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Environmental assessment of mycelium based straw insulation composite: A sustainability analysis at building material level

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ABSTRACT

The construction industry is increasingly adopting sustainable materials to mitigate environmental impacts. This study evaluates the environmental performance of Mycelium-Based Straw Insulation Composite (MBSIC), an innovative material combining mycelium and agricultural waste to create a biodegradable, lightweight, and thermally efficient insulation alternative. A Life Cycle Assessment (LCA), following ISO 14040 standards, examines the environmental impacts of MBSIC from raw material extraction to transportation, identifying opportunities for sustainability optimization. Additionally, a Multi-Criteria Analysis (MCA) compares MBSIC with conventional insulation materials based on cost, durability, and aesthetics. The methodology involves a cradle-to-gate LCA approach, assessing greenhouse gas emissions, resource consumption, and environmental impact categories such as global warming potential, acidification, and human toxicity. Two production scenarios—standard room conditions and climate chamber cultivation—are analyzed to determine their respective environmental implications. MCA integrates expert evaluations using Simple Additive Weighting (SAW) and Multiplicative Exponential Weighting (MEW) methods to assess MBSIC's comparative performance. Results indicate that MBSIC produced under standard room conditions significantly reduces greenhouse gas emissions and resource consumption compared to climate chamber cultivation. MCA findings demonstrate that MBSIC outperforms traditional insulation materials, such as rock and glass mineral wool, in key sustainability metrics. The study underscores MBSIC's potential for integration into sustainable construction practices, offering valuable insights for policymakers, industry stakeholders, and researchers.

1. Introduction

The use of biobased building materials responds to a complex set of challenges and opportunities in the construction industry. These materials are driven by a holistic understanding of sustainability, encompassing environmental, economic, and societal dimensions [29]. At its core, this shift towards biobased materials addresses environmental stewardship. Conventional construction materials, such as concrete and steel, are associated with substantial carbon emissions and resource depletion [7]. In response, biobased materials, including those made from recycled or low-impact sources, emerge as viable options to mitigate these environmental

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impacts and reduce the construction sector's carbon footprint [23]. Resource conservation is dominant in an era of population growth and resource scarcity. Biobased materials often draw from abundant or recycled resources, alleviating the strain on finite resources like timber and minerals [24]. This conservation effort aligns with the imperative for long-term sustainability. The energy efficiency of buildings is a key consideration, given the pressing need to reduce energy consumption and greenhouse gas emissions. Biobased materials, particularly those with superior insulation properties, contribute to improved energy efficiency, reducing operational costs and environmental harm. Waste reduction is another significant advantage offered by biobased materials [36]. Their production generates less waste, and they are often recyclable, addressing concerns related to landfill waste and overall ecological impact.

Local sourcing of biobased materials contributes to energy savings and supports local economies, fostering sustainability on multiple fronts. Innovation and resilience are integral to biobased materials, as ongoing advancements in materials science lead to improved performance, durability, and sustainability attributes [27]. Compliance with stringent building codes, environmental regulations, and consumer preferences for sustainable construction is facilitated by the adoption of biobased materials. Improved indoor air quality and health considerations also drive the use of certain biobased materials, which emit fewer harmful compounds [1]. The freedom of design and aesthetic possibilities provided by biobased materials encourages creativity and innovation in construction practices. Finally, biobased materials are instrumental in the preservation of cultural heritage, as they can be more compatible with historical contexts and traditional construction methods [3].

Insulation materials play a crucial role in enhancing energy efficiency and reducing the environmental footprint of buildings. Traditional insulation options, such as mineral wool and synthetic foams, often involve high embodied energy and generate non-biodegradable waste. As the demand for sustainable construction grows, biobased insulation materials present an opportunity to improve building performance while minimizing environmental impact. Mycelium Based Straw Insulation Composites (MBSIC) represent an innovative and sustainable approach to building insulation. They combine pure fungal mycelium, the root structure of fungi, with straw or agricultural waste materials to create a biodegradable, lightweight, and thermally efficient insulation material. These composites have garnered attention for their eco-friendliness, as they are renewable, require minimal energy during production, and can be easily composted at the end of their life cycle. Mycelium-based insulation also possesses fire-resistant and pest-resistant properties, making it a versatile option for green building practices. Its potential to reduce carbon emissions, conserve resources, and enhance energy efficiency positions it as a promising solution for environmentally conscious construction.

The primary objective of this study is to conduct a comprehensive environmental assessment of MBSIC. The study seeks to answer the question of the environmental impact of MBSIC, while also exploring opportunities for optimizing its sustainability in comparison to other building materials. The study aims to perform a Life Cycle Assessment (LCA) using ISO 14040 standards, focusing on the raw materials, manufacturing process, and transportation of MBSIC to identify areas for reducing environmental impact. The study also utilized parametric assessment techniques to optimize the sustainability of the material by exploring various production processes, with the goal of improving its overall environmental performance. At the whole building level, the study intends to assess the environmental impact of using MBSIC compared to other building materials using Multi-Criteria Analysis (MCA).

2. Theoretical background

Due to its superior thermal performance and biodegradability, fungal mycelium is a desirable alternative for producing a biocomposite. Thermal insulation materials made of lignocellulosic base injected with fungal mycelium, which are lightweight and environmentally friendly materials, are considered as potential replacements for synthetic and petroleum-derived foams. Jones, Reed [21] The composite, which is produced from organic substrate and fungal mycelium, has no emissions and is also affordable and recyclable. The management of by-products, the storage of carbon dioxide from the atmosphere, the reduction of the need for petrochemicals in manufactured materials, and recyclability, in addition to appealing aesthetic qualities, are the main justifications for employing mycelium-based bio composites. Sydor et al. [34]

Recent studies have revealed that mycelium containing composites exhibit low thermal conductivity, ranging from 0.043 to 0.056 $W \cdot m^{-1} \cdot K^{-1}$, which positions them among the lowest values recorded for biodegradable insulation materials [5]. Additionally, these thermal conductivity values are considerably lower than those of similar lignocellulosic biomass materials that incorporate inorganic binders, such as liquid glass Na2O(SiO2), which has a minimum recorded thermal conductivity of 0.0728 $W \cdot m^{-1} \cdot K^{-1}$ [6]. Dias et al. [9,26] MBC is mostly used for packing, thermal insulation, and various furniture types. Considering their great porosity and minimal rigidity, the mycelium-composite bricks and panels are frequently classed as insulating foams. Girometta et al., [17]

The kind of substrate and strain, the length of the incubation period, and the production procedure are all variables that affect the physicochemical properties of the composite. Alemu et al. [2] The study [11] showed that the selection of fibre has an impact on both the growth of mycelium-based composites and their mechanical characteristics. The condition of the fibre—loose, chopped, tow, or pre-compressed—has a greater impact on compressive strength than the fibre type (hemp, flax, wood, or flax waste).

The most common fibres which are considered as base substrates for mycelium containing insulating composites are analysed and

Table 1
Characteristics of available organic fibers used as a substrate for mycelium-based insulations Babenko et.al. [4,5], Cerny et.al. [6].

Material	Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	Density ($kg \cdot m^{-3}$)	Porosity, %	Cellulose, %	Lignin, %	Granulometric size, mm
Hemp	0.0544–0.0594	330	88	70–76	2–5	20–35
Flax	0.085	310–340	85	73–76	2–5	2–15
Wheat	0.05–0.065	30–100	89	28–39	15	20–40

represented in Table 1.

To create MBSIC, it is crucial to choose the right fungus species. Fast mycelial growth to bind the substrate is desirable, while rapid substrate breakdown rates are less desirable (and may potentially weaken the blocks) when selecting suitable fungi. It is also preferred that the substrate blocks' edges and centres exhibit uniform growth. The rate of degradation of straw, the primary kind of biomass residuals, must also be considered while choosing fungus species. It is appropriate for straw or another lignocellulosic substrate to quickly colonize. However, severe substrate degradation could result in the straw block's weakening. Xing et al. [35]

A growth of fungal mycelium can be impacted by a number of essential variables, including temperature and humidity. Fungal mycelium should continue to grow in an atmosphere with an appropriate high level of humidity, with the ideal temperature being between 18 and 24 °C. Hoa, Wang [18]. Different mycelium containing bio-composites with various functionalities will be produced by various fabrication techniques. The most popular approach is oven drying, which removes all remaining water from the substrate and pure mycelium and creating foams that are light and strong. Yang et al. [37]. For further study, raw material of flax, wheat and hemp samples were prepared (Fig. 1).

The studied references propose various combination of substrate and fungi species to grow and fabricate the mycelium based insulation materials. The proceeded analyse is represented in the Table 2.

MBSIC has not yet been the subject of detailed studies on environmental effects, including LCA. Therefore, the current study's objective is to ascertain any potential environmental effects associated with the development of the suggested composites based on three types of lignocellulosic biomass (wheat, hemp, and flax) and Ganoderma lucidum mycelium (Reishi fungi) at all stages of fabrication (plantation, growing, baking). Babenko et al. [5] developed mycelium-containing composites through a two-stage growth process. First, fungal mycelium is cultivated in a straw pile for one week using a small bulk substrate in a ventilated polyethylene bag. In the second stage, the composite is pressed into cylindrical molds made of removable cardboard wrapped in polyethylene, with ventilation holes, over two weeks, totaling 21 days of growth. The cardboard, 3 mm thick and 1890 g·m^{-2} dense, allows vapor and air permeability. Both stages occur in a climate chamber at 16–17 °C and 70–80 % humidity. After growth, samples are dried for 24 hours at 60 °C and 50 % humidity, resulting in cylindrical samples (96 mm diameter, 65 mm height) using pure fungal mycelium as a binder with various substrate fillers like chopped wheat, hemp, and flax straw (Fig. 2).

3. Methodology

The research design for this study was primarily focused on conducting a comprehensive environmental assessment of MBSIC. The research employed a mixed-methods approach, combining quantitative and qualitative data to achieve a holistic understanding of MBSIC's environmental impact and sustainability optimization potential.

3.1. Data collection

Data collection in this study was multifaceted, involving both primary and secondary sources. For the LCA, primary data were collected through direct measurements and surveys conducted in the MBSIC research field. The data collection process included the use of energy meters to monitor electricity usage during manufacturing stages and environmental sensors to assess greenhouse gas emissions. Structured questionnaires were administered to practitioners in sustainable construction to gather insights on material performance and production challenges.

Secondary data sources comprised established databases, including Ecoinvent and GaBi, for inventory data related to materials and energy use. Data analysis for the LCA was conducted using Gabi software [33], a specialized tool for LCA. Quantitative analysis included calculations of environmental impact indicators, such as carbon emissions, energy consumption, and resource use, to provide a comprehensive assessment of MBSIC's environmental footprint.

For the parametric assessment of production processes, qualitative data were collected through thematic surveys with experts in sustainable construction materials. These experts contributed specialized knowledge in areas such as sustainable building materials, environmental impact assessment, multicriteria analysis, regulatory compliance, material applicability, thermal efficiency, durability, and organic certification. The analysis involved thematic coding of qualitative data to identify key themes and patterns related to production process optimization.

Fig. 1. F: flax, H: hemp, S: wheat samples of pure straw.

Table 2
Review of the fungi growth conditions for production of mycelium-based straw insulation.

Substrate	Fungi	Substrat sterilization	Incubation	Drying	Field of Application	Reference
Flax dust, long flax fibers, wheat straw, hemp fibers, and shavings from pine wood	Trametes versicolor (M9912–5LSR−2 O447A)	Autoclaved at 121 °C for 20 min.	28°C for 16 days	70 °C for 5–10 hours	Thermal insulation	[11]
Wheat straw	Oxyporus latemarginatus, Megasporoporia minor, Ganoderma resinaceum	Autoclaving, 115 °C, 15 min	28 °C, 8 weeks	70 °C	Insulation materials	[35]
Hemp shives and hardwood chips	Trametes versicolor	Sterilized	22 ± 2 °C, 70 ± 5 % RH	93 °C	Lightweight, thermal insulation materials	[39]
Wheat straws (90 %), polypropylene with bacterial spores (10 %)	Ganoderma lucidum	30 °C, 30–35 days	30 °C, 30–35 days	80 °C, for 5–10 h	Insulating board	[30]
Rice straw, hemp pith, kenaf fiber, switch grass, sorghum fiber, cotton bur fiber and flax shive	Ganoderma lucidum	115 °C, 28 min	21 °C, 5 days in the plastic mold shaped as the piece to be fabricated.	60 °C, 8 h	Insulation panels	[28]
Hemp, flax and wheat straw fibers	Ganoderma lucidum	90–100 °C, 3 hours	17 °C, RH 70 %, 21 days	60 °C, RH 50 %, 24 hours	Insulation material	[5] and current research

Fig. 2. Flax (F.M.1),-hemp (H.M.1) and wheat (S.M.1) composite samples with fungal mycelium as a binder.

3.2. Environmental assessment

LCA was employed as the main quantitative research methodology, adhering to the ISO 14040 standard. This standard specifies principles and framework for conducting LCA, including goal and scope definition, inventory analysis, impact assessment, and interpretation [19]. The study conducted a cradle-to-gate analysis, covering the stages from raw material extraction to manufacturing and transportation to the construction site, due to the lack of data on the operational phase and lifespan of the material. Additionally, a qualitative research design was integrated to assess production processes parametrically, aiming to identify strategies for minimizing environmental impact and enhancing sustainability.

3.3. Multicriteria analysis

The aim of the Multicriteria Decision Making Analysis (MCDM) is to identify the best alternative for the thermal insulation of the wall using multi-criteria Simple Additive Weighting (SAW) [8,25] and Multiplicative Exponential Weighting (MEW) methods. The multicriteria analysis of thermal insulation materials involved several key steps to ensure a thorough and reliable evaluation (Fig. 3).

The first step was developing a criteria framework. The method used in this study is an expert approach, based on questionnaires filled in by experts, the collection of expert opinions and the application of the chosen methodology.

In order to verify the results to be obtained from the application of the SAW and MEW multi-criteria methods, a group of 11 experts was formed to rank and prioritise the 10 typical building thermal insulation material characteristics. The selected experts were persons with at least a master's degree in civil engineering field, scientists, experts, technical supervisors. A system of criteria for assessing

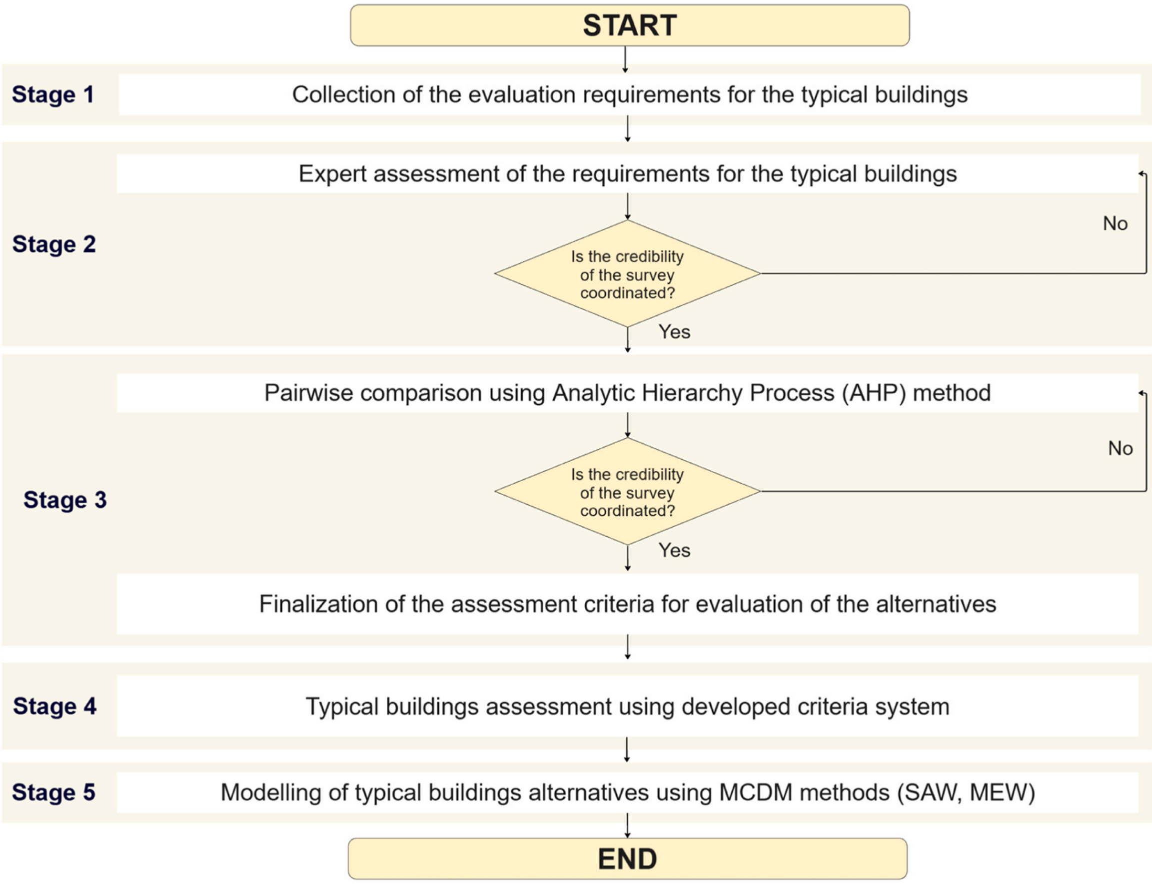

Fig. 3. Flowchart for the implementation of the Stages of the Evaluation Criteria Framework for Thermal Insulation Materials for Typical Buildings.

thermal insulation materials was developed using publicly available information and expert input. Criteria included Environmental Impact, Economic Cost, Durability, Resource Availability, Thermal Conductivity, Health and Safety, Technical Performance, Aesthetic Quality, Ease of Installation, and Regulatory Compliance. The consistency of expert evaluations was verified using Kendall's concordance coefficient [22] (W=0.83) (Table 9).

The second step was expert evaluation. Experts ranked the importance of each criterion using pairwise comparison and the Analytic Hierarchy Process (AHP) [32]. The experts were guided on completing the pairwise comparison questionnaires. Characteristics were arranged in both rows and columns to facilitate comparisons. The intersection of identical characteristics was marked with a value of one. The characteristic in the row was compared to the one in the column, with an integer assigned to indicate its level of importance. If the row characteristic was less important than the column characteristic, the inverse value was recorded. After collecting the questionnaires completed by the experts, it turned out that only 11 out of 13 experts had completed the pairwise comparison questionnaires correctly and according to the instructions provided, so further calculations were only carried out with the information received from the 11 experts.

To facilitate the calculation of significance values for characteristics, eleven matrices were developed, employing a structured pairwise comparison method. The reliability and consistency of these significance values are validated through rigorous assessment measures, including transitivity verification, the S_I compatibility index, and Kendall's concordance coefficient, ensuring alignment and agreement among expert evaluations (Table 12).

The third step involved the application of SAW and MEW methods.

W (Simple Additive Weighting) is the best known, one of the simpler and most widely used methods [10,31,38].

Steps of SAW ir MEW methods:

1) normalisation of the decision matrix,
2) multiplying each member of the normalised matrix for the same variant by its significance and adding it to the other members of the alternative (row).

First, a decision matrix X is constructed, where the rows denote the alternatives under consideration (m is the number of alternatives), and the columns denote the effectiveness indicators (n is the number of performance indicators) against which the alternatives are assessed [9].

$$X = \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2n} \\ \dots & \dots & \dots & \dots \\ x_{m1} & x_{m2} & \dots & x_{mn} \end{bmatrix} \tag{1}$$

Where: x_{ij}– the value of the i-th alternative, the j–th effectiveness indicator.

Significance values for indicators required for SAW and MEW calculations, that meet the condition:

$$\sum_{j=1}^{n} q_j = 1 \tag{2}$$

The values of the indicators in the decision matrix X to be maximised are normalised according to the formula:

$$\overline{x}_{ij} = \frac{x_{ij}}{x_i^{\max}}, \tag{3}$$

The values of the indicators to be minimised are normalised according to formula (4):

$$\overline{x}_{ij} = \frac{x_i^{\min}}{x_{ij}} \tag{4}$$

This gives the normalised matrix $\overline{X}$ (5) [38]:

$$\overline{X} = \begin{bmatrix} \overline{x}_{11} & \overline{x}_{12} & \dots & \overline{x}_{1n} \\ \overline{x}_{21} & \overline{x}_{22} & \dots & \overline{x}_{2n} \\ \dots & \dots & \dots & \dots \\ \overline{x}_{m1} & \overline{x}_{m2} & \dots & \overline{x}_{mn} \end{bmatrix} \tag{5}$$

To calculate the values of the SAW and MEW criteria for each alternative approach, the elements of the normalised matrix are multiplied by the significance values of the respective indicators and the resulting products are summed.

For each alternative, the value of the SAW criterion is calculated according to formula (6):

The values of the indicators in the decision matrix X to be maximised are normalised according to the formula [38]:

$$S_i = \sum_{j=1}^{n} \overline{x}_{ij} \cdot q_j \tag{6}$$

Where: $\overline{x}_{ij}$ – the normalised value of the j–*th* indicator of the i–*th* alternative, q_j – the significance value of the j-th indicator [38].

For each alternative, the value of the SAW criterion is calculated according to formula (7):

$$L_{\mathrm{i}} = \prod_{j=1}^{n} \left(\overline{x}_{\mathrm{ij}}\right)^{q_j} \tag{7}$$

Using formula (8) [38], the significances of the evaluation criteria for thermal insulation material were calculated. They are presented in Table 9.

$$q_j = \frac{1}{r}\sum_{i=1}^{r} q_{ij}, \quad (j = \overline{1,n}) \tag{8}$$

The final step in the application of the SAW and MEW methods is the ranking of the alternatives using the SAW and MEW methods according to the evaluation criteria developed by the experts (Table 13). The table shows the values of the SAW and MEW criteria and the rankings of the alternatives according to the value of the criterion. The results show that for both SAW and MEW, the better alternative meeting all the criteria is A1, i.e. mycelium-based straw insullation.

4. Results and discussion

4.1. Environmental assessment results

Goal and Scope

In this report, we present the results of an LCA conducted to assess the environmental implications of producing a MBSIC.

LCA provides an integrated approach, investigating a product's environmental impact, from raw material extraction to end-of-life considerations. It offers a holistic view of environmental effects, encompassing direct and indirect activities, aiding in informed decision-making for sustainable strategies [12]. Using LCA to evaluate MBSIC production highlights areas for optimization and ensures balanced environmental solutions. In summary, LCA serves as a pivotal instrument for elevating a product's environmental responsibility and addressing current sustainability challenges [13].

System Boundaries

This analysis is a Gate-to-gate LCA. Gate-to-gate LCA is a specific approach within the broader LCA methodology that focuses on assessing the environmental impacts of a product or process from a defined starting point (gate) to a defined endpoint (gate) in its life cycle [14] (Fig. 4).

This approach enables a detailed analysis of the environmental performance of a particular stage, considering factors such as resource consumption, energy use, emissions, and waste generation [15]. Gate-to-gate LCA provides valuable insights for optimizing processes and implementing targeted measures to enhance sustainability. However, it should be noted that this method offers a limited view and does not account for the broader environmental implications of upstream and downstream stages [20]. To obtain a comprehensive understanding, gate-to-gate results can be integrated into a cradle-to-grave or cradle-to-cradle LCA, which considers the entire life cycle of a product.

The schematic diagram presented in **Figure** illustrates the key stages encompassed within the scope of the study's process chain. These stages comprise the plantation, the growing and the baking.

Two studies were conducted on the cultivation process, Option A and B. Option B utilized a climate chamber for growth, while Option A was executed without such a chamber, under standard room conditions. The environmental assessment involved a LCA at both the material and building levels. The analysis used the Gabi software [16] and followed the ISO 14040 standard, focusing on a cradle-to-gate approach.

- Impact categories assessed included:
- Climate Change (GWP as CO_2 Equiv. Mass),
- Acidification Potential (AP as H+ Equiv.),
- Ozone Depletion (ODP as R11-Equiv. Mass),
- Abiotic Depletion (elements & fossil as Sb-Equiv. Mass),
- Photochemical Ozone Formation (POCP as NMVOC Equiv. Mass),
- Eutrophication Potential (EP as Phosphate Equiv. Mass),
- Freshwater Aquatic Ecotoxicity Potential (FAETP inf. as DCB-Equiv. Mass),
- Human Toxicity Potential (HTP inf. as DCB-Equiv. Mass).

Table 3 provides the Life Cycle Inventory data used for the LCA implementation.

Table 4 summarizes the LCA results for the selected impact categories for the two methods of producing 0.2 kg of MBSIC. Detailed results are provided in Appendices, while the primary significant pollutants identified in the process are listed in Table 5

The results of the LCA for the two methods of producing 0.2 kg of MBSIC are summarized in Table 4. The climate chamber method exhibited significantly higher environmental impacts across all categories compared to the standard room conditions method. For instance, the GWP for the climate chamber method was 886 kg CO_2-equivalent, whereas it was only 7.75 kg CO_2-equivalent for the standard room conditions. Similarly, the AP, ODP, ADP, POCP, EP, FAETP, and HTP values were markedly higher for the climate chamber method. The life cycle inventory data (Table 3) reveal that the climate chamber method required substantially more energy, particularly for sterilization and cultivation processes. 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 (Table 5) 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.

The results reveal significant differences in environmental impact between the two production methods of MBSIC, particularly in greenhouse gas emissions and resource consumption. The climate chamber method exhibited notably higher emissions, largely

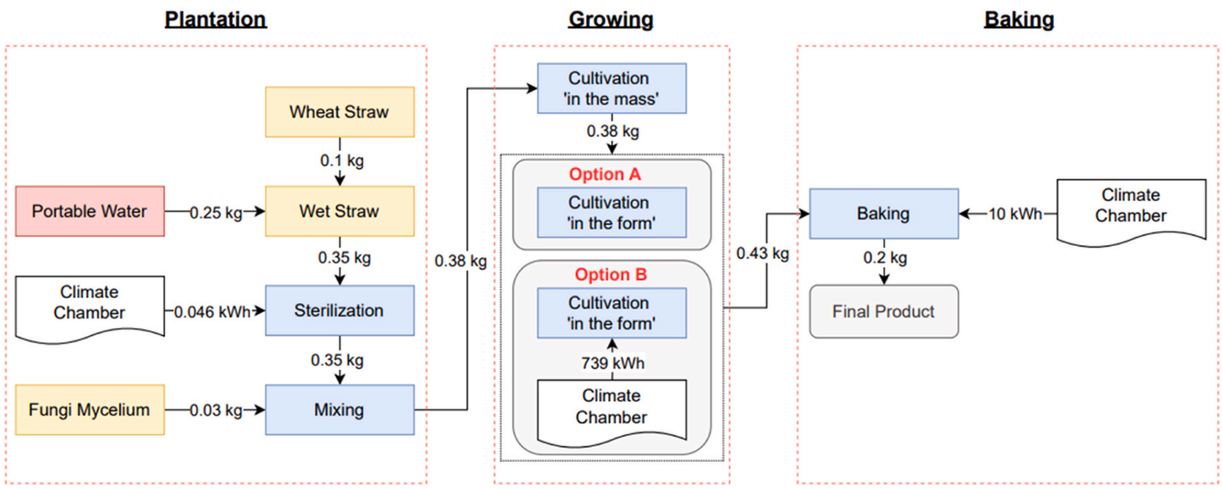

Fig. 4. LCA system under standard room conditions (Option A) and with the climate chamber (Option B).

Table 3
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

Table 4
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 5
Inputs and Outputs Comparison between Climate Chamber and Room Conditions.

	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	$6.41.10^{-6}$

attributed to its increased energy demand during sterilization and cultivation. In contrast, standard room conditions significantly reduced carbon footprint, making it a more sustainable alternative. The analysis highlights that non-renewable energy consumption is a key driver of impact, emphasizing the need for energy-efficient production strategies. Furthermore, comparing MBSIC to conventional insulation materials demonstrates its advantages in biodegradability and embodied carbon reduction, though improvements in mechanical durability may be necessary for broader adoption. These findings suggest that optimizing the manufacturing process, particularly through reduced energy-intensive steps, could enhance MBSIC's sustainability profile. Additionally, the results underscore the potential policy relevance of MBSIC, particularly in promoting bio-based materials in energy-efficient building practices. Future research should further investigate long-term performance and end-of-life disposal impacts to validate its full sustainability potential.

4.2. Multicriteria analysis results

The multicriteria analysis aimed to identify the best alternative for thermal insulation using the Simple Additive Weighting (SAW) and Multiplicative Exponential Weighting (MEW) methods. The evaluation criteria were developed and weighted based on expert input. The criteria included Environmental Impact, Economic Cost, Durability, Resource Availability, Thermal Conductivity, Health and Safety, Technical Performance, Aesthetic Quality, Ease of Installation, and Regulatory Compliance.

The criteria weights assigned based on expert evaluations are presented in Table 6.

The performance of the alternatives, mycelium-based straw and rock and glass mineral wool was assessed based on the established criteria. The summarized results for both the SAW and MEW methods are presented in Table 7 and Table 8, with detailed findings available in Appendices.

The performance of the two insulation alternatives was assessed based on these criteria. The results, summarized in Tables 7 and 8, indicate that mycelium-based straw outperformed rock and glass mineral wool in both SAW and MEW methods. Specifically, the SAW method yielded scores of 0.9465 and 0.9312 for mycelium-containing straw and rock and glass mineral wool, respectively, placing mycelium-based straw in the first rank. Similarly, the MEW method produced scores of 0.9326 for mycelium-containing straw and 0.8994 for rock and glass mineral wool, again ranking mycelium-based straw as the superior alternative.

These results suggest that mycelium-based straw is a more favourable insulation material when considering the weighted criteria, particularly excelling in aspects prioritized by the experts. This conclusion underscores the potential of mycelium-based straw as a sustainable and effective alternative to traditional insulation materials.

5. Conclusions

The environmental assessment and multicriteria analysis (MCA) conducted in this study underscore the significant sustainability potential of MBSIC as an alternative building material. The LCA, adhering to ISO 14040 standards, demonstrated that the production of MBSIC, particularly under standard room conditions, significantly reduces environmental impacts compared to using a climate chamber. Key findings highlight that the climate chamber method results in substantially higher greenhouse gas emissions, resource consumption, and overall environmental impacts across various categories such as Global Warming Potential (GWP), Acidification Potential (AP), and Human Toxicity Potential (HTP). For instance, the GWP for the climate chamber method was 886 kg CO_2-equivalent, whereas it was only 7.75 kg CO_2-equivalent for the standard room conditions. The MCA, employing both Simple Additive Weighting (SAW) and Multiplicative Exponential Weighting (MEW) methods, further reinforces the advantages of MBSIC. The evaluation criteria, which included Environmental Impact, Economic Cost, Durability, Resource Availability, Thermal Conductivity, Health and Safety, Technical Performance, Aesthetic Quality, and Ease of Installation, were weighted based on expert input. MBSIC

Table 6
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

Table 7
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 8
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

consistently outperformed traditional insulation materials, such as rock and glass mineral wool, in both the SAW and MEW analyses. Specifically, the SAW method yielded scores of 0.9465 for MBSIC compared to 0.9312 for rock and glass mineral wool, while the MEW method produced scores of 0.9326 for MBSIC against 0.8994 for rock and glass mineral wool.

Beyond its environmental benefits, MBSIC presents practical applications in sustainable building design, particularly in regions seeking to transition to low-impact, biobased construction solutions. Its biodegradability, fire resistance, and pest resistance contribute to improved building safety and longevity, making it a viable option for both residential and commercial applications. The findings also provide valuable insights for policymakers, standardization bodies, and industry stakeholders to consider integrating biobased materials into existing regulations and green certification frameworks. Future research should focus on optimizing MBSIC's mechanical properties, scalability in large-scale production, and long-term durability in real-world applications. Additionally, its potential integration into circular economy strategies and modular construction should be explored. By advancing the adoption of biobased insulation materials, this research supports broader sustainability goals in the construction sector, driving innovation in material science and reinforcing global efforts toward reducing the environmental footprint of buildings.

CRediT authorship contribution statement

Fokaides Paris: Writing – review & editing, Supervision, Project administration. **Klumbyte Egle:** Validation, Software, Resources, Methodology, Conceptualization. **Klitou Theoklitos:** Visualization, Resources, Formal analysis, Data curation. **Babenko Maryna:** Writing – original draft, Validation, Software, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.cscm.2025.e04572.

Data availability

Data will be made available on request.

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