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Mycelium-bound ash sawdust biocomposite as a sustainable thermal insulation material for construction applications

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ABSTRACT

Growing interest in sustainable construction materials has increased attention toward bio-based insulation systems with low density and renewable origin. This study presents an integrated experimental assessment of a mycelium-bound biocomposite produced from ash sawdust and Ganoderma lucidum as a potential alternative for selected non-load-bearing insulation applications. The fabrication process included substrate sterilization, controlled inoculation, incubation, and final drying to obtain stable test specimens. An exploratory laboratory assessment was conducted to determine density, moisture content, thermal conductivity, volumetric heat capacity, thermal diffusivity, compressive response, and indicative fire-response parameters. The average thermal conductivity was approximately 0.054 $W \cdot m^{-1} \cdot K^{-1}$, placing the material within the broader range reported for lightweight bio-based insulation materials, although above the level of high-performance synthetic foams. Compression testing indicated moderate mechanical resistance potentially suitable for selected non-load-bearing applications. Fire testing confirmed combustible behavior of the present formulation, indicating that further improvement in reaction-to-fire performance would be required for broader construction use. Overall, the results identify mycelium-bound ash sawdust composites as a promising renewable insulation concept. However, further studies on long-term durability, moisture resistance, dimensional stability, biological resistance, and reaction-to-fire optimization are necessary before practical construction implementation can be considered.

Keywords: mycelium biocomposite, thermal insulation, thermal conductivity, bio-based materials, Ganoderma lucidum, compressive behavior.

INTRODUCTION

The construction sector faces increasing pressure to reduce operational energy demand and embodied environmental impacts. Besides improving building energy efficiency, growing attention is being directed toward low-density renewable materials that can contribute to circular resource use and reduced dependence on fossil-derived products. According to data from the European Commission, buildings account for approximately 40% of total energy consumption and 36% of CO_2 emissions in the European Union [1–6]. Achieving climate neutrality requires not only improving the energy efficiency of buildings but also using construction materials with a low environmental footprint that comply with circular economy principles [7,8]. From a life-cycle assessment (LCA) perspective, such solutions can significantly reduce the carbon footprint of the construction sector, contributing to current decarbonization strategies and the broader transition toward climate-neutral construction [9–15].

Thermal insulation materials play a crucial role in reducing the energy demand of buildings. The most commonly used materials, such as expanded polystyrene (EPS), extruded polystyrene (XPS), mineral wool, glass wool, or polyurethane foams (PUR/PIR), are characterized by low thermal conductivity ($\lambda \approx 0.020–0.050$ $W \cdot m^{-1} \cdot K^{-1}$). However, their production is highly energy-intensive and based on petrochemical raw materials [16]. These materials are non-biodegradable, generating large quantities of persistent waste, while their recycling remains limited and economically inefficient [16]. Besides declared laboratory conductivity values, the stability of thermal performance under variable moisture conditions is particularly important for porous bio-based materials [17–21].

Thermal conductivity (λ) is a key parameter describing the heat-transfer performance of insulation materials. In porous composites, λ depends mainly on density, moisture content, temperature, and internal pore structure [22–27]. Moisture-related changes in heat-transfer behavior are especially relevant in lightweight lignocellulosic materials exposed to service humidity variations [28–32].

Recent studies have shown that mycelium composites can achieve thermal conductivity values comparable to several natural-fiber insulators, while offering low embodied energy, biodegradability, and waste valorization potential [33–35,36–43]. Among fungal binders, Ganoderma lucidum is of particular interest due to its dense and highly interconnected hyphal network, which can enhance particle bonding and structural cohesion [33,41,43]. However, limited research has examined hardwood sawdust systems bonded by Ganoderma lucidum with simultaneous evaluation of thermal, mechanical, and fire-related performance relevant to insulation applications [41–45].

The aim of this study was to provide an integrated experimental assessment of the physical, thermal, mechanical, and fire-related properties of a mycelium-bound biocomposite produced from ash sawdust and Ganoderma lucidum. The study examined density, moisture content, thermal conductivity, volumetric heat capacity, thermal diffusivity, compression behavior, and reaction-to-fire indicators. Part of the experimental dataset, including the basic physical, thermal, mechanical, and fire-response measurements, originated from an earlier academic study [44]. The novelty of the present manuscript lies in the integrated scientific interpretation of these results, their extended engineering discussion, the cautious comparison with conventional insulation materials, and the positioning of the ash-sawdust/Ganoderma lucidum composite as an early-stage bio-based insulation concept for selected construction applications.

MATERIALS AND METHODS

The selection of ash sawdust (*Fraxinus excelsior*) as the lignocellulosic substrate was motivated by its availability as a woodworking by-product and its relatively uniform particle structure, which supports homogeneous mycelial growth. Compared to agricultural residues such as straw or hemp, hardwood sawdust provides a denser and more stable matrix, which may influence both thermal and mechanical performance of the resulting composite. Ganoderma lucidum was selected due to its ability to form a dense and highly interconnected mycelial network, ensuring effective binding of substrate particles and improved structural cohesion of the composite. The research material consisted of a biocomposite based on *Ganoderma lucidum* mycelium and ash wood sawdust (*Fraxinus excelsior*). The selection of *G. lucidum* was motivated by its ability for intensive mycelial growth, high adhesion, and effective binding of lignocellulosic substrates. The substrate was composed of ash wood sawdust, dried to a moisture content below 10%. The particle size ranged from 0.5 to 3 mm, providing optimal conditions for mycelium growth [36, 43, 44].

The process of biocomposite fabrication consisted of four stages [40, 41, 44]:

1. Substrate sterilization – the sawdust was exposed to steam at a temperature of 121 °C for 30 minutes in a laboratory autoclave to eliminate competitive microorganisms.
2. Inoculation – after cooling the substrate to 25 °C, commercially available grain-based *G. lucidum* spawn inoculum was added under aseptic conditions in an amount equal to 10% of the dry substrate mass.
3. Incubation – the mixture was placed in perforated polypropylene molds with dimensions of 200 × 200 × 50 mm and kept in a growth chamber at a temperature of 26 ± 1 °C and relative humidity of 80–90% for 14 days, until full colonization of the substrate was achieved.

4. Drying and stabilization – after incubation, the material was subjected to convective drying at 45 °C until a constant mass was reached. The prepared samples exhibited a moisture content below 8%, ensuring dimensional stability and inhibition of further biological growth.

After drying and stabilization, test specimens for individual measurements were cut from the molded blocks to the dimensions required by the respective testing procedures. Particular care was taken to obtain flat, regular, and undamaged contact surfaces to ensure measurement repeatability. The selected process parameters (10% inoculum content, 14-day incubation period, and drying at 45 °C) were adopted as practical laboratory conditions based on preliminary cultivation trials and literature practice for stable colonization and moisture reduction. They should not be interpreted as globally optimized manufacturing parameters.

The produced material had a porous and visually homogeneous structure. The measured apparent density of the tested specimens ranged from 150 to 180 kg·m^{-3}, with an average value of 161.74 kg·m^{-3} (Table 1). From each production batch, 10 specimens were prepared for thermal tests and 5 specimens for mechanical compression tests, in accordance with the scope of the respective procedures. It should be noted that the number of specimens used for compression testing was limited to five. Therefore, considering the inherent heterogeneity of mycelium-bound composites, the mechanical results should be interpreted as preliminary engineering indicators rather than population-level material properties. Larger specimen series and multiple production batches will be required in future studies to assess repeatability and variability more comprehensively.

For thermal measurements, repeated readings were taken for each specimen and averaged before calculating series-level statistics. Results are reported primarily as mean values together with standard deviations, and coefficients of variation are provided where relevant to indicate data dispersion. Owing to the exploratory and laboratory-scale character of the study, the statistical analysis was used mainly to assess repeatability and variability within the tested series rather than to support population-level inference. Therefore, no advanced inferential modelling was applied, and the results should be interpreted as an initial engineering assessment of the developed material. Figure 1 presents a block of the mycelium-bound biocomposite used for testing. The material is lightweight, buoyant in water, and can take any shape depending on the mold. It is susceptible to microbiological degradation under high humidity conditions. It has a mild scent resembling a mix of wood and fungus but is not intense. The surface is covered with a visible layer of mycelium in a nonuniform white-yellow color, with some areas showing remnants of wood particles. When cut, the material reveals a compact structure with clearly visible sawdust particles bound together by white fungal tissue, which prevents the material from disintegrating.

The following material tests were conducted:

a) The bulk density was determined in accordance with PN-EN 1602:2013 [46]. Samples measuring 100 × 100 × 50 mm were weighed with an accuracy of 0.001 g after conditioning at a temperature of 23 ± 2 °C and relative humidity of 50 ± 5%. Moisture content was determined using the drying oven method in accordance with PN-EN 1604:2013 [47], by drying the samples

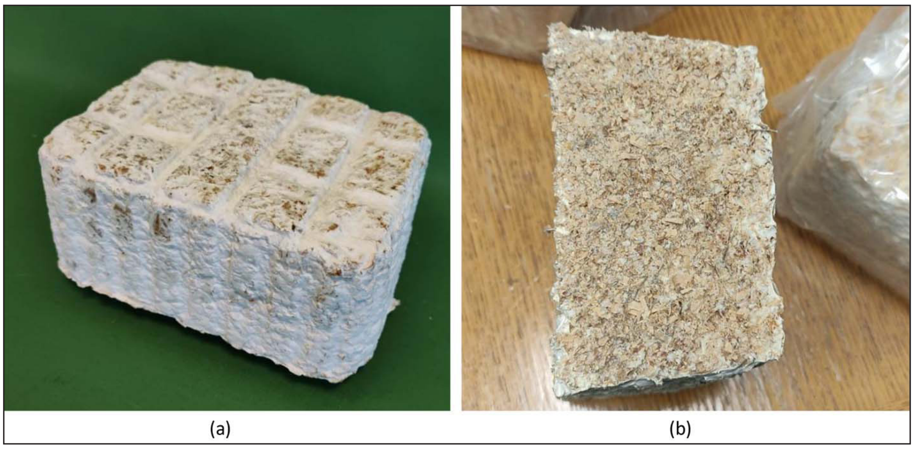

Figure 1. Mycelium-bound biocomposite block subjected to testing (a), cross-section of the tested block (b) [44]

at 105°C until constant mass was achieved.

b) The thermal conductivity coefficient (λ), volumetric heat capacity (C_p), and thermal diffusivity (a) were determined using the ISOMET 2114 measurement system (Applied Precision Ltd.) in accordance with PN-EN 12667:2002 [48] and PN-EN ISO 6946 [49]. The ISOMET 2114 system was selected due to its suitability for measuring thermal properties of heterogeneous and porous materials using a transient method. This technique allows for rapid determination of thermal conductivity, volumetric heat capacity, and thermal diffusivity under controlled conditions. Particular care was taken to ensure stable contact between the probe and the sample surface to minimize measurement errors associated with material heterogeneity. Measurements were performed at a temperature of 20 ± 1 °C under stable humidity conditions. Each reported value represents the average of 10 measurements performed on different samples. To assess the influence of moisture on thermal conductivity, an approach analogous to [17] was applied. Samples were conditioned to target moisture contents of 3%, 6%, and 9% through controlled humidification, and the achieved moisture levels were verified gravimetrically prior to remeasurement of λ. The selected moisture levels (3%, 6%, and 9%) represent typical conditions for building materials exposed to varying environmental humidity, allowing for a realistic assessment of thermal performance under service conditions.

c) Compressive strength was determined in accordance with PN-EN 826:2013 [50]. Samples with dimensions of 50 × 50 × 50 mm were subjected to loading at a strain rate of 10%/min, and the compressive stress corresponding to 10% strain was recorded in accordance with EN 826. The measurements were carried out using a ZwickRoell Z010 testing machine. The results were compared with the literature [37,40,41], where values in the range of 100–300 kPa are reported as sufficient for non-load-bearing thermal insulation applications.

d) Fire-response behavior was evaluated using a cone calorimeter (Cone Calorimeter Fire Testing) in accordance with ISO 5660-1:2015 [51]. Samples measuring 100 × 100 × 20 mm were exposed to a radiant heat flux of 35 $kW \cdot m^{-2}$. The time to ignition (TTI), peak heat release rate (PHRR), and total heat released (THR) were recorded.

Scanning electron microscopy (SEM) observations were performed using a QUANTA 250 microscope. Prior to imaging, the samples were dried and coated with a thin gold conductive layer to reduce charging effects. Micrographs were obtained at several magnifications in order to qualitatively examine the morphology of the biocomposite, including the mycelial network, pore distribution, and the contact zones between fungal hyphae and lignocellulosic particles. No quantitative image analysis was performed in the present study, and the SEM observations were used as qualitative microstructural support only.

RESULTS

SEM observations showed that the ash sawdust particles were surrounded by a visible mycelial network. At higher magnification, filamentous hyphal structures could be identified, whereas at lower magnification the material exhibited a porous and heterogeneous morphology typical of mycelium-bound lignocellulosic composites. Figure 2 presents representative SEM images obtained at magnifications of 40×, 100×, and 200×.

Qualitative SEM observations indicated a multilayered porous structure in which the mycelium formed an interconnected network surrounding lignocellulosic particles. The images suggest physical contact between the fungal hyphae and the sawdust particles, which may contribute to the cohesion of the composite. Voids of different sizes were also visible within the structure, which is consistent with the low-density character of the material. However, no quantitative pore-size analysis or image-based morphometric assessment was performed; therefore, the SEM results should be interpreted as qualitative support only.

The inner part of the cross-section appeared locally more compact than the outer regions, which may reflect non-uniform growth and consolidation within the sample volume. The observed morphology is generally consistent with the porous character of lightweight mycelium-based composites. Nevertheless, no quantitative microstructure–property correlation was established in the present study, and the SEM observations should not be interpreted as a predictive basis for the measured thermal or mechanical performance.

Future work may include quantitative image analysis of pore-size distribution, porosity, and degree of substrate colonization to better relate

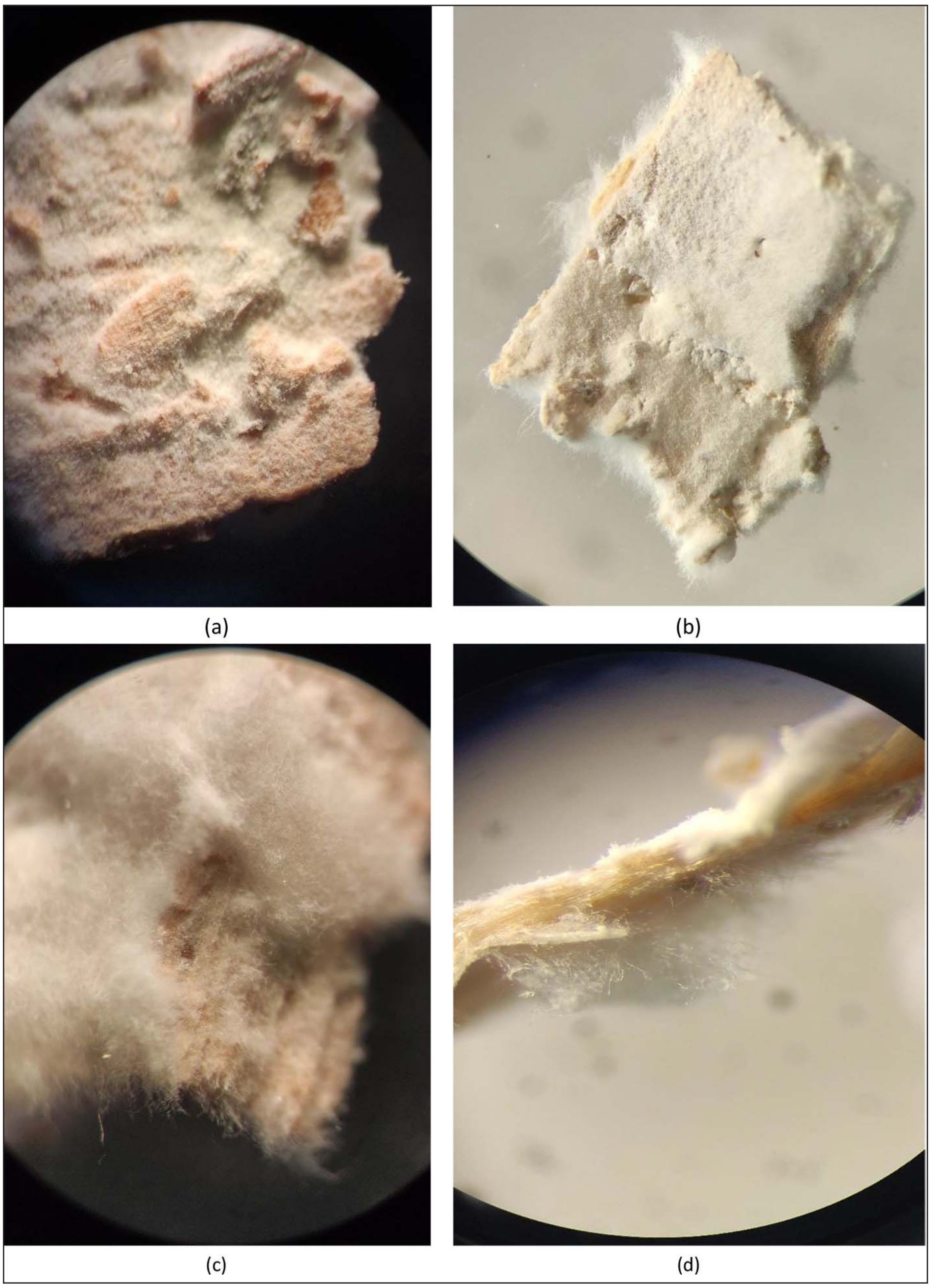

Figure 2. SEM image of wood chips overgrown with mycelium at magnifications: (a,b) 40×, (c) 100×, (d) 200× [44]

morphology to physical performance. As previously mentioned, the test specimens consisted of 10 biocomposite blocks (Ganoderma lucidum mycelium + ash sawdust). For each sample, dimensions, mass, density, and moisture content were determined. The average bulk density was 161.74 $kg \cdot m^{-3}$, while the moisture content was constant at 5.9% for all samples. Table 1 presents a summary of the basic parameters of the tested samples.

Thermal property measurements were carried out using the portable ISOMET 2114 system after prior calibration and configuration of the measurement method and ranges, in accordance with the procedure described in [17, 18]. The transient method was selected due to its suitability for rapid comparative assessment; however, local heterogeneity and contact quality may influence the absolute values obtained for porous biomaterials.

Figure 3 shows the measuring device and the sample during the test. For each sample, the following parameters were recorded:

- λ – thermal conductivity coefficient [$Wm^{-1}K^{-1}$],
- C_p – volumetric heat capacity [10^6 $Jm^{-3}K^{-1}$],
- A – thermal diffusivity [10^{-6} m^2s^{-1}],
- T_{mean} – mean temperature [°C],
- ΔT – temperature difference [K].

Table 1. Summary of the basic parameters of the tested samples [44]

No.	Dimensions, L–W–H	Volume	Mass	Density	Moisture content
	cm	cm^3	g	kg/m^3	%
1	14.5 × 10.5 × 7.0	1065.75	172.17	161.55	5.9
2	14.5 × 10.5 × 5.8	883.05	134.54	152.36	5.9
3	14.5 × 10.5 × 6.1	928.725	147.09	158.38	5.9
4	14.5 × 10.5 × 6.5	989.625	160.19	161.87	5.9
5	14.5 × 10.5 × 6.1	928.725	146.22	157.44	5.9
6	14.5 × 10.5 × 6.5	989.625	161.06	162.75	5.9
7	14.5 × 10.5 × 6.9	1050.525	166.60	158.59	5.9
8	16.0 × 11.5 × 6.9	1269.60	207.57	163.49	5.9
9	14.5 × 10.5 × 7.0	1065.75	172.66	162.01	5.9
10	15.5 × 12.0 × 7.0	1302.00	233.08	179.02	5.9
Mean				161.74	


(a) (b)

Figure 3. Measurement of parameters using the ISOMET 2114 device: measuring device (a), sample during testing (b) [44]

Measurements were performed for 10 blocks. Table 2 summarizes all the average values of each parameter obtained for the individual test samples. The corresponding standard deviations are also reported to reflect the dispersion of the measured values within the tested series. Additionally, an analysis of the effect of moisture content on the thermal conductivity coefficient λ was carried out. The samples were conditioned to three moisture levels: 3%, 6%, and 9% of mass, followed by measurements using the ISOMET 2114 system. The results clearly showed an increase in thermal conductivity with increasing water content in the material. For the 3% level, λ averaged 0.056 $W·m^{-1}·K^{-1}$; for 6%, 0.059 $W·m^{-1}·K^{-1}$; and for 9% moisture, it reached 0.063 $W·m^{-1}·K^{-1}$. These results indicate that moisture exposure may noticeably reduce the insulation efficiency of the material and should therefore be considered a relevant design limitation in practical applications. Accordingly, the present material should not be interpreted as a ready-to-use external envelope solution without further durability engineering.

This relationship can be interpreted as the effect of partial pore filling with water, which has significantly higher thermal conductivity than air (approx. 0.6 $W·m^{-1}·K^{-1}$), thereby reducing the thermal insulation capacity of the material. These results are consistent with the findings of [17, 18, 36], who demonstrated that even a small increase in the moisture content of bio-based materials can lead to a 10–20% rise in λ. The analysis confirms that maintaining a low moisture level is crucial for preserving stable thermal parameters of mycelium-bound composites.

Table 2. Average parameter values for individual samples and for the entire test series [44]

Parameter	λ	C_p	A	T_{mean}	ΔT
Unit	$Wm^{-1}K^{-1}$	10^6 $Jm^{-3}K^{-1}$	10^{-6} m^2s^{-1}	°C	K
Mycelium 1	0.0535	0.2105	0.2542	25.81	10.02
Mycelium 2	0.0526	0.1963	0.2679	26.00	10.11
Mycelium 3	0.0530	0.2113	0.2508	25.97	10.03
Mycelium 4	0.0535	0.2105	0.2542	25.81	10.02
Mycelium 5	0.0541	0.1889	0.2866	25.92	10.06
Mycelium 6	0.0533	0.2178	0.2447	25.83	10.01
Mycelium 7	0.0522	0.2126	0.2455	25.87	10.07
Mycelium 8	0.0553	0.2089	0.2648	26.22	10.11
Mycelium 9	0.0541	0.2048	0.2644	25.91	10.02
Mycelium 10	0.0586	0.2130	0.2750	25.84	10.08
Average value	0.0540	0.2075	0.2608	25.92	10.05
Standard deviation	0.0018	0.0087	0.0135	0.13	0.038
Coefficient of variation [%]	3.38	4.18	5.16	0.48	0.37

From an engineering perspective, the developed material may be considered for selected non-load-bearing indoor insulation applications, provided that adequate moisture protection and fire-safety measures are ensured.

The obtained values of volumetric heat capacity (C_p) and thermal diffusivity (a) provide additional insight into the thermal behavior of the material. The relatively low thermal diffusivity indicates that the material slows down heat propagation, which is beneficial for improving thermal inertia in building partitions. The C_p values, combined with low density, suggest that the material has moderate heat storage capacity, typical for porous bio-based insulation materials. These parameters are strongly influenced by the internal pore structure and the presence of air-filled voids, which dominate heat transfer mechanisms in such composites.

The observed trends are consistent with previous studies on lignocellulosic and mycelium-bound materials, where thermal performance is primarily governed by porosity and moisture content. The next test involved measuring the 10% deformation to determine the corresponding force, performed on a ZwickRoell Z010 testing machine in accordance with PN-EN 826 [50]. Figure 4 shows the mycelium biocomposite sample placed in the testing machine.

Figure 4. Test of 10% deformation of the mycelium biocomposite material [44]

Five tests were carried out, from which the following parameters were obtained:

- E_{mod} – apparent compressive modulus [kPa],
- σ_{10} – compressive stress at 10% strain [kPa],
- F_{10} – compressive force at 10% strain [N],
- ε_{10} – deformation corresponding to 10% strain [mm],
- W_{10} – work energy up to 10% strain [J].

The values reported in Table 3 are presented as mean values for the tested series, together with

Table 3. Results of mechanical strength tests [44]

Sample No.	E_{mod} [kPa]	F_{10} [N]	σ_{10} [kPa]	ε_{10} [mm]	W_{10} [J]
1	1108.761	3146.63	1258.65	20.86	25.46
2	1141.588	3435.99	1374.40	18.75	23.38
3	1129.846	2910.82	1164.33	18.77	20.039
4	1067.053	2960.94	1184.37	18.76	19.32
5	1187.734	3701.41	1480.56	18.94	26.67
Average value	1126.996	3231.16	1292.46	19.22	22.97
Standard deviation	44.260	333.87	133.55	0.92	3.24
Coefficient of variation [%]	3.93	10.33	10.33	4.80	14.11

standard deviations to indicate the variability of the compression response.

The obtained mechanical parameters indicate moderate compressive resistance combined with relatively low stiffness, which is characteristic of lightweight porous bio-based composites. The average compressive stress at 10% strain was $\sigma_1 \approx$ 1.29 MPa. This value is higher than the 100–300 kPa range reported in some studies for non-load-bearing insulation materials; however, these values should not be treated as directly equivalent, since they may refer to different material densities, testing procedures, specimen geometries, and mechanical descriptors. In the present study, σ_{10} was determined according to EN 826 and should be interpreted as an indicator of deformation resistance under compression rather than structural load-bearing capacity. The relatively high value may be associated with the compacted sawdust-based matrix, the apparent density of the tested composite, and the degree of mycelial bonding. Therefore, the result suggests potential dimensional stability in selected non-load-bearing insulation applications but does not imply suitability for structural use.

The relatively low modulus of elasticity is associated with the high porosity and fibrous microstructure of the composite. At the same time, the observed deformation capacity may be beneficial in applications where compliance is desirable. However, possible vibration-damping or acoustic benefits should be verified by dedicated tests before such functionality can be claimed. The final test performed was the evaluation of the mycelium biocomposites' fire reaction in accordance with [51]. The following parameters were measured:

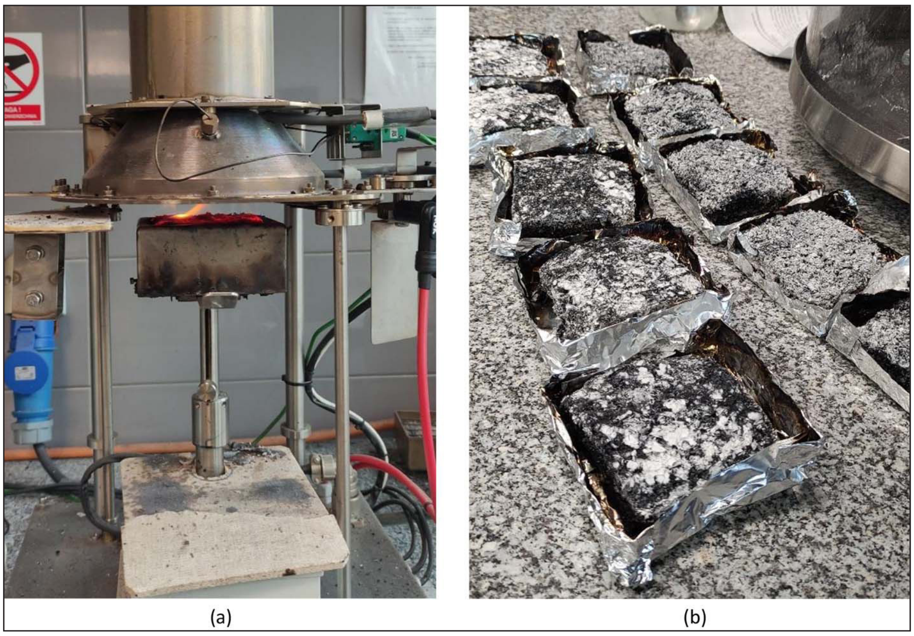

Figure 5. Sample of the biocomposite placed in the calorimeter (a), appearance of the biocomposite samples after the fire test (b) [44]

- PHRR – peak heat release rate [kWm^{-2}],
- Avg. HRR – average heat release rate [kWm^{-2}],
- THR – total heat released [MJm^{-2}],
- ARHE 180 s – average heat release rate after 180 seconds [kWm^{-2}],
- ARHE 300 s – average heat release rate after 300 seconds [kWm^{-2}].

The obtained results are summarized in Table 4 below. Figure 5 shows the sample placed in the calorimeter and the appearance of the samples after the fire test.

The results obtained from the cone-calorimeter tests are summarized in Table 4. Mean values are accompanied by standard deviations in order to indicate the scatter of the fire-response parameters across the tested specimens. The obtained parameters indicate combustible behavior of the mycelium-bound biocomposite, which is typical of organic materials with high porosity and cellulose content. Since no formal reaction-to-fire classification according to EN 13501-1 was performed, no specific fire class is assigned in the present study. The results should therefore be interpreted only in terms of the measured fire-response parameters, including PHRR, average HRR, THR, ARHE 180 s, and ARHE 300 s.

The fire-response behavior of the material is influenced by its organic composition and porous structure. The presence of lignocellulosic components contributes to combustibility, while local charring may affect flame propagation during thermal degradation. However, no detailed analysis of char formation or flame-spread mechanisms was performed in the present study.

The fire-response parameters presented in Table 4 show moderate scatter between specimens. The average peak heat release rate (PHRR = 113.24 $kW \cdot m^{-2}$) and total heat released (THR = 56.52 $MJ \cdot m^{-2}$) confirm that the developed biocomposite remains a combustible organic material. Although some charring effects may delay local flame propagation, the present formulation does not provide fire performance comparable to non-combustible insulation systems, confirming observations reported in the literature [40, 41]. The present results indicate that fire performance remains a key limitation of the tested formulation. Future studies may investigate mineral fillers, bio-based flame retardants, or protective surface layers as possible strategies for improving reaction-to-fire behavior.

Based on the obtained results, the following preliminary observations can be drawn:

- the biocomposite is characterized by low density (162 $kg \cdot m^{-3}$) and stable moisture content during testing (5.9%), which contributes to favorable thermal parameters;
- the measured thermal conductivity λ = 0.054 $W \cdot m^{-1} \cdot K^{-1}$ places the material within the range of lightweight insulators, accompanied by low thermal diffusivity and moderate volumetric heat capacity;
- the measured thermal and mechanical properties indicate potential suitability for selected non-load-bearing insulation

Table 4. Summary of the results obtained from the fire tests [44]

Sample No.	PHRR	Avg. HRR	THR	ARHE 180 s	ARHE 300 s
	kWm^{-2}	kWm^{-2}	MJm^{-2}	kWm^{-2}	kWm^{-2}
1	113.04	101.41	56.30	100.36	103.59
2	121.17	100.86	56.50	95.35	96.66
3	114.28	102.06	56.80	97.05	99.54
4	122.41	96.10	61,00	97.84	100.59
5	115.41	98.52	61.70	99.38	100.13
6	98.31	90.06	58.70	85.45	87.35
7	91.34	91.02	54.50	91.45	104.05
8	124.2	100.41	59.20	110.78	106.35
9	113.38	93.66	49.70	91.84	89.47
10	118.86	103.24	50.80	106.23	105.56
Average value	113.24	97.734	56.52	97.573	99.329
Standard deviation	10.58	4.75	3.97	7.32	6.49
Coefficient of variation [%]	9.34	4.86	7.03	7.51	6.53

applications, although durability under real environmental exposure requires further validation,
- cone-calorimeter testing indicated combustible behavior of the present formulation, suggesting that additional reaction-to-fire improvement strategies would be necessary before practical building implementation.

DISCUSSION

The present results should be interpreted within the scope of a laboratory-scale exploratory study with limited sample numbers and without long-term durability validation. From an engineering perspective, the obtained thermal conductivity ($\lambda \approx 0.054$ W·m^{-1}·K^{-1}) places the tested material within the broader range of lightweight bio-based insulation materials. However, this result alone does not constitute validation for construction use, since service performance also depends on moisture durability, dimensional stability, biological resistance, ageing, and reaction-to-fire behavior. No long-term validation under cyclic humidity, biological exposure, freeze-thaw action, or UV ageing was performed; therefore, the service durability of the material remains to be established.

However, the relatively low mechanical strength limits its application to non-structural elements. As a biodegradable bio-based composite, the material may also require protection against prolonged microbial or moisture-driven degradation during service life. Similarly, the cone-calorimeter results indicate combustible behavior of the present formulation, suggesting that additional protective layers or formulation modifications would be required for applications with stricter fire-safety requirements. Therefore, the current material configuration should be considered unsuitable for applications requiring elevated fire safety performance unless additional protective measures or formulation improvements are introduced. The research methodology applied in this study was an extension of the procedures used in [17, 18, 20, 21, 43], adapted to the specific nature of the organic material. Recommendations for assessing the thermal insulation properties of bio-based materials described in [36, 40, 41] were also followed.

The internal structure was analyzed using optical microscopy and macroscopic observations of fracture surfaces. The structure was characterized in terms of pore distribution uniformity and the degree of mycelial bonding, which was compared with the morphological descriptions provided in [43].

For comparative purposes, four commonly used construction materials were also analyzed:
- mineral wool,
- PUR foam,
- PIR foam,
- expanded polystyrene (EPS 70).

A comparison of the obtained results with the characteristic parameters of commercially available thermal insulation materials is presented in Table 5. Due to the different origins and testing conditions of the literature data, Table 5 should be interpreted only as an indicative comparison. In particular, the mechanical parameters are not

Table 5. Indicative literature-based comparison of selected thermal, mechanical, and fire-response parameters of insulation materials. The listed values originate from different sources, standards, densities, specimen geometries, and testing procedures; therefore, they are not directly equivalent and should be interpreted only as a broad contextual comparison

No	Material	Parameter				
		λ	Indicative compressive parameter [kPa]*	PHRR	THR	ARHE 300 s
		Wm^{-1}K^{-1}		kWm^{-2}	MJm^{-2}	kWm^{-2}
1	Mycelium biocomposite	0.054	1292	113.24	56.52	99.329
2	mineral wool	0.030-0.045	5000–15000	>5	>5	>5
3	PUR foam	0.022-0.028	10000–250000	100–300	30–120	50–150
4	PIR foam	0.021-0.026	150000–300000	30–100	15–50	30–100
5	Polystyrene	0.028-0.045	50000–700000	150–200	60–120	100–200

Note: *the listed compressive parameters are literature-based indicative values and may refer to different descriptors, including compressive stress or strength determined under different procedures. For the mycelium biocomposite, the value corresponds to σ10, i.e., compressive stress at 10% strain determined according to EN 826. Therefore, this column should not be used for direct ranking of mechanical performance.

fully equivalent, because they may represent different compressive descriptors and testing configurations. The table is therefore intended to provide engineering context rather than a direct performance ranking.

An analysis of the data presented in Table 5 indicates that the tested material — the mycelium-bound biocomposite — differs significantly in its parameters from conventional materials. It has a relatively high thermal conductivity for an insulating material, while its compressive strength shows that it cannot withstand large loads. These values suggest potential suitability as passive, non-structural insulation material in applications where high load-bearing capacity is not required. From an engineering perspective, the obtained results suggest potential use of the developed material in selected non-load-bearing insulation applications, provided that moisture durability and fire-performance limitations are adequately addressed. Direct comparison with commercial polymeric insulation products should be made cautiously, since fire behavior depends strongly on product formulation, density, additives, facing layers, and test configuration.

The results obtained in this study are consistent with current trends in sustainable construction, focused on reducing greenhouse gas emissions and improving energy efficiency in line with the European Green Deal [10–12]. Studies cited in [1, 2] show that climate change leads to an increased demand for cooling and a simultaneous decrease in heating requirements in buildings located in temperate zones. One of the key adaptation strategies is the use of materials with low thermal conductivity and a low carbon footprint. In the context of EU policy, the development and implementation of bio-based materials such as the studied mycelium composite align with the objectives of decarbonization and the circular economy [13, 14]. As noted by the authors of [13], raw material recycling and the use of renewable biomaterials are essential to reduce the environmental impact of the construction sector. Similarly, the authors of [11] emphasize the importance of combining material innovation with improvements in energy efficiency.

The measured thermal conductivity coefficient of the tested mycelium biocomposite was $\lambda = 0.054\ W\cdot m^{-1}\cdot K^{-1}$, placing the material within the range of lightweight bio-based insulation systems, although remaining less efficient than high-performance synthetic foams. This result is comparable to the values reported by other researchers [17, 18], who investigated the effect of humidity on the thermal properties of materials used in passive buildings, obtaining λ values in the range of 0.045–0.060 $W\cdot m^{-1}\cdot K^{-1}$.

Compared to conventional insulation materials such as polyurethane foams (PU), which typically exhibit $\lambda = 0.025–0.035\ W\cdot m^{-1}\cdot K^{-1}$ [16, 28, 29], the obtained value is somewhat higher. However, this should be considered in light of the material's renewable origin and potential end-of-life advantages, which require confirmation by dedicated environmental and biodegradation studies. The measured conductivity $\lambda = 0.054\ W\cdot m^{-1}\cdot K^{-1}$ is about 25–30% higher than that of typical synthetic materials such as EPS (0.035–0.040 $W\cdot m^{-1}\cdot K^{-1}$) or PUR (0.025–0.030 $W\cdot m^{-1}\cdot K^{-1}$), yet comparable to hempcrete (0.050–0.060 $W\cdot m^{-1}\cdot K^{-1}$) and other fibrous bio-insulators [36, 40]. This difference may be partly offset by the renewable origin and potential end-of-life advantages of the developed material; however, these aspects require confirmation by dedicated environmental and biodegradation studies. Similar observations were reported in [36], where the authors analyzed hempcrete and found that its thermal conductivity mainly depends on density and moisture content. Studies [31, 32] confirm that the thermal parameters of porous materials vary under dynamic conditions, which is relevant for both historic and low-energy buildings. The results presented in [44, 45] suggest that mycelium-bound materials can be effectively used in low-load building envelopes, particularly when combined with solutions that limit moisture migration (as specified in PN-EN ISO 6946:2017 [48]).

The obtained apparent modulus (1.13 MPa) and compressive stress at 10% strain (1.29 MPa) indicate sufficient resistance for non-structural insulation applications, while confirming that the material is not intended for load-bearing use. Similar values were reported by researchers in [27] for lightweight geopolymer concretes and in [25] for composite walls made from recycled concrete. In the context of mechanical strength, the obtained Young's modulus (~1.13 MPa) falls within the lower range of lightweight insulating materials but remains adequate for non-load-bearing applications, as confirmed by [41, 44]. Compared to mineral wool (~10–15 MPa) or rigid foams (up to 300 MPa), the tested biocomposite is less stiff. Its lower stiffness and higher compliance may be advantageous in applications where deformability is acceptable. However, acoustic absorption and vibration-damping performance were not measured in the present study and should therefore be treated as possible future research directions rather than demonstrated properties. Overall, the comparative data indicate that the developed mycelium composite should be positioned as a sustainable lightweight insulation material rather than a direct replacement for all conventional commercial systems. Its main advantages are renewable origin and low-density structure, whereas further improvements are required in fire performance, durability, and mechanical robustness.

The measured cone-calorimeter response confirms combustible behavior, but no formal reaction-to-fire classification was established in this study. The material showed lower THR and PHRR values than some values reported for typical polyurethane foams; however, such comparisons should be treated cautiously because fire response depends strongly on formulation, density, additives, facing layers, and test configuration. This indicates that, although combustible, the total energy released during combustion is significantly lower, which may indicate a less intense heat-release response under the specific test conditions used in this study. Consequently, the developed biocomposite may be positioned within the broader group of lightweight bio-based insulation materials, offering a potentially useful balance between thermal performance, renewable origin, and low-density structure, while fire-response and durability limitations still require further improvement. Further studies should focus on improving reaction-to-fire behavior through mineral additives, bio-based flame retardants, or protective surface layers, as well as enhancing thermal and moisture stability.

These results are consistent with the findings of [40], who reported limited fire performance of mycelium composites and discussed their potential environmental advantages compared with selected synthetic insulation materials. The incorporation of natural mineral additives, such as perlite, or other flame-retardant strategies may improve the reaction-to-fire behavior of such materials [19–22], although this requires dedicated verification for the present formulation.

It is also worth emphasizing the environmental potential of the developed material from a life cycle assessment (LCA) perspective. Although a detailed LCA has not yet been performed, preliminary process-level considerations suggest the potential for lower embodied energy than polyurethane and expanded polystyrene foams; however, this has not yet been verified through a full life-cycle assessment. This results from the low process temperatures (<50 °C) and the use of wood waste as the raw material.

The carbon-footprint considerations presented here should be regarded as preliminary and indicative only, since no formal life-cycle assessment was performed for the present material [13, 14, 40]. Importantly, within the life cycle of mycelium composites, part of the emissions may be offset by carbon sequestration within the lignocellulosic and fungal biomass structures. Future research should include a full "cradle-to-grave" LCA, covering the material's use phase and recycling after the end of its service life.

This study has several limitations that should be acknowledged. The material was produced under laboratory conditions, and scale-up effects may influence its density, microstructure, thermal properties, and mechanical repeatability. The compression test series was limited to five specimens, which is sufficient for a preliminary assessment but not for robust population-level characterization of a heterogeneous mycelium-bound composite. In addition, no long-term validation under cyclic humidity, biological exposure, dimensional stability changes, ageing, freeze-thaw action, or service conditions were performed. Future work should therefore include larger specimen series, semi-industrial production trials, hygrothermal ageing, biological durability assessment, dimensional stability tests, reaction-to-fire optimization, and full life-cycle assessment.

CONCLUSIONS

The results indicate that the biocomposite based on Ganoderma lucidum mycelium and ash sawdust shows potential as an early-stage bio-based material for selected non-load-bearing insulation applications. The measured thermal conductivity ($\lambda \approx 0.054\ W \cdot m^{-1} \cdot K^{-1}$) places the material within the range of several lightweight bio-based insulators. The specific contribution of the study lies in evaluating a relatively under-explored combination of Ganoderma lucidum with ash wood sawdust under integrated thermal, mechanical, and fire-response assessment.

The material offers potential advantages associated with renewable feedstock use and moldability during fabrication, while its environmental and end-of-life benefits should be confirmed by dedicated biodegradation and life-cycle studies. These characteristics make it a candidate for further development as an alternative insulation material where circular-material strategies are of interest.

The measured mechanical response suggests potential suitability for applications not requiring structural load-bearing capacity. Cone-calorimeter indicated that the present formulation remains combustible, meaning that further improvement or protective solutions would be required before broader practical implementation.

Qualitative SEM observations supported the presence of an interconnected porous microstructure in which mycelial growth bonded lignocellulosic particles into a lightweight composite. This structural arrangement is consistent with the low-density character of the material, although no quantitative microstructure–property correlation was established in the present study. The present conclusions should be interpreted within the scope of a laboratory-scale exploratory study.

Future work should focus on improving reaction-to-fire behavior, dimensional stability under moisture exposure, biological resistance, long-term durability, formulation optimization, larger-scale production repeatability, and full life-cycle assessment in comparison with conventional insulation materials.

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