment to the work plan but do not change the core of the task (e.g., also in the event of a change in project management)

No major changes were made to the core objectives of the project. However, adjustments were necessary in terms of the work plan and timelines, primarily due to delays in the earlier work packages (WP1 and WP3). These adjustments were reflected in the comparative charts provided in point 2, where the deviations from the original schedule and resource allocation are clearly outlined. Despite these minor changes, the essential goals and tasks of the project were achieved as planned, without altering the core objectives or the overall direction of the research.

4. Results that have become known in the meantime from third parties and are relevant for the implementation of the project

No relevant results from third parties have become known.

5. Necessary changes in the objectives

No changes were necessary in terms of the objectives of the project.

6. Updating of the exploitation plan.

At the present time, there are no changes or additions to the utilization plan for the project application.

a) Findings /Schutzrechtsanmeldungen

No inventions or applications for industrial property rights that are relevant to the project have become known.

b) Economic prospects of success after the end of the project

The economic prospects for success after the project's completion are promising, with the developed MBC positioned to meet the growing demand for sustainable building materials. The project's outcomes, including the LCA results and established partnerships with the project partners, provide a strong foundation for commercialization and future product development in eco-friendly industries.

c) Scientific and/or technical prospects of success after the end of the project

The scientific and technical prospects are strong, with the MBC offering potential for collaboration with research institutions and industry partners in sustainable construction and materials. To support this, scaling up production would be recommended, and the project's findings, including the Life-Cycle Assessment (LCA) data, can be integrated into public databases, e.g.,*Ökobaudat* and contribute to ongoing sustainability efforts, fostering innovation in eco-friendly industries.

d) Scientific and economic connectivity

To advance the adoption of mycelium-based composites in the construction industry, collaboration with construction firms and sustainability-focused organizations is essential for scaling production and replacing high-CO2 footprint materials. This connectivity can drive innovation, reducing the environmental impact of building materials and accelerating the shift toward more sustainable construction practices.

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