

Article

Enhanced Thermal Mass of Mycelium-Based Biocomposites for Timber Constructions: A Comparative Study

Benjamín Petržela ^{1,*}, Tadeáš Zachara ¹, Miroslav Jozífek ², Miloš Pavelek ¹ and Štěpán Hýsek ¹

¹ Department of Wood Processing and Biomaterials, Faculty of Forestry and Wood Sciences, Czech University of Life Sciences Prague, 16500 Prague, Czech Republic; hyseks@fd.czu.cz (Š.H.)

² Department of Horticulture, Faculty of Agrobiological Sciences, Food and Natural Resources, Czech University of Life Sciences Prague, 16500 Prague, Czech Republic

* Correspondence: petrzel@fd.czu.cz; Tel.: +420-773-210-276

Abstract

Summer overheating is an escalating challenge for lightweight timber constructions, which inherently lack the thermal mass of traditional masonry. This study investigates the thermo-physical properties of a mycelium-based biocomposite (MBB) insulation produced from industrial wood waste, with particular focus on volumetric heat capacity (C_v). The C_v and thermal conductivity (λ) of MBB were experimentally measured and benchmarked against seven reference insulation materials spanning bio-based, mineral, and petroleum-derived categories, with results visualized on an Ashby diagram. The areal heat capacity (κ) of nine representative wall assemblies was theoretically calculated per EN ISO 13786. Even though the MBB achieved the highest thermal conductivity ($\lambda = 0.0641 \pm 0.0024 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$) among the tested insulation materials, it offers 4.7 times higher C_v than EPS. Analytical modeling indicates a thermal phase shift of 8.2 h for a 185 mm layer, compared to 4.6 h for EPS. The softwood timber + MBB wall assembly achieved an areal heat capacity approaching the lower boundary of traditional masonry performance. These findings demonstrate MBB's potential as a bio-based, waste-derived insulation for significantly enhancing the thermal inertia of lightweight timber buildings and mitigating summer overheating risk.

Keywords: mycelium-based biocomposite; thermal mass; thermal inertia; bio-based insulation; timber construction; hardwood; volumetric heat capacity; summer overheating; building physics; fungal biocomposite

Academic Editors: Miklós Bak, Róbert Németh, Holger Militz, Christian Hansmann and Mátyás Báder

Received: 2 June 2026

Revised: 26 June 2026

Accepted: 28 June 2026

Published: 29 June 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

The escalating impacts of climate change are fundamentally transforming the species composition of Central European forests. Prolonged droughts and bark beetle outbreaks have severely compromised traditional coniferous monocultures, particularly Norway spruce (*Picea abies*), forcing a strategic silvicultural shift towards more resilient deciduous species [1,2]. This transition is particularly evident for European beech (*Fagus sylvatica* L.), whose climate vulnerability and adaptation potential in Central Europe have been extensively reviewed, with contrasting reports of both drought-induced growth reductions and capacity for managed adaptation as a climate-smart species [3,4]. Accordingly, the timber construction sector must adapt to this changing resource base by expanding the utilization of hardwood timber in engineered wood products (EWPs) such as cross-

laminated timber (CLT), glued laminated timber (glulam), and laminated veneer lumber (LVL), where high-density hardwoods can match or exceed the structural performance of conventional softwood elements [5–7]. Regional shifts are already measurable; in Slovenia, for instance, deciduous species recently overtook coniferous ones in total growing stock, with beech now exceeding spruce as the most abundant tree species [8]. While modern timber constructions utilizing these resources offer significant environmental benefits through carbon sequestration and low embodied energy, they face a critical building physics challenge: a distinct lack of thermal mass.

Understanding this challenge requires examining the thermodynamic mechanisms of passive heat accumulation. The ability of a building envelope to buffer temperature fluctuations is governed by the volumetric heat capacity of its constituent materials [9]. In traditional heavyweight construction systems, such as concrete or masonry, high density drives a high volumetric heat capacity. When placed inside the insulated thermal envelope, these materials absorb excessive solar and internal heat gains during the day and release them slowly as temperatures drop. This dynamic creates a thermal lag that has the potential to mitigate the risk of summer overheating and help stabilize indoor comfort [10].

Conversely, modern lightweight timber structures, despite their superior embodied carbon profile, inherently lack this thermodynamic buffer. While timber possesses a relatively high specific heat capacity, its low density results in poor overall volumetric heat accumulation [9]. Consequently, the thermal stability of a timber building becomes heavily reliant on the secondary components of its envelope. This exposes a critical vulnerability when paired with conventional insulation materials, such as Expanded Polystyrene (EPS) or glass wool. These materials are designed strictly to minimize thermal conductivity; because their densities are exceedingly low, their volumetric heat capacity is negligible [11]. As a result, the envelope effectively resists heat transfer but has a limited capacity to absorb transient heat peaks, which may contribute to indoor temperature spikes during summer months.

To address both the shift in forestry material flows and the need for enhanced thermal inertia in lightweight buildings, bio-based materials such as mycelium-based biocomposites (MBBs) have emerged as promising alternatives. MBBs utilize fungal mycelium as a natural binder for industrial waste wood, creating materials with competitive thermal resistance, low embodied carbon, and complete biodegradability [12]. This direction is part of a broader effort to develop building insulation panels from recycled, waste-derived, and otherwise alternative lignocellulosic feedstocks, including, e.g., adhesive-free insulation boards from hardwood tree bark fibers [13]. Due to their denser organic matrix and the inherently higher specific heat capacity of their cellular structure, MBB aims to provide thermo-physical performance comparable to existing high-thermal-mass bio-insulations, but achieves this through a fundamentally different, low-energy fabrication method without the need for synthetic adhesives. By substituting negligible-mass conventional insulations with higher-mass organic composites, the thermal inertia of the entire timber wall assembly can be drastically improved without reverting to high-carbon concrete or brick systems. Despite these prospects, the wider adoption of MBBs is currently constrained by several technical challenges. The material's porous organic structure makes it inherently susceptible to moisture absorption, which can compromise both its thermal performance and dimensional stability [14,15]. Furthermore, achieving consistent mechanical and physical properties remains difficult due to inherent biological variability in the substrate and fungal growth processes [14,16]. Fire performance and long-term durability in real-world hygrothermal conditions also remain critical areas requiring extensive standardization and validation before MBBs can be fully integrated into commercial building envelopes [17].

Prior comparative characterization of MBB has established a literature range of $\lambda = 0.036\text{--}0.10 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ for wood-based substrate formulations, with the inter-study variability driven primarily by substrate type, fungal species, and processing conditions [12,14,17–19]. Among the reference insulation types compared in this study, Schiavoni et al. [20] report $\lambda = 0.030\text{--}0.040 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ for EPS, $0.030\text{--}0.045 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ for glass and mineral wool, and $0.038\text{--}0.060 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ for bio-based alternatives such as hemp wool and wood fiberboard—products that, unlike petroleum-derived insulants, contribute meaningful volumetric heat capacity through their elevated density and specific heat capacity [9,20]. Thermal properties are measured using the transient needle probe method, which simultaneously resolves λ , C_v , and thermal diffusivity from a single rapid cycle [10]. For the organic insulation materials in this study—MBB, hemp wool, and wood fiberboard—moisture content is especially critical: hygroscopic organic matrices absorb moisture that substantially elevates both λ and C_v , and unconditioned specimens may appear thermally different from mineral or petroleum-derived insulants largely due to differential moisture content rather than intrinsic material properties [14,20], thus the methodological approaches in measuring hygroscopic materials are essential [21]. By conditioning all specimens to identical equilibrium conditions prior to testing and applying a single uniform measurement protocol, this study ensures that the comparative results are free from moisture-driven artifacts—making the cross-material benchmarking both methodologically consistent and physically meaningful.

Building upon previous research that established the fundamental thermal conductivity and U-value of the “MycoWall” concept, water vapor permeability of MBBs [22], as well as the mechanical characterization and digital/AI-assisted industrial production of the same biocomposite [23], this study investigates MBB within a highly specific, forward-looking wall assembly designed for the future material flow of European forestry. The adopted wall composition fundamentally explores the utilization of hardwood timber in combination with organic insulation. The main load-bearing structure consists of cross-laminated timber, secondary structural framing elements employ beech (*Fagus* sp.), and the exterior ventilated façade consists of oak (*Quercus* sp.) timber. The core insulation of this assembly is the MBB, cultivated from industrial waste wood. To evaluate the thermal mass potential of MBB for lightweight timber construction, this paper characterizes its volumetric heat capacity and benchmarks it against conventional and alternative insulation materials.

2. Materials and Methods

2.1. Materials

Different types of insulation materials were evaluated in three groups—bio-based, mineral and petroleum-derived insulation materials.

Bio-based insulation materials:

- Mycelium-Based Biocomposite (MBB): A mycelium-based thermal insulation from industrial waste wood (Kronospan, Jihlava, Czech Republic) bonded by *Ganoderma sessile* (Boston edison, Terrestrial fungi, Portland, OR, USA) in 3 biological replications.
- Recycled cotton fibers insulation panel (RC): origin EN-TEX (Enroll CZ, Nová Ves, Czech Republic), obtained from study [11].
- HempWool insulation board (HW): HempWool low density batt (Hempitecture Inc., Jerome, AZ, USA).
- Wood Fiberboard (FB): standard commercial grade, STEICO therm dry (STEICO SE, Feldkirchen, Germany).

Mineral insulation materials:

- Mineral Wool (MW): standard commercial grade, Isover Topsil (Saint-Gobain, La Défense, France).
 - Glass Wool (GW): standard commercial grade, Isover Domo Plus (Saint-Gobain, La Défense, France).
- Petroleum-derived insulation materials:
- Expanded Polystyrene Grey (EPS-G): standard commercial grade, Isover EPS GP 29 (Saint-Gobain, La Défense, France).
 - Expanded Polystyrene (EPS): standard commercial grade, Isover EPS 70 F (Saint-Gobain, La Défense, France).

The particle size fraction of industrial waste wood was determined by sieve analysis; the particle size distribution is presented in Table 1.

Table 1. Particle size distribution of recycled wood.

Sieve Size [mm]	8	3.15	2	1.6	0.8	0.5	0.25	0
Particles Share [%]	0.01	2.54	26.78	17.78	48.40	4.41	0.31	0.25

Figure 1 depicts macro-structural images from the different materials tested.

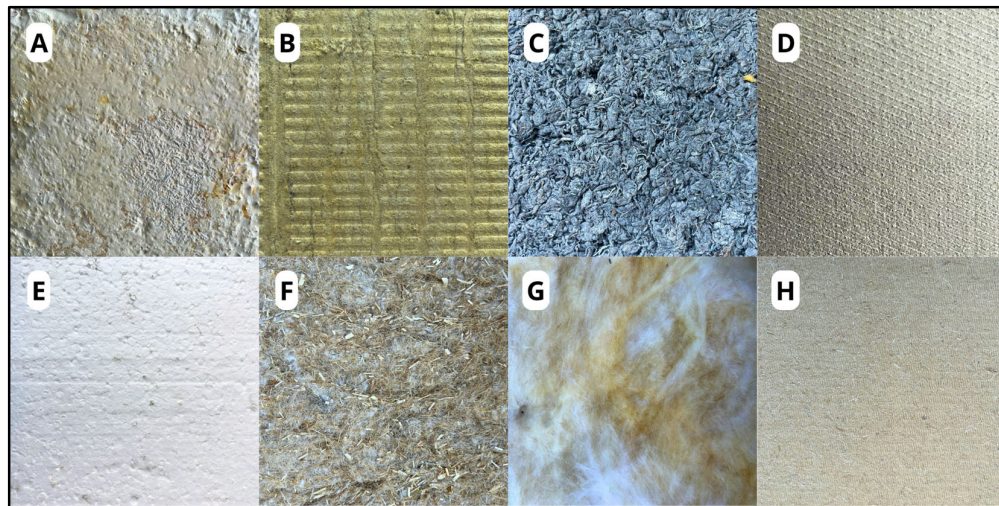


Figure 1. Materials. Note: (A) mycelium-based biocomposite—MBB, (B) mineral wool—MW, (C) recycled cotton—RC, (D) Expanded Polystyrene Grey—EPS-G, (E) Expanded Polystyrene—EPS, (F) HempWool—HW, (G) glass wool—GW, (H) fiberboard—FB.

2.2. Production

The production methodology follows that of Petržela et al. [22] and further demonstrated under non-sterile industrial conditions by Hýsek et al. [23]. A brief description is provided below.

The substrate (recycled wood, middle-layer PB fraction, Kronospan, Jihlava, Czech Republic) is sterilized in autoclave MLS-3781L (3 h, 121 °C, Sanyo Electric Co., Ltd., Moriguchi City, Japan), hydrated to absolute moisture 60%, and inoculated with 10% (w.w./w.w.) wheat grain spawn ($47 \pm 2\%$ m.c., De Heus a.s., Choceň, Czech Republic) of *Ganoderma sessile* (Boston edison, Terrestrial fungi, USA). This specific fungal strain was selected based on our previous experimental evaluations comparing various wood-decaying fungi, where *Ganoderma sessile* demonstrated suitable mechanical properties and reliable colonization [23]. The mixture was supplemented with gypsum (2.5% d.w.; KittfortPraha s.r.o., Neratovice, Czech Republic) in a flowbox (FAST H, Faster s.r.l., Cornaredo, Italy) and incubated in PP bags equipped with microfilter patches for optimal gas

exchange (model PP50/SEU4/V40-51, SAC O2 nv, Deinze, Belgium). The incubation was conducted in a growth chamber maintained at a constant temperature of 24 ± 1 °C and 70% ambient relative humidity in complete darkness. After 14 days, the colonized substrate is semi-automatically crushed by hammer crushing machine (Y2-1325-4, Chongqing Silesia Machinery & Electric Co., Ltd.; Chongqing, China) and loosely filled into PMMA detachable molds ($500 \times 500 \times 200$ mm) for 7 days without the application of any manual or mechanical compaction. Afterwards, the MBBs are post-grown without mold in a sealed XPS box ($\approx 27 \pm 6$ °C; 99%RH; 3, 5 days), then pre-dried (ventilation; 20 ± 3 °C; 40 ± 3 %RH; 10 days) and dried (drying chamber; 103 ± 3 °C; 0% RH; 24 h). MBBs are produced in 3 replications.

2.3. Measurement

The samples were conditioned at 20 ± 3 °C and $65 \pm 5\%$ relative humidity until a constant mass was achieved. Bulk density (ρ) in $\{\text{kg}\cdot\text{m}^{-3}\}$ was determined by measuring the dimensions and mass of the MBB specimens. For each reference material, ten independent specimens were measured (one measurement per specimen; $n = 10$), except RC, where three specimens were obtained from Zachara et al. [11] ($n = 3$). For MBB, three independent production batches were prepared; each batch specimen was subjected to ten repeated measurements to characterize within-batch instrument repeatability. For statistical analysis, the ten within-batch measurements were averaged to yield three batch-level means, which constitute the true independent replicates for MBB ($n = 3$). Reporting MBB from batch-level means avoids pseudoreplication that would arise from treating within-batch repeated measurements on the same specimen as independent observations. Transient thermal properties were measured using an ISOMET 2114 (Applied Precision Ltd., Rača, Slovakia) portable heat transfer analyzer equipped with an IPN 1100 needle probe based on ASTM D5334-22 [24]. This apparatus applies a dynamic heat pulse and analyzes the temperature response to determine thermal conductivity (λ) in $\{\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}\}$, volumetric heat capacity (C_v) in $\{\text{J}\cdot\text{m}^{-3}\cdot\text{K}^{-1}\}$ and thermal diffusivity (α) in $\{\text{m}^2\cdot\text{s}^{-1}\}$.

The specific (mass-related) heat capacity c [$\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$] was derived from the measured C_v and bulk density ρ as $c = C_v/\rho$. The ISOMET transient needle probe method tends to overestimate C_v relative to quasi-static calorimetric methods, particularly for low-density open-cell foams (EPS, EPS-G, GW), where the finite probe contact area and air-filled pore structure introduce a systematic positive bias in the measured C_v . The C_v and c values in this study therefore reflect instrument-specific measurement conditions and should not be directly compared to tabulated literature values determined by differential scanning calorimetry or steady-state methods. However, since all tested materials, including the MBB and reference insulants, were measured under identical experimental conditions using the same calibration protocol, the relative performance ranking remains valid. The observed differences in C_v between the MBB and reference materials significantly exceed the instrument's documented methodological uncertainty, thereby validating the comparative conclusions drawn in this work.

2.4. Calculation

Specific heat capacity (c) in $\{\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}\}$ was derived from the measured volumetric heat capacity and the calculated bulk density, using the following relationship (Equation (1)):

$$c = \frac{C_v}{\rho} \quad (1)$$

where C_v is volumetric heat capacity and ρ is bulk density.

The thermal phase shift (φ) of an insulation layer describes the time delay between the maximum external temperature wave and the peak internal heat flux. Phase shift was

calculated using Equation (2) (ISO 13786:2018 [25], adjusted) at the actual measured sample thickness of 185 mm (the as-produced thickness of MBB after mold shrinkage; see Table 2), consistently for all materials to enable a like-for-like comparative evaluation. Note that the separate reference thickness of 200 mm is used exclusively for areal heat capacity (κ) calculations in Equation (3), representing the target design thickness in the wall assembly.

$$\varphi = d * \sqrt{\frac{\pi * C_v}{\lambda * 86400}} \quad (2)$$

where φ is the thermal phase shift [radians], d is the layer thickness [m], C_v is the volumetric heat capacity [$\text{J} \cdot \text{m}^{-3} \cdot \text{K}^{-1}$], λ is the thermal conductivity [$\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$], and 86400 is the number of seconds per day [s].

Table 2. MBB production characteristics.

Replication	a [mm]	SH(a) [%]	b [mm]	SH(b) [%]	t [mm]	SH(t) [%]	m [kg]	ρ [$\text{kg} \cdot \text{m}^{-3}$]
1	487.0 $\pm$ 0.4	2.6 $\pm$ 0.1	487.0 $\pm$ 0.7	2.6 $\pm$ 0.1	184.0 $\pm$ 0.7	8.0 $\pm$ 0.4	6.23	142.8 $\pm$ 0.6
2	488.0 $\pm$ 0.8	2.4 $\pm$ 0.2	488.0 $\pm$ 1.6	2.4 $\pm$ 0.3	185.0 $\pm$ 1.6	7.5 $\pm$ 0.8	7.04	159.8 $\pm$ 1.5
3	486.0 $\pm$ 1.6	2.8 $\pm$ 0.3	484.0 $\pm$ 1.3	3.2 $\pm$ 0.3	186.0 $\pm$ 1.0	7.0 $\pm$ 0.5	6.31	144.3 $\pm$ 1.0

Where a, b, t = dimensions (5 measurements, expressed as mean $\pm$ SD); SH = shrinkage; m = mass; ρ = bulk density (uncertainty of bulk density was propagated from the standard deviations of the three linear dimensions).

The phase shift in hours (τ) was obtained as $\varphi \cdot 24 \cdot (2\pi)^{-1}$. Equation 2 is an analytical solution for a homogeneous slab under sinusoidal periodic boundary conditions (after Carslaw and Jaeger [26]) and is applied here for comparative screening across materials at a uniform thickness. It assumes steady-periodic conditions and isotropic material properties; it is not equivalent to the dynamic transfer-matrix method prescribed by EN ISO 13786:2018 for building components. Results should be interpreted as comparative indicators of relative thermal delay between materials and are not equivalent to dynamic wall performance assessments; normative phase-shift values for building components require the dynamic transfer-matrix method of EN ISO 13786:2017 [25] applied to complete multi-layer assemblies under in-service boundary conditions.

To quantify the thermal storage capacity of complete wall assemblies, the areal heat capacity (κ) of each layer was calculated according to EN ISO 13786:2017 [25] as the product of the volumetric heat capacity and the layer thickness (Equation (3)):

$$\kappa_i = C_{v,i} * d_i \quad (3)$$

where κ_i is the areal heat capacity of layer i [$\text{kJ} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$], $C_{v,i}$ is the volumetric heat capacity of layer i [$\text{kJ} \cdot \text{m}^{-3} \cdot \text{K}^{-1}$], and d_i is the layer thickness [m]. The total areal heat capacity of the wall assembly (κ_{total}) was obtained as the sum of the layer contributions. For the measured insulation materials, $C_{v,i}$ was expressed as mean $\pm$ SD. For structural layers, $C_{v,i}$ was taken as the minimum–maximum range from the literature sources and the combined κ_{total} range was reported as $[\kappa_{s,\text{min}} + (C_{v,i} - \text{SD}) \cdot d_i; \kappa_{s,\text{max}} + (C_{v,i} + \text{SD}) \cdot d_i]$, where $\kappa_{s,\text{min}}$ and $\kappa_{s,\text{max}}$ represent the literature minimum and maximum for the structural layer, and SD is the standard deviation of the measured insulation C_v . This interval represents a conservative performance window combining the full literature range of structural material variability with one standard deviation of insulation measurement uncertainty and is not a formal combined standard uncertainty.

2.5. Wall Composition

Wall composition is fundamentally driven by predictive future composition of Central European forests, where deciduous species will thrive over conifers. This composition explores the utilization of hardwood timber.

The wall composition design (Figure 2) utilizes MBB from industrial waste wood (Kronospan, Jihlava, Czech Republic) as a core insulation with exterior cover by Egger DHF (Egger, St. Johann in Tirol, Austria). For main load-bearing structure, a cross-laminated timber (CLT) is used (CLT Novatop Solid; AGROP NOVA a.s., Czech Republic). Secondary structural elements employ beech (*Fagus* sp.) protected by novel lavender oil treatment. A ventilated façade consists of oak (*Quercus* sp.) profiles protectively treated by transparent finish DColor FK 47 UV Protect, a coating developed at Czech University of Life Sciences Prague, Faculty of Forestry and Wood Sciences, which contains metal oxide nanoparticles for UV stabilization [27,28].

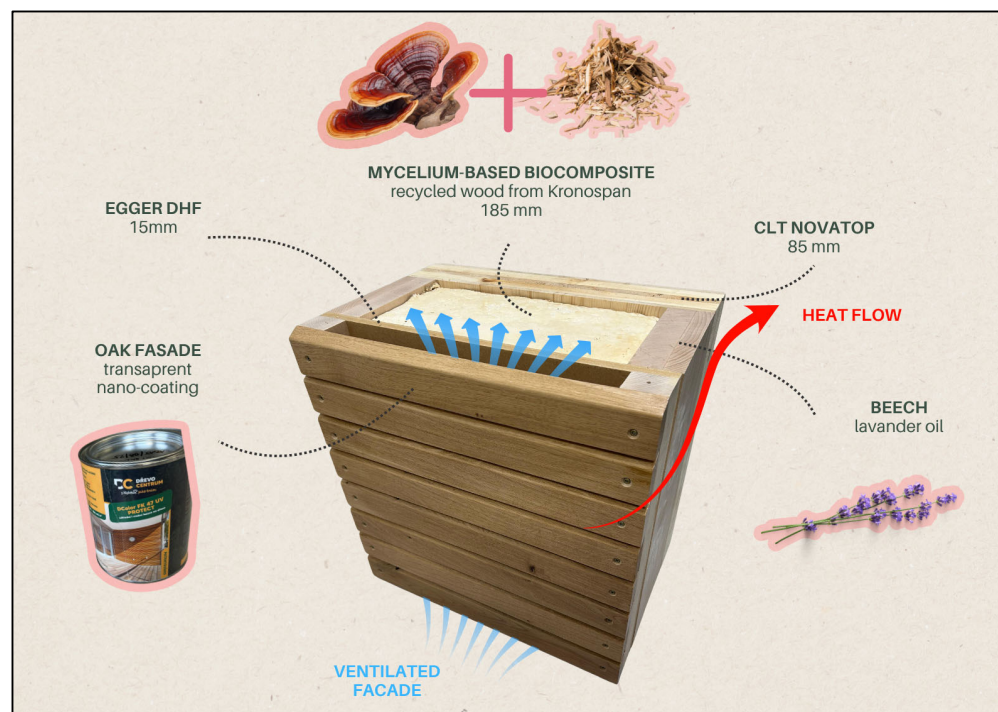


Figure 2. Composition of MycoWall.

For the comparative assessment of areal heat capacity (Table 4), a low-energy building configuration with a structural layer thickness of 200 mm and an insulation layer thickness of 200 mm was adopted as the reference wall geometry. Eight additional reference wall systems were constructed by pairing the measured insulation materials with four structural materials commonly used in Central European construction: softwood timber, fired clay brick (Porotherm), autoclaved aerated concrete (AAC/YTONG), and reinforced concrete, each represented by the literature minimum–maximum range of volumetric heat capacity. The combined κ_{total} range of each wall system was calculated by summing the lower bound of the structural range with the measured insulation mean minus SD, and the upper bound of the structural range with the measured insulation mean plus SD, thereby propagating both literature and measurement uncertainty. Areal heat capacity has been established as a key discriminating parameter for comparing the dynamic thermal buffering performance of differently insulated wall assemblies [29].

2.6. Statistical Analysis

Differences in thermo-physical properties between material groups were compared by ANOVA-based methods using the independent units: $n = 10$ specimen measurements per reference material ($n = 3$ for RC) and $n = 3$ batch-level means for MBB. Given the nature of the measured thermo-physical properties and the absence of evidence suggesting substantial departures from normality, parametric methods were considered appropriate. Homogeneity of variances was assessed using Levene's test. Post hoc pairwise comparisons were performed using Dunn's test with Bonferroni correction. All analyses were performed in TIBCO Statistica 14 (TIBCO Software Inc., Palo Alto, CA, USA); significance level $\alpha = 0.05$.

2.7. Use of Artificial Intelligence Tools

During the preparation of this manuscript, the following artificial intelligence tools were used. Connected Papers (connectedpapers.com, accessed 4 June 2026) was used for literature mapping via keyword-based paper discovery (keywords: mycelium; mycelium-based composite; thermal conductivity; volumetric heat capacity; thermal mass; insulation material) and related-paper graph exploration seeded from key manuscripts cited in this study [11,12,18,22]. Scite (scite.ai, Research Solutions, Brooklyn, NY, USA) was used for supplementary literature pre-screening and citation classification. Claude (models: Sonnet 4, Opus 4; Anthropic, San Francisco, CA, USA) was used to improve manuscript readability, language style, and consistency, and assist in organizing tabulated numerical data compiled from the published literature. Canva AI (Canva Pty Ltd., Surry Hills, Australia) was used for graphical abstract preparation, specifically for background removal from photographs and application of visual effects to illustrative images; no AI-generated imagery was produced. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

3. Results

3.1. MBB Production

Table 2 represents final dimensions, mass, bulk density (after conditioning at 20 ± 3 °C; $65 \pm 5\%$ RH) and production shrinkage of all three MBB replication batches.

3.2. Thermo-Physical Characteristics

Table 3 presents the measured thermo-physical properties of all insulation materials. MBB exhibited a thermal conductivity of $\lambda = 0.0641 \pm 0.0024 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ and a volumetric heat capacity of $C_v = 201.8 \pm 30.3 \text{ kJ}\cdot\text{m}^{-3}\cdot\text{K}^{-1}$. While its λ is the highest among the tested insulations, reflecting the density of its organic matrix, its C_v exceeds EPS by a factor of 4.7, EPS-G by 2.7, glass wool by 4.3, and HempWool by 2.1. Among all materials, recycled cotton (RC, $C_v = 476.8 \pm 36.5 \text{ kJ}\cdot\text{m}^{-3}\cdot\text{K}^{-1}$) achieved the highest volumetric heat capacity, followed by MBB, wood fiberboard (FB, $249.4 \pm 4.2 \text{ kJ}\cdot\text{m}^{-3}\cdot\text{K}^{-1}$), and mineral wool (MW, $136.8 \pm 2.0 \text{ kJ}\cdot\text{m}^{-3}\cdot\text{K}^{-1}$). The lowest specific heat capacity (c) was measured in MBB ($1351 \pm 158 \text{ J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$), attributable to its relatively high density, while wood fiberboard exhibited the highest c ($4393 \pm 73 \text{ J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$), consistent with its high cellulose content.

Group differences in C_v were assessed following the analytical approach of Section 2.6. Using the correct independent units— $n = 3$ batch-level means for MBB and $n = 10$ specimen measurements for each reference material—the one-way ANOVA yielded $F(7, 58) = 912.33$, $p < 0.001$. The Shapiro–Wilk test of residuals returned $W = 0.982$ ($p = 0.445$), confirming that normality is satisfied. Post hoc Dunn's test with Bonferroni correction confirmed significant differences between all material pairs except EPS vs. GW and EPS-G vs. HW; homogeneous subsets are indicated by letter codes in Table 3 (a = lowest C_v , f =

highest). The MBB vs. RC comparison is statistically significant ($p = 0.021$) but should be interpreted with caution: both groups have $n = 3$, making the comparison sensitive to variance heterogeneity. The between-batch variability of MBB (Batch 1: $C_v = 196.3 \text{ kJ}\cdot\text{m}^{-3}\cdot\text{K}^{-1}$, $\lambda = 0.0624 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$; Batch 2: $C_v = 233.9 \text{ kJ}\cdot\text{m}^{-3}\cdot\text{K}^{-1}$, $\lambda = 0.0671 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$; Batch 3: $C_v = 175.2 \text{ kJ}\cdot\text{m}^{-3}\cdot\text{K}^{-1}$, $\lambda = 0.0629 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$) represents a between-batch SD of $29.8 \text{ kJ}\cdot\text{m}^{-3}\cdot\text{K}^{-1}$ (ca. 15% of the grand mean), broadly consistent with inter-study ranges reported for lignocellulosic-substrate mycelium composites [14,18]. The RC thermo-physical data ($C_v = 476.8 \pm 36.5 \text{ kJ}\cdot\text{m}^{-3}\cdot\text{K}^{-1}$, $\lambda = 0.0738 \pm 0.0003 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, $n = 3$) were adopted from the study by Zachara et al. [11], who characterized cold-pressed recycled cotton insulation boards tested via the same methodology. The calculated phase shift of a 185 mm MBB layer amounts to 8.2 h, compared to 4.6 h for EPS at the same thickness—a 78% increase in thermal phase shift.

Table 3. Thermo-physical properties of tested insulation materials.

Abbrev.	ρ [$\text{kg}\cdot\text{m}^{-3}$]	λ [$\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$]	C_v [$\text{kJ}\cdot\text{m}^{-3}\cdot\text{K}^{-1}$]	c [$\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$]	τ [h]	R_{185} [$\text{m}^2\cdot\text{K}\cdot\text{W}^{-1}$]
EPS	13.1 ± 0.4	0.0436 ± 0.0022	42.8 ± 0.6 (a)	3262 ± 116	4.6 ± 0.2	4.2 ± 0.2
EPS-G	32.0 ± 1.1	0.0332 ± 0.0007	73.5 ± 0.7 (b)	2300 ± 87	6.9 ± 0.2	5.6 ± 0.1
GW	17.2 ± 0.9	0.0452 ± 0.0040	46.7 ± 1.3 (a)	2719 ± 172	4.7 ± 0.4	4.1 ± 0.4
HW	38.0 ± 2.3	0.0558 ± 0.0027	96.6 ± 5.9 (b)	2548 ± 202	6.1 ± 0.5	3.3 ± 0.2
MW	62.8 ± 3.1	0.0408 ± 0.0012	136.8 ± 2.0 (c)	2178 ± 32	8.4 ± 0.3	4.5 ± 0.1
FB	56.8 ± 4.0	0.0580 ± 0.0011	249.4 ± 4.2 (e)	4409 ± 272	9.6 ± 0.2	3.2 ± 0.1
MBB	149.0 ± 7.7	0.0641 ± 0.0024	201.8 ± 30.3 (d)	1351 ± 158	8.2 ± 1.3	2.9 ± 0.1
RC	300.0 ± 0.0	0.0738 ± 0.0003	476.8 ± 36.5 (f)	1589 ± 122	11.7 ± 0.9	2.5 ± 0.0

Mean $\pm$ SD; $n = 10$ per material, except RC thermo-physical properties adopted from Zachara et al. [11] ($n = 3$); MBB $n = 3$ (batch-level means; 10 technical replicates per batch). $R_{185} = d/\lambda$ at $d = 185 \text{ mm}$ [$\text{m}^2\cdot\text{K}\cdot\text{W}^{-1}$]. Different lowercase letters (a)–(f) denote lowest–highest.

Figure 3 displays an Ashby-type diagram plotting λ against C_v for all tested materials and reference building materials, with shaded areas indicating literature ranges for each material class. The MBB datapoint occupies a region not conventionally populated by insulation materials, clustering close to structural bio-based materials rather than petroleum-based insulants. This dual-function position of moderate thermal resistance combined with high thermal mass distinguishes MBB from all conventional insulation alternatives.

Figure 4 presents a comparison of volumetric heat capacity across insulation materials and selected structural building materials. The results emphasize that EPS, EPS-G, and glass wool exhibit C_v values that approach negligible levels relative to structural materials, confirming their inability to contribute to building thermal inertia. MBB and RC approach the lower range of structural masonry materials, highlighting their potential to provide meaningful thermal buffering within the insulation layer itself.

Table 4 presents the areal heat capacity (κ) of nine representative wall assemblies, calculated for a low-energy configuration with 200 mm structural and 200 mm insulation layer thicknesses. The softwood timber + MBB assembly achieves $\kappa_{\text{total}} = 156\text{--}262 \text{ kJ}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$, substantially outperforming the most of timber assemblies paired with conventional insulation: timber + GW (131–226 $\text{kJ}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$), timber + HW (140–236), and timber + MW (149–244). Only timber + FB (171–267) and timber + RC (210–319) exceed MBB assembly. Compared to a widely used lightweight masonry reference (AAC/YTONG + EPS, 59–169 $\text{kJ}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$), the softwood timber + MBB assembly achieves approximately 1.8 times higher mid-range areal heat capacity across the combined uncertainty ranges. While the timber + MBB assembly does not match heavyweight masonry (fired clay brick + EPS, 264–409; reinforced concrete + EPS, 378–509), the overlap in the upper range of timber + MBB with

the lower range of brick-based walls demonstrates that all-bio-based timber constructions can approach the thermal inertia of traditional masonry systems without the associated embodied carbon.

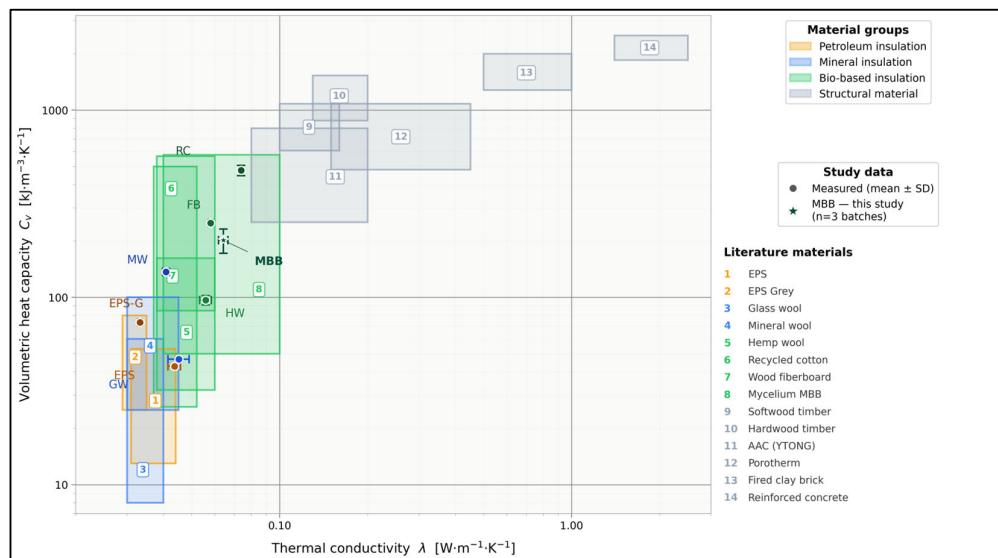


Figure 3. Ashby diagram: thermal conductivity vs. volumetric heat capacity for tested materials and representative literature ranges for each material class. Literature ranges (shaded regions) for each material class were compiled from: Schiavoni et al. [20] (EPS, EPS-Grey, glass wool, mineral wool, hemp wool, wood fiberboard); Jones et al. [12], Appels et al. [14], and Elsacker et al. [18] (mycelium-based biocomposites); Zachara et al. [11] (recycled cotton); Glass & Zelinka [30] (softwood and hardwood timber); Kim et al. [31] (fired clay brick); Narayanan & Ramamurthy [32] (autoclaved aerated concrete, AAC/YTONG); EN ISO 10456:2007 [33] (Porotherm, reinforced concrete). Study data are shown as markers with error bars (mean $\pm$ SD).

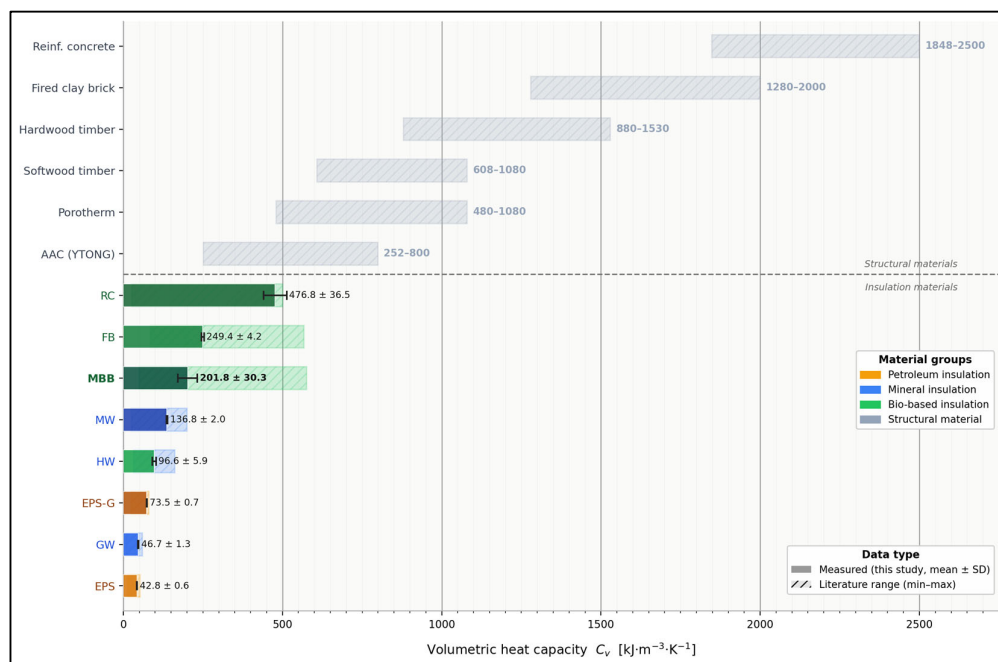


Figure 4. Volumetric heat capacity: comparison of measured insulation materials and literature ranges (min-max) for structural building materials. Literature C_v ranges were compiled from: Schiavoni et al. [20] (EPS, EPS-Gray, glass wool, mineral wool, hemp wool, wood fiberboard); Jones

et al. [12], Appels et al. [14], and Elsacker et al. [18] (mycelium-based biocomposites); Zachara et al. [11] (recycled cotton); Glass & Zelinka [28] (softwood and hardwood timber); Kim et al. [31] (fired clay brick); Narayanan & Ramamurthy [32] (autoclaved aerated concrete, AAC/YTONG); EN ISO 10456:2007 [33] (Porotherm, reinforced concrete). Measured values from this study are shown with $\pm$ SD bars.

Table 4. Areal heat capacity (κ) of representative wall systems (structural + insulation layer), calculated for a low-energy building configuration with layer thicknesses of 200 mm each.

Wall System	C_v Structural (lit.) [kJ·m ⁻³ ·K ⁻¹]	C_v Insulation [kJ·m ⁻³ ·K ⁻¹]	κ_{total} [kJ·m ⁻² ·K ⁻¹]
Reinf. concrete + EPS	1848–2500	42.8 $\pm$ 0.6	378–509
Fired clay brick + EPS	1280–2000	42.8 $\pm$ 0.6	264–409
Softwood timber + RC	608–1080	476.8 $\pm$ 36.5	211–319
Softwood timber + MBB	608–1080	201.8 $\pm$ 30.3	156–262
Softwood timber + FB	608–1080	249.4 $\pm$ 4.2	171–267
Softwood timber + MW	608–1080	136.8 $\pm$ 2.0	149–244
Softwood timber + HW	608–1080	96.6 $\pm$ 5.9	140–236
Softwood timber + GW	608–1080	46.7 $\pm$ 1.3	131–226
AAC (YTONG) + EPS	252–800	42.8 $\pm$ 0.6	59–169

Structural values from literature (min–max range); insulation values measured in this study (mean $\pm$ SD, $n = 3$ –10). The combined κ_{total} range accounts for both sources of variability. Rows ordered by descending mid-range κ_{total} . Calculation: $\kappa = \Sigma(C_{v,i} \cdot d_i)$ per EN ISO 13786:2017 (Equation (3)) [25]. Structural literature sources: softwood timber—Glass & Zelinka [28]; fired clay brick—Kim et al. [31]; reinforced concrete—Narayanan & Ramamurthy [32]; AAC (YTONG) and Porotherm—EN ISO 10456:2007 [33]. Abbreviations: EPS—Expanded Polystyrene; GW—glass wool; MW—mineral wool; HW—hemp wool; FB—wood fiberboard; MBB—mycelium-based biocomposite; RC—recycled cotton; AAC—autoclaved aerated concrete.

4. Discussion

The thermo-physical characterization presented in this study positions MBB in a region of the Ashby diagram not conventionally occupied by insulation products. With $\lambda = 0.0641 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$, MBB exhibits a higher thermal conductivity than EPS ($0.0436 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$) by 47% and mineral wool ($0.0408 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$) by 57%. This is primarily attributable to its elevated bulk density ($149.0 \pm 9.4 \text{ kg} \cdot \text{m}^{-3}$), which is more than eleven times higher than EPS ($13 \text{ kg} \cdot \text{m}^{-3}$). Jones et al. [12] reviewed mycelium-based composites and reported thermal conductivities in the range of 0.0400 – $0.1000 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ for various substrate and fungal combinations, confirming that the measured MBB value is consistent with expectations for this material class, and a comparable value ($\lambda = 0.055 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$) was independently measured for waste-wood MBB by Petržela et al. [22]. A review of 19 published studies by Wildman et al. [34] confirms a field-wide λ range of 0.026 – $0.18 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ for MBBs, with inter-study variability attributed primarily to density differences driven by substrate type and fungal colonization degree; the $\lambda = 0.0641 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ of the present formulation falls in the mid-range of this distribution, consistent with its elevated bulk density. The higher λ of MBB should therefore be evaluated in the context of its enhanced thermal mass rather than as an isolated performance deficit relative to petroleum-based insulants [10].

The measured $\lambda = 0.0641 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ for *Ganoderma sessile* MBB on waste-wood substrate positions this study's formulation within the mid-to-upper range of literature-reported values for wood-chip substrate composites. Girometta et al. [17] reviewed physico-mechanical and thermodynamic properties across multiple fungal species and substrate types, establishing a literature range of $\lambda = 0.036$ – $0.20 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ and bulk densities of 30–

200 kg·m⁻³, with the wide inter-study variability attributed to substrate type, fungal colonization density, and post-processing treatment. Irbe et al. [19] evaluated MBB produced from local wood processing and agricultural waste using *Trametes versicolor*, finding that hemp-shive-based formulations achieved $\lambda = 0.040 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ —competitive with EPS and XPS—while denser birch sawdust variants reached $\lambda \approx 0.050 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, consistent with the density dependence of λ in wood-substrate MBBs and with the present results. The between-batch volumetric heat capacity variability observed here ($\pm 30.3 \text{ kJ}\cdot\text{m}^{-3}\cdot\text{K}^{-1}$, ca. $\pm 15\%$) is in line with inter-study ranges for substrate-bonded mycelium composites reported by Appels et al. [14] and Elsacker et al. [18], confirming that biological batch variability is a characteristic feature of the material class rather than a measurement artifact. Bonga et al. [35] further demonstrated that MBB from agro-waste substrates can achieve thermal performance competitive with conventional insulation materials, a finding aligned with the Ashby diagram position of MBB established in the present study, which bridges the gap between conventional insulation and structural bio-based material zones.

The volumetric heat capacity of MBB ($C_v = 201.8 \text{ kJ}\cdot\text{m}^{-3}\cdot\text{K}^{-1}$) is the most practically significant finding from a building physics perspective. Verbeke and Audenaert [9] identified C_v as the primary determinant of a material's contribution to building thermal inertia, emphasizing that conventional insulation layers contribute near-zero thermal mass due to their inherently low densities. The 4.7-fold C_v advantage of MBB over EPS arises from the combined effect of a 11.4-fold density difference (149 vs. 13 kg·m⁻³), partially offset by a lower mass-specific heat capacity of MBB ($1351 \text{ J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$) relative to EPS ($3259 \text{ J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$) as measured by the transient probe method. Since $C_v = c \cdot \rho$, literature MBB formulations with lower-density substrates ($\rho = 30\text{--}80 \text{ kg}\cdot\text{m}^{-3}$ [17]) necessarily achieve C_v values approximately 2–5 times lower than the present waste-wood formulation (149 kg·m⁻³), confirming that substrate particle density, rather than mass-specific heat capacity, is the primary lever for maximizing volumetric thermal mass in mycelium composites. The Ashby diagram position of MBB—bridging the insulation and structural bio-based material zones—is a distinctive material characteristic not shared by any other tested insulation, including hemp wool ($C_v = 96.6 \text{ kJ}\cdot\text{m}^{-3}\cdot\text{K}^{-1}$) and mineral wool ($136.8 \text{ kJ}\cdot\text{m}^{-3}\cdot\text{K}^{-1}$). Only fiberboard (FB, $C_v = 249.4 \text{ kJ}\cdot\text{m}^{-3}\cdot\text{K}^{-1}$) and recycled cotton (RC, $C_v = 476.8 \text{ kJ}\cdot\text{m}^{-3}\cdot\text{K}^{-1}$) exceeded MBB, which is expected given its substantially higher density ($\sim 300 \text{ kg}\cdot\text{m}^{-3}$) [11] of RC and fiberboard cellulose content.

The calculated phase shift of 8.2 h for a 185 mm MBB layer exceeds the threshold of 8 h often cited in passive design guidelines as a reference for effective thermal mass. While this indicates promising thermal inertia, this value is a material-level calculation based on an analytical approximation for a homogeneous medium. In real-world applications, the actual thermal performance is influenced by the complexity of multi-layered wall assemblies. Nevertheless, the 3.6 h additional delay in heat wave transmission compared to EPS suggests that MBB has the potential in contribution to reduce peak cooling loads by shifting interior heat gains towards late evening hours, when passive ventilation strategies are more effective. While a direct reduction in energy demand cannot be quantified from these material-level data alone, the findings of Kučzyński et al. [36] support the general principle that increasing the thermal mass of building envelopes can mitigate indoor temperature spikes, justifying further research into MBB-integrated wall systems.

In the context of timber construction, the incorporation of MBB, FB or RC as an insulation layer can substantially compensate for the inherent low thermal mass of structural timber. Expressed as the physically meaningful areal heat capacity (κ per EN ISO 13786:2017 [25]), the softwood timber + MBB wall system (200 mm/200 mm) achieves $\kappa_{total} = 156\text{--}262 \text{ kJ}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$, which corresponds to a 1.8-fold improvement over AAC (YTONG) + EPS ($\kappa_{total} = 59\text{--}169 \text{ kJ}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$), a widely used lightweight masonry reference, and a 40–60%

improvement over timber + EPS ($131\text{--}226\text{ kJ}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ for timber + GW, taken as a representative conventional insulation; timber + EPS yields an almost identical range due to the similar κ of EPS and GW). In the present analysis, the upper bound of the timber + MBB range ($262\text{ kJ}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$) almost reaches the lower bound of the fired clay brick + EPS assembly ($264\text{ kJ}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$) and FB ($267\text{ kJ}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$) and RC ($317\text{ kJ}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$) overlaps it. The comparison of wall systems is based on areal heat capacity (κ), which serves as a comparative indicator of thermal storage potential rather than a comprehensive dynamic analysis. As real-world building performance is a complex function of thermal resistance, diffusivity, decrement factor, and admittance, our results should be interpreted as an assessment of the material's thermal mass potential rather than a definitive energy simulation. While MBB does not match the upper thermal mass range of heavyweight clay masonry systems, this demonstrates that an all-bio-based, all-timber wall construction can approach the thermal inertia of traditional masonry without recourse to heavyweight structural elements, simultaneously retaining the low embodied carbon advantages of timber construction [9]. Importantly, the choice of insulation dominates the thermal mass of timber-based walls: within a timber configuration, the insulation layer can increase areal heat capacity by values from 9% (HW x softwood timber, max range) up to 78% (RC x softwood timber, min range), whereas in heavyweight systems the structural layer dominates the insulation, which can contribute only by 2% (EPS x reinf. Concrete) up to 17% (EPS x ACC, min range). This inversion of the insulation-layer role in lightweight constructions motivates the use of high- κ bio-based insulants such as MBB, fiberboards or recycled cotton, which actively contribute to building thermal inertia rather than serving a purely resistive function. The wall assembly comparison presented above is based on the steady-state areal heat capacity product (Equation (3)) applied to simplified, homogeneous layer configurations without dynamic simulation or climate-specific boundary conditions; its purpose is to provide a general order-of-magnitude illustration of the thermal mass benefit achievable by substituting low- C_v insulants with high- C_v bio-based alternatives, rather than to predict the performance of specific assemblies under defined climatic loading.

The reference insulation materials selected for comparison encompass the principal commercial categories—petroleum-derived (EPS, EPS-G), mineral (GW, MW), and bio-based (HW, FB, RC)—enabling a full-spectrum benchmarking of MBB. Schiavoni et al. [20] report literature thermal conductivities of $0.030\text{--}0.040\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ for EPS, $0.030\text{--}0.045\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ for glass and mineral wool, and $0.038\text{--}0.060\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ for bio-based insulants such as wood fiberboard and hemp wool. The values measured in this study for EPS ($0.0436\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$), GW ($0.0408\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$), HW ($0.0499\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$), and FB ($0.0580\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$) fall within or near the upper boundary of these literature ranges, with slight elevation attributable to measurement at $23\text{ }^{\circ}\text{C}$ rather than the declared reference temperature of $10\text{ }^{\circ}\text{C}$ and to the transient probe methodology. Critically, the thermal properties of bio-based insulation materials are sensitive to moisture content in a manner fundamentally different from mineral or petroleum-derived insulants: organic matrices absorb moisture, and even modest moisture uptake elevates λ through the replacement of air-filled pores by water—which conducts heat approximately 25 times more efficiently than air. Unconditioned organic materials can therefore differ thermally from mineral insulants largely due to differential moisture content rather than intrinsic material properties. To eliminate this confounding factor, all specimens in this study were conditioned to equilibrium at identical temperature and relative humidity prior to measurement, ensuring that comparative differences in λ , C_v , and c reflect genuine intrinsic material properties.

The uniform application of the ISOMET 2114 transient needle probe [24] to all materials under identical conditions further strengthens the internal validity of the cross-material comparison. Steady-state and transient methods are known to carry different systematic biases across material types: steady-state approaches (guarded hot plate, heat flow

meter) provide high accuracy for thermal conductivity but require long equilibration and are sensitive to contact resistance in fibrous materials, while transient probes tend to overestimate C_v for low-density open-cell foams such as EPS and glass wool due to finite probe-contact geometry and air-filled pore effects [10,20]. The derived specific heat capacity of wood fiberboard (FB, $c = 4409 \pm 272 \text{ J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$) substantially exceeds the tabulated design value of $1700 \text{ J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$ specified in EN ISO 10456:2007 [33] and the literature range of approximately $1700\text{--}2100 \text{ J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$ reviewed by Schiavoni et al. [20]; analogous overestimation is observed for EPS (3262 vs. $\sim 1350 \text{ J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$) and glass wool (2719 vs. $\sim 840 \text{ J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$ tabulated). This pattern is attributable to a documented limitation of transient needle probe methods for porous and fibrous insulation materials: the probe heats only a small volume near its surface, and imperfect contact between the needle and the fibrous air-filled matrix underestimates the effective thermal diffusivity, thereby inflating the derived C_v and, consequently, specific heat capacity [37]. Ghazi Wakili et al. [37] independently confirmed this effect and reported $c \approx 1200 \text{ J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$ for wood fiber insulation measured using a guarded hot plate apparatus. Because all eight materials were characterized by the identical ISOMET 2114 protocol under the same conditions [24], this systematic offset applies uniformly, so the relative ranking of C_v , the primary thermal-mass indicator used in this work remains unaffected. Applying different methods to different material subsets would introduce systematic inter-method offsets that compound with genuine material differences and undermine comparative ranking. By applying the ISOMET 2114 [24] to all eight materials under identical conditions, any systematic method-level offset is applied uniformly, ensuring that the relative ranking of λ , C_v , and c values reflects intrinsic material differences rather than inter-method artifacts. This consideration is especially important for comparisons spanning organic and inorganic insulation categories, where moisture sensitivity creates an additional dimension of measurement bias. The transient probe's rapid measurement cycle (ca. 45 min per reading) additionally ensures that negligible moisture redistribution occurs during measurement itself—a critical advantage when characterizing hygroscopic organic materials [20]. Together, standardized pre-conditioning and uniform measurement protocol provide a methodologically rigorous basis for the cross-material benchmarking of insulation products spanning organic, mineral, and petroleum-derived categories.

Several limitations of the present study merit consideration. MBB characterization was based on three independent biological batches ($n_{\text{batches}} = 3$), each subjected to ten repeated ISOMET measurements ($n_{\text{measurements}} = 10$ per batch; $n_{\text{total}} = 30$). Throughout this study, the reported n and associated statistics reflect this pooled dataset. The SD reported for MBB (e.g., λ : ± 0.0024 , C_v : $\pm 30.3 \text{ kJ}\cdot\text{m}^{-3}\cdot\text{K}^{-1}$) captures both within-batch instrument repeatability and between-batch biological variability, rendering it a conservative estimate of material uncertainty. However, for mycelium-based composites, where fungal colonization density, growth kinetics, and moisture uptake during production introduce inherent batch-to-batch variation, a minimum of $n_{\text{batches}} \geq 3$ independent production runs is recommended for robust material characterization. This is identified as the primary limitation of the present characterization and the key target for extended replication in future work. The between-batch variability observed in this study (ca. $\pm 15\%$ for C_v) is broadly consistent with inter-study ranges reported by Appels et al. [14] and Elsacker et al. [18] for substrate-bonded mycelium composites. While reproducibility within each sample was high (SD = $0.0024 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ for λ), expanded inter-batch replication would be required to characterize the biological variability inherent in fungal growth processes. The phase shift values reported are based on the simplified analytical approximation (Equation (2)), and the areal heat capacity values on the steady-state layer product (Equation (3)). Both should be interpreted as comparative indicators of relative material perfor-

mance and are explicitly not equivalent to dynamic wall performance assessments. Deriving normative phase-shift values for specific building components would require the dynamic transfer-matrix approach of EN ISO 13786:2018 [25] applied to complete multi-layer assemblies with actual in-service boundary conditions and dynamic climatic loading. The wall assembly comparison is intentionally simplified: its purpose is to illustrate the general order-of-magnitude improvement in areal heat capacity achievable by substituting low- C_v insulants with high- C_v bio-based alternatives across representative construction typologies, rather than to predict the performance of specific assemblies under defined climatic loading—which would require full dynamic building energy simulation with assembly-specific configurations, moisture-dependent material properties, and location-specific climatic boundary conditions. A dedicated hygrothermal simulation study of MBB-insulated timber wall assemblies is planned as follow-up work. Finally, the hygrothermal behavior of MBB—including the dependence of λ and C_v on moisture content—was not assessed in the present work. Bio-based insulants are susceptible to moisture uptake, which increases λ and alters C_v ; for mycelium composites, Appels et al. [14] reported that moisture absorption varies substantially with substrate type and fungal species, while Elsacker et al. [18] demonstrated that hydrophobic surface treatment can substantially reduce uptake without compromising mechanical performance. Future work should include λ and C_v determination across a range of moisture contents and sorption isotherm characterization per ISO 12572 [38] and EN ISO 10456 [33] to support hygrothermal simulation of MBB-insulated assemblies under realistic climatic boundary conditions. Additionally, the study does not address long-term durability: dimensional stability and creep under sustained load, resistance to fungal degradation under service conditions, and the effects of accelerated aging on thermal properties are all critical for building certification and practical deployment and represent identified priorities for future work.

5. Conclusions

This study characterized the thermo-physical properties of mycelium-based biocomposite (MBB) insulation produced from hardwood substrate and compared them to seven reference insulation materials. The following principal conclusions are drawn:

- (1) MBB exhibits a thermal conductivity of $\lambda = 0.0641 \pm 0.0024 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, which is the highest among the tested insulation materials, consistent with its elevated bulk density ($149.0 \pm 9.4 \text{ kg}\cdot\text{m}^{-3}$) and within the literature range for mycelium-based composites [12]. Its thermal resistance performance is therefore best interpreted alongside its thermal inertia properties rather than against conventional low-density insulants alone.
- (2) The volumetric heat capacity of MBB ($C_v = 201.8 \pm 30.3 \text{ kJ}\cdot\text{m}^{-3}\cdot\text{K}^{-1}$) is 4.7 times higher than EPS, positioning MBB in the Ashby diagram between conventional insulation and structural bio-based material zones. While materials with similar thermo-physical behavior already exist in the form of dense bio-based insulations, the true novelty of MBB lies in its sustainable fabrication, achieving this dual-function position purely through natural mycelial growth on recycled industrial waste.
- (3) At the design thickness of 185 mm, MBB achieves a thermal phase shift of 8.2 h, compared to 4.6 h for EPS. The additional 3.6 h delay in peak heat wave transmission supports passive thermal buffering and reduced peak cooling loads in summer overheating scenarios [36]. It should be noted that these phase shift values are derived from the simplified analytical approximation (Equation (2)) and serve as comparative indicators of relative material performance; they are not equivalent to dynamic wall performance assessments, which would require the transfer-matrix method of EN ISO 13786:2018 [25] applied to complete assemblies under dynamic climatic boundary conditions.

- (4) In a softwood timber frame wall assembly with 200 mm structural and 200 mm insulation layer thicknesses, the timber + MBB system achieves an areal heat capacity of $\kappa_{total} = 156\text{--}262 \text{ kJ}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$, representing a 1.8-fold improvement over the AAC (YTONG) + EPS baseline ($59\text{--}169 \text{ kJ}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$) and its upper range almost reaches that of fired clay brick + EPS.

These findings support the development of MBB, produced from industrial wood waste, as a high-thermal-mass insulation component with the potential to improve the thermal inertia of lightweight timber frame buildings. However, it is acknowledged that these material-level improvements do not automatically translate into lower cooling energy consumption on a whole-building scale. Future work should include extended inter-batch replication, dynamic building energy simulation, hygrothermal characterization, and a formal life-cycle assessment (LCA) to support full design integration into building envelopes.

Author Contributions: Conceptualization, B.P. and Š.H.; methodology, B.P., T.Z. and M.J.; investigation, B.P. and M.J.; resources, B.P., M.J. and Š.H.; data curation, B.P. and T.Z.; formal analysis, B.P.; writing—original draft preparation, B.P.; writing—review and editing, T.Z., M.J., M.P. and Š.H.; visualization, B.P.; supervision, M.P. and Š.H.; project administration, Š.H. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Internal Grant Agency of the Faculty of Forestry and Wood Sciences, Czech University of Life Sciences Prague [IGA A no. A_04_25].

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors gratefully acknowledge Jindřich Vítovec for his assistance in obtaining the necessary materials. Artificial intelligence tools used during manuscript preparation (Connected Papers 2026; Scite 2026; Claude Sonnet 4.6, Opus 4.7 (Anthropic); and Canva 2026 Magic Design, Magic Media) are disclosed in detail in Section 2.7. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AAC	Autoclaved aerated concrete
BES	Building energy simulation
CLT	Cross-laminated timber
C_v	Volumetric heat capacity [$\text{kJ}\cdot\text{m}^{-3}\cdot\text{K}^{-1}$]
c	Specific heat capacity [$\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$]
EPS	Expanded Polystyrene
EPS-G	Expanded Polystyrene Grey (graphite)
FB	Wood fiberboard
GW	Glass wool
HW	Hemp wool
ISOMET	Transient impulse heat-transfer analyser (Applied Precision Ltd.)
MBB	Mycelium-based biocomposite
MW	Mineral wool
RC	Recycled cotton insulation board
VHC	Volumetric heat capacity (alternative notation, see C_v)
YTONG	Brand name of autoclaved aerated concrete (Xella International)

α	Thermal diffusivity [m^2s^{-1}]
λ	Thermal conductivity [$\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$]
Φ	Thermal phase shift [radians]
τ	Thermal phase shift [hours]
ρ	Bulk density [$\text{kg}\cdot\text{m}^{-3}$]

References

- Hanewinkel, M.; Cullmann, D.A.; Schelhaas, M.-J.; Nabuurs, G.-J.; Zimmermann, N.E. Climate Change May Cause Severe Loss in the Economic Value of European Forest Land. *Nat. Clim. Change* **2013**, *3*, 203–207. <https://doi.org/10.1038/nclimate1687>.
- Seidl, R.; Thom, D.; Kautz, M.; Martin-Benito, D.; Peltoniemi, M.; Vacchiano, G.; Wild, J.; Ascoli, D.; Petr, M.; Honkaniemi, J.; et al. Forest Disturbances under Climate Change. *Nat. Clim. Change* **2017**, *7*, 395–402. <https://doi.org/10.1038/nclimate3303>.
- Leuschner, C. Drought Response of European Beech (*Fagus sylvatica* L.)—A Review. *Perspect. Plant Ecol. Evol. Syst.* **2020**, *47*, 125576. <https://doi.org/10.1016/j.ppees.2020.125576>.
- Schuldt, B.; Buras, A.; Arend, M.; Vitasse, Y.; Beierkuhnlein, C.; Damm, A.; Gharun, M.; Grams, T.E.E.; Hauck, M.; Hajek, P.; et al. A First Assessment of the Impact of the Extreme 2018 Summer Drought on Central European Forests. *Basic Appl. Ecol.* **2020**, *45*, 86–103. <https://doi.org/10.1016/j.baee.2020.04.003>.
- Ehrhart, T.; Steiger, R.; Lehmann, M.; Frangi, A. European Beech (*Fagus sylvatica* L.) Glued Laminated Timber: Lamination Strength Grading, Production and Mechanical Properties. *Eur. J. Wood Wood Prod.* **2020**, *78*, 971–984. <https://doi.org/10.1007/s00107-020-01545-6>.
- Arriaga, F.; Wang, X.; Íñiguez-González, G.; Llana, D.F.; Esteban, M.; Niemz, P. Mechanical Properties of Wood: A Review. *Forests* **2023**, *14*, 1202. <https://doi.org/10.3390/f14061202>.
- De Araujo, V.; Aguiar, F.; Jardim, P.; Mascarenhas, F.; Marini, L.; Aquino, V.; Santos, H.; Panzera, T.; Lahr, F.; Christoforo, A.L. Is Cross-Laminated Timber (CLT) a Wood Panel, a Building, or a Construction System? A Systematic Review on Its Functions, Characteristics, Performances, and Applications. *Forests* **2023**, *14*, 264. <https://doi.org/10.3390/f14020264>.
- Plos, M.; Fortuna, B.; Šuligoj, T.; Turk, G. From Visual Grading and Dynamic Modulus of European Beech (*Fagus sylvatica*) Logs to Tensile Strength of Boards. *Forests* **2022**, *13*, 77. <https://doi.org/10.3390/f13010077>.
- Verbeke, S.; Audenaert, A. Thermal Inertia in Buildings: A Review of Impacts across Climate and Building Use. *Renew. Sustain. Energy Rev.* **2018**, *82*, 2300–2318. <https://doi.org/10.1016/j.rser.2017.08.083>.
- Al-Homoud, M.S. Performance Characteristics and Practical Applications of Common Building Thermal Insulation Materials. *Build. Environ.* **2005**, *40*, 353–366. <https://doi.org/10.1016/j.buildenv.2004.05.013>.
- Zachara, T.; Šedivka, P.; Borůvka, V.; Kubista, K.; Holeček, T.; Lexa, M.; Sahula, L.; Sikora, A. Cold-Pressed Insulation Boards from Recycled Cotton Fibers Using a Water-Borne PVAc–Starch Binder: Processing, Structure and Properties. *Materials* **2026**, *19*, 1097. <https://doi.org/10.3390/ma19061097>.
- Jones, M.; Mautner, A.; Luenco, S.; Bismarck, A.; John, S. Engineered Mycelium Composite Construction Materials from Fungal Biorefineries: A Critical Review. *Mater. Des.* **2020**, *187*, 108397. <https://doi.org/10.1016/j.matdes.2019.108397>.
- Mialeshka, V.; Kowaluk, G.; Pásztor, Z. Sustainable Insulation Panels Made of Tree Bark Fibers: Thermal and Fire Performance. *Forests* **2026**, *17*, 26. <https://doi.org/10.3390/f17010026>.
- Appels, F.V.W.; Camere, S.; Montalti, M.; Karana, E.; Jansen, K.M.B.; Dijksterhuis, J.; Krijgheld, P.; Wösten, H.A.B. Fabrication Factors Influencing Mechanical, Moisture- and Water-Related Properties of Mycelium-Based Composites. *Mater. Des.* **2019**, *161*, 64–71. <https://doi.org/10.1016/j.matdes.2018.11.027>.
- Elsacker, E.; Vandeloock, S.; Van Wylick, A.; Ruytinx, J.; De Laet, L.; Peeters, E. A comprehensive framework for the production of mycelium-based lignocellulosic composites. *Sci. Total Environ.* **2020**, *725*, 138431. <https://doi.org/10.1016/j.scitotenv.2020.138431>.
- Haneef, M.; Ceseracciu, L.; Canale, C.; Bayer, I.S.; Heredia-Guerrero, J.A.; Athanassiou, A. Advanced materials from fungal mycelium: Fabrication and tuning of physical properties. *Sci. Rep.* **2017**, *7*, 41292. <https://doi.org/10.1038/srep41292>.
- Girometta, C.; Picco, A.M.; Baiguera, R.M.; Dondi, D.; Babbini, S.; Cartabia, M.; Pellegrini, M.; Savino, E. Physico-Mechanical and Thermodynamic Properties of Mycelium-Based Biocomposites: A Review. *Sustainability* **2019**, *11*, 281. <https://doi.org/10.3390/su11010281>.
- Elsacker, E.; Vandeloock, S.; Brancart, J.; Peeters, E.; De Laet, L. Mechanical, Physical and Chemical Characterisation of Mycelium-Based Composites with Different Types of Lignocellulosic Substrates. *PLoS ONE* **2019**, *14*, e0213954. <https://doi.org/10.1371/journal.pone.0213954>.

19. Irbe, I.; Kirpluks, M.; Kampuss, M.; Andze, L.; Milbreta, U.; Filipova, I. Assessing the Conformity of Mycelium Biocomposites for Ecological Insulation Solutions. *Materials* **2024**, *17*, 6111. <https://doi.org/10.3390/ma17246111>.
20. Schiavoni, S.; D'Alessandro, F.; Bianchi, F.; Asdrubali, F. Insulation Materials for the Building Sector: A Review and Comparative Analysis. *Renew. Sustain. Energy Rev.* **2016**, *62*, 988–1011. <https://doi.org/10.1016/j.rser.2016.05.045>.
21. Giuffrida, G.; Caponetto, R.; Nocera, F. Hygrothermal Properties of Raw Earth Materials: A Literature Review. *Sustainability* **2019**, *11*, 5342. <https://doi.org/10.3390/su11195342>.
22. Petržela, B.; Jozífek, M.; Richter, J.; Pavelek, M.; Hýsek, Š. Valorisation of Industrial Waste Wood in Mycelium-Based Biocomposites for Thermal Insulation: A Hygrothermal and Microstructural Analysis. *Ind. Crops Prod.* **2026**, *246*, 123411. <https://doi.org/10.1016/j.indcrop.2026.123411>.
23. Hýsek, Š.; Petržela, B.; Jozífek, M.; Němec, M. Mycelium-Based Biocomposites as Key Enabling Technology in Industry 5.0: Application of Laser Cutting, 3D Scan, X-Ray CT Scan and AI-Based Prediction in Heat Insulation Industrial Production. *Wood Mater. Sci. Eng.* **2026**, 1–9. <https://doi.org/10.1080/17480272.2026.2674758>.
24. ASTM D5334-22; Standard Test Method for Determination of Thermal Conductivity of Soil and Rock by Thermal Needle Probe Procedure. ASTM International: West Conshohocken, PA, USA, 2022.
25. ISO 13786:2017; Thermal Performance of Building Components—Dynamic Thermal Characteristics—Calculation Methods. International Organization for Standardization: Geneva, Switzerland, 2017.
26. Carslaw, H.S.; Jaeger, J.C. *Conduction of Heat in Solids*, 2nd ed.; Oxford University Press: Oxford, UK, 1959.
27. Dvořák, O.; Kvietková, M.S.; Šimůnková, K. The Influence of the Initial Treatment of Oak Wood on Increasing the Durability of Exterior Transparent Coating Systems. *Polymers* **2023**, *15*, 3251. <https://doi.org/10.3390/polym15153251>.
28. Pánek, M.; Dvořák, O.; Štěrbová, I.; Šimůnková, K.; Zeidler, A.; Šedivka, P. Oak Wood-Based Material with Extended Colour Stability for Exterior Wooden Structures. CZ Patent No. 309 200 B6, 11 May 2022.
29. Stazi, F.; Ulpiani, G.; Pergolini, M.; Di Perna, C. The Role of Areal Heat Capacity and Decrement Factor in Case of Hyper Insulated Buildings: An Experimental Study. *Energy Build.* **2018**, *176*, 310–324. <https://doi.org/10.1016/j.enbuild.2018.07.034>.
30. Glass, S.V.; Zelinka, S.L. Moisture Relations and Physical Properties of Wood. In *Wood Handbook: Wood as an Engineering Material*; Gen. Tech. Rep. FPL-GTR-190; U.S. Department of Agriculture, Forest Service, Forest Products Laboratory: Madison, WI, USA, 2010; Chapter 4.
31. Kim, K.-H.; Jeon, S.-E.; Kim, J.-K.; Yang, S. An Experimental Study on Thermal Conductivity of Concrete. *Cem. Concr. Res.* **2003**, *33*, 363–371. [https://doi.org/10.1016/S0008-8846\(02\)00965-1](https://doi.org/10.1016/S0008-8846(02)00965-1).
32. Narayanan, N.; Ramamurthy, K. Structure and Properties of Aerated Concrete: A Review. *Cem. Concr. Compos.* **2000**, *22*, 321–329. [https://doi.org/10.1016/S0958-9465\(00\)00016-0](https://doi.org/10.1016/S0958-9465(00)00016-0).
33. EN ISO 10456:2007; Building Materials and Products—Hygrothermal Properties—Tabulated Design Values and Procedures for Determining Declared and Design Thermal Values. International Organization for Standardization: Geneva, Switzerland, 2007.
34. Wildman, J.; Shea, A.; Walker, P.; Henk, D. Extrinsic and Intrinsic Determinants of Thermal Conductivity in Mycelium Composites. *Build. Serv. Eng. Res. Technol.* **2025**, *46*, 317–338. <https://doi.org/10.1177/01436244241306631>.
35. Bonga, K.B.; Bertolacci, L.; Contardi, M.; Paul, U.C.; Zafar, M.S.; Mancini, G.; Marini, L.; Ceseracciu, L.; Fragouli, D.; Athanassiou, A. Mycelium Agrowaste-Bound Biocomposites as Thermal and Acoustic Insulation Materials in Building Construction. *Macromol. Mater. Eng.* **2024**, *309*, 2300449. <https://doi.org/10.1002/mame.202300449>.
36. Kučzyński, T.; Staszczuk, A.; Ziembicki, P.; Paluszak, A. The Effect of the Thermal Mass of the Building Envelope on Summer Overheating of Dwellings in a Temperate Climate. *Energies* **2021**, *14*, 4117. <https://doi.org/10.3390/en14144117>.
37. Ghazi Wakili, K.; Rädle, W.; Rohner, T. Measuring the Specific Heat Capacity of Thermal Insulation Materials Used in Buildings by Means of a Guarded Hot Plate Apparatus. *Int. J. Thermophys.* **2023**, *44*, 15. <https://doi.org/10.1007/s10765-022-03133-7>.
38. ISO 12572:2016; Hygrothermal Performance of Building Materials and Products—Determination of Water Vapour Transmission Properties—Cup Method. International Organization for Standardization: Geneva, Switzerland, 2016.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.