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Acoustic Performance and Life Cycle Assessment of a Mycelium-Based Insulation Composite Produced from Agricultural Waste

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Abstract

Mycelium-based composites (MBCs) have already been applied in various fields, like construction, architecture, packaging, waste management and many others, as sustainable replacement materials. The composites created from such materials are lightweight, biodegradable and can take many different geometrical shapes. As there are many different combinations of fungal mycelium and organic substrates, it is not only important to investigate and determine which of these combinations perform best from an acoustic perspective but also from an environmental point of view. The sound absorption qualities of these biocomposites have been investigated. It was found that the sound absorption coefficients range from 0.33 to 0.49 in the mid-high frequency range for the four different mixtures of substrate and oyster mushroom (*Pleurotus ostreatus*). The results from the acoustic testing are promising, but the environmental impact of these mycelium-based composites also needs to be determined. The impacts from water and especially from energy, used during the growth and preparation cycles, are the main contributors to the environmental impact of MBCs, which is also confirmed by the relevant literature. A cradle-to-grave life cycle assessment (LCA) was conducted, utilizing the ReCiPe method, with selected environmental impact categories, based on real-world production data and the scientific literature. The results obtained were also compared with a commercially produced acoustical stone wool panel. The influence on environmental impact of the different substrates is also analyzed, determining which MBC is the most environmentally friendly and has the best acoustical properties.

Keywords: sustainability; sound absorption coefficient; mycelium-based composites; life cycle assessment; acoustics; environmental impact; circular economy

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1. Introduction

There is a legislative push in the European Union for the creation and implementation of more sustainable materials and practices in the hopes to decrease the environmental impact of various industries [1], with the construction industry being no exception. The construction and operation of various buildings heavily impact climate change, as a great deal of energy (up to 40% of global consumption) [2] and resources are being spent on them, creating a huge amount (up to 37% globally) of greenhouse gases (GHG) in the process [3]. Existing materials (cement, metals, and polymers), including their high production and

processing costs, the need for various equipment and the lack of recycling potential, create environmental problems and pollution. As the demand for new housing and other types of structures will only increase in the future, it is important to create alternatives for non-renewable building materials that not only have a lower environmental impact than their commercially available counterparts but also meet the necessary requirements set for these materials.

Currently, research is being conducted on biocomposites—composite materials developed from a mixture of natural or renewable materials. Mechanical, thermal, and insulating properties of biocomposites are being researched and developed for broader application purposes, with the aim of reducing the excessive exploitation of non-renewable resources and increasing the possibilities for the reuse of organic waste, thus responding to the principles of the circular economy [4–7]. A natural material that has rapidly gained popularity and whose properties and potential uses are being investigated is fungal mycelium. Composite materials based on mycelium are distinguished by their biodegradability and lower carbon footprint. Fungal mycelium is being implemented in many different fields: construction [8,9], automotive [10,11], textiles [12,13] and electronics [14,15]. One of the earliest and currently most common applications for mycelium-based composites (MBCs) is thermal insulation [3,16] or as an acoustic insulation material [16,17], the latter of which is the object of this research article.

With the acceleration of urbanization and technological development, not only is the material and energy consumption increasing, but so are the associated environmental challenges, including noise pollution [18,19]. Noise, long considered merely an annoying environmental factor, is increasingly recognized in modern society as a serious public health problem. European Union Directive 2002/49/EC emphasizes the need to assess the impact of environmental noise, and the World Health Organization classifies noise as a health hazard due to the psychological and physiological stress it causes [20,21]. Studies show that noise exceeding 65 dB can cause negative chronic effects on the autonomic nervous and endocrine systems over time, while acute physiological effects can be observed at sound levels of 80–85 dB [22]. A study conducted by the European Environment Agency showed that more than 20% of European residents experience long-term, unhealthy noise levels exceeding 55 dB around the clock, including during nighttime hours [23–25]. Besides noise pollution, acoustic insulation materials have been dominated by glass fiber or mineral wool, which do have high sound absorption properties due to their fibrous structure, but also have significant negative characteristics—not only are they difficult to recycle, but they also pose a risk to human health, for example, by inhaling dust or individual fiber particles [26].

Because of the circular economy and noise reduction reasons, it is important to create new solutions to decrease the environmental footprint as well as increase the effectiveness of sound insulation materials. As there are many different fungi species and different substrates that can be processed with different techniques, many different composite materials can be created with various mechanical and chemical properties [27]. Such composites comprise mycelium growing in a certain mold to ensure the required geometry and organic substrate material to provide sustenance for the fungi's growth. After the substrate is fully colonized, the fungi need to be deactivated by heat, which also removes the moisture content of the mycelium-based composite, improving mechanical parameters. Substrates can range from wood chips, straw or grain to practically any organic material or waste [16,28], which creates an opportunity to implement agricultural wastes in MBCs. The mycelium added to any of the aforementioned organic substrates creates a three-dimensional network that acts as both binder and fiber [29,30].

A less researched area of such MBCs is their environmental impact. This type of biocomposite is more environmentally friendly than standard solutions, as suggested by

existing research [31,32], but it still has an impact on the environment, however small it may be. To solve this problem, life cycle assessments (LCA) are being carried out for MBCs [3,33], to determine what potential effect on the environment this type of composites have and what additional improvements MBC production may require to counter the possible negative effects. This study contributes to the development of sustainable green building materials by demonstrating that mycelium-based composites derived from agricultural waste can serve as environmentally friendly acoustic insulation solutions, supporting circular economy principles and reducing reliance on non-renewable materials. The conducted research also aims to address the current knowledge gap by concurrently evaluating the acoustic performance and conducting a comprehensive life cycle assessment of various localized agricultural waste-based mycelium biocomposites. Such an integrated approach facilitates the identification of the most suitable substrate by considering both functional performance and environmental sustainability dimensions.

The aim of this study is to experimentally determine the sound absorption coefficient of the mycelium-based composite samples made from agricultural waste material in order to determine whether such a composite could be used as an eco-friendly alternative to a standard acoustic panel and conduct a life cycle assessment of a mycelium-based composite acoustic insulation panel, determining its carbon footprint with the help of the SimaPro 9.5.0.1 LCA software package and the Ecoinvent v3.3 database, both provided by the "SimaPro" company (Amersfoort, The Netherlands), substituting any missing information with scientific literature. The newly developed MBC is also compared to an existing commercially available acoustic insulation panel to determine whether it is more environmentally friendly than existing solutions and what environmental impact differences occur when changing substrates for the same fungus mycelium (*Pleurotus ostreatus*). This assessment will help determine the potential environmental effects of such a mycelium-based acoustic insulation panel. It is important to investigate these parameters for such newly designed biocomposites, as it expands the existing knowledge base, which will help future research into MBCs and also potentially help in creating more sustainable alternatives for materials, achieving circular economy goals.

2. Materials and Methods

In this section, the methodology to prepare the MBC acoustic sample and obtain the sound absorption coefficient is described in detail, together with the methodology and case parameters of the conducted LCA for the acoustic insulation panel comparison with the commercially available counterpart and different substrate effects on the life cycle of MBCs.

2.1. Preparation and Testing of Mycelium-Based Composite Acoustic Samples

Agricultural waste is most commonly used as substrates for the production of mycelium-based composites because they can be effectively decomposed by fungi [34–36]. The type of agricultural waste used as a substrate for the production of mycelium-based composites is based on the type of agricultural waste that is most abundant in the selected geography. The type and composition of agricultural waste can directly affect mycelium growth, as hyphae come into direct contact with the substrate surface and, as is well known, use the necessary nutrients obtained from the substrate [34–38]. It should also be noted that adding various additional nutrients to the substrates can artificially stimulate the development of fungal mycelium [35]. The ideal substrate has sufficient nitrogen and carbohydrates for rapid fungal mycelium growth [27]. According to the scientific literature, the most commonly used substrate for creating mushroom mycelium-based composites is wood or wood waste, as they are composed of cellulose [39,40]. Other agricultural waste products such as various grains, hemp, cereal residues, etc., are also a promising choice [27]. In the

case of this research article, widely available agricultural waste in Lithuania was chosen as substrates (oat (coarse—average length of the chaff is 1.5 cm/fine—average length of the chaff is 0.75 cm), rye, and wheat waste (husks/straw) (Figure 1, Table 1)). Wheat, rye, and oat straws/husks were selected because they are rich in cellulose, hemicellulose, and lignin, which provide carbon for mycelial growth [41,42]. The relatively high cellulose content in wheat and rye straw residues is anticipated to enhance fiber rigidity and interfacial bonding with the mycelial network [43]. Finally, agricultural-waste-based mycelium composites tend to be highly porous and have a low density, making them suitable for absorbing and dissipating sound waves [44] while simultaneously decreasing agricultural waste streams. The oyster mushroom (*Pleurotus ostreatus*) was chosen as the binding agent (Figure 2), as it is one of the most commonly chosen cultures in the scientific literature for the creation of MBC acoustic panels due to this fungus's ability to bind a mechanically strong composite with good acoustic properties [5,45,46]. The mushroom culture was purchased from grybų auginimas.lt (Vilnius, Lithuania).



(**a**) (**b**) (**c**) (**d**)

Figure 1. Different substrates used for the MBC: (**a**) oat husks/straw (fine); (**b**) wheat husks/straw; (**c**) rye husks/straw; and (**d**) oat husks/straw (coarse).

Table 1. MBC acoustic specimen mixtures.

Fungi Species	Substrate	Water Content
Pleurotus ostreatus spawn (4 g)	Oat husks/straw (coarse) (20 g)	13 mL
Pleurotus ostreatus spawn (4 g)	Oat husks/straw (fine) (20 g)	13 mL
Pleurotus ostreatus spawn (4 g)	Rye husks/straw (20 g)	13 mL
Pleurotus ostreatus spawn (4 g)	Wheat husks/straw (20 g)	13 mL

Each type of substrate (four in total) was separated from the others using fabric bags and sterilized in water heated to 80 °C (in an oven) for 1 h. The amount of inoculum was chosen based on the literature, as the optimum inoculation density is 10–32% inoculum to substrate (by volume), depending on the used inoculum, whether in liquid or solid form [47]. Subsequently, 20% of the inoculum by specimen volume of oyster mushroom culture (4 g) was introduced into all four different sterilized moist substrates (20 g of dry substrate and 13 mL of water).

These four different mixtures were placed in disinfected round plastic containers (diameter—9 cm, height 1.5 cm) and left to grow for 4 weeks at a temperature of 22 °C and an average humidity of 32% (ranging from 19.69% to 41.17%). Moisture in specimens was maintained by adding a specific amount of boiled water every three days to maintain

the humidity of 65% of specimen volume, depending on how much mass evaporated, to prevent the samples from drying out and to keep the fungal mycelium active [40]. After 4 weeks, the obtained MBC acoustic specimens (Figure 3) were heated for 20 min at 140 °C in order to densify the composite, creating more adhesive bonds between the mycelium and the substrate, also biologically deactivating the mycelium [5,46]. Three 30 mm diameter samples were cut from each different MBC sample, and their sound absorption coefficient was measured using an impedance tube.



Figure 2. Oyster mushroom (*Pleurotus ostreatus*) sprouted culture.



(**a**) (**b**) (**c**) (**d**)

Figure 3. MBCs obtained after 4 weeks: (**a**) oat husks (fine); (**b**) wheat husks; (**c**) rye husks; and (**d**) oat husks (coarse).

An impedance tube is a device for measuring acoustic parameters, which can be used to determine the sound absorption coefficient and sound reflection factor of the material under investigation (in this case, a mycelium-based biocomposite) [48]. The working principle of an impedance tube involves sending a plain sound wave using broadband white noise down a rigid tube toward a test sample put against a reverberant termination and measuring the proportions of sound that are reflected and absorbed [49]; for the chosen 30 mm diameter tube and specimens, the possible testing frequency range is from 150 Hz to 6600 Hz. This device consists of (Figure 4):

- Sound source (4);
- Three microphones (1–3) (Microphone type: 1/4″, BNC (female) coaxial connector, class 1 precision with a frequency range of 20 Hz to 20 kHz);
- Place for fixing the sample (Specimen is inside the tube) (5);
- Tube through which sound waves travel (6).

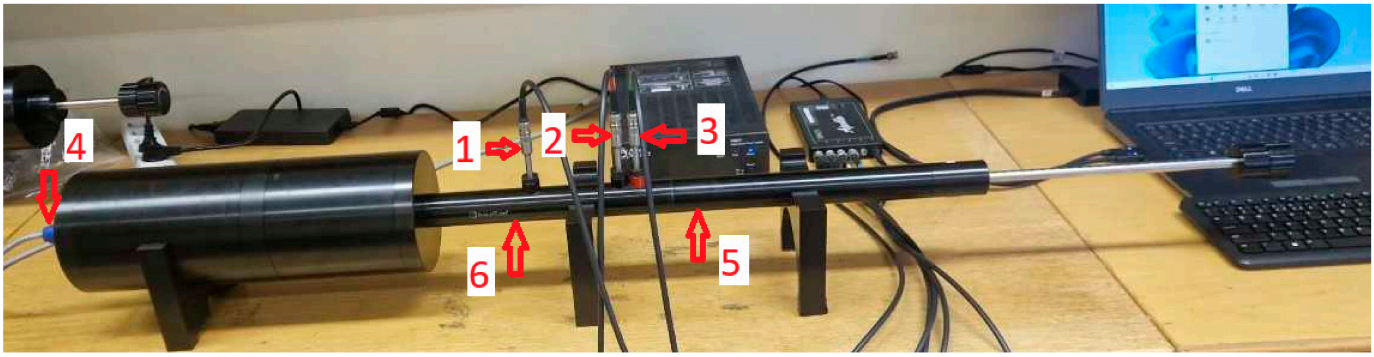


Figure 4. Impedance tube used during acoustic testing.

The sound absorption coefficient in impedance tubes is determined by applying a standard approach outlined in ISO 10534-2, commonly known as the two-microphone technique [50]. Microphones (1) and (3) were used to measure the low-frequency sound absorption coefficient (160–1000 Hz), while microphones (2) and (3) were used for the high-frequency range (1000–5000 Hz). The spacing between microphones (1) and (2) was 100 mm, that between microphones (2) and (3) was 20 mm, and the distance from microphone (3) to the sample was 60 mm. These distances were selected based on wavelength considerations: low-frequency waves have longer wavelengths and require greater microphone spacing to capture accurate data, whereas high-frequency waves have shorter wavelengths and therefore require smaller spacing. The sound absorption coefficient results are presented in 1/3-octave bands, with 50 averages applied.

MBC samples tested by an impedance tube had a diameter of 30 mm. This was because, in order to reliably measure the sound absorption coefficients of such lightweight porous absorbers (MBCs), especially in the mid-high frequency range, the most appropriate specimen diameter was 30 mm. Larger specimen diameters are more suited for lower-frequency analysis. The measurements were performed with an "AcoustiTube" impedance tube produced by AED (Dresden, Germany), which meets first-class accuracy standards. The data is acquired by 2/4 simultaneously sampled analog input channels with BNC connectors and IEPE (Integrated Electronics Piezo-Electric) conditioning. After the pressure generated by the sound waves is captured by the microphones, the collected data is sent and analyzed by the "AcoustiStudio" software (version 2.2.1), specifically developed for use with the impedance tube applied in this study. The exact calculation methodology is provided in previous research [45]. The interior of the impedance tube must have a very smooth surface so that the results obtained when measuring the acoustic parameters of the test materials are as accurate as possible [51]. Temperature and humidity conditions in the laboratory were maintained using laboratory climate control equipment. A constant temperature of 21 ± 1 °C and humidity of 30–50% were maintained. The results of the acoustic tests are provided in Section 3.

2.2. Life Cycle Assessment Methodology of Acoustic Panels Employing Different Substrates

The mycelium-based acoustic insulation panel will be evaluated by employing a reliable and widely applied life cycle assessment methodology. This method allows the systematic evaluation of all the environmental impacts of the selected product, as well

as identifies the most impactful categories that need improvement. A LCA is a system structured in a way that takes into account both production and consumption, which in turn allows the interpretation of emissions, categorized into damage categories [8].

LCAs are divided into 4 steps that are required to conduct a full and precise life cycle assessment [52]: 1. Goal and scope definition; 2. Inventorization; 3. Impact assessment; and 4. Interpretation. Goal and scope definition and inventorization are presented in this Section, while impact assessment and interpretation are included in the Results Section.

2.2.1. Goal and Scope

The goal of this life cycle assessment is to evaluate the possible environmental effects of the novel mycelium-based composite acoustic insulation panel and compare the results to available data of an existing acoustic insulation panel commonly used around the world, including Europe. The analysis will help evaluate the environmental impact of the acoustic insulation panel comprising 0.5568 kg of fungi (20% of substrate weight) and 2.793 kg of wheat husk substrate. This analysis also helps in pinpointing the possible environmental hot spots in the panel's production, allowing improvement in these areas. The results of this study can be used to further improve this type of composite material. Figure 5 represents the boundaries of this study, processes and inputs required for the production of the mycelium-based acoustic insulation panel, excluding transportation, which is provided in the appropriate inventory tables.

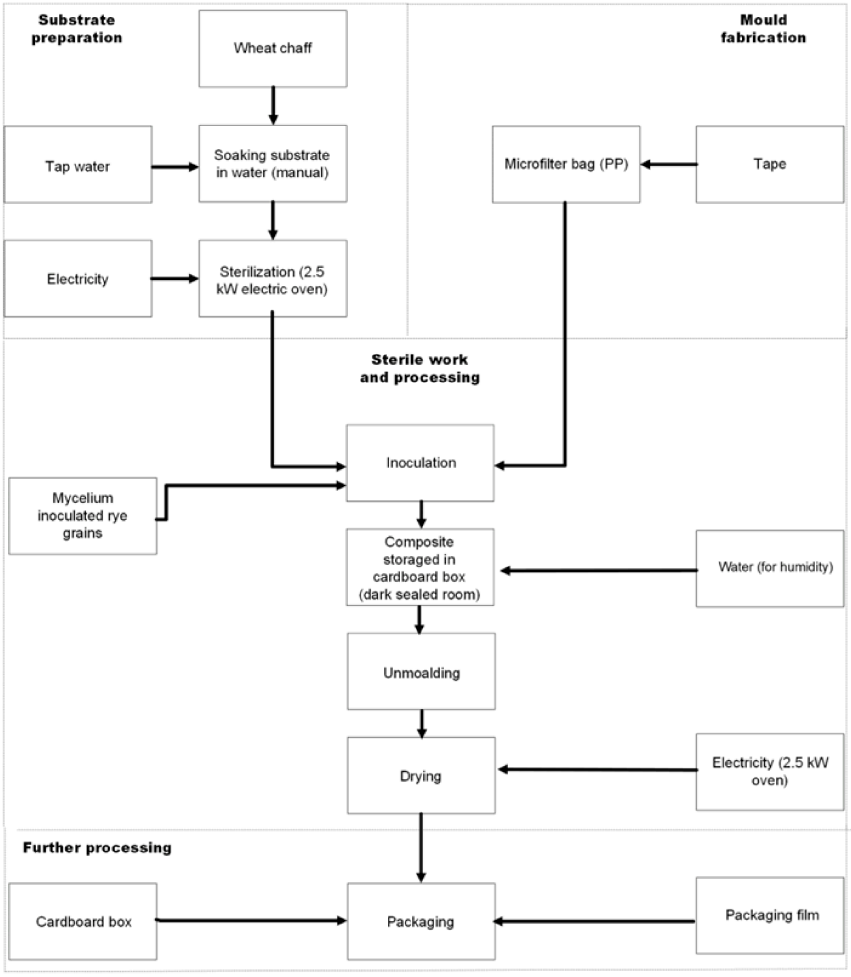


Figure 5. Flowchart of the processes and inputs during the production of the acoustic insulation panel.

It is assumed that the place of production is the city of Vilnius in Lithuania and that wheat husks are transported 90 km from Varėna district to Vilnius, while the fungi and additional acoustic panel installation materials are transported 15 km from the city of Vilnius; the consumer is located in Kaunas, and it is assumed that the distance to the consumer is 100 km, while the distance to the utilization site is roughly 10 km, because an assumption is made that the site of utilization is located in Jėgainės street 6, Biruliškės, 54,469 Kaunas County municipality, where a cogeneration power plant is located. The manufacturing process of the panel was completed on a lab scale. The declared unit (FU) was chosen as 1 m^2. A declared unit was chosen over a functional unit as no standard for a functional unit reflecting the functional qualities of acoustic absorbers has been established [17,53]. The acoustic insulation panel was 100 × 100 cm, which is 2.5 cm thick, weighing 3.351 kg.

A cradle-to-grave LCA was carried out, including the extraction of raw materials, product manufacturing, product use, product transportation, and product disposal, for both acoustic panels. The MBC and commercially available panels' service time is assumed to be 60 years (the same as commercially available counterparts) [54]. An additional LCA analysis for the commercial acoustic panel will not be carried out as all the required information is obtainable from a publicly available Environmental Product Declaration (EPD), in which the LCA results are already presented [54].

Two acoustic panels—the commercially produced panel and the MBC panel, made from agricultural waste husks and oyster mushroom (Pleurotus ostreatus) mycelium—will be compared according to the following criteria: global warming potential, freshwater eutrophication potential, water depletion potential, and fossil depletion potential, as they are the available criteria provided in the EPD, as well as the criteria that are closely related to energy and water consumption.

Additionally, the environmental impact during the production stage of the substrate is evaluated, when different substrates are used for the MBC—oat, wheat, and rye husks—which make up approximately 80% of the total volume of the acoustic panel. They will also be evaluated using the global warming potential, water depletion potential and freshwater eutrophication potential environmental criteria. The aim is to determine which type of substrate would have the lowest environmental impact. For the comparison, 1 kg of each specific type of substrate will be assessed.

2.2.2. Inventory

The acoustic panel was made from wheat husks (2.793 kg) and oyster mushroom (*Pleurotus ostreatus*) culture (0.5586 kg) in a laboratory environment. Inventory information regarding raw material extraction and transportation is provided in Table 2.

Water was used in the MBCs' production process: 0.5 L of water was used for a 71.6 cm^2 sample of the acoustic panel, which equals 69.83 L used for the whole 1 m^2. The husks were pasteurized for 1.5 h using a 2.5 kW electric oven, equaling 3.75 kWh of electricity consumed. During cultivation, plastic (PP) bags measuring 15 × 60 cm (900 cm^2) were used, each weighing 15 g. It was assumed that 12 units are required to produce 1 m^2 of such MBC. The samples were left to grow in a 0.2191 kg cardboard box. To prevent the samples from drying out, moisture was added regularly, and an additional 5 L of boiled water (for sterility) was used during the entire production process. This also required an additional 0.60 kWh of electricity. At the end of production, a 2.5 kW electric stove was used for 2 h to dry the specimen, and this single process consumed an additional 5 kWh of electricity. The full production inventory is provided in Table 3.

Table 2. Raw material extraction and transportation inventory.

Process Name	Amount	Literature Source
Mycelium—inoculated rye grains production	0.5586 kg	[55]
Mycelium—inoculated rye grains transportation	15 km (from contributor (Vilnius district) to manufacturing site (Vilnius))	Ecoinvent database v3.3
Wheat chaff production	2.793 kg	Ecoinvent database v3.3 (proxy: straw)
Wheat chaff transportation	90 km (from contributor (Varėna) to manufacturing site (Vilnius))	Ecoinvent database v3.3
Mounting materials transportation	15 km (from contributor (Vilnius district) to manufacturing site (Vilnius))	Ecoinvent database v3.3

Table 3. Acoustic insulation panel production inventory.

Process Name	Sub-Process Name	Amount	Literature Source
Sterilization of the substrate	Substrate	2.793 kg	Primary data
	Water	69.83 L	Primary data
	Electricity (low voltage)	3.75 kWh	Primary data
Fungal inoculation	Sterilized substrate	2.793 kg	Primary data
	Mycelium—inoculated rye grains	0.5586 kg	[55]
	PP bags for the substrate	0.18 kg	Ecoinvent database v3.3
	Cardboard box	0.1095 kg	Ecoinvent database v3.3
	Plastic tape	0.024 kg	Primary data
Humidity preservation	Water	5 L	Primary data
	Electricity (low voltage)	0.6 kWh	Ecoinvent database v3.3
Drying/stabilization	Acoustic insulation panel	3.351 kg	Primary data
	Electricity (low voltage)	5 kWh	Ecoinvent database v3.3
Transportation to the sale site	Acoustic insulation panel	3.351 kg	Primary data
	Mounting materials	1.116 kg	[17]
	Cardboard box	0.86 kg	[17]
	Packaging film	0.02934 kg	[17]
	Product transportation	100 km	Ecoinvent database v3.3
Mounting the panel	Acoustic insulation panel	3.351 kg	Primary data
	Mounting materials	1.116 kg	[17]
	Electricity (low voltage)	0.06 kWh	[17]
Dismounting the panel	Electricity (low voltage)	0.06 kWh	[17]
Transportation to the waste disposal site	Acoustic insulation panel	3.351 kg	Primary data
Waste disposal	Transportation	10 km	Primary data
	Biological waste, municipal waste incineration	3.351 kg	Ecoinvent database v3.3
	Plastic waste, melting and granulation	0.302 kg	Ecoinvent database v3.3
	Wood waste, municipal waste incineration	1 kg	Ecoinvent database v3.3
	Paper waste, municipal waste incineration	0.86 kg	Ecoinvent database v3.3
	Metal waste, melting and molding	0.048 kg	Ecoinvent database v3.3

When production of the panel is completed, the acoustic insulation panel is taken to a place of sale, which is assumed to be at the same place as the customer located 100 km away from the production site (lab). All the transportation distances and component weights are provided in Table 3. It has to be noted that mounting materials consist of 4 units of softwood lath (1 kg), 4 units of plastic dowels (0.48 kg), 4 units of screws (0.048 kg) and 4 units of 3D printed plastic mounting accessories (0.020 kg). Total weight of mounting materials was 1.116 kg, consisting of 0.068 kg of plastic, 0.048 kg of metal materials and 1 kg of wood materials. After the acoustic insulation panel and mounting materials are brought to the installation site, the panel is installed, which consumes an additional 0.06 kWh of electricity (low voltage). After the panel's service life is over, it will be dismounted, consuming an additional 0.06 kWh of low-voltage electricity (assumption that the dismounting operation uses the same amount of electricity). The acoustic insulation panel is then transported to the waste disposal site, which is located 10 km away from the installation site, where the panel and other waste (paper and wood waste) generated from the dismantling of the panel will be burned; plastic waste will be melted and granulated, while metal waste will be melted and remolded. The transportation to utilization and the utilization inventory are also provided in Table 3.

When the whole chain of the mycelium-based composite acoustic insulation panel is evaluated, the required information about its emission inventory is obtained from the Ecoinvent database v3.3 or the supplementary scientific literature. The ReCiPe life cycle assessment method was used to evaluate the potential environmental impacts from the life cycle inventory data, as it is one of the most established and widely used methods. The ReCiPe hierarchist V1.08 perspective was selected, as it is the perspective created for scientific analysis. This methodology groups impact into two levels: 18 midpoint categories and three endpoint categories. The midpoint categories being: particulate matter, tropospheric ozone formation (hum), ionizing radiation, stratospheric ozone depeltion, human toxicity (cancer), human toxicity (non-cancer), global warming, water use, freshwater ecotoxicity, freshwater eutrophication, tropospheric ozone (eco), terrestrial ecotoxicity, terrestrial acidification, land use/transformation, marine ecotoxicity, marine eutrophication, mineral resources and fossil resources. As mentioned before, the impact categories that will be compared with the commercially available acoustic panel are global warming potential, freshwater eutrophication potential, water depletion potential, and fossil depletion potential.

3. Results

This Section discusses the results gained after completing the acoustic testing and life cycle assessment. The performance of the acoustic specimens when absorbing different frequency sounds and the environmental impact comparison of the different acoustic panels are presented.

3.1. Sound Absorption Results of Mycelium-Based Composite Acoustic Samples

After the MBC specimens were ready, they were taken out of their molds and weighted. After the weighting process, the specimen thickness was measured, and their volume and density were calculated. All of the obtained physical parameters are provided in Table 4.

The MBC specimen made with coarse oat husks was the heaviest of all the specimens (5.51 g) and was the densest (0.77 g/cm^3); however, in terms of volume (7.77 cm^3) and thickness (1.1 cm), it was the smallest. Specimens made with rye and wheat husks were the lightest (4.22 g and 4.37 g respectively) and had a lower density (0.47 g/cm^3) than the other specimens, but a higher volume (8.94 cm^3 and 9.18 cm^3) and thickness (1.26 cm and 1.3 cm). The specimen with fine oat husks was more similar to wheat and rye husk

specimens (Table 4). It was expected that the thickness of the samples would be 1.5 cm; however, during the drying process, the specimens experienced shrinking. The physical property results indicate that a smaller particle size (oat (fine), rye, and wheat husks) results in lower density and higher porosity of the MBC, allowing better dispersion of sound waves that hit the MBC's surface. The trapped sound wave dissipates inside the more intricate pore structures. Smaller particle sizes (oat (fine), rye, and wheat husks) also have lower shrinkage when compared to the coarser oat husks.

Table 4. MBC specimen physical properties.

Specimen Name	Thickness, cm	Mass, g	Volume, cm^3	Density, g/cm^3
Oat husks (fine)	1.27	4.9	8.95	0.55
Wheat husks	1.3	4.37	9.18	0.47
Rye husks	1.26	4.22	8.94	0.47
Oat husks (coarse)	1.1	5.51	7.77	0.77

After the physical properties of all the specimens were determined, the acoustic testing was carried out with the impedance tube. After the testing was finished, the sound absorption coefficient was calculated by the same methodology as in Ružickij et al. [49]. A graph was created, showing the resulting sound absorption coefficient depending on the sound frequency (Figure 6) for all different MBCs.

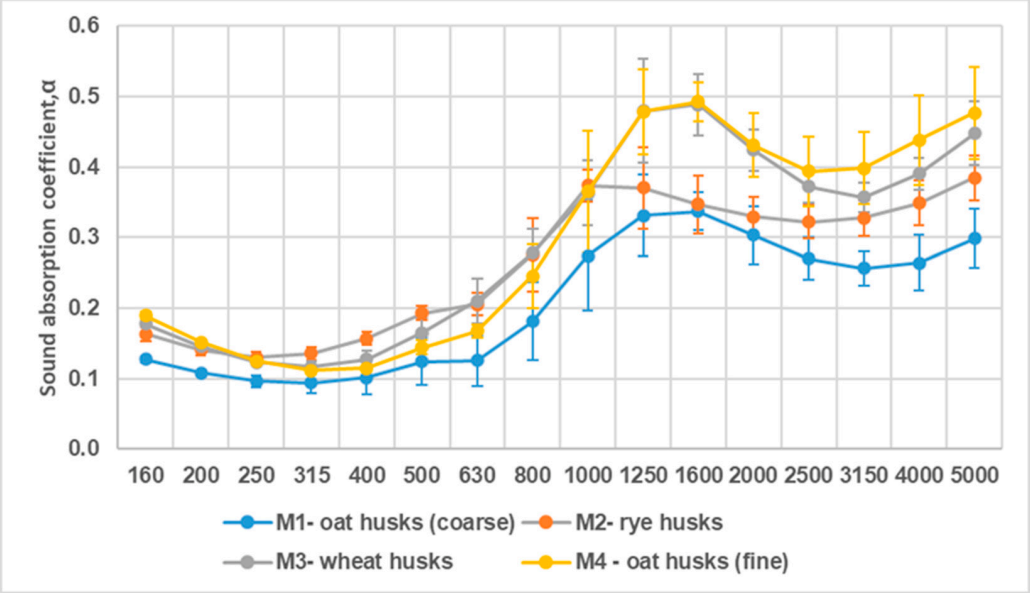


Figure 6. Results of the sound absorption coefficient of different MBC samples.

Sound absorption results obtained from the MBC of coarse oat husks and mycelium indicate moderate sound absorption properties, with relatively better sound absorption occurring at mid-to-higher frequencies—at 1250 Hz (sound absorption coefficient of 0.33) and 1600 Hz (sound absorption coefficient of 0.34). The sound absorption results obtained from the rye husks and mycelium MBC indicate moderate sound absorption, with relatively better sound absorption occurring in the mid-to-higher frequencies—at 1000 Hz (sound absorption coefficient of 0.37) and 1250 Hz (sound absorption coefficient of 0.37). The sound absorption results obtained from the wheat straw and mycelium MBC indicate moderate sound absorption, with relatively optimal sound absorption occurring in the mid-to-high frequencies—at 1250 Hz (sound absorption coefficient of 0.48) and 1600 Hz (sound absorption coefficient of 0.49). Sound absorption results obtained from an MBC of

fine oat husks and mycelium indicate moderate sound absorption, with relatively better sound absorption occurring at mid-to-high frequencies—specifically at 1250 Hz (sound absorption coefficient of 0.48) and 1600 Hz (sound absorption coefficient of 0.49). In all cases, no significant sound absorption was observed at lower frequencies (160–800 Hz), as the samples were too thin to effectively absorb longer low-frequency sound waves.

3.2. Comparison of the Mycelium-Based Specimens and Commercially Available Acoustical Panel Sound Absorption Coefficients

After the absorption tests were conducted with the MBC specimens, the obtained results were compared with those of the commercially produced 'Mono' acoustical panel Elegant Render (color) model (Figure 7).

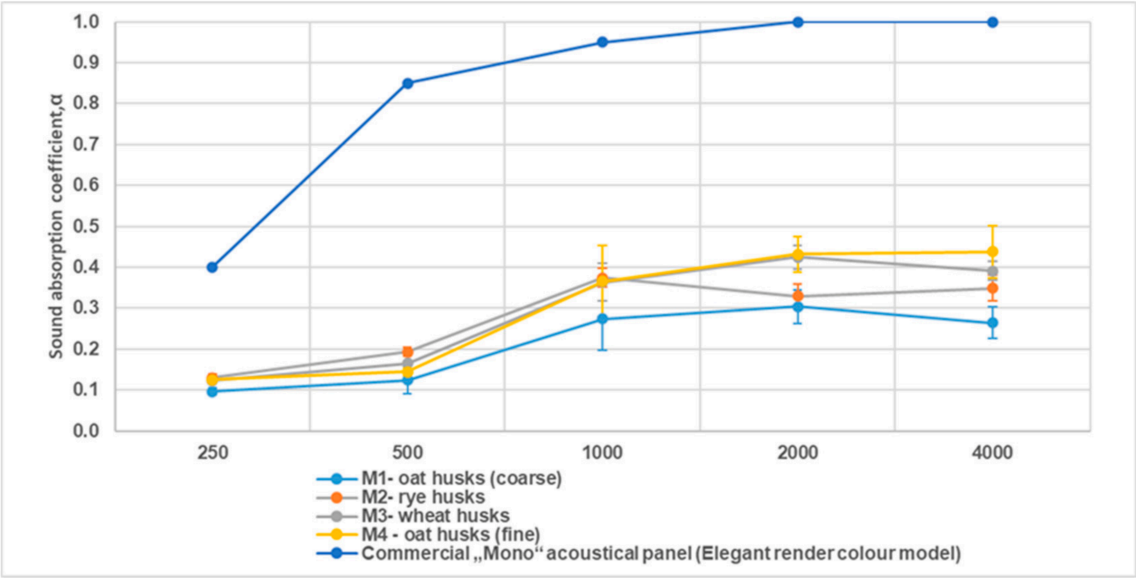


Figure 7. Comparison of sound absorption coefficient results of MBC specimens and the commercially available "Mono" acoustical elegant render (color) model.

The sound absorption performance of the commercially produced 'Mono' Acoustical Elegant Render (color) model (2.5 cm thickness) was as follows: the sound absorption coefficient reached 0.10 at 125 Hz, 0.40 at 250 Hz, 0.85 at 500 Hz, 0.95 at 1000 Hz, and 1.00 at both 2000 and 4000 Hz. The frequency scale for comparison was selected in accordance with the methodology used for the commercially produced 'Mono' Acoustical Elegant Render (color) model results (250–4000 Hz) [56]. The physical properties of the MBC specimens and the commercially available acoustical panel are presented in Table 5.

Table 5. MBC specimen physical properties comparison with commercially available "Mono" acoustical Render (color) model.

Product	Weight	Thickness
Commercial "Mono" acoustical panel (Elegant render color)	6 kg/m^2	2.5 cm
Biocomposite (Oat husks (fine))	6.93 kg/m^2	1.27 cm
Biocomposite (Wheat husks)	6.2 kg/m^2	1.3 cm
Biocomposite (Rye husks)	5.97 kg/m^2	1.26 cm
Biocomposite (Oat husks (coarse))	7.8 kg/m^2	1.1 cm

To achieve more effective sound absorption at low frequencies, the samples should be fabricated with greater thickness in future studies. Overall, the results obtained at higher frequencies are promising. Commercially produced acoustic panels with a thickness of 2.5 cm typically achieve sound absorption coefficients of approximately 0.8–1 at higher frequencies [56]. Therefore, by optimizing the composition of the samples and refining key physical properties, such as thickness and density, it would be possible to further enhance the sound absorption performance of the specimens.

3.3. Results of the Mycelium-Based Biocomposite Life Cycle Assessment

After completing the life cycle assessment of the mycelium-based composite panel, results were obtained on all the environmental impact categories provided by the ReCiPe life cycle assessment method, 18 midpoint values.

The life cycle assessment of the mycelium-based acoustic insulation panel revealed a global warming potential of 3.271 kg CO_2 eq and a stratospheric ozone depletion potential of 3.6×10^{-6} kg CFC11 eq. The impact associated with ionizing radiation reached 0.062 kBq Co-60 eq, while ozone formation was 0.008 kg NOx eq for human health and 0.0085 kg NOx eq for terrestrial ecosystems. Fine particulate matter formation was 0.0043 kg $PM_{2.5}$ eq, terrestrial acidification reached 0.0092 kg SO_2 eq, freshwater eutrophication 2×10^{-4} kg P eq, and marine eutrophication 4.6×10^{-4} kg N eq. Terrestrial ecotoxicity was 12.348 kg 1.4-DCB, with freshwater and marine ecotoxicity of 0.0036 kg 1.4-DCB and 0.0104 kg 1.4-DCB, respectively. Human carcinogenic and non-carcinogenic toxicity potentials were 0.0526 kg 1.4-DCB and 1.188 kg 1.4-DCB. In terms of resource-related indicators, land use amounted to 0.958 m^2a crop eq, mineral resource scarcity to 0.011 kg Cu eq, and fossil resource scarcity to 1.152 kg oil equivalent, which was subsequently converted to megajoules (MJ) by applying a conversion factor of 42 MJ per kilogram of oil equivalent, reflecting the average lower heating value (LHV) of crude oil in order to make it comparable with the commercially produced acoustical panel results provided in MJ, while total water consumption over the life cycle was 0.0901 m^3. The results are presented in Table 6.

Table 6. Results of the 18 midpoint categories.

Impact Category	Unit	Total Impact
Global warming	kg CO_2 eq.	3.271
Stratospheric ozone depletion	kg CFC11 eq.	0.0000036
Ionizing radiation	kBq Co-60 eq.	0.062
Ozone formation, Human health	kg NO_x eq.	0.008
Fine particulate matter formation	kg PM2.5 eq.	0.0043
Ozone formation, Terrestrial ecosystems	kg NO_x eq.	0.0085
Terrestrial acidification	kg SO_2 eq.	0.0092
Freshwater eutrophication	kg P eq.	0.0002
Marine eutrophication	kg N eq.	0.00046
Terrestrial ecotoxicity	kg 1.4-DCB	12.348
Freshwater ecotoxicity	kg 1.4-DCB	0.0036
Marine ecotoxicity	kg 1.4-DCB	0.0104
Human carcinogenic toxicity	kg 1.4-DCB	0.0526
Human non-carcinogenic toxicity	kg 1.4-DCB	1.188
Land use	m^2a crop eq.	0.958
Mineral resource scarcity	kg Cu eq.	0.011
Fossil resource scarcity	kg oil eq.	1.152
Water consumption	m^3	0.0901

In the LCA analysis of the developed eco-friendly biocomposite alternative to a commercially available acoustic insulation panel, a generalized "Straw {RER} | market for

straw | Cut-off" process was applied, assuming that cereal crops are cultivated under similar conditions and that significant differences in emissions would therefore be negligible. However, to verify whether such differences exist, additional LCA analyses were conducted for each substrate type (oat, wheat, and rye chaff), comparing their respective production processes ("rye husks production at farm, LT", "wheat husks production at farm, LT", and "oat husks production at farm, LT").

From the obtained results, global warming potential, freshwater eutrophication potential, water depletion potential and fossil depletion potential were compared to the commercially available acoustic panel made from stone wool [50]. The results showed that the MBC acoustic panel prototype made from agricultural waste (substrates) and oyster mushroom (Pleurotus ostreatus) mycelium generates 49.9% less kg of CO_2 equivalent than the stone wool panel (3.27 kg vs. 6.53 kg) across all system boundaries, contributing far less to global warming (Figure 8a). When comparing the MBC panel by fossil depletion potential, the required fossil resource amount was 52.2% lower than that of the commercially available stone wool acoustic panel (Figure 8b). Both global warming potential and fossil depletion potential are categories that are closely connected to energy consumption, which is known to be the highest contributor to the environmental impact of mycelium-based composites.

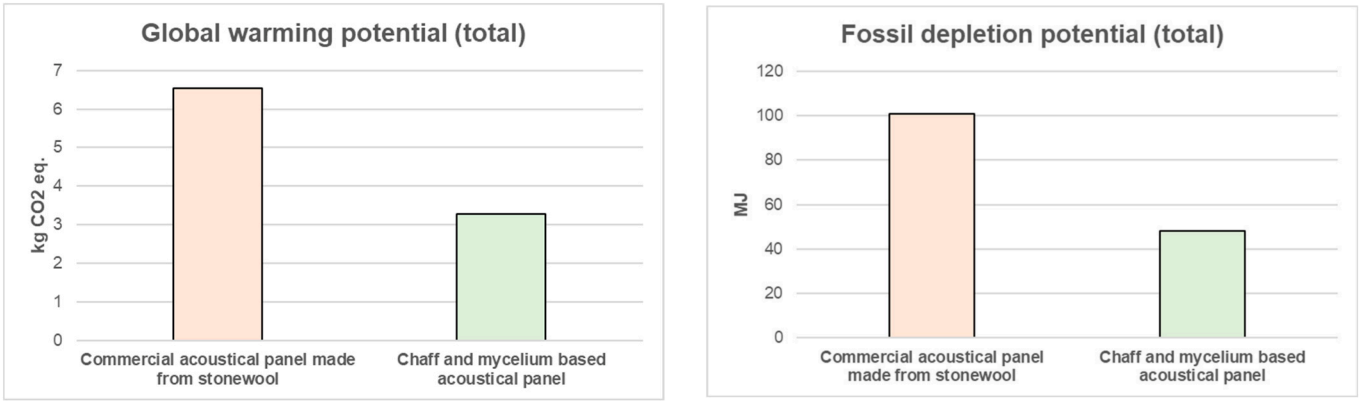


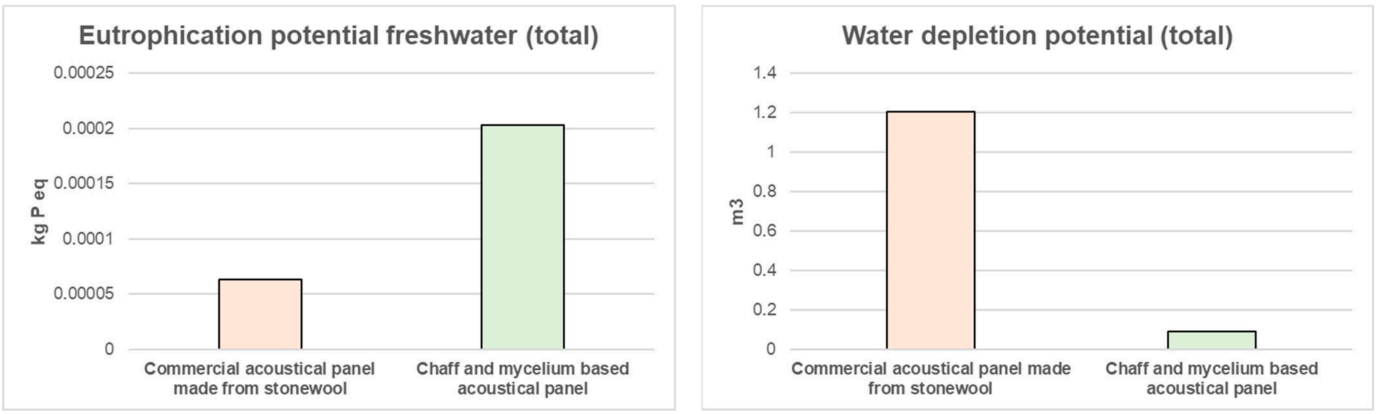
Figure 8. Global warming potential and fossil depletion potential results: (**a**) global warming potential comparison between MBC acoustic insulation panel and stone wool panel; (**b**) fossil depletion potential comparison between MBC acoustic insulation panel and stone wool panel.

Another known resource heavily affected by the production of MBCs is water. The closest impact categories representing water consumption, also provided for the stone wool acoustic insulation panel, are water depletion potential and eutrophication potential (freshwater) (Figure 9). Eutrophication potential (freshwater) was found to be more than three times higher (321.71%) for our mycelium-based acoustic insulation panel than that of the stone wool panel (0.0002030 kg of P eq vs. 0.0000631 kg of P eq). However, water depletion potential for the MBC panel was found to be more than thirteen times lower (1336.3% lower) than that of the stone wool acoustic insulation panel (0.0901 m^3 vs. 1.204 m^3).

The results show that when compared to a commercially available acoustic insulation panel, the MBC panel requires fewer fossil resources and has a lower carbon footprint, while also requiring less water resources. However, the downside of such a biocomposite is that it has a higher impact on freshwater ecosystems, as the eutrophication potential is more than three times higher.

After completing the comparison between the MBC panel and the commercially available stone wool panel, it was found that freshwater system eutrophication potential was exceedingly high for the MBC panel, so another life cycle analysis was completed,

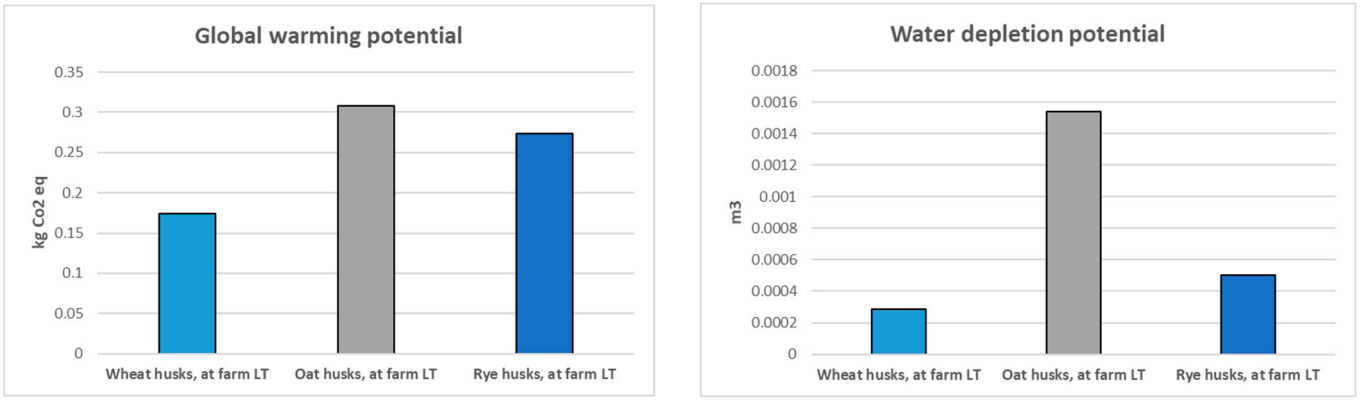
taking into account only the production stage of the mycelium-based composite panel, with an emphasis on the modeling of the chosen substrate (Oat, wheat, and rye husks).



(**a**) (**b**)

Figure 9. Eutrophication potential (freshwater) and water depletion potential results: (**a**) eutrophication potential (freshwater) comparison between MBC acoustic insulation panel and stone wool panel; (**b**) water depletion potential comparison between MBC acoustic insulation panel and stone wool panel.

After the additional LCA was completed with the functional unit being 1 kg of the chosen agricultural waste and the boundaries limiting the analysis only to the production stage, the results were compared for all three different substrates. It was found that wheat husks contribute the least to global warming potential—0.174 kg of CO_2 eq, if using oat husks—0.308 kg of CO_2 eq; rye husks—0.273 kg of CO_2 eq (Figure 10a). The same tendency can be seen with the results of water depletion potential, where the least amount of water is consumed during the production stage of wheat husks (0.000284 m^3). The highest water resource depletion potential occurs when using oat husks (0.00154 m^3), while rye husks reach 0.0005 m^3 (Figure 10b).



(**a**) (**b**)

Figure 10. Life cycle assessment results of the different substrates of MBC: (**a**) global warming potential of the different substrates; (**b**) water depletion potential of the different substrates.

In the case of freshwater eutrophication potential, the same trend is observed, where the substrate from wheat husks has the lowest impact. The wheat husk freshwater eutrophication potential value would reach 0.0000809 kg of P eq. When rye husks are used, this indicator would reach 0.000150352 kg of P eq., while the use of oat husks would contribute the most to freshwater ecosystem eutrophication (0.000164 kg P eq.) (Figure 11).

After the life cycle assessment results were gained, it was found that the MBC panel was superior to the stone wool panel in all compared impact categories except freshwater

eutrophication potential. Trying to lower this environmental impact, a life cycle assessment of the different substrates was completed, finding that wheat husks have the lowest impact in the same analyzed categories (global warming potential, water depletion potential, and freshwater eutrophication potential) when compared to rye or oat husks and is the preferred substrate if the goal is to achieve the lowest environmental impact possible, while using agricultural wastes. The interpretation of both acoustic and life cycle assessment results is provided in the Discussion Section.

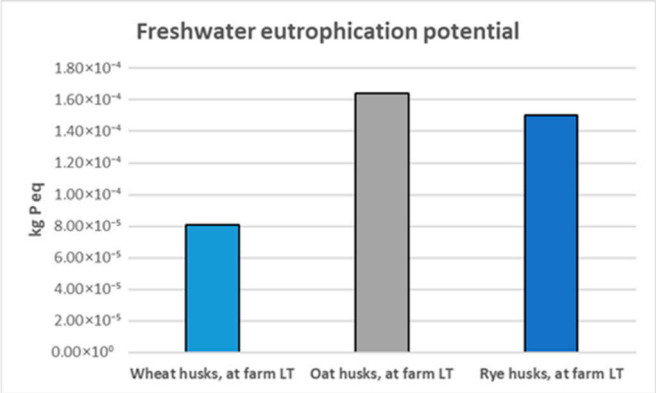


Figure 11. Freshwater eutrophication potential result of different substrates.

4. Discussion

The testing of the physical properties and sound absorption coefficient of mycelium-based composites (oyster mushroom and various substrates (Oat, rye, and wheat)) revealed that all tested specimens exhibited moderate sound absorption in the mid-to-high frequency range (1000–1650 Hz), where the sound absorption coefficients ranged from 0.33 to 0.49 (Figure 6). No significant sound absorption was observed at lower frequencies. As this is a prototype MBC, further improvement will be sought in the composition of the biocomposite to increase its sound absorption qualities at lower frequency ranges.

The MBC made from coarse oat husks exhibited the lowest sound absorption properties (sound absorption coefficient of 0.33–0.34 at the mid-to-high frequency range). This sample had the highest density (0.77 g/cm^3) and the thinnest thickness (1.1 cm), so the denser structure reduced the number of open pores and air movement within the material, resulting in less sound energy loss and, consequently, lower sound absorption coefficients.

The rye and wheat husk/straw mycelium-based composites had a lower density (0.47 g/cm^3) and greater thickness (1.26 cm and 1.3 cm, respectively) and volume (8.94 cm^3 and 9.18 cm^3, respectively), which created more favorable conditions for the loss of sound wave energy within the material. The wheat husk/straw biocomposite showed relatively good results, with sound absorption coefficients reaching up to 0.49 at higher frequencies. This may be attributed to a favorable pore structure and a larger internal surface area.

The biocomposite made from fine oat husks, which had a more porous structure, exhibited the best sound absorption properties. The finer particles allowed the mycelium to cover the substrate more evenly, forming more individual and interconnected pores. This facilitated more effective absorption of sound energy, particularly in the mid-to-high frequency range.

After analyzing the results, it is clear that the sound absorption properties of mycelium-based biocomposites directly depend on their physical characteristics: density, thickness, and substrate particle size. Lower density, greater thickness, and finer substrate fractions create more favorable conditions for more effective sound absorption, as observed in the cases of wheat (sound absorption coefficient of 0.48–0.49 in the mid-to-high frequency range), rye (sound absorption coefficient approx. 0.37 in the mid-to-high frequency range)

and fine oat (sound absorption coefficient of 0.48–0.49 in the mid-to-high frequency range) husk/straw specimens. The physical property results show that smaller particle size, lower density and higher porosity allow better dispersion of sound waves that hit the MBC's surface. This is also confirmed by the existing literature [57,58]; when the sound wave enters the porous structure of the MBC, which is more intricate with a longer and denser network of pores, if finer particle sizes are used for substrates, the sound waves travel through the pores, repeatedly hitting the pore walls and dissipating more effectively, turning the sound wave to heat through friction. Lower density indicates a more porous material. The results obtained show that mycelium and agricultural waste substrate biocomposites have the potential to be used as eco-friendly sound-absorbing materials in interior acoustics solutions, particularly where attenuation of mid and high-frequency sounds is a priority. However, these novel MBCs show no significant sound absorption properties in the low frequency range. Modifying the preparation and production of MBCs to achieve higher sound absorption results at low frequencies is a possible further topic of research, as well as improving the sound absorption coefficient further to be closer to that of commercially available solutions.

After the sound absorption properties were determined, an LCA was completed, evaluating the whole product chain of the novel mycelium-based composite, simulating its production in the Eastern European geography, more specifically, the country of Lithuania. Evaluation of the MBC panels' environmental impact was conducted by employing the ReCiPe Midpoint hierarchist LCA method. The boundaries were set to cradle to grave, and a functional unit of 1 m^2 of MBC acoustic insulation panel was chosen.

The MBC acoustic insulation panel LCA results indicate that the mycelium-based acoustic insulation panel exhibits a global warming potential of 3.271 kg CO_2 eq across its cradle-to-grave life cycle, a stratospheric ozone depletion of 3.6×10^{-6} kg CFC11 eq and an ionizing radiation impact of 0.062 kBq Co-60 eq. Ozone formation potential was 0.008 kg NOx eq (human health) and 0.0085 kg NOx eq (terrestrial ecosystems), with fine particulate matter formation at 0.0043 kg $PM_{2.5}$ eq and terrestrial acidification at 0.0092 kg SO_2 eq; eutrophication effects included freshwater (2×10^{-4} kg P eq) and marine (4.6×10^{-4} kg N eq) contributions. Toxicity profiles showed a terrestrial ecotoxicity of 12.348 kg 1,4-DCB and freshwater/marine ecotoxicity of 0.0036 and 0.0104 kg 1,4-DCB. Human health risks were 0.0526 kg 1,4-DCB carcinogenic and 1.188 kg 1,4-DCB non-carcinogenic. Land use was at 0.958 m^2a crop eq, mineral scarcity at 0.011 kg Cu eq, fossil resource scarcity at 1.152 kg oil eq, and water consumption at 0.0901 m^3 per m^2 panel—highlighting opportunities for optimization in substrate selection and energy-intensive drying processes compared to commercial stone wool alternatives.

After comparing the LCA results of the commercially produced stone wool acoustic panel with those of a biocomposite made from fungal mycelium (oyster mushroom) and agricultural waste substrate (oat, rye, and wheat husks/straw), which could serve as an ecological alternative, the results revealed that this MBC acoustic panel alternative demonstrates more than 13 times lower water consumption throughout its entire life cycle (0.0901 m^3 vs. 1.204 m^3 (Figure 9b)), nearly two times lower global warming potential (3.27 kgCO_2eq. vs. 6.53 kgCO_2eq. (Figure 8a)), and also contributes two times less to fossil fuel depletion (48.236 MJ vs. 100.973 MJ (Figure 8b)). However, the results also showed that such an acoustic panel alternative contributes approximately three times more to freshwater ecosystem eutrophication (Figure 9a). This is mainly because approximately 80% of this alternative acoustic panel consists of cereal husks/straw, and during their production stage, nitrogen, phosphorus, and other nutrient fertilizers are used. These nutrients represent significant risk factors, as their runoff into surface freshwater ecosystems may lead to increased eutrophication.

In order to identify a solution for reducing the impact of the ecological acoustic panel alternative on freshwater ecosystem eutrophication, an additional LCA analysis was conducted, with a different functional unit of 1 kg of the specific substrate (oat, rye, and wheat husks/straw). During this analysis, the use of different types of cereal husks during their production stage (wheat, oat, and rye) was compared. The results indicated that in order to create a biocomposite made from fungal mycelium and cereal culture husks that contribute as little as possible to freshwater ecosystem eutrophication, wheat husks should be used as the primary base material. The life cycle assessment of wheat husk production revealed that the indicator reflecting the impact on freshwater ecosystem eutrophication reaches 0.0000809 kgPeq. In comparison, the use of rye husks would result in a value of 0.000150352 kgPeq., while the use of oat husks would contribute the most to freshwater ecosystem eutrophication (0.000164 kg P eq.) (Figure 11).

When comparing additional environmental criteria related to the use of different cereal husk types in the development of the alternative acoustic panel, it was determined that the use of wheat husks is the most optimal option, as it shows the lowest global warming potential (0.174 kg CO_2 eq.; when using oat husks—0.308 kg CO_2 eq.; rye husks—0.273 kg CO_2 eq.) and the lowest water consumption (0.000284 m^3; rye husks—0.0005 m^3; oat husks—0.00154 m^3) (Figure 10).

All the results show that the best choice out of the substrates used in the mycelium-based composites production, the most environmentally friendly and having the best acoustic properties, was the mixture composed of wheat husks/straw. It has one of the highest sound absorption coefficients (0.49), similar to that of the fine oat husk mixture, and also the lowest environmental impacts throughout all analyzed impact categories, global warming potential, water depletion potential and freshwater eutrophication potential, making this substrate the best choice for the production of MBC sound insulation panel (Figures 10 and 11).

5. Conclusions

The use of MBCs as a construction material helps decrease the environmental impact of the construction industry. After more research is conducted and the sound absorption qualities of mycelium biocomposites are improved, this kind of acoustic insulation material will have the required environmental properties to change its commercially available counterparts. Unlike conventional mineral-based acoustic materials, mycelium-based composites offer additional advantages such as biodegradability, potential for composting at end-of-life, and reduced environmental and health impacts, making them promising candidates for sustainable building applications. The LCA analysis results are provided for all 18 midpoint categories as a reference point. At the current stage, our novel MBC panel already has a lower carbon footprint (49.9% lower), lower consumption of water (1336.3% lower) and requires fewer fossil resources (52.2%) than the commercially available stone wool panel. The only environmental impact category that is higher than its stone wool counterpart is freshwater eutrophication potential (321.71% higher), because of the use of fertilizers during the production of the different substrates, which is later used to grow the mycelium fungi (oyster mushroom).

It was also found that, from the four different agricultural waste substrates (oat, rye, and wheat husks/straw), the best environmental and acoustic properties were those of the wheat substrate. The wheat substrate exhibited promising sound absorption qualities (sound absorption coefficient of 0.48–0.49 in the mid-to-high frequency range) and had the lowest global warming potential (0.174 kg CO_2 eq.), water depletion potential (0.000284 m^3), and freshwater eutrophication potential (0.0000809 kgPeq) from all the other substrates. While the fine oat husk MBC had similar acoustic properties (sound absorption coefficient

of 0.48–0.49 in the mid-to-high frequency range), it was the highest in all of the analyzed environmental impact categories: global warming potential (0.308 kg CO_2 eq.), water consumption (0.00154 m^3) and freshwater ecosystem eutrophication (0.000164 kg P eq.). While coarse oat husks and rye husk performed comparatively worse acoustically (sound absorption coefficient of 0.33–0.34 and 0.37, respectively, in the mid-to-high frequency range), rye husks have a comparatively average environmental impact in the selected categories: global warming potential (0.273 kg of CO_2 eq), water consumption (0.0005 m^3) and freshwater ecosystem eutrophication (0.000150352 kg of P eq.).

A downside of the MBC is the fact that comparing the acoustical properties of this biocomposite to a commercially available "Mono" acoustical (elegant render color model) panel, the MBC only shows average sound absorption (maximum sound absorption coefficient reached 0.49 at 1600 Hz and higher frequencies compared with maximum sound absorption coefficient of 0.95 at 1000 Hz and 1 at 2000 Hz and higher frequencies (Figure 7). However, such commercial acoustic panels are usually thicker (2.5 cm compared to MBC, 1.1–1.3 cm), and their volume is around 6 kg/m^2 compared to MBC specimens, 5.97–7.8 kg/m^2. There is room for improvement by further refining the physical properties of the MBC material: increasing porosity and thickness and lowering density, and by applying different preparation and production techniques, the results can be improved. The further enhancement of the acoustic properties is a future research goal.

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Abbreviations

The following abbreviations are used in this manuscript:

MBC	Mycelium-based composite
LCA	Life cycle assessment
GHG	Greenhouse gases
kg CO_2 eq.	Kilograms of carbon dioxide equivalent
kg CFC11 eq.	Kilograms of trichlorofluoromethane equivalent
kBq Co-60 eq.	Kilobecquerels of Cobalt-60 equivalent
kg NO_x eq.	Kilograms of nitrogen oxides equivalent
kg $PM_{2.5}$ eq.	Kilograms of fine particulate matter equivalent
kg SO_2 eq.	kilograms of sulfur dioxide equivalent
kg P eq.	Kilogram of phosphorus equivalent
kg N eq.	kilograms of nitrogen equivalent
kg 1.4-DCB	kilograms of 1,4-dichlorobenzene equivalent (toxicity potential)
m^2a crop eq.	square meter-years crop equivalent (land use impact)
kg Cu eq.	kilograms of copper equivalent (resource scarcity)
kg oil eq.	kilograms of oil equivalent (42–46 MJ/kg)
MJ	Mega joule (unit of energy measurement)

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