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RETHINKING MATERIAL CYCLES: COMBINING MYCELIUM AND PAPER WASTE FOR THE DEVELOPMENT OF SOUND ABSORBERS.

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ABSTRACT

Due to different environmental challenges, using sustainable materials has become increasingly important. Mycelium-based materials show promising potential in many applications within architecture, such as sustainable acoustic absorbers. Here we present results on the acoustic and thermal performance of mycelium panels that use paper waste as substrate for the growth of Pleurotus Ostreatus. Regarding the substrate choice, the potential application of the widely accessible residue material in combination with acoustic application was examined. Mycelium-based materials show a sustainable life cycle, which is amplified by using residual materials as a base. The panels were created using different growing times and mixtures of inoculated and non-inoculated substrate and dried in convection ovens to deactivate the fungi and remove the moisture excess. Samples were tested using an in-situ method with a Pressure-Particle velocity probe (PU probe). The acoustic absorption turns out to be highly dependent on the processing method, growing time and mixture use, though overall maximum absorption is found around 1kHz. The thermal conductivity was found to be around 0.07 W/(m.K).

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1. INTRODUCTION

The increasing urgency of environmental challenges has led to a growing interest in developing sustainable and functional materials. Mycelium-based composites have emerged as a particularly promising class of biomaterials due to their biodegradability, renewability, and ability to repurpose waste. Formed from the filamentous root structure of fungi, mycelium can bind together various lignocellulosic substrates into lightweight, insulating, and biodegradable composites. Their potential as an alternative to conventional, resource-intensive construction materials positions them at the forefront of sustainable innovation in architecture and design [1].

Among the various applications of mycelium-based materials, acoustic conditioning is gaining traction. Mycelium panels have shown significant sound absorption capabilities, particularly in the mid-frequency range around 1kHz, making them suitable for use in interior environments seeking eco-friendly acoustic solutions. The structure of the mycelium network, combined with the porosity of the substrate, contributes to these properties. Traditional acoustic materials such as fiberglass and polystyrene often come with health or environmental drawbacks, thus supporting the application of mycelium as a safer, greener alternative [1].

Most fungal strains used for the development of mycelium composites are saprotrophic Basidiomycota, thus, nutrient-rich lignocellulosic materials such as wood, hemp, straw, or cotton are effective substrates for mycelium growth [2]. Paper waste, an abundantly available lignocellulosic material, was chosen as the substrate for this research. Cultivating mycelium on paper waste has substantial potential to be a cheap and sustainable solution. Paper waste follows a complex life cycle, typically beginning as virgin fiber harvested from trees and processed into paper products for packaging, printing, or hygiene purposes. After use, a part of this material enters recycling streams, while the rest, especially low-grade or contaminated paper, ends up in landfills or incinerators, contributing to carbon emissions. Even when recycled, paper fibers degrade in quality, eventually becoming unsuitable for further reuse and becoming a waste burden. Repurposing this terminal-stage paper waste as a substrate for mycelium growth presents a sustainable alternative that intercepts the material before disposal. Rich in cellulose, this waste becomes a nutrient source for fungal colonization. Using waste cardboard and paper not only diverts significant volumes of material from landfills but also enhances the circular economy by transforming low-value residues into high-performance biomaterials [3]. Moreover, this approach reduces the environmental footprint of the material production process and opens up possibilities for decentralized, local manufacturing of building materials.

The fabrication of mycelium composites requires careful control of several variables, including substrate composition, moisture levels, pH, temperature, and sterilization procedures. Failure to optimize these conditions can result in contamination, uneven growth, or insufficient binding strength. Research has shown that substrates rich in cellulose and hemicellulose, like paper products, can support fungal growth, especially when paired with fungi such as Pleurotus Ostreatus [1], [3].

Recent studies have also highlighted the role of processing variables such as growing time and the use of mixed inoculated and non-inoculated substrate batches. These parameters significantly affect the mechanical and acoustic properties of the final composites [2]. For instance, longer growth periods typically lead to denser mycelial networks [4], while different substrate blends can influence porosity and structural cohesion. Post-growth treatments like oven-drying are critical to halting fungal activity and stabilizing the material [3], [5].

This paper investigates the performance of mycelium panels grown on wastepaper substrates in combination with fungal species Pleurotus Ostreatus, emphasizing their acoustic absorption and thermal conductivity and the influence of different parameters. Section 2 defines the methodology followed to develop the mycelium composites and the techniques used for its characterization, section 3 includes the results and discussion on the materials performance.

2. MATERIALS AND METHODS

2.1 Materials and sample preparation

Shredded paper and Pleurotus Ostreatus spawn were acquired from the Universidad Politécnica de Madrid recycling center and by a local provider in Spain, respectively.

The general procedure for the development of the mycelium composite consisted in different stages: sterilization of the substrate, inoculation and mixing, cultivation and a drying process.

Paper was introduced into a pot with water taking it to the boiling point for approximately two hours to reduce potential contamination. After cooling, mycelium spawn and the sterilized substrate were mixed in a food processor, avoiding paper paste lumps and distributing the mycelium spawn in the substrate, resulting in a looser and lighter texture. The mix was filled into 3D printed square molds, of 15 x 15 x 4 cm^3, with small openings on four sides allowing for airflow, promoting uniform growth. The samples were placed inside a curing chamber, which kept the humidity at relative 90%, and the temperature at 22°C. Upon reaching the desired growth time, the samples were dehydrated in a convection oven at a temperature of 40˚C until reaching constant weight. Fig. 1 shows a generalized procedure on the mycelium composite development process.

Three different mycelium composite types were developed. In all cases the amount of mycelium spawn, substrate and the total mass of the mixture before drying were kept constant at 68.5% for paper waste and 31.5% mycelium spawn and 0.4 kg for the total mass of the composite, corresponding to a density of 0.44 g/cm^3.

The main variable was the incubation time, Group A was let to grow for 4 days, group B for 14 days and group C 19 days. Fig. 2 shows a diagram of the compositions and growing time for each sample group.

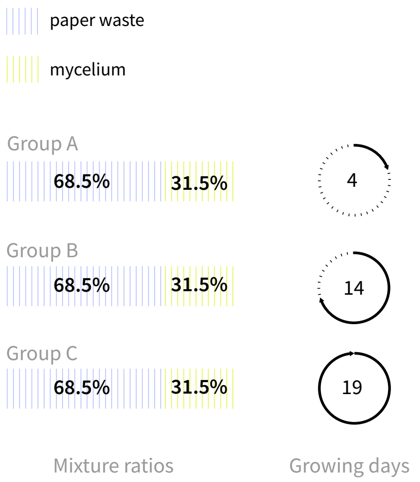

Figure 1. Generalized paper-based mycelium composite developing process.

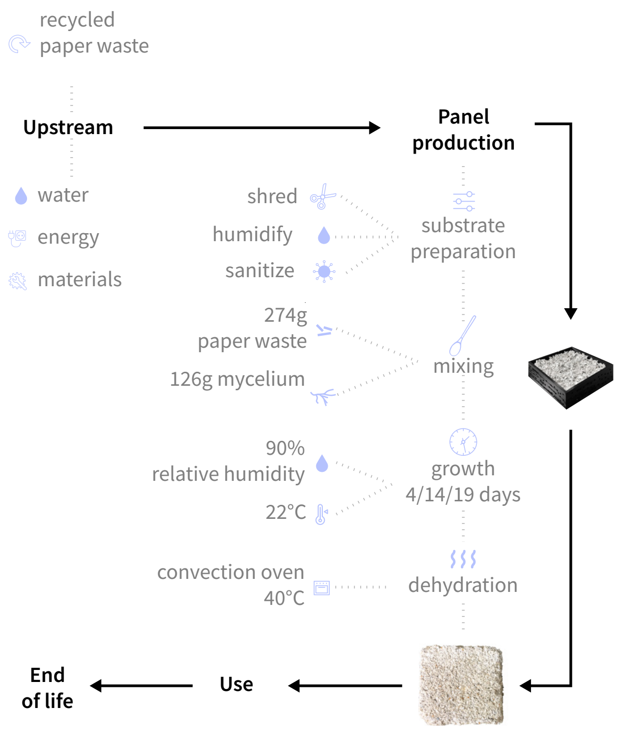

Figure 2. Mixture ratio and growing times for different paper-based mycelium composites.

2.2 Sound absorption coefficient

A Microflown Technologies' PU impedance gun (In-situ sound absorption testing setup), was employed to perform sound absorption measurements. This equipment includes a spherical loudspeaker along with a combined pressure and particle velocity sensor (PU probe). The measurements were conducted across a frequency range of 500 Hz to 8 kHz. During the tests, the loudspeaker generated broadband noise, and the PU probe simultaneously captured pressure and velocity data. The plane wave model was selected for calculating the sound absorption coefficient in this study, owing to its minimal sensitivity to variations in the measurement environment and the distance between the probe and sample surface, as well as its alignment with results from the impedance tube method [6]. Atmospheric conditions (pressure and temperature) were integrated into the model. While reflections from surrounding objects could theoretically influence outcomes, their effect was negligible in practice due to the proximity between the sample and the PU probe. Nevertheless, prior to measurements, the impedance gun was calibrated under free-field conditions to minimize interference. The absorption coefficient was determined as the average of three measurements conducted at the sample's. center.

2.3 Thermal conductivity

The thermal conductivity of the samples was measured using the heat flow meter method. A heat flow meter model HFM 436 Lambda was used, samples were placed between two heated plates, set at different temperatures. A calibrated heat flux transducer measured the heat flow through the sample, following EN ISO 12667 standard. The thermal conductivity was measured at 5-degree intervals over the temperature range of 15°C to 35°C.

3. RESULTS AND DISCUSSION

Once the growing and drying of the mycelium based composites was finished, the density of the samples was calculated, Table 1, shows the results by each composite group.

Table 1. Density of Mycelium composites after drying for the different sample types.

Sample	Density(kg/m³)
A	318 ± 21
B	240 ± 18
C	257 ± 51

The average results for sound absorption coefficient on each sample type and standard deviations are shown in Fig 3. Typical porous materials behaviour is observed for all samples, with the sound absorption being low at low frequencies. Towards higher frequencies, the three groups showed a similar particularity, with a first peak around 1 kHz, and a considerable dip around 2.5kHz. There are also some systematic differences between the different sample groups. Group C shows as an offset from the other curves, thus might be due to a reduced porosity, given the longer cultivation time, the mycelium had more time to grow over the porous network of the samples.
It is expected that the first absorption peak would be related to a particle velocity maxima associated with the thickness of the sample. It was observed that the first absorption peak was obtained around 1 kHz instead of 1.7 kHz, suggesting that this material has a high tortuosity which would slow down acoustic waves, effectively making the path of the wave larger.

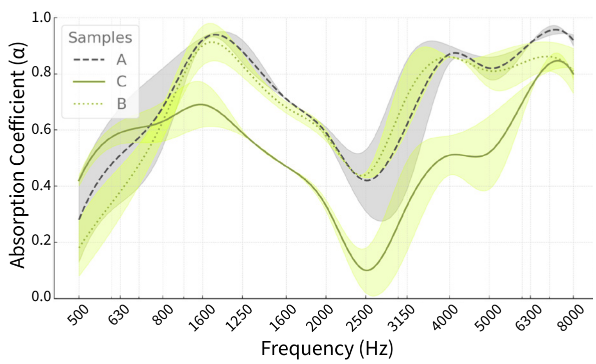

Figure 3. Sound absorption coefficient for different paper based mycelium composite samples.

Figure 4 shows the thermal conductivity for the developed samples in the range of temperatures from 15 to 35 in steps of 5. It is observed that the as temperature increases so does the thermal conductivity, aside from that, by a small margin, group B has a increased performance compared to the other types of samples, with group C showing the higher thermal conductivity consistently thorough the temperature range.
As heat transport is strongly influenced by the porosity and density of a material, the differences in thermal conductivity between group C and the others could be associated with a decreased porosity as shown in table 1, the densities of sample group C and B are comparable, and regardless of that it shows higher thermal conductivity.

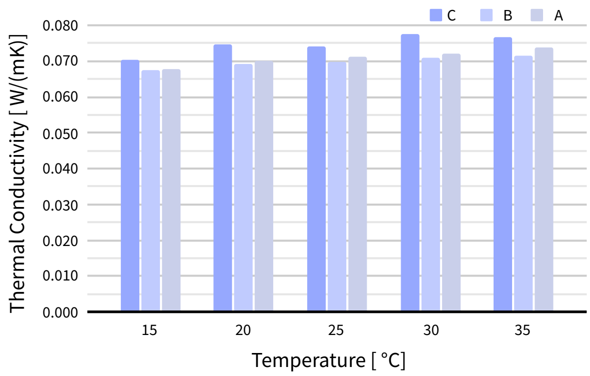

Figure 4. Thermal conductivity in function of temperature for different the developed mycelium composites.

Table 2 shows the average thermal conductivity of the samples after testing them at temperatures ranging from 15-35°C. All types of samples showed low variance in thermal conductivity among the different temperatures.

Table 2. Thermal conductivity for mycelium composites.

Sample	Thermal conductivity (W/m·K)
A	0.071 ± 0.002
B	0.070 ± 0.002
C	0.075 ± 0.003

Thermal conductivity performance shows more insulating capabilities that other mycelium based materials and are close to 0.06 W/(m·K), below which the material could be considered thermally insulating. Thus if the fabrication method is slightly improved it could position the material as a potential replacement for mineral-based wools for instance in vertical partition walls.

4. CONCLUSIONS

This study confirms that paper-based mycelium composites are also effective as absorbing materials, particularly in the mid-frequency range. The findings emphasize the importance of substrate selection and growth duration in tuning both acoustic and thermal performance. The peak absorption around 1 kHz in a 4 cm thick sample suggests a surprisingly high tortuosity which should be confirmed on a later stage by direct characterization.

Among the three sample types, those with longer incubation time, hence higher colonization, showed lower sound absorption coefficient.These insights support the continued development of mycelium-based composites as low-impact alternatives to synthetic insulation materials. Future work should explore optimized mold geometries, thicker sample configurations for low-frequency performance, and quantitative modeling using Johnson-Champoux-Allard frameworks to further refine acoustic predictions.

5. ACKNOWLEDGMENTS

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