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Dissertation Thesis Abstarct

The use of agricultural waste for the production of construction materials with zero pollution

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Abstract

This dissertation investigates the potential of agricultural waste—specifically wheat, flax, and hemp straw—as a sustainable raw material for the production of bio-based composites aligned with zero-pollution construction principles. The study presents a comprehensive evaluation of thermal and hygrothermal properties of both straw-sodium silicate and mycelium-bound composites, alongside their environmental performance through Life Cycle Assessment (LCA). Flax straw-based composites achieved a thermal conductivity as low as 0.078 $W\cdot m^{-1}\cdot K^{-1}$, with optimized compressive strength reaching 0.56 MPa at a flax-to-sodium silicate ratio of 1:2.65, and densities ranging from 250 to 345 $kg\cdot m^{-3}$. Mycelium-based insulation samples demonstrated average thermal conductivity between 0.045 and 0.056 $W\cdot m^{-1}\cdot K^{-1}$, and densities from 107 to 220 $kg\cdot m^{-3}$, depending on the substrate. The highest thermal conductivity-to-weight ratio (TC-WR) was observed in wheat - mycelium composites, measured at 0.148 $W^{-1}\cdot kg^{-1}\cdot m^{4}\cdot K$, outperforming other straw-based variants. The materials also showed favorable hygrothermal behavior, with moisture sorption stabilizing within 0.003% to 0.52% under changing humidity conditions. SEM and EDS analyses confirmed the effective integration of sodium silicate on straw fibers, contributing to structural strength and water resistance. Environmental analysis revealed that the proposed materials could reduce embodied energy and carbon emissions by up to 40% compared to conventional insulation (e.g., mineral wool, EPS). Mycelium-based composites exhibited carbon-negative footprints ranging from −244 to −298 kg CO_2/m^3. Additionally, the reuse of regional agricultural residues addresses a pressing waste management issue in the EU, where over 700 million tons of agricultural waste are generated annually. The outcomes demonstrate that straw-based bio-composites are not only technically viable but also economically and environmentally advantageous for building applications, especially in the context of low-energy renovations and sustainable construction.

Abstrakt

Dizertačná práca sa zaoberá využitím poľnohospodárskeho odpadu – konkrétne pšeničnej, ľanovej a konopnej slamy – ako udržateľného surovinového zdroja na výrobu bio-kompozitných materiálov v súlade s princípmi výstavby bez znečistenia (zero pollution). Práca poskytuje komplexné hodnotenie mechanických, tepelných a hygrotermálnych vlastností kompozitov viazaných na silikát sodný a hubové mycélium a taktiež ich environmentálnu výkonnosť prostredníctvom analýzy životného cyklu (LCA). Kompozity na báze ľanovej slamy dosiahli tepelnú vodivosť až 0,078 $W\cdot m^{-1}\cdot K^{-1}$, optimalizovanú pevnosť v tlaku 0,56 MPa pri pomere ľan\:silikát sodný 1:2,65, a hustotu v rozsahu 250 až 345 $kg\cdot m^{3}$. Izolačné vzorky s mycéliom preukázali priemernú tepelnú vodivosť v rozsahu 0,045 až 0,056 $W\cdot m^{-1}\cdot K^{-1}$ a hustotu 107 až 220 $kg\cdot m^{3}$ v závislosti od použitého substrátu. Najvyšší pomer tepelnej vodivosti k hmotnosti (**TC-WR**) bol nameraný u kompozitov pšenica - mycélium s hodnotou **0,148 $W^{-1}\cdot kg^{-1}\cdot m^{4}\cdot K$**, čo prevyšuje ostatné testované organické varianty. Materiály vykázali priaznivé hygrotermálne vlastnosti, pričom sorpcia vlhkosti sa stabilizovala v rozmedzí 0,003 % až 0,52 % pri rôznych režimoch vlhkosti. Analýzy SEM a EDS potvrdili účinnú integráciu silikátu sodného na povrchu slamených vlákien, čo prispelo k zlepšeniu pevnosti a odolnosti voči vode. Environmentálne hodnotenie ukázalo, že navrhované materiály môžu znížiť zabudovanú energiu a uhlíkové emisie až o 40 % v porovnaní s konvenčnými izoláciami (napr. minerálna vlna, EPS). Kompozity s mycéliom dosiahli negatívnu uhlíkovú stopu v rozsahu −244 až −298 kg CO_2/m^3. Opätovné využitie regionálnych poľnohospodárskych zvyškov zároveň predstavuje riešenie naliehavého problému spracovania odpadu v EÚ, kde sa ročne vyprodukuje viac než **700 miliónov ton poľnohospodárskeho odpadu. Výsledky práce potvrdzujú, že kompozity na báze slamy sú technicky uskutočniteľné, ekonomicky výhodné a environmentálne prínosné pre aplikáciu v stavebníctve, najmä v oblasti nízkoenergetickej obnovy a udržateľnej výstavby.

Introduction

The majority of buildings in the European Union predate energy efficiency directives such as Directive 2002/91/EU, prompting increased interest in retrofitting with high-performance insulation systems *(EC, 2003)*. Advanced materials like mineral fiber panels, vacuum insulation panels, thermochromic coatings, and hempcrete have demonstrated low thermal conductivity (<0.015 $W \cdot m^{-1} \cdot K^{-1}$) and significant energy-saving potential *(F. Ascione et al., 2016; E. Parcesepe et al., 2021)*. The 2022 energy crisis has intensified demand for energy-efficient solutions due to elevated energy costs *(Eurostat, 2022)*. Simultaneously, agricultural by-products such as straw, rich in cellulose, hemicellulose, and lignin, offer thermally effective, low-cost, and environmentally sustainable alternatives to synthetic insulation materials. Straw and similar plant-based residues—like hemp and flax shives—exhibit thermal conductivities comparable to conventional insulants and require minimal processing or transport *(Babenko et al., 2018)*.

Hemp shivs and flax shives, both lignocellulosic in nature, are derived from the inner core of their respective stalks and are increasingly utilized as fillers or insulation due to their mechanical stability and hygroscopic behavior *(Arslanoglu et al., 2022)*. Flax cultivation not only enhances soil quality but also sequesters approximately 250,000 tons of CO_2 annually, though significant volumes of flax straw remain unrecycled *(CELC, 2015)*. The EU generates approximately 700 million tons of agricultural waste per year, underscoring the urgency for scalable material recovery strategies *(Babenko et al., 2018)*.

Mycelium-Based Composites (MBCs), created by combining fungal mycelium with agricultural residues, offer a biodegradable, fire-resistant, and thermally effective insulation solution *(M. Babenko et al., 2025)*. MBCs and bio-based insulants exemplify a materials science pathway toward circular, low-impact building technologies aligned with sustainable development goals.

1. Objectives of the dissertation work

The objective of this research is to develop and evaluate construction composites derived from agricultural residues—specifically wheat, flax, and hemp straw—with the aim of achieving thermally efficient, biodegradable, and carbon-negative building materials. The study focuses on optimizing the physicomechanical, thermal, and hygrothermal performance of straw-based composites using sodium silicate and fungal mycelium as binding agents. The work aims to conduct comparative assessment through laboratory-scale testing and Life Cycle Assessment (LCA) to quantify environmental benefits, including reductions in embodied energy and carbon emissions. The integration of Scanning Electron Microscopy (SEM) and Energy-Dispersive X-ray Spectroscopy (EDS) are considered to provide structural and compositional validation of the developed materials. Ultimately, the research aims to propose viable, sustainable alternatives to conventional insulation materials within the framework of zero-pollution construction principles.

2. Experimental methodology

This research employed a comprehensive experimental methodology to evaluate bio-based composites made from agricultural waste (flax, hemp, wheat straw), using sodium silicate and fungal mycelium as binders. The methodology included physical, thermal, hygrothermal, and microstructural analyses, along with life cycle and environmental performance assessments.

2.1 Laboratory Testing of Designed Materials

2.1.1 Thermal Conductivity, Moisture Content, and Density

Thermal properties were assessed using a transient thermal needle probe method (ASTM D5334-08) and Isomet 2114 device (*Figure 1)*. Measurements were taken under controlled lab conditions (20 °C, 50% RH). Each sample was tested twice and covered in plastic to prevent convective heat loss. Density was determined using precision scales and volumetric dimensions. Moisture content *MC* (%) in samples was manually measured by weight drying at 20 °C following ISO 16979:2003. The Thermal Conductivity to Weight Ratio (TC-WR) was introduced to evaluate insulation efficiency relative to material mass.

$$Thermal\ Conductivity\ -\ Weight\ Ratio\ coefficient\ (TC - WR) = \frac{1}{\lambda \times \rho} = (W^{-1} \cdot kg^{-1} \cdot m^{4} \cdot K) \tag{1}$$

Where λ represents the thermal conductivity of the material measured in $W \cdot m^{-1} \cdot K^{-1}$, while ρ denotes the density of the material expressed in $kg \cdot m^{-3}$.

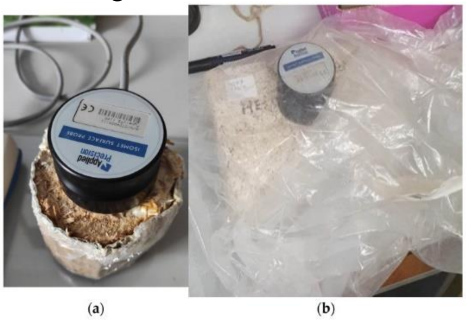


Figure 1: Measuring the thermal conductivity of the samples (a) the surface probe; (b) plastic foil covering for the samples

2.1.2 Thermal Analysis (DSC/DTG)

Thermal degradation and stability were analyzed using the STA 449 F3 Jupiter® system in air atmosphere. Flax and hemp straw-based lightweight concrete samples were heated from 26–900 °C at 10 K/min. The analysis provided insight into material decomposition stages and energy release profiles essential for assessing recyclability and end-of-life impacts (*Table 1*).

Table 1: The parameters of the thermal analysis of the straw-based lightweight concrete

Lightweight concrete	Initial mass, mg	Heating rate, K/min	Temperature interval, °C	Atmosphere
Hemp straw concrete (HSC)	12.73	10	26-900	air
Hemp straw concrete (HSC)	17.87	10	27-900	air

2.1.3 Scanning Electron Microscopy (SEM/EDS)

A SEM VEGA3 SBU (TESCAN) with SE and BSE detectors was used for surface topography and composition analysis. Samples were vacuum coated with non-oxidizing metals (*Figure 2*). Imaging parameters included 30 kV beam, 14.87–18.98 mm working distance, and 3 nm resolution. SEM revealed fiber morphology, binder adhesion, and substrate porosity—key factors influencing mechanical bonding and durability.

Figure 2: Prepared composites for SEM analysis (A): Coated particles with non-oxidizing metals (B)

2.1.4 Mechanical Testing (Compression)

Compressive strength was determined using an automatic CONTROLS 50 – C99/B press per EN 826:1998 and DSTU B.V.2.7-214:2009 (*Figure 3)*. Testing was performed on 70×70×70 mm and 100×100×100 mm samples after oven drying.

Figure 3: Compression test with CONTROLS, model 50 – C99/B

2.1.5 Particle Size Distribution

A Fritsch ANALYSETTE 22 NanoTec laser particle sizer (wet mode) was used to measure shredded straw substrate granularity in compliance with ISO 13320. This analysis helped optimize milling procedures for improved composite homogeneity and binder interaction.

2.1.6 Hygrothermal Properties

Sorption isotherms were established using a BINDER KBF 240 climate chamber under varying humidity conditions (20%, 50%, 80%, 95% at 20 °C) per ISO 12571:2013. Moisture content at equilibrium was determined through weight gain/loss, essential for predicting in-service performance in humid environments.

2.2 Design and Preparation of Straw-Based Samples

2.2.1 Pure Straw Substrates

Raw wheat, flax, and hemp straw were sourced from local farms. After chopping (10–25 mm), they were manually compressed into molds (70×70×90 mm). Stored under controlled RH and temperature, these samples served as baseline substrates (*Figure 4*).

Figure 4: Samples of pure straw denoted as F (flax), H (hemp), and S (wheat straw)

2.2.2 Sodium Silicate Composites (FSC & HSC):

Straw fractions (15–35 mm) were mixed with sodium silicate solution (ρ = 1.30 g/cm³). Flax straw concrete (FSC) and hemp straw concrete (HSC) samples were cast in molds and dried at 60–100 °C (*Table 2, Figure 5*).

Table 2: Composition of the composite mixture

Concrete	Mass fractions			
	Straw	**Water**	**Portland cement**	**Water**
HSC	1	1	1	4
FSC	1	1.5	0	0

a) b)

Figure 5: The lightweight concrete samples: a) HSC- based on hemp straw ($1^{K}{}_{2}$); b) FSC – based on flax straw ($L1_2$)

2.2.3 Flax Straw Composite

To optimize fiber–binder adhesion, varying amounts of liquid glass ($Na_2O{\cdot}SiO_2$) were added to flax-based composite mixtures, aiming for complete fiber surface wetting and improved mechanical performance. The optimal ratio of plant filler to binder was determined experimentally by evaluating bulk density and compressive strength at 10% deformation, following EN 826:2013. Compositions were prepared by thoroughly mixing straw for 2 minutes, then adding liquid glass and mixing for an additional 2–3 minutes until homogeneity was achieved. Samples were manually compressed into 100 × 100 × 100 mm metal molds in three layers, held for 24 hours under ambient conditions, and dried to constant weight through a two-stage process—first indoors (48 h, 20 °C, 50% RH), then in a drying chamber (48 h, 60 °C). The determination of optimal binder content was based on the rule of greatest incremental increase in resistance to deformation per unit increase in binder mass (*Table 3, Figure 6-7*). Equilibrium moisture content and constant weight criteria were strictly followed, with allowable mass change not exceeding 0.05% of total sample weight.

Table 3: Composition of the mixture

Form	Quantity of samples (labels)	Flax straw, mass fractions	Liquid glass, mass fractions
C (cube)	3 (A_1, A_2, A_3)	1	3
P (panel)	1 (P_1)	1	2

a) b)

Figure 6: Flax straw composite insulation in a form of panel (FSI P): a fresh mixture in a form; b dried P-sample

a) b)

Figure 7: Flax straw composite insulation in a form of cubes (FSI A): a fresh mixture in the forms; b dried A-samples

2.2.4 Mycelium-Based Composites (MBC):

Straw fibers were sterilized (100 °C, 3 hrs) and inoculated with Ganoderma lucidum mycelium. Growth occurred in two stages—mass phase and mold phase—under 15–17 °C and 70–80% RH. After colonization, samples were baked (60 °C, 24 hrs) to deactivate the fungi *(Figure 8-9)*.

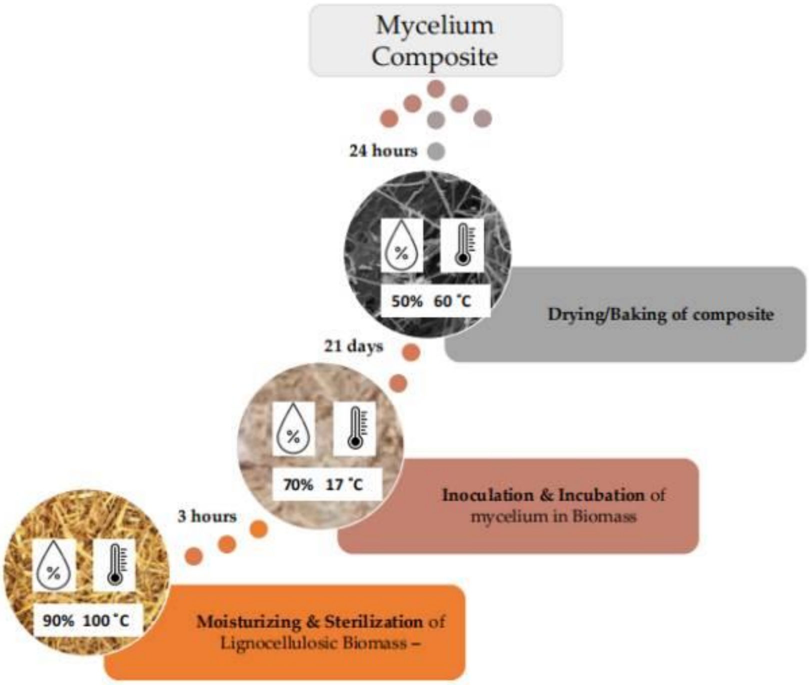


Figure 8: Process of preparing Mycelium based straw insulation

Figure 9: Samples based on wheat-flax-hemp and mycelium as a binder

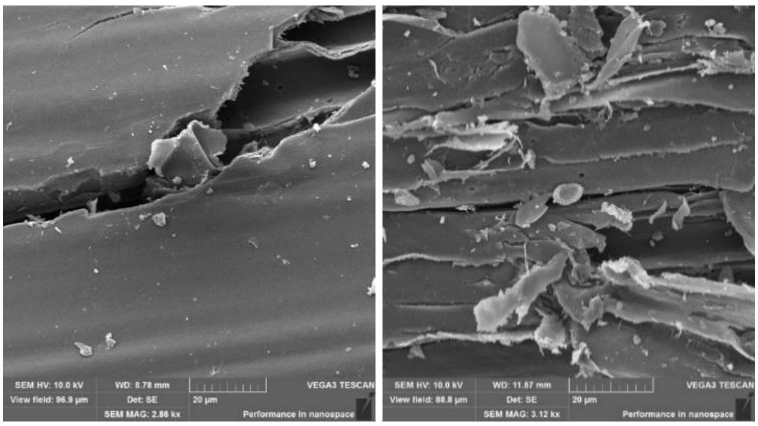
3. Results of the designed insulation materials laboratory testing

3.1 Pure Straw: physical, granulometric, and microstructural analysis

According to the initial characterization study, the physical and morphological properties of raw flax, hemp, and wheat straw were evaluated (*Table 4*). SEM imaging demonstrated that all straw types possessed a porous internal structure, vascular channels, and distinct external surface roughness, which are favourable for binder adhesion (*Figure 10*). Particle size analysis revealed that flax straw—after additional milling—exhibited the smallest average particle size (10.44 µm), facilitating enhanced surface area and interaction with binders (*Figure 11*).

Table 4: Characteristics of straw substrates for mycelium-based composite

Origin of straw	Bulk density, kg.m^{-3}	Fraction, mm	Coefficient of thermal conductivity, W.m^{-1}.K^{-1}
Wheat	90 – 110	10 – 25	0.045 – 0.050
Hemp	70 – 90	10 – 15	0.048 – 0.060
Flax	65 – 80	5 – 15	0.040 – 0.057



a) *b)*

Figure 10: Outside surfaces (a) and inside surfaces (b) of the straw fibers

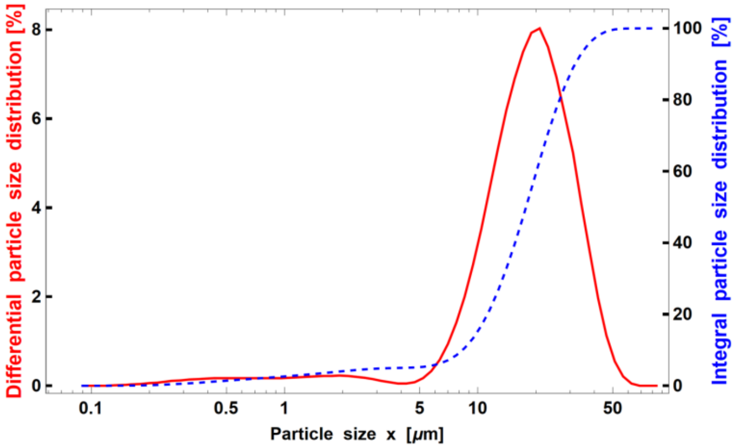


Figure 11: Shredded straw measurements of particularities size definition in wet environment mode (ANALYSETTE 22 NanoTec)

3.2 Flax and hemp straw composites (FSC and HSC): Mechanical, Physical, and Thermal Performance

Mechanical and thermal characterization of lightweight composites fabricated with flax and hemp straw using sodium silicate as a binder was carried out following EN 826 (1998) for compressive strength and ASTM D5334-08 for thermal conductivity (*Table 5*). Flax straw composites exhibited superior thermal insulation properties, achieving a conductivity value of 0.078 $W \cdot m^{-1} \cdot K^{-1}$ compared to 0.09 $W \cdot m^{-1} \cdot K^{-1}$ in hemp-based samples. Conversely, the hemp composite achieved marginally higher compressive strength (0.38 MPa versus 0.36 MPa). Differential thermogravimetry (DTG) and differential scanning calorimetry (DSC) revealed that flax-based composites decomposed at higher temperatures and exhibited more complex thermal transitions, indicating better thermal stability and energy release potential in end-of-life scenarios (*Table 6, Figure 12-13*). These findings affirm the thermal and mechanical competitiveness of straw-based composites relative to conventional insulation materials.

Table 5: Results of the mechanical and physical studies

Name of lightweight concrete sample	Average density of the material, kg/m^3	Thermal conductivity coefficient, W/(m·K)	Strength at 10% deformation, MPa	Moisture, %
HSC	300	0.09	0.38	38
FSC	250	0.078	0.36	41

Table 6: Temperature ranges of the degradation and corresponding mass losses (air atmosphere) of the straw-based lightweight concrete components

Sample	Temperature ranges for degradation of components				
	Peak 1, °C	Peak 2, °C	Peak 3, °C	Peak 4, °C	Total mass loss, %
HSC	–	103.0	277.9	–	46.94
FSC	70.0	108.1	278.9	807.4	53.08

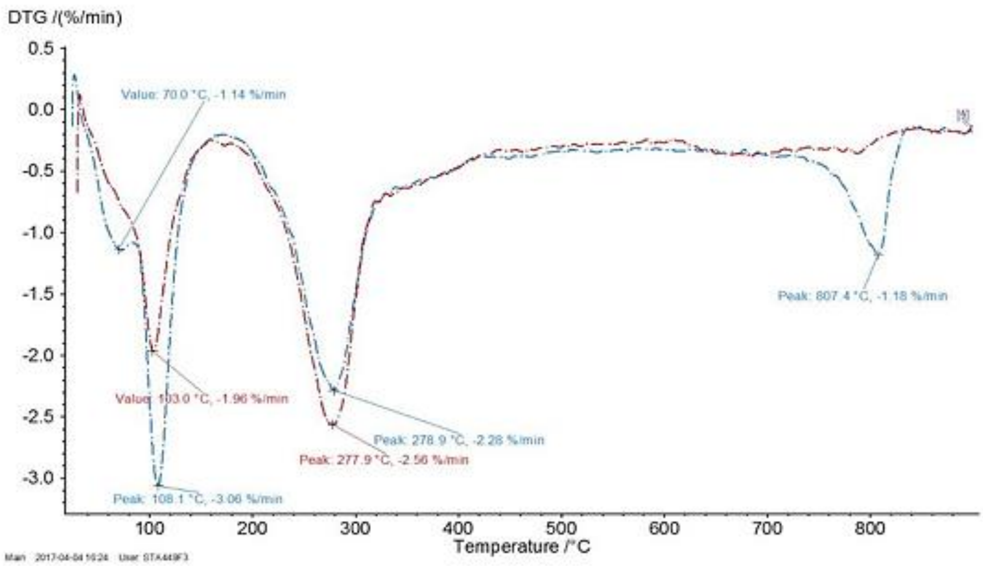


Figure 12: DTG curves for flax and hemp straw-based lightweight concretes: ■ - flax straw-based lightweight concrete; ■ - hemp straw-based lightweight concrete

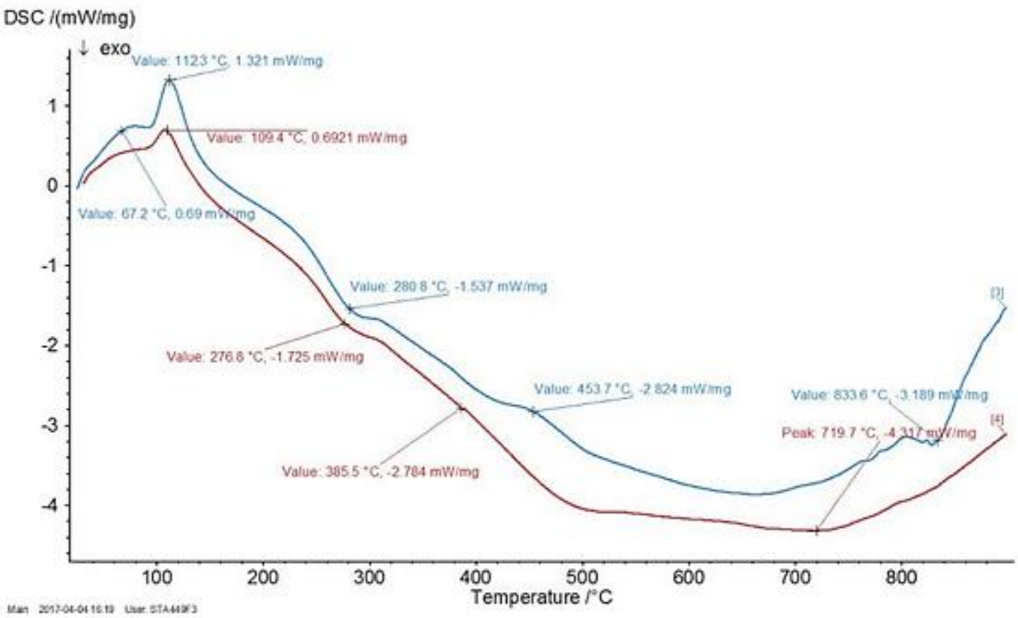


Figure 13: DSC curves of the flax and hemp samples: ■ - flax straw-based lightweight concrete; ■ - hemp straw-based lightweight concrete

3.3 Flax straw composite: compressive strength optimization via binder ratio adjustment

A targeted study was conducted to optimize the compressive strength of flax-sodium silicate composites by varying the flax-to-binder mass ratio. Seven sample series were tested under axial compression at 10% deformation. Results demonstrated that a 1:2.65 flax-to-sodium silicate ratio produced an optimal strength of 0.56 MPa and a corresponding density of 345 kg·m^{-3} *(Table 7)*. The compressive strength improved with increasing binder content, but gains diminished beyond this ratio, indicating an efficiency threshold. These outcomes suggest that binder optimization is a critical parameter for balancing mechanical performance and material economy in straw-based composite production.

Table 7: The range of testing samples of compositions based on flax straw fibers

Sample No.	**Flax straw, mass fraction**	**Liquid glass, mass fractions**	**Compressive strength at 10%-deformation (MPa)**	**Density (kg m^{-3})**
1	1	1.5	0.36	250
2		1.7	0.36	265
3		1.85	0.40	280
4		2.13	0.42	290
5		2.3	0.42	305
6		2.65	0.56	345
7		3	0.62	375

3.4 Flax Straw Composite: Hygrothermal Behavior Under Cyclic Humidity Conditions

Hygrothermal testing of flax-based samples was performed in a controlled climate chamber (BINDER KBF 240) following ISO 12571:2013, to simulate real-world fluctuations in ambient humidity. The moisture sorption behavior was evaluated under absorption and desorption cycles at 20%, 50%, 80%, and 95% relative humidity. The sorption isotherms demonstrated a low and stable moisture uptake, with values ranging from 0.003% to 0.52%, confirming dimensional and thermal stability under dynamic environmental conditions (*Table 8, Figure 14-15*). These results validate the hygrothermal reliability of flax straw composites for use in energy-efficient building envelopes.

Table 8: Parameters of samples for test

Composition/Sample		Width (mm)	Length (mm)	Thickness, (mm)	Mass after natural drying (g)	Mass after primary drying in climate chamber (g)	Density (kg m−3)
Flax straw insulation FSI Panel	P1	200	250	35	689.5	517.6	295.77
Flax straw insulation FSI Cube	A1	98	90	98	486.6	296.1	342.70
	A2				492.9	302.7	350.35
	A3				509.9	316.2	365.97

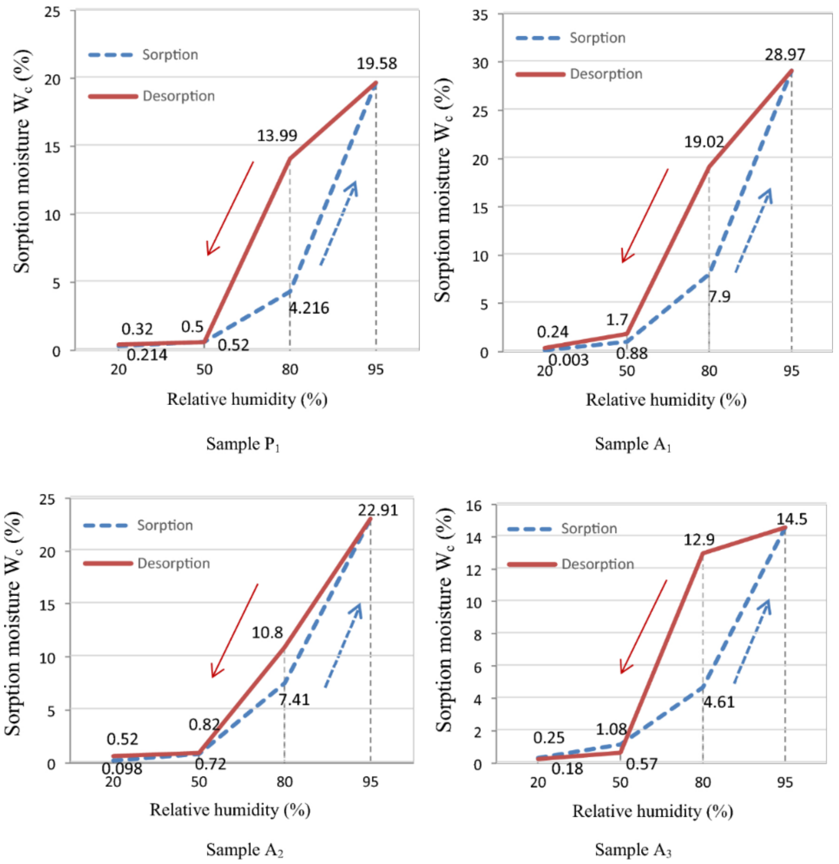


Figure 14: Sorption and desorption isotherms for samples (A_1, A_2, A_3 and P_1) at 20 °C

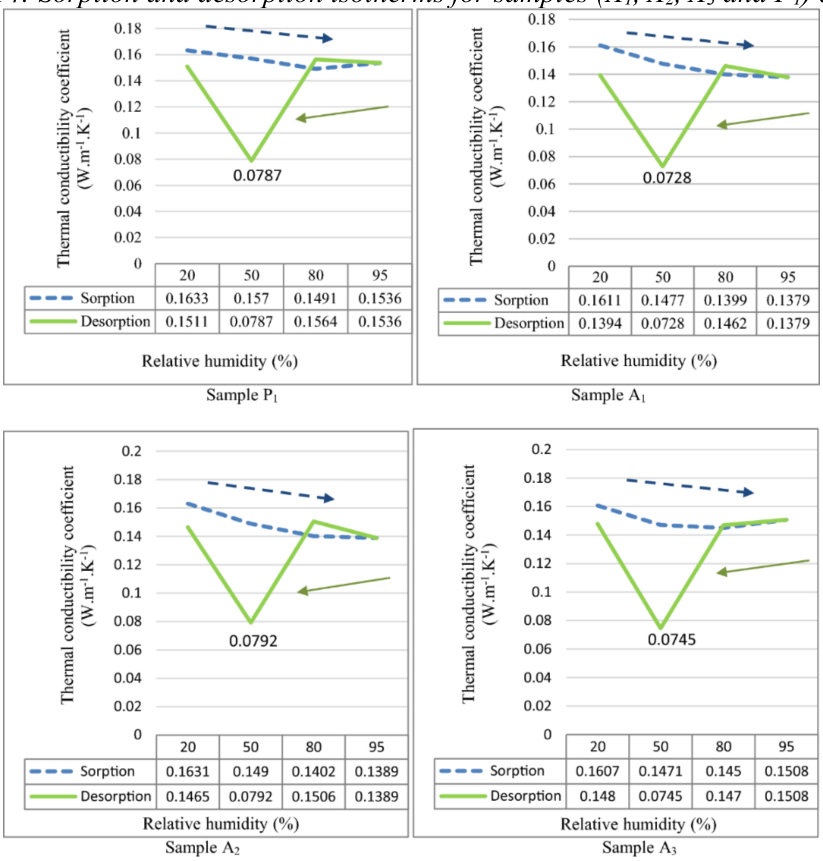
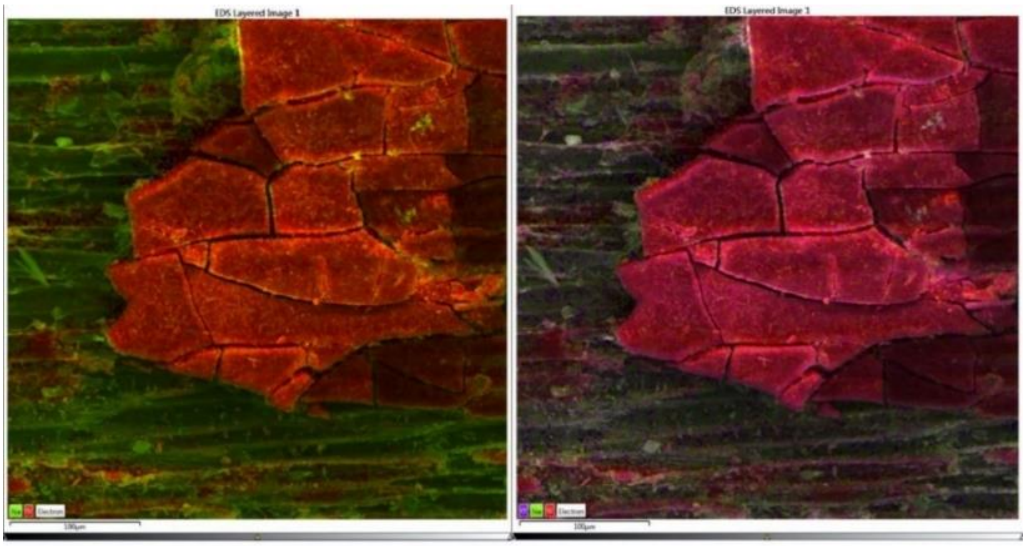


Figure 15: The thermal conductivity coefficient of samples (P_1, A_1, A_2 and A_3) at sorption and desorption

3.5 Flax Straw Composite: Surface Topography and Elemental Composition Analysis

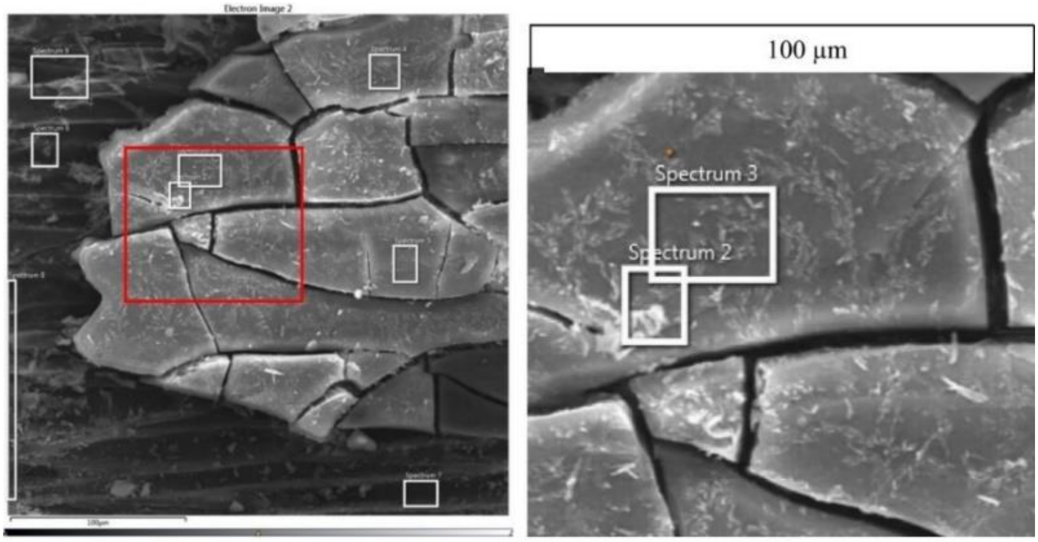
SEM and Energy-Dispersive X-ray Spectroscopy (EDS) were utilized to examine the integration of sodium silicate within the flax fiber matrix *(Figure 16-18)*. The analysis confirmed uniform binder dispersion and effective coverage on the fiber surface. The presence of silica and oxygen detected via EDS spectra supported the chemical bonding between the binder and the straw substrate. Surface topography analysis showed sufficient roughness and interfacial compatibility, contributing to improved mechanical resistance and water durability. These microstructural observations corroborate the material’s structural cohesion and long-term performance potential.



a) b)

*image a) Na - Albite (Na), Si - Silicon (SiO_2);
image b) Si - Silicon (SiO_2), Na - Albite (Na), O - Oxygen (O_2);

Figure 16: a, b Spectral illumination of chemical elements on the surface of the composite sample A_2



a) **b)**

Figure 17: a Scanned surface image by electronic microscope with 7 random squares for spectral analysis by EDS; b Enlarged scale of the material surface in the location of sectors 2 and 3

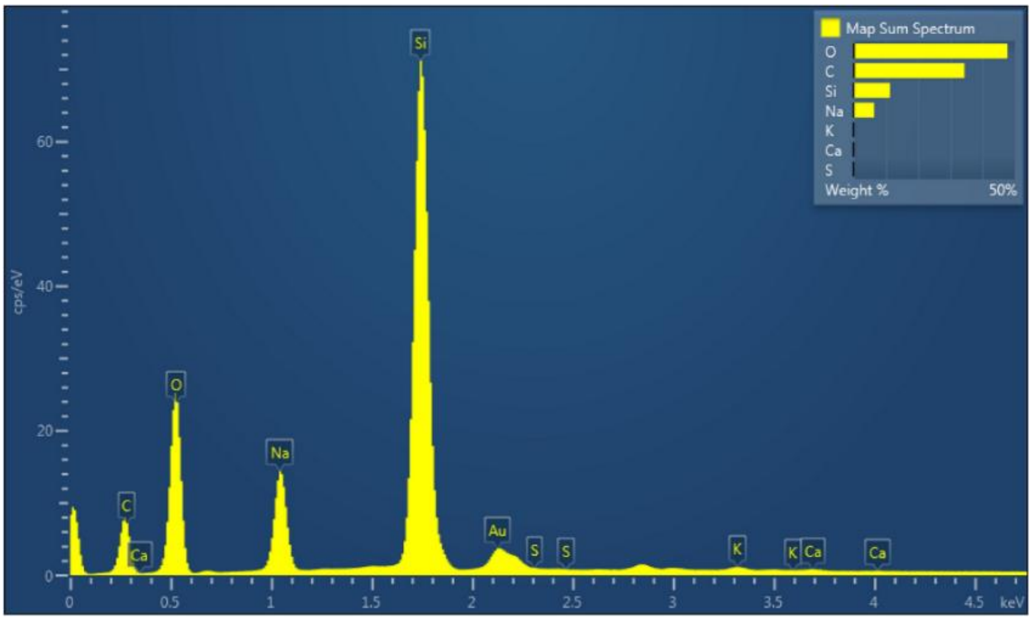


Figure 18: Map sum spectrum of chemical elements on a surface of studied composite based on BSE-analysis

3.6 Mycelium-Based Composites: Physical Properties and Microstructure

Composites formed by inoculating wheat, flax, and hemp straw substrates with fungal mycelium (Ganoderma lucidum) underwent thermal, mechanical, and density testing. The materials displayed thermal conductivity values between 0.045 and 0.056 $W \cdot m^{-1} \cdot K^{-1}$, with corresponding densities ranging from 107 to 220 $kg \cdot m^{-3}$, depending on the substrate (*Table 9*).

Table 9: Measured values of Thermal conductivity [$W \cdot m^{-1} \cdot K^{-1}$] and Density [$kg \cdot m^{-3}$] for 15 test samples at an ambient temperature of 20°.

Biocomposite, Sample No.	**Thermal Conductivity, λ [$W \cdot m^{-1} \cdot K^{-1}$]**	**Density, ρ [$kg \cdot m^{-3}$]**
Flax + Mycelium, 1	0.045	158
Flax + Mycelium, 2	0.046	220
Flax + Mycelium, 3	0.047	146
Flax + Mycelium, 4	0.045	155
Flax + Mycelium, 5	0.045	169
Hemp + Mycelium, 1	0.047	227
Hemp + Mycelium, 2	0.045	156
Hemp + Mycelium, 3	0.046	119
Hemp + Mycelium, 4	0.046	138
Hemp + Mycelium, 5	0.050	219
Wheat + Mycelium, 1	0.043	137
Wheat + Mycelium, 2	0.043	107
Wheat + Mycelium, 3	0.056	142
Wheat + Mycelium, 4	0.054	156
Wheat + Mycelium, 5	0.045	150

The wheat-based mycelium composites achieved the highest thermal conductivity-to-weight ratio (0.148 $W^{-1} \cdot kg^{-1} \cdot m^{4} \cdot K$), indicating optimal insulation efficiency per unit mass *(Figure 19)*. SEM images revealed dense hyphal colonization across all substrates, forming an interconnected matrix that enhances mechanical stability and bioresistance. The results affirm that mycelium-bound composites are promising candidates for low-impact, biodegradable insulation materials *(Figure 20)*.

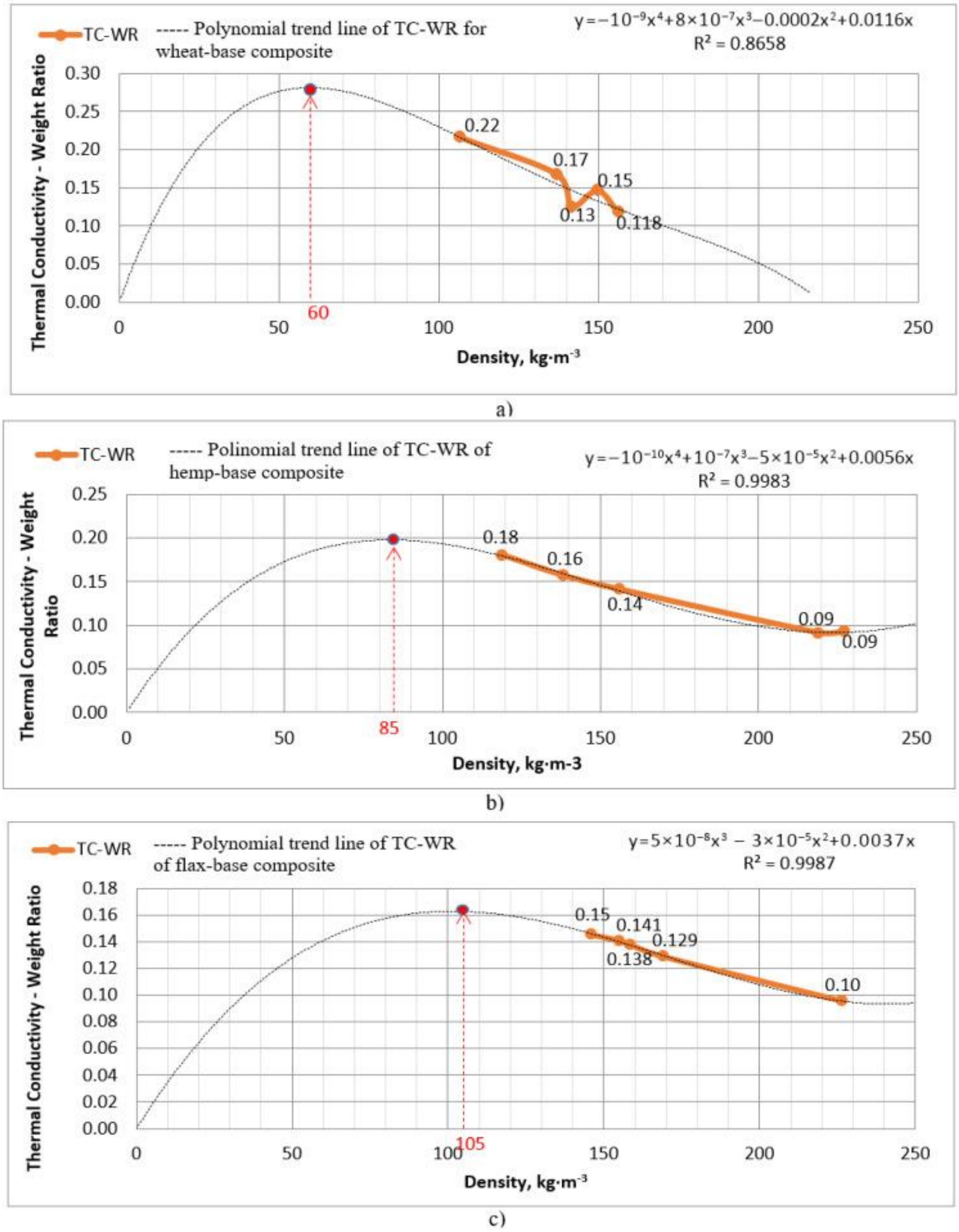


Figure 19: TC-WR values for measured types of biomass samples (orange line) and polynomial trend lines of TC-WR for density range of 0–250 (kg·m^{-3}) with the approximation reliability values (R^2) between 0.865 and 0.998 and O*-density point for wheat (**a**), hemp (**b**) and flax (**c**) straw composites with mycelium binder*

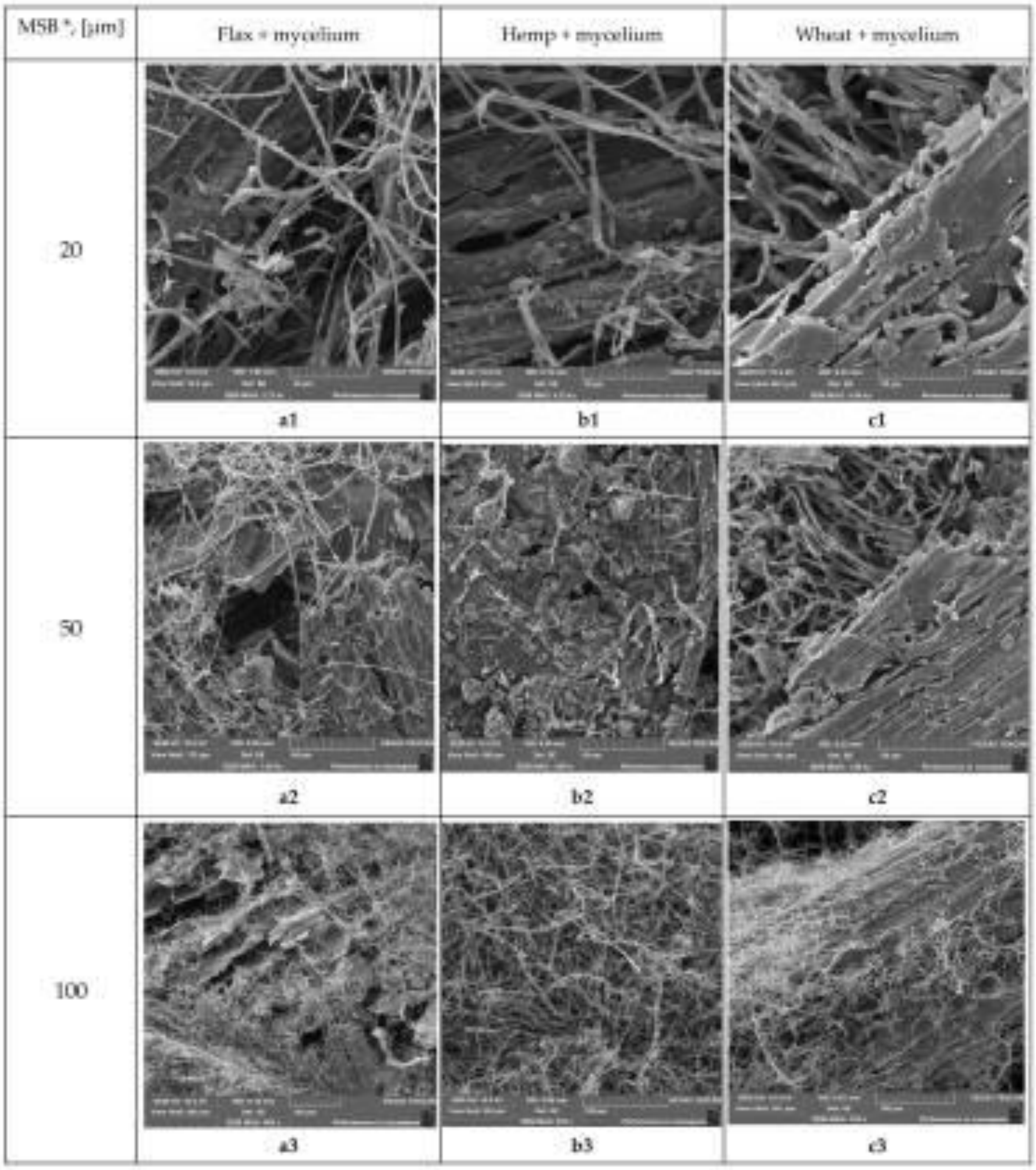


*Figure 20: Scanning electron microscopic images of biomass–micelium composites obtained in this study: The surfaces of straw-micelium composites produced from Ganoderma lucidum mycelium with flax straw (**a1–a3**), hemp straw (**b1–b3**) and with wheat straw (**c1–c3**). Legend: MSB *—Magnification scale bar*

4. Life Cycle Assessment of mycellium-based composite

4.1 Methodology for Life Cycle Assessment at the material level

The approach complies with ISO 14040 and ISO 14044 standards, applying both cradle-to-gate and cradle-to-grave boundaries. The assessment integrates primary experimental data from laboratory-scale manufacturing with secondary data sourced from established life cycle inventory databases. The aim is to quantify key environmental impacts, including carbon emissions and primary energy demand.

4.1.1 Data Collection

Material-specific life cycle inventory data were compiled based on empirical measurements of input materials, energy consumption, and yield rates during the fabrication of bio-based composites. Complementary secondary data were obtained from the Ecoinvent database to fill data gaps and ensure system completeness. All data were structured and normalized according to defined functional units and system boundaries. This comprehensive dataset served as the foundation for environmental modeling in subsequent assessment stages.

4.1.2 Environmental Assessment

Environmental impact calculations focused on global warming potential (GWP), embodied energy, and CO_2-equivalent emissions. Mycelium-based composites exhibited negative cradle-to-gate carbon balances, with values ranging from −244 to −298 kg CO_2/m^3, attributed to carbon sequestration in the fungal biomass. Composites incorporating sodium silicate as a binder showed up to 40% lower GWP compared to conventional insulation benchmarks. The findings confirm the effectiveness of agricultural waste-based materials in reducing the environmental burden of construction components.

4.1.3 Multicriteria Analysis

A multicriteria evaluation was performed using Simple Additive Weighting (SAW) and Multiplicative Exponential Weighting (MEW) to integrate environmental and technical performance indicators. Parameters considered included thermal conductivity, material density, mechanical strength, and GWP (*Figure 21*).

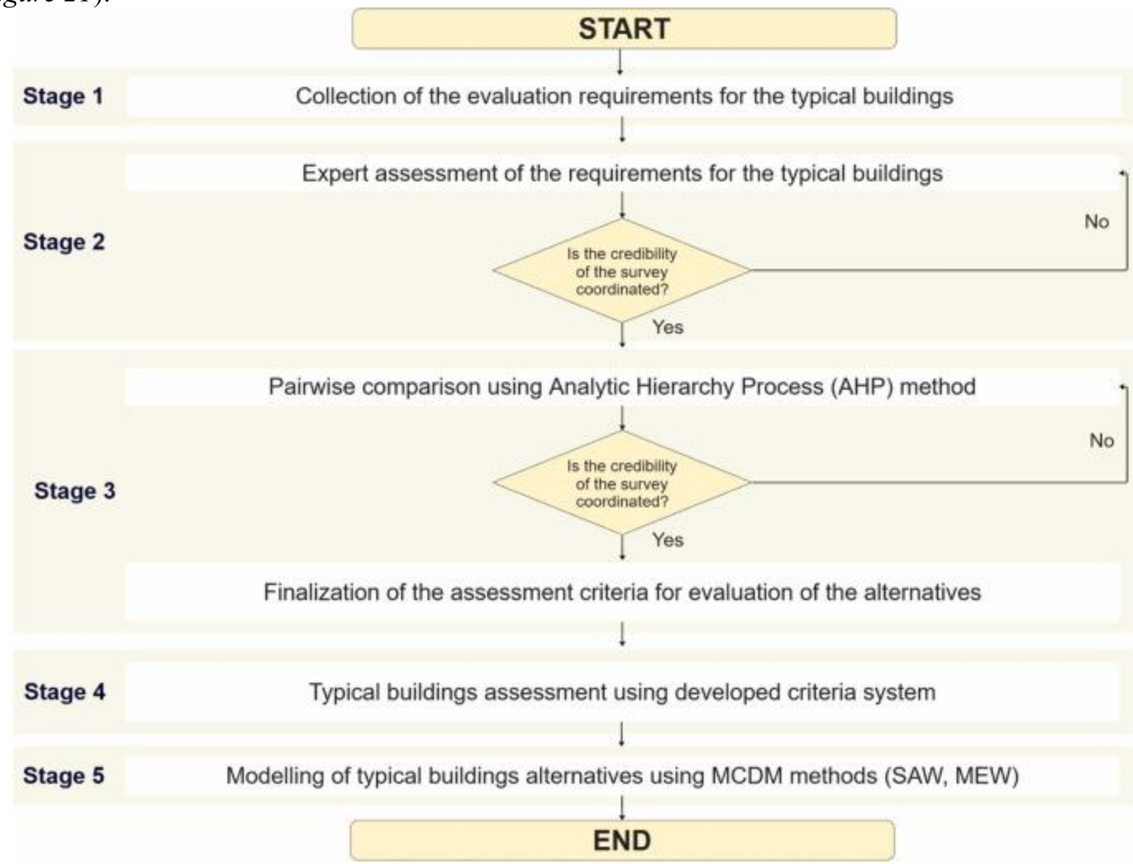


Figure 21: Flowchart for the implementation of the Stages of the Evaluation Criteria Framework for Thermal Insulation Materials for Typical Buildings

4.2 Environmental Assessment Results at the material level

The main steps included in the study's process chain are depicted in the schematic design shown in *Figure 22*. The plantation, growth, and baking phases are all included in these phases. Option A and Option B, two investigations on the cultivation process, were carried out. Option A was carried out under normal room settings without a climate chamber, but Option B used one for growth. Both the material and building stages of an LCA were used in the environmental evaluation. Using a cradle-to-gate methodology, the analysis adhered to ISO 14040 and made use of the Gabi program *(GaBi)*. *Table 10* provides the Life Cycle Inventory data used for the LCA implementation.

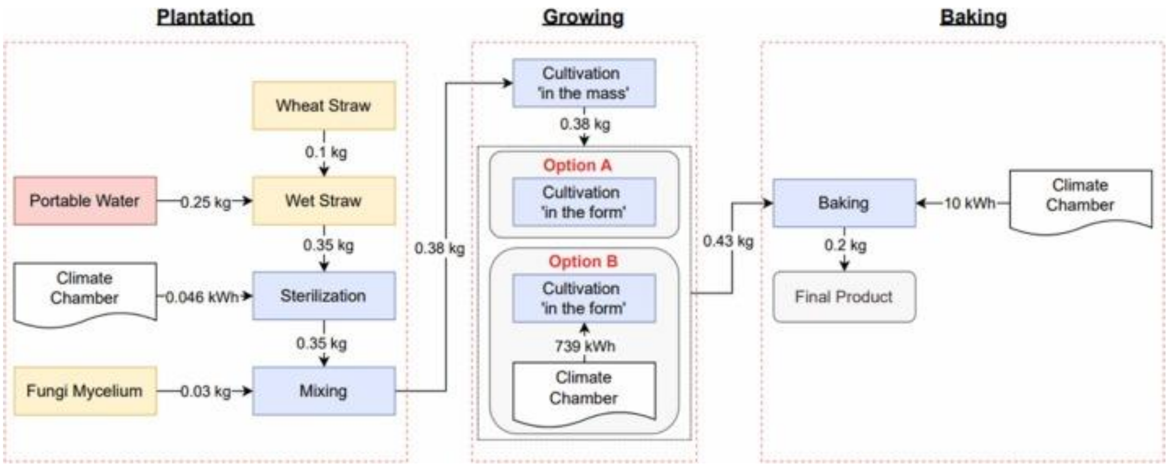


Figure 22: LCA system under standard room conditions (Option A) and with the climate chamber (Option B).

Table 10: Life Cycle Inventory

Process & Materials	Value	Units
Wheat Straw	0.1	kg
Portable Water	0.25	kg
Fungi Mycelium	0.03	kg
Climate Chamber-Sterilization	0.046	kWh
Climate Chamber-Cultivation (V1)	1109	kWh
Climate Chamber-Cultivation (V2)	0	kWh
Climate Chamber-Baking	10	kWh

The LCA results for the chosen impact categories for the two processes of creating 0.2 kg of MBC are compiled in *Table 11 Table 12* lists the main important contaminants found during the process *(M.Babenko, et al., 2025)*.

Table 11: Environmental Impact Comparison of Climate Chamber and Standard Room Conditions

Impact Category	Climate Chamber	Standard Room Conditions
GWP (kg CO_2-Equiv.)	886	7.75
AP (Mole of H+-Equiv.)	258	0.0122
ODP (kg R11-Equiv.)	$4.39.10^{-11}$	3.93E−13
ADP elements (kg Sb-Equiv.)	$9.90.10^{-5}$	4.07E−09
ADP fossil (MJ)	$1.10E.10^{4}$	0.451
POCP (kg Ethene-Equiv.)	0.288	1.18E−05
EP (kg Phosphate eq.)	0.218	8.97E−06
FAETP inf. (kg DCB-Equiv.)	8.16	0.000335
HTP inf. (kg DCB-Equiv.)	91.3	0.00375

Table 12: Inputs and Outputs Comparison between Climate Chamber and Room Conditions

Empty Cell	Climate chamber	Room conditions
Inputs	Kg	kg
Wheat Straw	0.1	0.1
Portable Water	0.25	0.25
Fungi Mycelium	0.03	0.03
Non-renewable energy resources	259	2.33
Material resources in total	$8.03.10^{4}$	$7.21.10^{2}$
Non-renewable elements	0.351	0.00315
Non-renewable resources	21	0.188
Outputs		
Final Product	0.2	0.2
Emissions		
Emissions to air	8290	74.4
Inorganic emissions to air	4540	40.8
Carbon monoxide (CO)	0.291	0.00261
Carbon dioxide (CO_2)	863	7.75
Nitrogen oxides (NOx)	1.36	0.0122
Nitrogen monoxide	$1.31.10^{-3}$	$1.17.10^{-5}$
Sulphur dioxide (SO_2)	3.98	0.0357
Water (evapotranspiration)	$1.93.10^{3}$	$1.73.10^{1}$
Water vapour	$1.73.10^{3}$	$1.55.10^{1}$
Particles to air (kg)	0.146	0.00131
Dust (> PM10)	0.0464	0.000416
Dust (PM2.5 – PM10)	0.0356	0.000319
Dust (PM2.5)	0.0645	0.000579
Emissions to fresh water	$7.28.10^{4}$	$6.53.10^{2}$
Inorganic emissions to fresh water	24.7	0.222
Chloride	23.7	0.213
Particles to fresh water	1.36	0.0122
Radioactive emissions to fresh water	303	2.72
Emissions to sea water	$1.16.10^{2}$	1.04
Inorganic emissions to sea water	3.64	0.0327
Particles to sea water	0.0682	0.000613
Emissions to agricultural soil	−0.000189	$-1.69.10^{-6}$
Inorganic emissions to agricultural soi	$1.31.10^{-1}$	$1.17.10^{-12}$
Emissions to industrial soil	0.000714	$6.41.10^{-6}$

Table 12 provides a summary of the LCA findings for the two processes used to produce 0.2 kg of MBC. In every category, the climate chamber approach showed noticeably greater environmental effects than the conventional room conditions approach. For example, the GWP for the climate chamber approach was 886 kg CO_2-equivalent, but the GWP for typical room settings was just 7.75 kg CO_2-equivalent. Likewise, the climate chamber approach had much higher values for AP, ODP, ADP, POCP, EP, FAETP, and HTP. The climate chamber approach used much more energy, especially for the sanitation and culture procedures, according to the life cycle inventory data (Table 17). The total non-renewable energy resources consumed for the climate chamber method were 259 kg, compared to 2.33 kg for the standard room conditions. Additionally, the emissions data highlight that the climate chamber method resulted in higher emissions to air, fresh water, and sea water. For example, CO_2 emissions for the climate chamber method were 863 kg, while only 7.75 kg for the standard room conditions *(M.Babenko, et al., 2025)*.

4.3 Multicriteria Analysis Results

Results from both SAW and MEW methods identified wheat- and flax-based mycelium composites as the top-performing materials when assessed across environmental, thermal, and structural metrics. The analysis indicated that reliance on singular environmental indicators may be insufficient, and that optimal material selection requires a balance of ecological and functional criteria. The multicriteria framework employed provides a replicable decision-support tool for material evaluation in the context of low-emission construction strategies.

Table 13 displays the criteria weights that were determined by expert reviews *(M.Babenko, et al., 2025)*.

Table 13: Criteria weights

Criterion	Weight
Environmental Impact	0.016
Economic Cost	0.049
Durability	0.088
Resource Availability	0.053
Thermal Conductivity	0.039
Health and Safety	0.039
Technical Performance	0.116
Aesthetic Quality	0.205
Ease of Installation and Use	0.252

The performance of the substitutes, rock and glass mineral wool and mycelium-based straw, was evaluated using the predetermined standards. Both the SAW and MEW methods' summarized results are shown in Tables 14 and 15, while the Appendices contain the full data *(M.Babenko, et al., 2025)*.

Table 14: Results for SAW method

Alternative	SAW Score	SAW Rank
1.Mycelium-Based Straw	0.9465	1
2.Rock and Glass Mineral Wool	0.9312	2

Table 15: Results for MEW method

Alternative	MEW Score	MEW Rank
1.Mycelium-Based Straw	0.9326	1
2.Rock and Glass Mineral Wool	0.8994	2

The findings, which are compiled in *Table 15*, show that in both the SAW and MEW procedures, mycelium-based straw performed better than rock and glass mineral wool. In particular, mycelium-based straw was ranked first by the SAW technique, which produced scores of 0.9465 and 0.9312 for mycelium-containing straw and rock and glass mineral wool, respectively. Similarly, mycelium-based straw was ranked as the better option by the MEW method, which yielded scores of 0.9326 for it and 0.8994 for rock and glass mineral wool. *(M.Babenko, et al., 2025)*.

5. LCA of Building Design Concept with Zero Pollution Materials

5.1 Environmental Assessment Methodology for the building scale with One Click LCA tool

The building-level life cycle assessment was conducted in accordance with EN 15978, using the One Click LCA platform to evaluate environmental impacts across stages A1–A3 (product stage), B6 (operational energy), and C1–C4 (end-of-life). Scenarios were modeled for buildings using traditional insulation (mineral wool, EPS) and for alternatives using mycelium- and straw-based composites. Functional equivalence was ensured through matched thermal performance and service life assumptions. All emissions were normalized per m² of usable floor area over a 50-year reference period.

5.2 Life Cycle Assessment Results of the building model

The environmental impact analysis revealed substantial reductions in carbon emissions for the building scenarios utilizing bio-based insulation. Buildings incorporating mycelium composites achieved up to 65% lower embodied carbon in stages A1–A3 compared to the EPS baseline. Substitution of synthetic insulation with flax-straw composites also yielded reductions of approximately 45%. The greatest environmental savings were observed in GWP and non-renewable primary energy demand, confirming the efficacy of the material substitution strategy in mitigating climate impacts *(Kudryk, Y., & Babenko, M., 2025)*.

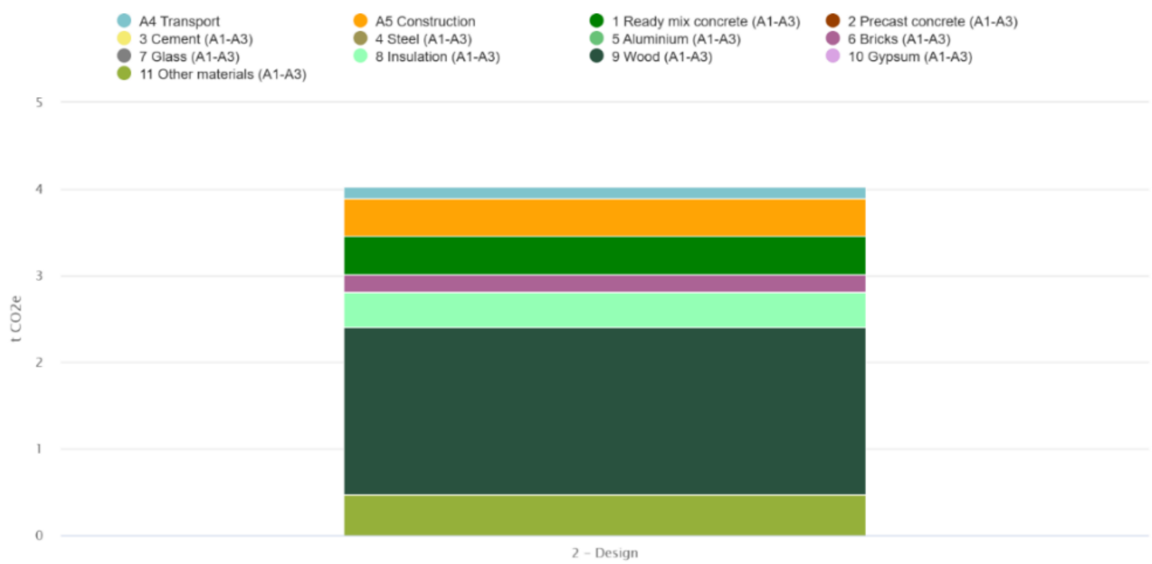


Figure 23: Global Warming Potential by material categories and life cycle stages

6. Conclusions

This dissertation explored the feasibility of utilizing agricultural waste—specifically straw from wheat, hemp, and flax—as raw materials for sustainable insulation composites. The laboratory testing and life cycle assessments confirmed that this agricultural waste can be transformed into high-performance insulation materials suitable for eco-conscious construction practices. The composites developed from these straws demonstrated thermal conductivity values ranging from 0.043 to 0.056 $W \cdot m^{-1} \cdot K^{-1}$ and densities between 107 and 220 $kg \cdot m^{-3}$. These values are comparable to those of conventional insulation materials such as mineral wool and cellulose fiber, placing them among the viable bio-based alternatives. Notably, the wheat and mycelium composite achieved the highest thermal conductivity-to-weight ratio (TC-WR) among the studied organic materials at 0.148 $W^{-1} \cdot kg^{-1} \cdot m^4 \cdot K$, making it the most efficient bio-based insulator in terms of thermal performance per weight.

Among the straw-based composites, flax straw-based concrete (FSC) offered the best balance of thermal and hygroscopic performance. It achieved a thermal conductivity of 0.078 $W \cdot m^{-1} \cdot K^{-1}$, a compressive strength of 0.36 MPa, and a moisture content of 41%. When optimized using a flax-to-liquid sodium silicate ratio of 1:2.65, the compressive strength increased to 0.56 MPa while the density rose to 345 $kg \cdot m^{-3}$. A panel sample prepared with a 1:2 ratio showed a density of 296 $kg \cdot m^{-3}$ and maintained thermal conductivity around 0.14 $W \cdot m^{-1} \cdot K^{-1}$ under high humidity (80–95%), confirming its strong hygrothermal performance. The findings suggest that flax straw composites are especially suitable for insulating applications in variable climate conditions.

The use of fungal mycelium as a bio-binder proved highly effective. Composites inoculated with Ganoderma lucidum and Trametes versicolor fungi exhibited thermal conductivity in the range of 0.045 to 0.050 $W \cdot m^{-1} \cdot K^{-1}$ and densities between 119 and 227 $kg \cdot m^{-3}$. For example, the flax + mycelium composites had an average conductivity of 0.046 $W \cdot m^{-1} \cdot K^{-1}$ and density of 171 $kg \cdot m^{-3}$. The wheat + mycelium samples performed particularly well, achieving the highest TC-WR of 0.148 among all agricultural mycelium-based composites. These developed mycelium bio composites also showed excellent environmental performance, with estimated carbon footprints ranging from −244 to −298 kg CO_2/m^3, positioning them as truly carbon-negative materials.

The Life cycle assessment indicated that proposed mycelium composites significantly reduce environmental impacts at both material and building scales. Embodied energy and greenhouse gas emissions were reduced by up to 40% compared to standard mineral wool-based insulation. At the material level, life-cycle emissions of the proposed bio composites were found to be at least 35% lower than conventional options.

7. Suggestions for further research

While this research provides a comprehensive foundation for the development of bio-based insulation composites from agricultural waste, several areas remain open for future exploration:

1. Long-Term Durability and Aging Studies: Further investigation is needed into the long-term behavior of the developed composites, especially under varying environmental conditions such as freeze-thaw cycles, UV exposure, and biological degradation over time.
2. Fire Resistance and Safety Certification: Given the organic nature of the materials, detailed fire performance assessments must be conducted, including reaction-to-fire classification (EN 13501-1), to ensure regulatory compliance, especially for multi-story applications.
3. Acoustic and Air Quality Performance: While the thermal properties have been well-documented, further research should evaluate the acoustic absorption coefficients and impact on indoor air quality (IAQ), especially VOC emissions from fungal-treated materials.
4. Industrial Scalability and Processing Methods: Future studies should explore automation and industrial-scale manufacturing techniques, including low-energy curing, panel molding, and robotic assembly for prefabricated eco-panels.
5. Digital Design Integration: Advanced digital tools such as Building Information Modelling (BIM) and parametric optimization could be applied to integrate these materials into circular construction workflows and optimize their use in zero-emission building designs.

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