Growing a Mycelium Composite Insulation Material for Non-Combustible Applications

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Background Information

The construction industry has shown a growing interest in sustainable alternatives to traditional insulation materials, which are often energy-intensive to produce and difficult to revalorize at end-of-life. Fibreglass and Rockwool, for example, require significant energy for production due to the high temperatures needed to melt and fiberize glass or rock material, contributing to their overall Global Warming Potential (GWP), e.g. the net amount of greenhouse gases emitted during a product's life cycle as a metric for its contribution to climate change (Füchsl, Rheude, & Röder, 2022). Furthermore, the disposal of fibreglass poses environmental challenges as it generally ends up in landfills with limited potential for recycling (Biermeier, 2010). Since fibreglass insulation is currently dominating the insulation market in the US, innovative materials with similar applications could have a large-scale impact (Home Innovation Research Labs, 2019). As a promising alternative, bio-based materials have emerged, capable of biodegrading at end-of-life with fewer energy requirements for manufacturing. However, no bio-based insulations have been developed for non-combustible applications, making it difficult to replace conventional materials in high occupancy buildings such as schools, hospitals, malls, high rises, etc. (Philippe St-Jean, Senior Sustainability Construction Officer at McGill University, personal communication, 11 March 2024). This project focused on a specific type of bio-based material: mycelium composites. Mycelium is the vegetative part of a fungus and can be grown on various organic substrates, resulting in a mixed material composed of degraded substrate and a mycelium structural network. Such materials have shown potential for effective thermal insulation, acoustic absorption, and inherent fire resistance (Elsacker E. V., 2021; Gauvin, Tsao, Vette, & Brouwers, 2021). This project was conducted over the full year of 2024 and targeted the optimization of mycelium-based insulation to meet the environmental and functional demands of sustainable construction. This section summarizes the information and work done over the winter semester. A dedicated report was written to detail the process (Tovar, Bégin, & Parnell, 2024).

The initial stages of this project were directed at researching and gathering information on the different parameters involved in the development of a new bio-based construction material. This led to the development of a Pugh chart (Table 1) to analyze the proper characteristics of the targeted material and its desired functionality. Eight critical parameters were identified and justified for this project's objectives. These included thermal conductivity, fire resistance, moisture and rot resistance, GWP, life expectancy, revalorization potential, and scalability. These weighted factors ensured the material met the complex and multifaceted functional demands of insulation materials, surpassing industry standards in sustainability while demonstrating the potential for scalability and commercial production.

Following these criteria, different options were considered, researched, and evaluated. Slightly outperforming cattail and hemp insulation, mycelium composites showed the best set of characteristics for this project, especially because of their fire-resistant potential. They also offered flexibility on many levels, such as the choice of mushroom strain, growing substrate, additives, and post-growth treatments. However, this versatility also meant that scientific literature to date was not focused on any recipe or process, making the research and later development of growing protocols less straightforward. Two fungal strains, *Trametes versicolor* and *Ganoderma lucidum*, were chosen for their resilience, favourable insulating properties, and local availability. Furthermore, scientific literature was already heavily investigating the properties of these strains and their mycelium for various purposes.

The mentioned research, report, and everything involved in between set the stage for the next eight months of the project, in the summer and fall of 2024, which are covered by the present report. The focus was now on establishing growth parameters, developing a growing protocol, acquiring or building the required equipment, optimizing material properties, and testing their properties to validate the functionality of mycelium composites as a non-combustible insulation material. Finally, theoretical analyses were conducted from all the data collected during the project to assess at a high level the sustainability and scalability of the final product developed.

Table 1. Pugh chart comparing alternative bio-based insulation materials to fibreglass as a baseline for non-combustible applications. Alternative solutions A, B, and C designate mycelium-based, cattail-based, and hemp-based insulation respectively. The two columns for each solution (e.g. A and W-A) represent the score and the corresponding weight for each criterion.

				ALTERNATIVE SOLUTIONS					
#	**Criteria**	**Weight**	**Fiberglass (baseline)**	**A**	**W-A**	**B**	**W-B**	**C**	**W-C**
1	Thermal Insulation	15	0	-1	-15	-2	-30	0	0
2	Fire Resistance	12	0	-1	-12	-3	-36	-3	-36
3	Moisture Resistance	8	0	2	16	2	16	0	0
4	Rot Resistance	5	0	-2	-10	-1	-5	-2	-10
5	Global Waring Potential	15	0	3	45	3	45	3	45
6	Life Expectancy	10	0	-1	-10	0	0	-1	-10
7	Revalorization Potential	10	0	3	30	3	30	3	30
8	Scalability Potential	8	0	-3	-24	-2	-16	-1	-8
	TOTALS		**0**		**20**		**4**		**11**

Abstract

This project explores the designing and development of a mycelium-based composite insulation material to replace conventional insulation with an emphasis on creating a product that is far superior in terms of sustainability. The material is specifically designed for above grade non-combustible settings. Through research and testing, we have determined that mycelium as a binder shows important properties for fire retardation, thermal resistance and the potential for moisture control. Coupled with a bio-based substrate composed of industry byproducts such as hemp or straw, the material produced has the potential to be a more environmentally friendly alternative to conventional insulation products. Throughout the project, many combinations of mushroom strains, substate material and additives were tested to determine the optimal mixture for best performance and growth. The material we produced demonstrated thermal resistance nearing the performance rockwool, while also showing potential for fire retardancy. However, challenges such as moisture control, contamination and strong variation between samples were identified and further research should be conducted to counteract these problems. Sustainability assessment has shown a significant reduction in the material environmental impact from production to disposal, highlighting its potential as a replacement for conventional insulation. Furthermore, the scalability assessment revealed promising results to produce this material at industrial scale, but more research must be conducted to optimise the consistency of the product. This project acts as a proof of concept for the material as a viable alternative while creating a foundation for further research of mycelium-based, biological products as a replacement for insulation materials.

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1. Introduction

This report details the development of a bio-based insulation material designed for non-combustible applications in the context of a Capstone project for BREE 495: Engineering Design 3. Throughout the semester we focused on designing a mycelium-based material that could replace conventional insulation for non-combustible above-grade applications to provide the construction industry with a more environmentally friendly and scalable solution. This problem was identified through discussions with Mr. Philippe St-Jean, Senior Sustainability Construction Officer at McGill University, who provided an insightful industry perspective throughout the project. Mentorship from bio-based materials, bio-inspired materials, and sustainable buildings experts, Dr. Idaresit Ekaette, Dr. Abdolhamid Akbarzadeh and Dr. Michael Jemtrud facilitated the development and testing of this material. Additional mentoring on project management, production methods, mushroom cultivation and controlled environments from Dr. Grant Clark, Mr. William Boyd, the Mycoboutique staff and Dr. Mark Lefsrud were also invaluable for the realization of this project.

The conventional non-combustible insulation industry has had to make strides in its technologies, processes and material choices to become increasingly efficient. Brought on primarily by increasingly stringent building codes and standards, the environmental and health considerations of these products have had to adapt, but the industry still fails to achieve high sustainability performance (Edelenbosch, Rovelli, Levesque, Marangoni, & Tavoni, 2021). Current insulation technologies have very high insulating properties, minimizing the energy losses for building heating and cooling. This results in lower GHG emissions related to heating, but as the energy grid transitions towards renewable sources, the environmental considerations for insulation materials shift away from their thermal efficiency during their useful life towards their production and disposal impacts. In short, sustainable construction consultants in Quebec have noticed that the environmental impacts of manufacturing conventional insulation materials undermine their energy-saving benefits during their useful life (Philippe St-Jean, Senior Sustainability Construction Officer at McGill University, personal communication, 11 March 2024).

This brings us to our designed mycelium-based insulation for above-grade non-combustible settings. This biobased material can reduce energy requirements during production, provide efficient insulation properties and much better disposal options and effects as compared to conventional insulations. The objective of our design is to create a mycelium-based insulation capable of performing equally in terms of thermal insulation, fire and moisture resistance as to conventional insulation. Our design must also be significantly more sustainable during its production and end-of-life phase and show the capability of having a useful life comparable to building life expectancy. Finally, our design must show the potential to be scalable without compromising previous objectives.

The project encompasses an extensive literature review, research, testing and prototyping. The design process initially started with a narrowing of substrate, mushroom strains and additives materials that would be tested. Mycelium composites with hemp, straw-based substrates were determined to be most favorable for our project. *T. versicolor* and *G. lucidum* were selected as the mushroom strains for their properties. The first batches of experiments focused on determining optimal growth conditions and establishing the prime substrate and additive mixtures that would yield the best results in terms of meeting our described goals.

The second phase of our design project focused on testing material properties to evaluate the materials ability to replace conventional insulation. Thermal testing was conducted on a large number of samples to determine thermal conductivity which could be compared to insulations sold on the market. Testing was also completed for fire spread, in order to determine if the product would be applicable in non-combustible settings. Finaly, the material was tested for water vapour permeability and compared to conventional insulation.

The third phase of design focused on determining the sustainability and scalability potential of our mycelium insulation. We performed a small-scale LCA analysis on our designed product and compared the results to conventional insulation LCA's with similar scopes. This phase also determined the life expectancy and the material safety of our product. In terms of scalability, we investigated the cost-competitiveness of our product compared to conventional insulation. We also determined if each step of the laboratory protocol could be reasonably translated to an equivalent industrial process and determined whether key parameters of the bioprocesses could be realistically scalable.

This report is divided into sections to provide context, assumptions, goals, reasonings, design consideration, prototyping, testing, results and conclusion. This report shows the potential of mycelium-based insulation material as a viable sustainable alternative to conventional insulation.

2. Underlying Theory, Assumptions, and Practical Aspects

2.1. Current issues with non-combustible insulation materials

The insulation industry has seen significant changes in the last century. As pressure increases in terms of sustainability in all sectors of manufacturing, the insulation industry has had to adapt. The insulation industry has had a long, troubled history when it comes to human health impacts, like in the case of asbestos, and must therefore remain a leader in sustainability to preserve a fragile public perception. Research and development have gone into producing insulative materials with reduce human health impacts, low cost and lower greenhouse gas emissions (GHG) from household heating all while maintaining efficient thermal resistance. Although the industry has made important strides, little attention was given to reducing GHG emissions during the production of these materials. As the world transitions away from fossil fuel energy grids, the GHG emission savings from reduced heating energy requirement due to insulation are lowered all while shifting the balance of GHG emission towards the production of these products. This is to say that energy efficient insulations are found to undermine their environmental benefits due to high production-phase emissions. Alternative insulation with lower manufacturing GHG emissions already exist on the market but they lack factors such as non-combustibility reducing their adoption in the overall construction industry. The industry is in need of a bio based, sustainable, scalable insulation with low production requirements, low human health impact and high end-of-life revalorisation potential all while maintaining insulative efficiency.

2.2. Why bio-based solutions?

Bio-based solutions have been found to perform better than other insulation types such as inorganic or organic synthetic in terms of environmental risks from raw material acquisition, manufacturing, and end-of-life disposal (Tovar et al., 2024; Füchsl, Rheude, & Röder, 2022; Schulte, Lewandowski, Pude, Wagner, & Moritz, 2021). The factors measured for environmental risk encompass land deterioration, energy consumption, GHG emissions, eutrophication potential, loss of natural resources, or air, water, and soil pollution. However, biobased solutions present shortcomings like lower durability, performance, and resistance which reduce their applicability and market share (Schulte, Lewandowski, Pude, Wagner, & Moritz, 2021). Despite this, bio-based materials present promising functional properties stimulating research and development in this field.

2.3. Objectives and requirements

In order to reach or goal of creating an alternative insulation out of mycelium and hemp that has the potential to replace conventional material considering the need for efficiency and sustainability from cradle to grave, we had to reach certain Objectives that are outlined below.

2.3.1. Objective 1: This material must be multifunctional and performant for building insulation.

This objective was put in place to assure that our designed material can replace conventional insulation on a practicality, efficiency and durability metric. This objected is divided into 3 requirements which are further described in the testing section of the report:

Requirement 1.1: This material must have thermal insulating properties comparable to conventional insulators. In our case, this meant comparing results to mineral wool in terms of thermal conductivity and R-value. This is further described in the thermal conductivity section.

Requirement 1.2: This material must display fire-resistant properties adequate for non-combustible applications as defined in the National Building Code in section D-4 1.1.2. This is further described in the fire spread section.

Requirement 1.3: This material must exhibit moisture resistant properties for above-grade applications similar to conventional insulation. Our mycelium insulation samples were compared to mineral wool, this is further described in the water vapour permeability section.

2.3.2. Objective 2: This material must embrace the circular economy and sustainability principles.

This objective ensures that our designed material outperforms significantly conventional insulation on a sustainability basis in line with the goal of our design. The methods of testing and data collection are described in detail in the sustainability assessment section of the report. This objected is divided into 3 requirements.:

Requirement 2.1: This material must perform significantly better than conventional non-combustible insulation from a life cycle assessment (LCA) perspective.

Requirement 2.2: This material must have a useful life equivalent to that of an average building life expectancy.

Requirement 2.3: This material must be safe to handle and destroy.

2.3.3. Objective 3: This material must have the potential to be manufactured at an industrial scale.

The purpose of this objective is to ensures that our designed material can be scale up for industrial manufacturing without compromising the other objectives and requirements. This guarantees that our material will provide the same benefits when scale up as when designed in a small-scale laboratory setting. The methods for assessing scalability are explained in greater detail in the scalability potential assessment section of the report. This objected is divided into 3 requirements:

Requirement 3.1: This material must be cost-competitive with conventional non-combustible insulation.

Requirement 3.2: Each step of the laboratory protocol must be reasonably translated to an equivalent industrial process.

Requirement 3.3: The LCA (see Requirement 2.1.) results must be valid when processes are modeled on an industrial scale.

3. Analysis and Specification

3.1. *The Science of Mycelium Cultivation Parameters*

The following growth parameters were all specifically chosen or engineered to result in an optimal mycelium composite for non-combustible thermal insulation. The influence and importance of each are presented, but the specific designs and technical optimizations developed during the last 12 months are presented in section *4. Prototyping*. Finally, it is worth mentioning that the parameters are presented individually here, but that most are strongly interdependent and were selected as such.

3.1.1. Growth Molds

Growth molds play a pivotal role in the production of mycelium composites, especially as construction materials where uniformity of properties is critical (Elsacker E. V., 2021). They serve as the container within which fungal mycelium grows and binds to a substrate, shaping the material in its final form. Apart from the obvious structural implications of the molds, the integrated filters are essential to regulate the growing environment by controlling oxygen and humidity exchanges while protecting the substrate from foreign microbial contaminants (Elsacker E. V., 2021). The mold materials selection is an important consideration, as they must withstand the sterilization process, fungal activity, and mechanical stresses from handling without degrading or deforming significantly. The reusability of the molds is an interesting feature to promote the overall sustainability of the production process, so resistant and easily washable materials are preferred.

The importance and complexity of this parameter were unforeseen until relatively late in the project. The team underestimated its impact on many crucial factors for proper growth, often with contradicting specifications (e.g. increasing gas exchanges could also increase contamination risks). In the end, it was revealed to be the growth parameter that required the most engineering work. With limited time and resources for this project, the optimization of this parameter was in the end unsatisfactory and left the door open for future experiments.

3.1.2. Strains

The selection of fungal strains is a decisive design parameter for mycelium materials. Among thousands of fungi species with varied growth behaviours and properties, one must select those with highly performant characteristics for the desired application (Elsacker E. V., 2021). Based on the extent of scientific information available, growth time, density and porosity, fire resistance, final rigidity, and local availability were defined as crucial parameters to design thermal insulators. Two candidates were retained for this project: *Trametes versicolor* and *Ganoderma lucidum*, both medicinal mushrooms that have already been explored as suitable insulator candidates as defined by the previously stated criteria. They also require similar nutrient sources such that they can be cultivated on the same substrates and additives (Elsacker E. V., 2021; Jones, Mautner, Luenco, Bismarck, & John, 2020). However, some differences between these species made them worth exploring in parallel for this project. While results vary, *T. versicolor* generally displays a more rapid and consistent growth across different substrates, while *G. lucidum* has been associated with lower thermal conductivity (Elsacker E. , Vandelook, Brancart, Peeters, & De Laet, 2019; Schritt, Vidi, & Pleissner, 2021). In the end, while the initial choice of fungal strain is important, it is critical to design the rest of the cultivation parameters accordingly to optimize substrate colonization. This opens an interesting research field in genetics, focused on improving and optimizing fungal strains to meet specific properties or grow more quickly in a more diverse set of conditions.

3.1.3. Substrate

In mycelium composites, the substrate's role is twofold: serving as the primary nutrient source for the mycelium and structurally contributing to the final material properties. Different fungi strains thrive on different substrates. With the selection of fungi species *T. versicolor* and *G. lucidum*, the nutrient requirements aligned with lignocellulosic materials such as wood-based substrates or some agricultural residues such as straw or rice husks (Elsacker E. V., 2021). The size, texture, and density of the substrate considerably impact the growth and the final product properties.

The substrates used in this project were selected based on these criteria, as well as on the availability of supply, preferably from waste streams for cost and sustainability reasons. Hemp, oat straw, aspen shavings and hardwood sawdust were selected, either to be used alone or mixed. Chopped-up hemp stems have a high lignin and cellulose content, which makes them an ideal medium for the chosen white-rot fungi species (Jones, Mautner, Luenco, Bismarck, & John, 2020). Furthermore, since the legalization of industrial hemp in 1998, and that of cannabis in 2018 in Canada, hemp has established its agricultural presence, ensuring relatively local availability and abundance (Government of Canada, 2018). Straw is an abundant agricultural by-product with lignocellulosic content. It is readily available, scalable and cost-effective, making it an already popular choice in commercial horticultural mushroom production (Elsacker E. , Vandelook, Brancart, Peeters, & De Laet, 2019). Just like hemp, straw has a relatively low density which results in better air circulation within the composite to promote growth (Schritt, Vidi, & Pleissner, 2021). Finally, aspen woodchips and hardwood sawdust were chosen for their woody nature, and common use for mushroom cultivation. Their finer texture and higher surface area made them interesting to use in combination with straw (Sydor, Cofta, Doczekalska, & Bonenberg, 2022).

The moisture content of the substrate is also a more important sub-component than anticipated. Few studies specify the moisture level of the substrate, but some recommend 2/3 water content by weight of the final substrate as a rule of thumb (Elsacker E. , et al., 2020). An overly saturated substrate can inhibit growth by limiting oxygen availability within. This was not tracked with precision in this project; the substrate was simply humified before sterilization by soaking and draining. Lack of diligent tracking of the water content and oversaturation may have been responsible for unsatisfactory colonization in some treatments.

3.1.4. Additives

To enhance the nutrient profile of the substrate and potential final fire resistance, inorganic additives were experimented with. Gypsum powder was added to enhance fire retardant properties as it is inherently non-combustible and can release water vapour when exposed to heat, thereby reducing the temperature of the material and slowing the spread of flames (National Research Council Canada, 2022). It is also already commonly used in the mushroom industry to complete the substrate nutrient profile with calcium (Misz, et al., 2024). Furthermore, gypsum is abundantly used in construction and constitutes a significant portion of the waste generated (Lushnikova & Dvorkin, 2016). This creates an opportunity for circularity by reintroducing it into buildings. Lime powder was also tested for its available calcium, non-combustibility and its ability to create a high pH environment. This helps inhibit the colonization of undesirable microorganisms, which could compromise the composite's performance (Martínez, Ernest Bernat-Maso, & Gil, 2023). Since *T. versicolor* and *G. lucidum* were introduced in a controlled manner with a strong inoculation phase, we expected them to bypass the inhibitory effects of lime. This effect was also mitigated by maintaining relatively low concentrations of alkaline additives.

3.1.5. Growth Conditions

The growth conditions for mycelium growth are critical to ensure rapid and uniform colonization while reducing contamination risks. Key parameters such as temperature, relative humidity, and airflow must be carefully controlled to create the best environment for the selected fungal strains. The ideal temperature range for growing mycelium varies from 21C° to 30 C° but seems to settle in the higher range for *T. versicolor* and *G. lucidum* (Elsacker E. V., 2021). A target temperature of 26C° was therefore selected for this project. High humidity levels between 70 and 100% are recommended for mycelium growth (Elsacker E. V., 2021). To reduce condensation that could cause contamination or corrosion of electronics inside the growth environment, a target of 85% was selected for this project. Mycelium growth is aerobic, requiring a continuous supply of oxygen to allow for cellular respiration (Elsacker E. V., 2021). Controlled airflow within the growth environment was maintained with a low-speed fan to homogenize conditions and avoid CO_2 build-up or O_2 depletion around the growth containers, while the design of the molds themselves aimed at ensuring gas exchanges with the substrate. A delicate balance was to be respected to avoid increasing contamination risks or disruption in moisture levels.

3.1.6. Curing

The curing process is critical for functional mycelium materials to ensuring their stability, durability, and readiness for practical use by terminating growth. Typically, the curing and drying phases described here are combined (Elsacker E. V., 2021). However, this project considered them separate steps to avoid overspending energy to kill the fungi and drying the material. While processes vary greatly, temperatures around 120°C in an oven or autoclave for 15 minutes is sufficient to kill living organisms, while very high temperatures above 200°C might compromise the structural integrity of the composite (Elsacker E. V., 2021).

3.1.7. Drying

Finally, drying the composite material removes any residual moisture from the composite, which is critical for preventing future microbial activity, reducing weight, and reducing thermal conductivity (Elsacker E. V., 2021). Again, there is no clear literature prescribing drying temperatures and durations because initial moisture content and material thickness influence these values dramatically. Using low range drying temperatures around 50°C might let the fungi survive (Elsacker E. V., 2021). In this project, temperatures of 77°C and 105°C for 12 hours to 2 days were tested, with the latter yielding satisfactory results.

3.2. *Canadian National Building Code Legal Framework*

A top-down perspective was adopted to define the specifications to be met by the final insulation material. This approach guided testing design by referring to the Canadian National Building Code, and any related industry standards to understand the requirements for the desired application (National Research Council Canada, 2022). The building code is a comprehensive set of rules and regulations establishing minimum standards for design and construction based on the occupancy and usage of buildings across Canada. Fire protection is emphasized with strict minimum performance ratings to ensure the safety of occupants. This is particularly outlined for major occupancy or high-risk buildings (group B), such as schools, hospitals, industrial or commercial infrastructures, for which material selection must usually meet non-combustible or similar criteria, and for which biological materials are readily discarded. This project aims at designing and evaluating the potential of mycelium composite insulation for such applications. Specifications for various performance criteria are defined in subsequent sections.

4. Prototyping

4.1. *Summer Growth Protocol Development*

With the established theoretical foundation and objectives, the summer operations focused on transitioning to practical experimentation. Building on the comprehensive review of substrates, fungal strains, additives, and growth conditions, the team sought to refine these elements into a cohesive method for producing mycelium insulation composites. The primary goal was to experimentally develop a growth process capable of achieving the desired material properties while adhering to the sustainability objectives. Some images of these operations are available in Appendix 1.

4.1.1. Equipment and Setup

The setup required specialized equipment to ensure the success and reproducibility of methods and results: an autoclave, a homemade laminar flow hood, a small greenhouse, automated humidity and temperature controllers with their respective equipment, along with small, modified containers for growth molds. The autoclave and laminar flow hood were vital to maintain sterile conditions, while the other equipment served to maintain specific temperature, humidity, and oxygen availability conditions (Van Wylick, Elsacker, Yap, Peeters, & de Laet, 2022).

A used, Presto, 15 psi pressure canner was purchased for all sterilizing operations. The laminar flow hood (LFH) was built out of a rectangular fan. A frame was fixed to the sides to properly attach HEPA filters at the front and carbon prefilters at the back of the fan. Manipulating samples in front of the LFH provided clean air and a working area less prone to contamination. A 4-tier, portable mini greenhouse was obtained and disinfected to provide a controlled growth environment. A standard humidifier and a seedling heating mat were bought to maintain desired relative humidity levels and temperature. These two components were respectively controlled with an Inkbird IHC-200 humidity controller and a Inkbird ITC-308 temperature controller. Finally, small circular “snapware” plastic containers were purchased. These were perforated with 1” holes on the lid, meant to provide some gas exchange capacity with the substrate, each of which were filled with synthetic wadding to act as a basic filter and reduce contamination risks.

4.1.2. Growing Protocol Development

Liquid cultures for *T. versicolor* and *G. lucidum* were purchased from Mycoboutique, a local mushroom store, and were used to grow 8 jars of grain spawn (Mycoboutique, 2024). Commercially available food-grade brown rice and hardwood sawdust were tested as grain spawn substrates. This step is crucial to strengthen the mycelium culture before the actual substrate inoculation by using a highly nutritious grain substrate that allows for faster growth in the final woody substrate. The growth conditions described in section 3.1.5 were respected for this operation. The 4 brown rice jars were all very successful, fully colonizing the rice within 15 days. The sawdust jars barely showed signs of growth, disqualifying this material as a spawning substrate. This was not surprising as sawdust is not very nutritious but was considered as an option that would avoid the presence of grains in wall insulation that could attract pests.

From there, 6 different combinations of fungal strain, substrate, and additive were mixed and tested to help establish different elements of the mycelium growing process. First, the different manipulations, from preparing the substrate themselves to drying the sample, were performed and the difficulties encountered were noted. Second, the successful growth of the desired mycelium in these conditions was confirmed. While this might seem straightforward, it was very useful to experimentally validate the effectiveness of the growing protocol’s draft, since no prior experience in mushroom cultivation was acquired by any member of the team at that point. Finally, this test batch provided guidance on the best "recipes" (combination of substrate, fungal strain, and additive concentration) to successfully and quickly grow robust mycelium for each of the two fungal strains.

During the summer operations, rigorous data collection was conducted to properly document the knowledge and experience acquired during those tests. Considering the relatively ambitious targets of the project and the time required to grow each batch of samples, there was little room for error. Therefore, these were meant to provide initial guidance and valuable lessons to all team members, shaping the best approach for the fall semester rather than yielding direct scientific contributions to the project. This focus on iterative improvement and experimental protocol refinement explains why the summer operations are summarized in this section, rather than being presented as formal results. The insights gained during this period laid a strong foundation for more focused experimentation and testing in the subsequent phase.

4.1.3. Lessons Learned

The summer operations provided critical insights into the practical challenges of growing mycelium composites. One of the most significant lessons was the importance of oxygen availability within the growth containers. Both *T. versicolor* and *G. lucidum* showed sensitivity to limited airflow, leading to the realization that container designs needed further modifications to enhance airflow without increasing contamination risks.

Another key finding was the necessity of pre-soaking substrates before inoculation. Simple mixing of the substrate in water proved insufficient for ensuring uniform moisture absorption and distribution, which negatively affected mycelial growth. By pre-soaking the substrates for some hours and then draining it, the team was able to ensure sufficient moisture levels for the duration of the mycelium growth, ensuring better colonization and consistency throughout the substrates. The impact of recipe density also became apparent. Using the same density for all samples introduced issues, as relatively heavy additives like gypsum powder unbalanced the substrate recipes, negatively affecting mycelium growth performance. Adjustments in additive proportions and substrate packing methods were identified as necessary steps for achieving better growth conditions.

These lessons emphasized the need for meticulous protocol adjustments for the remaining months of the project, guiding the project toward more reliable and reproducible methods. By addressing challenges in airflow, substrate moisture, and recipe consistency, the groundwork was laid for achieving the targeted material properties.

4.2. *Growth Experiment 1 (G1)*

The first round of growth was completed between September 21st and October 13th, 2024. This section summarizes growth protocols and main observations throughout the process to guide further optimization. The experiment was carried out in Dr. Ekaette's laboratory at the Technical Services Building of McGill University, Macdonald Campus.

4.2.1. Growth Molds

Considering previous concerns about oxygen availability inside the containers, this experiment used growth bags equipped with a 0.5-micron filter, which was recommended by the Mycoboutique staff as being preferred for mycelium growth. The substrate mix was packed at the bottom of the bag and the bags were closed using metal wires. These specialty plastic bags are designed to withstand autoclaving conditions. Inoculation required opening the bags in front of the laminar flow hood to rapidly insert the grain spawn. This step was revealed to be quite cumbersome due to the stickiness of the grain spawn and the thickness of the bags; the spawn would keep sticking to the bag's sides instead of mixing with the substrate. After inoculation, the substrate would get shaped to the dimensions of rectangular aluminum molds (about 10 x 6 x 3 cm) which were cut on one side to be able to see and take pictures of the mycelium growth over time. As can be seen in Figure A5 in Appendix 2, the thickness and rigidity of the growth bag did not allow for proper molding of the material to the desired shape.

4.2.2. Recipes (Strains, Substrates, and Additives)

Six recipes composed of a combination of the mushroom strains, substrates, and additives previously selected were tested as presented in Table 2. Each treatment had five replicates to account for variability and calculation of significance in future testing, which accounted for a total of 60 specimens. Additive quantities were determined by keeping substrate mass constant for all treatments but adding 10% of the substrate mass in additive. For example, 30 grams of dry substrate was used for each sample, so 3 grams of additive was added to the appropriate treatments. The wet mass per specimen was between 109 g and 110 g (about 60% water weight). The mixed substrate was composed of 15% straw, 17% aspen and 68% sawdust by weight. Despite the lower portion of straw per weight, it still occupied most of the volume due to its low density. 3 g of grain spawn was added to each sample for inoculation, which seemed sufficient.

Table 2. Mycelium composite recipe components with label codes in parenthesis. All combinations of substrate, strain and additive were cultivated.

Substrate	Mushroom species	Additive (10% w/w)
Hemp (H)	*Trametes versicolor* (V)	Gypsum (G)
Straw-aspen-sawdust (S)	*Ganoderma lucidum* (L)	Lime (M)
-	-	Control (C)

All *G. lucidum* treatments got contaminated by a foreign fungus during this experiment, marked by a dark green growth that took over very quickly; they had to be discarded. It is suspected that the origin of contamination was the grain spawn jar used because of the uniformity of contamination. Meanwhile, all *T. versicolor* treatments grew fully over two weeks. By taking daily pictures of all samples, it was observed that most reached a superficial growth stabilization after 10 to 12 days (e.g. the samples become whiter as the mycelium colonizes the substrate until there is no more visible change). Specimens were left to grow for 14 days.

Although the tests for critical material properties had not yet been developed by the time growth ended, a decision still had to be taken to select the recipes preserved for a second growth experiment. Basic data collection after drying to measure density was conducted and is reported in Table A1 in Appendix 2. Because of the higher standard deviation of straw-based treatments and their overall higher risk of variability, it was preferred to pursue only hemp substrate to expect better uniformity of material properties.

4.2.3. Growth Conditions

The growth conditions targeted are outlined in section 3.1.5. and the automated equipment used is mentioned in section 4.1.1. Temperatures inside the greenhouse varied between 24.6°C and 26.4°C; this required setting the room temperature at about 24°C to 25°C (McGill University buildings do not allow for warmer settings), insulating the greenhouse, and placing the heating mat at the bottom of the greenhouse to radiate heat upwards. Relative humidity varied greatly between 93% and 45% during growth. This was due to the placement of the humidifier inside the greenhouse because the only space available was at the uppermost shelf, but this made refilling very inconvenient and created a lot of condensation on the surfaces of the growing environment, so the humidifier would constantly be emitting and empty out quickly. The fan's speed was reduced from a medium-max to a low setting midway through the experiment in an attempt to mitigate this but without satisfactory results. The fan was also on the uppermost shelf pointing down to circulate the rising hot air. Figure 2 shows the growing environment setup with all samples and equipment.

4.2.4. Curing and drying

All non-contaminated samples were unmolded and cured in a conventional cooking oven at 135°C (275°F) for 15 minutes. This was done per treatment and was satisfactory. Drying of all samples simultaneously was also done with a conventional oven at 77°C (170°F) for about 12 hours. This drying method was unsatisfactory and resulted in the contamination of some samples over the following weeks. This may be due to the high density of samples, low temperature or lack of specialized equipment; the oven used was not a convection oven that could have provided more consistent heating or a drying oven that could have carried out the moisture efficiently.

4.3. *Growth Experiment 2 (G2)*

The second round of growth was completed between October 26th and November 16th, 2024. This section summarizes changes to the growth protocols as attempts to resolve problems encountered during the first growth experiment and main observations. The experiment was carried out in the same location and with the same equipment as G1.

4.3.1. Growth Molds

To try to ensure proper airflow within the substrate and to give a prismatic shape to the samples, the growth molds were customized. They consisted of a larger aluminum tray than for G1 (about 7 × 14 × 5 cm) lined at the bottom by a plastic cellular tray (originally an aquarium egg isolation board) and on the two shorter sides by synthetic air filters (made of intertwined plastic filaments) used as spacers. These spacers aimed to create airspace directly surrounding the substrate to promote a more even oxygen distribution within. The aluminum tray with the spacers was then filled with 150 g of substrate and the whole assembly was placed inside a growth bag (same as G1) with the filter centred on the upper face (see Figure A7 in Appendix 2). The bag was neatly folded in and sealed with aluminum foil tape. All mold components were tested individually for a round of autoclaving to ensure they could withstand high pressures and temperatures.

These molds did allow for more consistent shape and growth of the mycelium composite; however, the cellular spacers were revealed to be counterproductive upon unmolding. The mycelium would get stuck to the spacers such that even removing them delicately would result in the tearing of the thicker surface mycelium layer. This greatly hurt the structural integrity of many samples (see Figure A8 in Appendix 2). These molds also made the inoculation process more tedious as it required cutting open a small section of the bag to insert grain spawn and then sealing it back shut; this made the process time-consuming and difficult to distribute the grain spawn evenly (see Figure A7 in Appendix 2).

4.3.2. Recipes (Strains, substrates and additives)

Only hemp-substrate recipes with additives were grown (HVG, HVM, HLG, HLM) for a total of 20 samples (see Table 2 for reference of labels). Inoculation of specimens with *G. lucidum* was done using a different grain spawn jar than for G1 which successfully avoided contamination. Since the substrate mass was greater, 4 g of grain spawn was used to inoculate G2 samples. Although the proportion of inoculate to substrate weight was kept consistent (about 2.7%), it is suspected the relationship should not be linear or that this proportion is insufficient, which might be responsible for relatively poor colonization over 14 days of growth time. Finally, substrate humidification had to be rushed because of time restrictions, which resulted in a shorter drainage time after soaking. Although water content was not rigorously monitored, it is suspected to have been above 70% of the final substrate weight, which might have obstructed oxygen distribution and inhibited fungal growth.

4.3.3. Growth Conditions

The same growth conditions as G1 were targeted. The temperature during growth ranged between 24.8°C and 26.6°C and the relative humidity was successfully maintained between 81% and 87% by lowering the position of the humidifier and by refilling it every two days or so. The fan was kept on the uppermost shelf, but its speed was kept low and its orientation was adjusted to push air laterally to circulate air more slowly and reduce pressure on the heating and humidification systems.

4.3.4. Curing and drying

Curing followed the same procedure as for G1. Drying was done using a proper laboratory-grade drying oven at 105°C for 2 days. This ensured the complete dehydration of the samples, but also made them a lot more friable. Future methods could use more rigorous water content monitoring to dry samples enough to avoid any unwanted fungal growth yet maintain some moisture (between 5% and 15% perhaps) for structural integrity and maybe even to enhance fire resistance (see section 5.2.) (Elsacker E. , et al., 2020).

5. Testing Material Properties

The testing of material properties for our mycelium insulation samples is critical to assess the success of our project and determine if our material follows our objective 1. Following the requirements for our material, we strived to create a material with thermally insulating properties comparable to conventional insulators. Our material also needs to display fire-resistant properties adequate for non-combustible applications and must exhibit moisture and rot-resistant properties for above-grade applications. The results and test methods used for each requirement are outlined below.

5.1. *Thermal Conductivity*

Thermal conductivity is the measure of material's ability to conduct heat. This is expressed by the amount of heat that passes through the material of a given thickness as a matter of time. The construction industry relies heavily on these materials, playing a crucial role in conserving heating and colling energy within buildings. Insulation with low thermal conductivity helps to slow down the heat transfer from the inside temperature of the building to the outside temperature, creating a more stable indoor environment by minimizing heat loss during colder weather and heat gain during warmer weather.

The symbol for thermal conductivity is typically K, it represents the rate of heat transfer through a material per unit thickness, per unit area, and per unit temperature difference. In SI units, thermal conductivity is watts per meter per kelvin (W/m*K), where watts (W) measure the rate of heat transfer, meters (m) represent the thickness or distance through the material and kelvin (K) is the temperature gradient across the material. Another very important measure of an insulator's performance, and more widely used in the construction industry is the R-value. R-value is the measure of a materials ability to resist the flow of heat, its thermal resistance. This unit is used to describe the material's effectiveness at insulating. A high R-value is desired as it means that the material has a greater insulating performance, therefore reducing heat transfer. R-value is expressed typically as (F*ft2*hr/BTU*in). R-value is the most widely used metric to describe thermal resistance in conventional insulation sold on the market. This unit is used as it facilitates calculation for optimal insulation thickness depending on local climate and insulation type.

Thermal conductivity is arguably the most important metric of an insulation material because it directly impacts how effective the material is at reducing heat transfer. Reducing heat transfer has an impact on the energy efficiency of a building. Low thermal conductivity insulation materials resist the flow of heat and therefore reduce heat loss during cold temperatures and heat gain during warm temperatures. This in consequence reduces the energy required to maintain the inside temperature constant, lowering the energy bill. R-value and therefore thermal resistance are key components in building codes across the nation and must be taken into consideration during the design and construction if the building is to meet the building code for the intended use. In essence, understanding and selecting insulation materials with optimal thermal conductivity is critical for creating efficient, cost-effective, and sustainable buildings.

5.1.2. Testing methodology

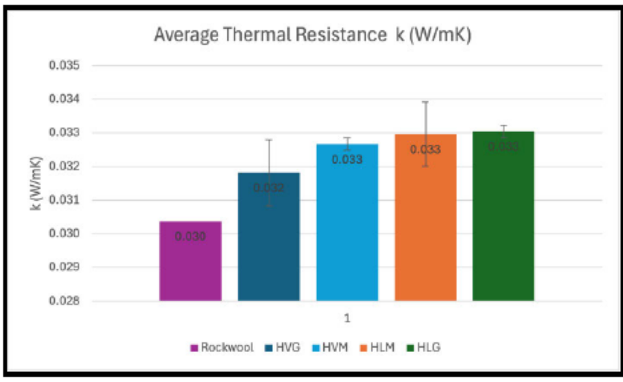
The testing of thermal conductivity is fairly straightforward but requires the use of a high-precision thermal testing machine. In our case, thanks to the help of Dr. Akbarzadeh, we were able to use the TCi Thermal Conductivity Analyser by C-Therm. This machine functions by measuring thermal conductivity using a patented technology called the Modified Transient Plane Source (MTPS) method (C-Therm, 2024). It functions by producing a small amount of heat on the sample material through the sensor while simultaneously measuring the temperature rise on its surface as the heat flows into the sample. This machine is capable of testing all sort of materials under different phases with a wide range of thermal conductivities at very high precision. Although this machine can function well with all sorts of materials, the sensor must have a nice smooth surface contact between it and the test sample.

Before the sampling of each test material can be done a few steps must be taken. Firstly, to have the most accurate data possible, each sample must be properly dried, as moisture will have a large effect on the results of the test. Secondly, each sample must go through a visual inspection to determine if testing is a worthwhile option. Our first growth experiment saw a lot of failed samples due to contamination and poor growth; those samples do not provide any important data when it comes to thermal testing. Our second experiment saw a much higher success rate and therefore all but one sample were tested. Lastly, the smoothest location on each sample must be found, this location must not be too close to the edge of the material as that can also cause problems. Some samples do not have any particularly smooth locations and must therefore be smoothed out using pressure or cutting off some protruding parts.

The results exported into Excel can now be post-processed. The average and standard deviation of thermal conductivity for each sample is calculated followed by the same calculation for treatment types. The thermal conductivity is also translated into R-value per inch following a conversion method outlined in our Excel file. These values are then represented as bar graphs comparing thermal conductivity and R-value for each treatment type among each other and to our conventional Rockwool insulation which was tested following the exact same procedures as our mycelium samples. The testing of the Rockwool insulation using the same procedures as our samples were done to reduce the risk of our C-Therm machine being differently calibrated to the machines used to measure thermal conductivity in papers found online. This removes any uncertainty and provides the same base layer thermal calculations for all our samples.

5.1.3. Results

The results of the thermal testing done using the C-Therm TCi machine are displayed below in Figures 1 and 2 and summarized in Table 3. This testing encompasses the results for the second growth experiment with both mycelium strains, hemp substrate and either gypsum or lime as additives. Each treatment (HVG, HVM, HLM, HLG) has 5 samples. The averages and the standard deviation were taken for each treatment. The results from Figure 1 were translated to R-value per inch in Figure 2.



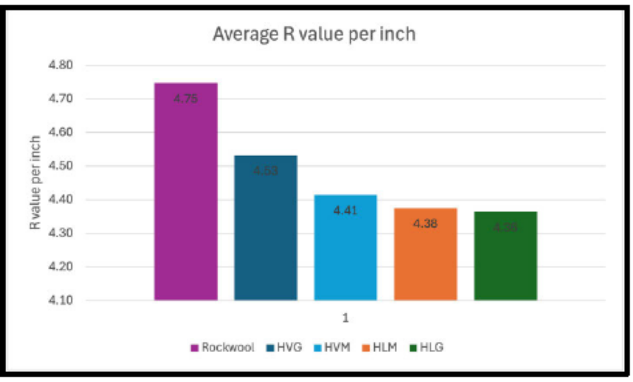


Figure 1. (Left) Average thermal resistance (W/mK) measured using the C-Therm TCi.
Figure 2. (Right) Average R-value per inch for each treatment.

Table 3. Results from Figure 1 & Figure 2 along with percent difference from mycelium insulation to Rockwool

MATERIAL	CONDUCTIVITY	STANDARD DEVIATION	R-VALUE PER INCH	% DIFFERENCE
ROCKWOOL	0.03038	n/a	4.75	n/a
HVG	0.03182	0.00098	4.53	4.5
HVM	0.03267	0.00018	4.41	7.0
HLM	0.03296	0.00096	4.38	7.8
HLG	0.03305	0.00018	4.36	8.1

Testing on the first growth experiment was also performed, which included samples with straw-woodchip-sawdust mix substrate, but we believe that the data obtained is not representative of real insulation potential. Although mycelium-straw insulation did show promising results, uneven and inefficient drying of the samples led to large variations in thermal conductivity measurements and overall worse values, likely due to the remaining water content reducing air pockets. The remaining moisture also caused the loss of several samples due to post-growth contamination, so each treatment had a different number of replicates tested (between 2 and 5). The lowest measurement was SVM with 0.038 ± 0.0023 W/mK and the highest was SVC with 0.059 ± 0.0353 W/mK. Hemp insulation recipes were also tested despite the remaining moisture with values between 0.047 ± 0.0002 W/mK and 0.052 ± 0.0149 W/mK for HVC and HVM respectively. All values obtained are significantly higher than those from the second growth experiment.

5.1.4. Analysis and Discussion of Results

In conclusion, looking at the results obtained in Figure 1, Figure 2, and Table 3 that our designed mycelium-hemp insulation material offers great thermal resistance, with the best treatment within 4.5% of Rockwool, the tested conventional insulation. The four treatment types are labelled with the first letter H representing hemp as a substrate. The second letter V or L represents *T. versicolor* or *G. lucidum* respectively as the inoculated mushroom strain and the third letter G or M represents gypsum or lime respectively. The results show that even in a small-scale setting we are able to consistently reach high levels of thermal resistance with a low amount of standard deviation. The biggest problem facing bio products is consistency from batch to batch or in our case, sample to sample. Although our four treatments composed each of 5 samples show a relatively small standard deviation, it still represents a range of approximately ± 3% for the HVG treatment, it is a difference that can have noticeable affects when considering the insulation market as a whole. Having to add 3 extra percent of material to assure a minimum consistency in thermal resistance throughout a building can results in large increase of material usage which will have effects throughout the construction process in terms of cost, design requirements, sustainability, etc. It is therefore important to consider the sample size of our designed and tested material when viewing the data above. But what this data shows more than anything is proof of concept that mycelium-hemp insulation can replace conventional insulation on a thermal resistance basis.

5.2. *Flame spread*

Evaluating the fire resistance properties of materials is complex. Combustibility can be broken down into a multitude of characteristics like time to ignition, heat release rate, ignition temperature, smoke development, etc. From the perspective of developing an insulation material for non-combustible applications, it is crucial to look at industry standards and requirements. The Canadian National Building Code determines non-combustibility based on compliance with the CAN/ULC-S114, "Standard Method of Test for Determination of Non-Combustibility in Building Materials". This test consists of heating a small specimen of material in a furnace at 750°C and ensuring that the material doesn't flame or contribute to temperature rise by recording parameters like the furnace's temperature, mass loss and flame perdurance after exposure. Materials that do not meet certain thresholds are classified as combustible, whereas materials like steel, concrete or mineral insulation typically meet the non-combustible criteria (National Research Council Canada, 2022, p. 726). CAN/ULC-S114 offers little comparative power between materials as results simply classify specimens as combustible or not. This is somewhat undesirable in a research and development context where indications of relative performance would be helpful to guide further optimization.

The building code uses other relevant tests to evaluate material properties related to flame exposure. For *major occupancy* buildings (Group B), which require high performance for fire resistance, the building code allows for walls and ceilings with a *flame spread rating* no greater than 25 (National Research Council Canada, 2022, pp. 28, 177). This means wall assemblies, including insulation, can be composed of *non-combustible* and *combustible* materials with a low flame spread, typically referring to fibreglass or Rockwool. Flame spread rating is determined based on at least three tests conducted per CAN/ULC-S102, "Standard Method of Test for Surface Burning Characteristics of Building Materials and Assemblies" (National Research Council Canada, 2022, p. 177). This test is conducted in a Steiner Tunnel, which is a 7.5 meter long and relatively thin furnace with an ignition flame at one end and windows along a side. The test consists of igniting the surface at an extremity of the material and recording the position of the flame front over 10 minutes of exposure. The resulting maximum flame front curve over time is analyzed and the area under the curve is converted to flame spread by established equations (Spensieri, 2020).

5.2.1. Testing Methodology

To evaluate the fire performance of mycelium-composite materials for this project, an in-house test was designed based on CAN/ULC-S102 and its variant S102.2, which mainly differs in how the specimen is supported. Qualitative observations inspired by CAN/ULC-S114 were also reported. Testing was carried out in the welding room in the Technical Services Building of McGill University, Macdonald Campus. The main parameters of the Steiner Tunnel were considered and scaled down based on space, equipment and time availability. A comparison of standard and in-house Steiner Tunnel parameters is provided in Appendix 3 along with justifications for these decisions and pictures for visualization. The in-house Steiner tunnel consisted of a tunnel constructed from refractory bricks (9" x 4.5" x 4.5" or 2.25" each). The flame was provided by a handheld propane torch stabilized and held horizontally with the nozzle at a downward 45° angle. A viewing window was placed lengthwise on one side. This window was initially made of cell-cast acrylic, as this material was clear and readily available. However, after the accidental combustion of the window during testing, an inner layer of glass was added. Steel plates were sandblasted, graded by centimetre using a height gage and tick welded to a total of 60 cm long. The plate was held in place at the interior back wall of the tunnel using a magnetic support.

The testing procedure consisted of placing or aligning in sequence the specimens inside the tunnel, igniting the top surface at one end, and recording the flame front position over five minutes by 10-second intervals. To standardize testing, the sample and the center of the torch nozzle were aligned at the zero mark, and the center of the torch nozzle was placed three centimetres above the specimen's top surface, which is proportional to the scaling in ignition flame length and power between standard and in-house equipment (see Appendix 3). These distances were maintained despite the variety of sample dimensions by adjusting specimen or torch supports which were provided by simple spacers of mixed materials and by a vice. The tunnel was then closed from the top while leaving an open space at the end opposite the flame as exhaust to avoid condensation on the window. Exhaust vents from the welding shop were also used during testing to remove any smoke but were placed far enough to avoid creating a vacuum effect inside the tunnel. A stopwatch with auditory indicators for data collection was initiated as the flame was ignited. The position of the flame front was recorded over test time. The flame front position was defined as the point of the furthest live flame at the material surface.

Curves of maximum flame front position were drawn and compared. These curves ignore any flame recession because it is considered that the further the fire progresses, the likelier it will ignite something else, and this is not mitigated by a flame recession (Spensieri, 2020). CAN/ULC-S102 converts these curves to flame spread values by established formulas, however, this was not attempted for the in-house test as equation constants are calibrated to a standard Steiner Tunnel and attempting to derive custom constants to obtain sensible values seemed highly speculative and imprecise due to the lack of consistent scaling or replication. Comparing flame front curves was considered sufficient to analyze the relative fire properties of tested materials. Mycelium composites were compared to standard materials with an established flame spread rating tested under the same conditions. Untreated oak and concrete are the calibration materials used for CAN/ULC-S102 with flame spreads (FS) of 100 and 0 respectively (Spensieri, 2020). Rockwool was used as the FS 0 material for the in-house test, as it was more relevant in this context.

5.2.2. Results

Maximum flame front position curves are presented in Figure 3. Each curve represents a single test as material quantities were insufficient to perform triplicate destructive tests for each treatment. To cover the length of the tunnel, most samples from the same treatment had to be lined up, and even those that were not destroyed during testing were not suitable or sufficient for another iteration. The dashed lines are for reference materials. Color-coded solid lines are for mycelium materials with the corresponding recipe and growth experiment (G1 or G2) indicated in the legend. Treatment HVC/HVG/HVM refers to a combination of *T. versicolor* on hemp substrate specimens with different additives from the first growth experiment. These were tried together as post-drying contamination made most samples from these treatments unsuitable for testing, hence requiring the alignment of specimens with similar treatments (in the order suggested by the label) to observe flame spread. Only two treatments from the second growth experiment were tested because testing revealed poor mycelium coverage and results simply reflected the combustion of the substrate. Testing the remaining two recipes seemed irrelevant and time-consuming. Before and after pictures of these tests are provided in Appendix 4.

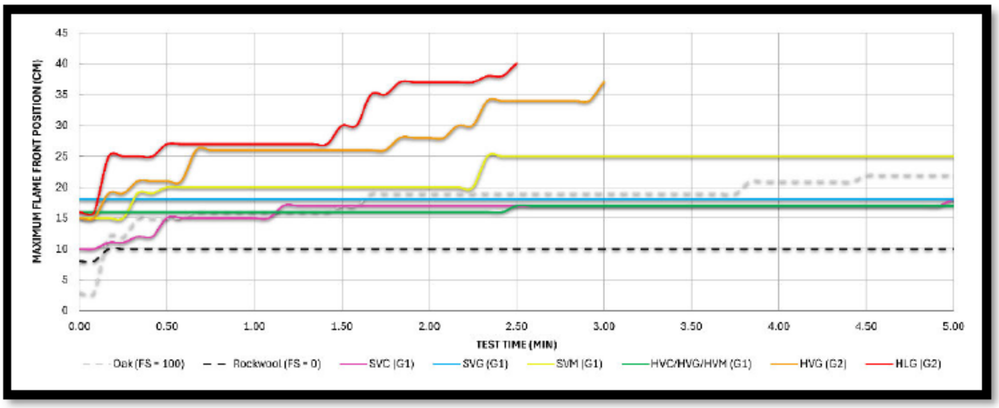


Figure 3. Maximum flame front position over test time for reference materials and mycelium composite materials. Material codes refer to recipe labels defined in Table 2. (G1) and (G2) indicate the growth experiment from which specimens were obtained.

Three treatments from G1, SVG, SVC and HVC/HVG/HVM showed a maximum flame front position between 15 and 18 cm of flame progression. This approaches the oak curve, which steadily progresses but stabilizes around 20 to 25 cm over 5 minutes of flame exposure. However, mycelium-composites behaved differently with the flame front advancing rapidly in the early part of the test, and then slowing down or receding and remaining stable around 12 to 14 cm, although this is not shown by maximum position curves. Data points are presented in Appendix 4. The later values instead approach the Rockwool curve, suggesting some fire spread resistance properties for mycelium material. Rockwool wouldn't contribute to flame spread but melted around the flame impact. Mycelium materials also showed little flame persistence after exposure, but they would remain very hot and smoulder after testing, in some cases even for hours, which would suggest risk of spontaneous re-ignition. Significant mass loss seemed to occur mostly for the first specimen in the alignment, while other specimens would get charred at the top surface yet maintain their structural integrity.

That said, other treatments like SVM (G1) and all treatments from G2 showed very high flame spread. The test even had to be stopped after 2:30 or 3 minutes for the second growth experiment as the whole material ignited and could no longer progress further. Only ash remained after these tests, and temperatures would reach high enough temperatures to discolour the steel plate (which otherwise only occurred with oak) or severely warp and ignite the acrylic window.

5.2.3. Analysis and Discussion of Results

This test concludes that mycelium composites are not non-combustible, but they can act as fire retardants with the right composition. The inconsistent fire reaction of mycelium materials seems dominated by their moisture content, which has been suggested to have remained high for G1 samples, and to degree of mycelium colonization, which was poorer in G2 samples. SVM also showed better thermal insulation properties (see section 5.1.), yet worse fire resistance within G1, it also had a lower average density than other G1 samples. This suggests that thermal and fire properties are also influenced by material composition or density but are influenced in opposite directions: a material with leftover moisture results in worse insulation performance, but better fire spread resistance, yet increases the risk of post-drying contamination. Few studies have looked jointly at the thermal and fire properties of mycelium products, it has been suggested that substrate and strain selection with inherent valuable properties and post-growth treatments that densify the composite structure could improve both properties (Jones, Tanmay, Wang, Moinuddin, & John, 2017; Al-Qahtani, Koç, & Isaifan, 2023). The specimens that showed greater fire resistance demonstrated similar behaviour to the one expected from materials with low thermal inertia (like insulation), where the flame front advances rapidly initially, and then recedes and remains stable with little flame persistence (Spensieri, 2020). However, the risk of re-ignition from smouldering material has been mentioned as a concern for commercial biological insulation like chemical-treated cellulose, which should be addressed to ensure the safety of building occupants (North American Insulation Manufacturers Association, 2016).

Finally, much research reporting the remarkable fire resistance properties of mycelium materials relies on calorimeter tests demonstrating low peak heat release rate or mass loss compared to conventional foam insulation (Jones M. P., Bhat, Huynh, & Kandare, 2018a; Jones, Tanmay, Wang, Moinuddin, & John, 2017). This test is defined by ULC-S135 "Standard Test Method for the Determination of Combustibility Parameters of Building Materials Using an Oxygen Consumption Calorimeter (Cone Calorimeter)". This standard is also referenced in the National Canadian Building Code to define combustibility, but it is seldom used to determine for which applications combustible materials can be used. There is no accepted method to convert results from ULC-S135 to CAN/ULC-S102, although it is often assumed in academic settings that materials with low heat release rates should also have low flame spread (Jones M. , et al., 2018b). Calorimeters are common in early-stage research when material quantities are insufficient for Steiner Tunnel testing, however, to envision commercializing mycelium construction materials in the future, an approach focused on applicability would be beneficial to guide optimization requirements.

5.3. Water Vapor Permeability

Water vapor permeability is a material property that describes the rate at which water vapor passes through a material. In the context of construction material, this property is essential for ensuring proper moisture management within building assemblies and inside (Gauvin, Tsao, Vette, & Brouwers, 2021). Adequate water vapor permeability helps prevent the buildup of moisture, which can lead to mold growth, structural degradation, and reduced thermal performance over time (Gauvin, Tsao, Vette, & Brouwers, 2021).

This important property is typically expressed using the permeance units, the US Perm (Carr, 2021). It quantifies the amount of water vapor in grains that can pass through a material in an hour, over a 1 square foot area of material, per inch of mercury vapor pressure difference. Materials with higher permeance allow for more water vapor to pass through, making them "breathable" (Gauvin, Tsao, Vette, & Brouwers, 2021). For insulation materials, water vapor permeability must be carefully considered, as it is often naturally the point where condensation occurs in a wall assembly (Carr, 2021).

$$1\ US\ Perm = \frac{1\ grain\ of\ water}{hour * square\ foot * inch\ of\ mercury\ vapor\ pressure\ difference}$$

5.3.1. Testing Methodology

Water vapor permeance for the mycelium composite samples was tested using a similar methodology than its corresponding standard in the industry, ASTM E96 (Kelechava, 2022). The water method involves placing a material over a cup of water and sealing it to prevent moisture from escaping through anything other than the tested sample (Kelechava, 2022). By monitoring the temperature and relative humidity (RH) on both sides of the material, the duration of the test, and the weight of the setup before and after, it is possible to calculate the rate of water vapor transmission through the material in US perm (Kelechava, 2022).

The experiment described in this standard was reproduced for this project. Three identical containers were used to contain the water, sensors, and support the mycelium composite samples. A circular hole of 5 cm diameter was made in the lid of each of the container. One DHT-22 sensor was used per container to monitor the temperature and RH inside the containers, and a fourth one outside the containers to record those same metrics but in the room. The data from all four sensors was collected and stored in a SD card module. All the electronics were connected to an Arduino Uno board with the proper wiring and resistances, powered by a 9V jack barrel adaptor plugged into a standard outlet.

For the two sample recipes tested, the following method was followed. All containers were filled with approximately a cup and a half (400ml) of tap water before being closed. Then, the samples were placed on top of the perforated lids, making sure that they were covering all the holes. These were then weighted and left alone in an unvisited room for approximately 48 hours. Then the setups were weighted again, and the data was retrieved from the SD card. All the required data was then available to perform the calculations. Some images of the testing and setup are available in Appendix 5.

5.3.2. Results

The results were found to be unexpectedly high for the two batch of samples tested. This is likely due to a combination factors. As shown in Figure 4, the permeance values are far beyond typical ranges, even for traditional insulation materials (Efficiency Matrix, 2024). Mycelium composites were rarely tested in scientific literature for such material properties but even then, results are more reasonable than the ones obtained in this project (Gauvin, Tsao, Vette, & Brouwers, 2021).

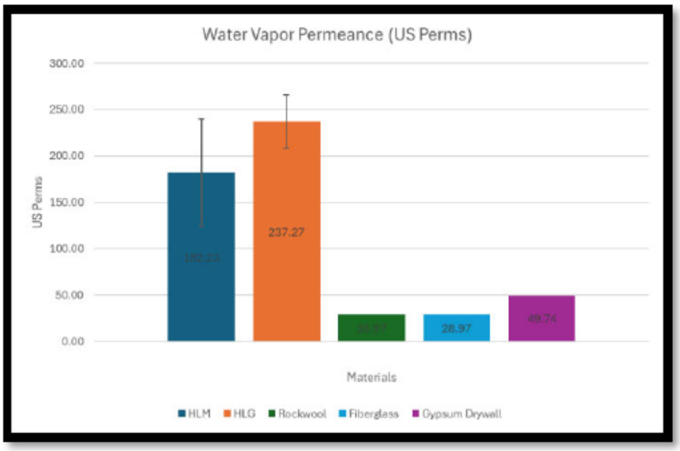


Figure 4. Water vapor permeance results of HLM and HLG mycelium composite compared to traditional construction materials.

5.3.3. Analysis and Discussion of Results

Several factors probably contributed to these high results. First, the experimental setup could have influenced the readings in many ways. The lack of sealing around the samples once they were in place possibly allowed water vapor to escape through the sides, due to the relatively irregular surface and shape of the tested samples. Further tests should focus on refining these procedures to minimize water vapor escapes while allowing the reuse of the testing containers.

Another factor is the inherent porous structure of mycelium composites, which may allow for higher permeance compared to traditional insulation materials. As a biobased material, it may naturally exhibit a more open and fibrous structure, which could contribute to more unpredictability in the material properties (Gauvin, Tsao, Vette, & Brouwers, 2021). While this characteristic might be considered beneficial for certain applications, such as moisture regulation in building assemblies or indoor environments, it might present challenges relating to the material property consistency and future rating.

Ultimately, these results highlight the need for further refinement of both the experimental methods and the formulation of the mycelium composite. More rigorous testing with better-controlled conditions, along with adjustments to the material’s composition, will be necessary to achieve more realistic permeability values. These initial findings provide a valuable starting point for understanding the potential of mycelium composites in construction, but additional work is required to ensure that the material can meet the specific performance standards for water vapor management in building insulation.

6. Optimization

Every step of our current production process likely has some form of possible optimization. Many of the optimization techniques in terms of larger scale and higher consistency manufacturing will be explored in the scalability section. But when it comes to lab scale and prototyping of our design, we have faced many challenges and hurdles that had to be dealt-with to arrive at our point. Every new growth batch saw the use of new techniques and tools learnt from the failures and short comings of the batch before it. Our last batch was successful in producing over 20 samples with zero contamination, a problem we faced in other growths. Unfortunately, the last batch was not without its problems, many of the samples lacked full mycelium coverage and had very rough surfaces. The major challenges faced throughout of project was contamination issues, poor substrate consistency before growth and lack of full mycelium coverage on all sides of the samples. Thankfully, we were able to solve the first two problems, but the full coverage still remains and issue.

6.1. Growth optimization

In terms of growth optimization, further testing should be done with different mixtures of substrate, additives and mushroom strains. Although we spent a good portion of the semester testing with a variety of substrate materials like hemp, straw and sawdust, as well as additives like gypsum and lime, further testing should be done to find the most optimal mixture for mycelium coverage and aligning with our described objectives and requirements. Through our tests we found that a hemp substrate resulted in the best growths, but it was based on a relatively small sample size. Therefore, it important to continue testing for different mixtures if this design is ever to go large scale. Furthermore, research and testing in mushroom strains should be explored as the variety and differences in mushrooms are practically endless. It could be possible to find a mushroom not explored in our design that may exhibit superior characteristics.

Another avenue to explore is inoculation method. Optimal placement of mushroom inoculant on the substrate may lead to better and quicker colonisation. It is therefore important to test different quantities, placements and density of inoculant on overall mycelium coverage at the end of the grown period.

6.2. Environmental Controls

We believe that lack of proper oxygenation throughout the sample substrate is one of the causes of poor mycelium coverage. A very important avenue that should be explored to optimize growth is proper container aeration. The container has purpose of holding the substrate, molding the material into a desired shape and providing proper conditions for growth (oxygen, humidity, heat) all while protecting the sample from contamination. The containers themselves don’t provide oxygen, humidity and heat, but they must be capable of transferring efficiently these growth chamber conditions to the sample without compromising on contamination and molding. We tested different ideas such as plastic bag with incorporated microfilter and aluminum molds with internal grid systems for theoretically better air flow. These ideas did not fix the colonisation issue and resulted in samples with very uneven surfaces. Therefore, in term of optimization, we believe that an aluminum mold with a high number of pin needle sized holes covering the entire container would result in better oxygenation to the sample on all sides. This would also reduce the risk of mycelium growing into the holes and getting stuck, resulting in breakage when removing the samples from the molds. This idea would be coupled to a closed growth chamber system, meaning that no outside contaminants would be able to make their way into the chamber. This could be done using HEPA filters, properly sealing the chamber and using distilled water for the humidifier. These techniques would result in an optimised growth environment, removing the need for each sample to have its own contamination protection all while increasing oxygenation throughout the sample.

7. Sustainability Assessment

The sustainability assessment of our material is a very important aspect of our overall design and it's what will set it apart from its conventional insulation counterparts. We outlined 3 requirements that our material must meet. It needs to perform better than conventional insulation from an LCA perspective, it must have a useful life equivalent to that of average building life expectancy and must be safe to handle and destroy.

7.1. Mycelium Insulation LCA

Unfortunately, a complete LCA assessment of our material is not possible with the time constraint we have on this project, but a summarised version can be conducted. This can be done by reviewing the inputs, the outputs and losses of our designed insulation material. There are 4 methodological phases to conduct an LCA as outlined in ISO standards (Hauschild, 2018).

7.1.1. Goal & Scope Definition

The purpose of the goals and scope section is to define the goal of the study, the intended use of the LCA and determining the audience of the study (Hauschild, 2018).

The goal of our LCA is to evaluate the environmental impacts of our designed mycelium-based insulation as an alternative to conventional insulation. We aim to determine whether our product provides a large enough environmental difference compared to standard insulation to justify its application in the construction market. The functional unit can be defined as 1 R over 1 m^2 calculated by using this formula: $FU = R*\lambda*\rho*A$. In the next two sections, the functional unit will be defined as 1kg of mycelium insulation for ease of calculation, it will then be translated into the original functional unit later. The system boundaries are a cradle-to-grave approach encompassing the raw material acquisition, the production of the mycelium insulation and the end-of-life disposal. The key impact category is global warming potential (GWP) as kilogram of CO_2 equivalent. And we can assume that the hemp substrate is an agricultural waste product, that the insulation is produced in a region were the electrical grid primarily based on renewable sources and that the mycelium insulation if fully compostable in exception for inorganic additives such as gypsum or lime. Finaly, some exclusions such as transportation and use phase are ignored as they are assumed to provide a similar GWP between different insulation alternatives.

7.1.2. Life cycle inventory analysis

This section collects an inventory and quantifies the physical and energy flows for each stage of the life cycle of the product (Hauschild, 2018).

In the raw material acquisition phase, GWP of hemp as a waste product must be considered. Other raw materials such as gypsum or lime additives were added to the mycelium insulation but for the purpose of this LCA, their respective GWP will be ignored. The reason behind this decision is that they are present in such small quantities that they can be considered negligeable. Aluminum mold and plastic bags are also used during the production phase. In the case of the aluminum mold and plastic bags, they are intended to be reused as much as possible, surviving multiple batches of mycelium insulation production. Their respective GWP will also be ignored as the data produced in this LCA will be compared to the LCA's of other insulation material where mold and reusable processes are outside the scope of their research. In terms of outputs, all GWP for production of raw material must be considered as well as the GWP of the energy requirement during the sterilisation phase (autoclave). The sterilisation process requires approximately 100 minutes on medium heat on a stove top.

During the production phase, GWP for growth conditions, heat sterilisation and drying must be considered. Growth conditions within a thermal and moisture insulated growth chamber are required to be kept at about 27°C with a relative humidity of 85%. While the heat sterilization requires 275 F in an oven for 15 min. The drying time can vary requiring 170 F in an oven for about 12 hours.

Finaly, during the end-of-life phase, we are considering in our LCA that all mycelium insulation products primarily biodegrade in a composting site as the product is assumed to be biodegradable in its entirety. Output of emissions in the form of methane or CO_2 are assumed and can be calculated in terms of GWP.

Table 4: Inputs and outputs for each life cycle stage

Life Cycle Stage	Inputs	Outputs
Raw material	Hemp as a waste product (kg)	Emissions related to production (kg CO2)
	Sterilization heat (kWh)	Grid emissions (kg CO2)
Production	Growth conditions (kWh)	Grid emissions (kg CO2)
	Sterilization heat(kWh)	Grid emissions (kg CO2)
	Drying Heat (kWh)	Grid emissions (kg CO2)
End-of-life	Mycelium decomposition (kg)	Emissions related to decomposition (kg CO2)

7.1.3. Impact assessment

In this section, the data collected in the inventory analysis is translated into impacts on the environment (Hauschild, 2018). As mentioned earlier, this means translating the outputs from the different life cycle stages into GWP. In order to perform many of the GWP calculations, the GHG emitted during the production of electricity in Quebec's electrical grid must be used. The province's grid produces 1.2 grams of CO_2 equivalent per kilowatt-hour of energy production (CER, 2022).

In the raw material life cycle stage, we can determine the GWP for 1 kg of dried hemp biomass. One hectare of fibre hemp production was found to produce 2330 kg CO_2 equivalent (GWP) (van der Werf, 2004). Hemp as a biomass crop produces 12 tons per hectare of dried biomass on the low end (Amir, 2023). Using this data, we can calculate that one kilogram of dried hemp fiber production produces approximately 0.194 kg CO_2 equivalent (GWP).

For the sterilization phase of the raw material cycle, we first need to determine the wattage of a stovetop burner. A typical large-sized stovetop burner similarly used to heat up the autoclave consumes 3000 watts (Direct Energy, 2023)for 100 minutes. Since the autoclave is too small to support 1 kg of dried hemp, two autoclaving cycles are required. This equivalates to 10 kWh combined for both cycles and therefore produces 12 grams CO_2 equivalent (GWP).

In the production phase, both the heating pad and the humidifier can be assumed to run continuously for ease of calculation. The heating pad consumes 30 watts while the humidifier consumes 15 watts. The growing stage takes 14 days or 336 hours and therefore consumes 15.12 kWh and creates 18.14 grams of CO_2 equivalent (GWP) for the entire growth phase.

During the heat-curing and drying phase, an oven will consume 5000 watts on the high end when running at full heat (Direct Energy, 2023). In our case, the oven will remain below 275 F, which is usually half the max temperature output of a typical oven. In order to simplify calculations and remove uncertainties we will assume the oven is running at full wattage for 13 hours, which encompasses both the heat-killing and drying phase of 1 kg of mycelium insulation. 5000 watts for 13 hours is 65 kWh and therefore produces 78 grams CO_2 equivalent (GWP).

Finally, at the end-of-life stage, the decomposition of mycelium insulation in a composting environment does account for some GHG emissions. This part is extremely hard to calculate precisely, as the data for a specific material such as hemp fibre and mycelium does not exist on a measurable scale for our design. Research has been conducted on the emissions of municipal solid waste in terms of food waste and biological products such as leaves and branches from yard cleanup. It has been found that one kilogram of municipal solid waste produces 0.3 kg of CO_2 equivalent (GWP) when composted in a facility (Wang & Geng, 2015). Although this number encompasses every type of biomass, it can be assumed for the purpose of this LCA that the emissions would be similar for mycelium insulation.

Table 5: Environmental outputs for each life cycle stage

Life Cycle Stage	Inputs	Outputs
Raw material	Hemp as a waste product (kg)	0.194 kg CO2 equivalent (GWP)
	Sterilization heat (kWh)	0.012 kg CO2 equivalent (GWP)
Production	Growth conditions (kWh)	0.019kg CO2 equivalent (GWP)
	Sterilization heat(kWh)	0.078kg CO2 equivalent (GWP)
	Drying Heat (kWh)	
End-of-life	Mycelium decomposition (kg)	0.3 kg CO2 equivalent (GWP)
TOTAL	1 kg of Mycelium insulation	0.603 kg CO2 equivalent (GWP)

As shown in table 5, our estimated GWP for our designed mycelium insulation produces 0.603 kg of CO_2 equivalent per kg. This number is very similar to the study by Volk, et al where they calculated 0.69 kg of CO_2 per 1 kg of mycelium hemp insulation (Volk, et al., 2024). The mineral wool used as the comparison alternative insulation was measured to have a density of 45 kg/m^3 while our mycelium hemp insulation was measured to have a density of 92 kg/m^3. Using the functional unit described in the goal and scope section, we calculated that the FU of mycelium hemp insulation is 2.94 and for mineral wool it is 1.35. This means that to have equivalent insulation property for 1 kg of mineral wool, you would need 2.17 kg of mycelium-based insulation. Research has shown that 1 kg of mineral wool has GWP of 2-5 kg of CO_2 equivalent (Füchsl, Rheude, & Röder, 2022), whereas 2.17 kg of mycelium insulation would have a GWP of 1.31 kg of CO_2 equivalent according to our LCA research. This would mean a potential 35% saving in GWP on the low end and as high as 74% on the high end.

7.1.4. Interpretation

In this section we aim to analyse the results from above to answer the question posed in the goal and scope section (Hauschild, 2018). We first identify the significant results, provide a small sensitivity analysis, find some of the uncertainties and limitations and provide a conclusion.

In terms of the significant results, mycelium-based insulation shows a significant reduction in global warming potential compared to its mineral wool insulation counterpart. Obviously, due to the time constraints of this project, a full scale LCA was not possible and therefore there are some shortcomings in the extrapolated LCA data. It is important to note that our LCA on mycelium is not identical in terms of scope of the LCA conducted on mineral wool by Füchsl et al., but that the similarities are close enough to provide a meaningful comparison. Furthermore, aspects such as carbon sequestration are not taken into account and may lead to improved GWP for mycelium insulation.

For the sensitivity analysis, we looked into the energy grid dependencies and the end-of-life scenarios. GWP for mycelium insulation and mineral wool insulation is heavily based on the electrical grid mix, meaning that in the context of Quebec's green energy grid, GWP will be much lower than in places more reliant on fossil fuels for their power. Furthermore, the end-of-life scenario assumes that all mycelium insulation will be composted rather than thrown into a land fill or incinerated. Composting will create far less GWP compared to landfills where biomaterials are subject to creating higher quantities of methane, a highly potent greenhouse gas. It must therefore be taken into consideration that the LCA depends on factors have the potential to be changed depending on where and how the material produced and disposed.

In terms of uncertainties and limitations, the LCA relies on a mixture of primary data collected through our experiment and secondary data collected through literature review. This has the potential to introduce variability as the methods and robustness of obtaining data may be different between alternative sources. Some of the data collected also relies on assumptions as long-term experimental data cannot be collected with the time constraints we have as well as the novelty of this material. The scaling up of this product will likely produce changes in the GWP of the material as processes become potentially more efficient while also introducing new factors that may have negative effects on GWP.

In conclusion, the findings in our LCA show that mycelium insulation presents strong reduction in GWP as compared to mineral wool. It is important to note however that the scope of the LCA is limited and that many factors beyond our control have the potential to disrupt our finding. Furthermore, the LCA is limited to GWP when many other environmental factors such as water use, cumulative energy demand, acidification potential, etc. are important points to consider when assessing environmental impacts.

7.2. Material Life Expectancy

The life expectancy for our designed mycelium-hemp insulation was not measured in any empirical test as the time constraint of our project could not allow for long-term testing. The life expectancy determination will therefore rely primarily on existing literature. In order to estimate life expectancy for our product we must first determine the environmental conditions the material will be subject to during its useful life. In a normal insulation setting, the material will remain above grade, will not be subject to water or high humidity rates and will remain within a reasonable temperature range i.e. not subject to extreme highs due to heating elements or other. This is within reason as water damage due to flooding will require the replacement of insulation material regardless of composition. It has been estimated that the useful life of hemp insulation in these conditions is between 50 to 70 years (Julia Liu, Pomponi, & D'Amico, 2023; Schulte, Lewandowski, Pude, Wagner, & Moritz, 2021)

With an estimated life expectancy of 50 to 70 years, this is smaller than the 70 to 100 years life expectancy of buildings depending on the sources (IDI Distributors, 2023) (Larusso, 2023). However, this product is very new and even though some research does exist, there are many uncertainties and therefore the data must be taken with a grain of salt.

7.3. Material Safety

The safety of our mycelium hemp insulation is of outmost importance. Care has gone into the choice of raw materials to reduce any risk to human health. Insulation materials have had a history of severe health consequences such as asbestos, and public sentiment with these products are fragile and therefore must be handled with care. Our hemp insulation is made up primarily of two parts: hemp fiber and mycelium. The mycelium strains used in the production of our material is either *Ganoderma lucidum* known as Reishi or *Trametes versicolor* known as Turkey Tail.

G. lucidum has a long history of use for promoting health and longevity. It is used extensively in all sorts of health products with some scientific support in its health claims (Wachtel-Galor, Yuen, Buswell, & Benzie, 2024). Although some negative side effects are possible such as nausea, itching, rash etc. when taken orally, no study has linked the presence of *G. lucidum* to health consequences (WebMD, 2024).

T. versicolor shows similar trends to *G. lucidum* in terms of its health consequences. If ingested orally while undergoing chemotherapy, this mushroom has the risk of causing nausea, low white blood cell count, liver problems etc. but studies have not determined whether this is due to the mushroom or the treatment (WebMD, 2024). While not undergoing chemotherapy, *T. versicolor* is likely safe for most adults when taken orally and shows no consequences when in the presence of the mushroom (WebMD, 2024).

It is important to note that in both cases the mycelium has been heat killed and has therefore no chance of continued growth or spreading during its useful life.

The hemp fibers are dried and contained within a mycelium crust which will theoretically prevent the possible release of dust particles from the hemp fibers. Although, hemp dust is not related to any known health consequences, a reduction in dust can lower risk of allergens within the house.

We can therefore conclude that mycelium-hemp based insulation has very little risk of posing any sort of health consequences during handling or during its useful life.

8. Scalability Potential Assessment

The hurdles to the scalability of biomaterials are often a limiting factor to their commercialization. The scalability of the mycelium composite is here evaluated based on two main requirements: each step of the process must be able to be reasonably scaled to an industrial equivalent, and the material must be cost-competitive. The hypothetical sustainability of a scaled process will be commented on but not quantified due to the lack of necessary information. Parallels with established processes in commercial horticultural mushroom production are described as facilitators to scaling although they would need adaptations for mycelium material production.

The biggest concerns identified during this project for mycelium as a construction material are the difficulties in achieving product uniformity, the long turnover time (growth time), and the labour-intensive steps (like manual handling to prepare the growth medium or the delicate inoculation process that are not generally fully automated in the industry) (Wondastic Tech, 2023). Additionally, most knowledge available is aimed at optimizing the production of a fruiting body (e.g. the edible part of the mushroom) instead of the mycelium network, so research and development are still required to design specialized machinery.

8.1. Industrial Scaling of Mycelium Composites Production

Since the expertise of the team is not in industrial or process engineering, imagining scaling from a laboratory process is mostly speculative. This evaluation is based on the current availability of inputs and specialized industrial machinery.

The main inputs of this process are the mycelium culture, the substrate ingredients (hemp, gypsum, lime, water), and energy. Mycelium culture can be sourced initially in very small quantities from any mushroom shop or directly extracted from mushroom spores of the desired species. It can then be replicated and bred in-house almost indefinitely to obtain specialty strains with optimized properties, growth rates or resistance to environmental stressors. This could help shorten the turnover time of mycelium materials with a shortened growing period. Propagation is done through a combination of sterile laboratory practices (it could even involve genetic engineering) to ensure consistency and scalability while preserving genetic integrity (Salazar-Cerezo, Vries, & Garrigues, 2023).

Substrate ingredients are all common byproducts from agricultural or construction industries. Circularity of inputs is preferred although relying on waste streams for large-scale industrial processes is riskier and is subject to more product availability variations, so a combination of sourcing from new and waste sources would be more realistic. As mentioned earlier, industrial hemp production has been growing in Canada since its legalization and would benefit from processes that revalorize woody waste (Government of Canada, 2018). Gypsum is one of the most common and available construction materials (plasterboards) and accounts for 9% of construction and demolition waste in Canada (Bottero, 2024). Gypsum waste recycling is uncommon but possible through separation, grinding and purification. Most recycling facilities however only accept new or clean drywall for recycling due to the difficulties of sorting complex post-consumer waste (Bottero, 2024). Lime (limestone) is a common carbonate rock used as an agricultural soil additive or a concrete aggregate in construction. Its commercial availability is well established; however, it is seldom recycled due to its low end-point concentration, making recovery of limestone waste impractical (Bliss, Hayes, & Orris, 2008). Finally, substrate hydration may be water-intensive, but it is estimated that requirements would be relatively low compared to mineral-based insulations which use considerable amounts of water for cooling and fibre processing (UKGBC, 2024).

Energy availability to operate machines for sterilization, incubation (e.g. controlled environment systems), curing and drying is evaluated by comparing operating conditions with mineral-based insulation manufacturing processes. The highest temperatures required in the mycelium-composite material production process occur at the sterilization and curing stages which must reach at least 120°C. This is much lower than temperatures reached by furnaces and spinners melting glass or basalt rock at temperatures over 1500°C (Rockwool, n.d.). Environmental assessments have also estimated mycelium material production to be less energy-intensive than conventional processes (see section 7.1.).

Finally, the availability of specialized industrial machinery is based on that used for commercial mushroom production. Such machinery includes large-capacity substrate mixers and/or tractors, an atmospheric steamer for sterilization and curing, an industrial laminar flow hood, incubation racks as molds, a climate control system with HEPA air purifier, and a continuous or batch dryer. All these units exist commercially but would need to be customized or purchased in multiple units to satisfy production demand and compensate for the long turnover time. The following section reports a cost analysis of these systems and details their specifications (see Appendix 6).

8.2. Cost Comparison with Conventional Products

This cost comparison consists of identifying the manufacturing steps differing from conventional insulation and estimating associated costs. This means costs related to baling, transport, rent, etc. are omitted as they would likely be similar for any insulation product. To scale to realistic production capacity, a hypothetical production volume of 3000 kg of insulation was established as a unit of comparison between mycelium- and mineral-based insulation. The determination of this comparison value is explained in Appendix 6.

Appendix 6 lists the required equipment for insulation production and their associated capacity. This analysis estimated the capital expenses for a mycelium-composite insulation production plant to about 1.4 MCAD, for a production capacity of a bit over 3000 kg of insulation per hour. This is likely an overestimation as the machinery available is designed for horticultural purposes processing much smaller loads. This was compensated by multiplying the maximum cost per unit by the number of units required to meet the production requirements. However, economies of scale would likely reduce machinery costs if they can be optimized for larger capacities. Some cost estimates are also fully hypothetical (ex. for the incubation shelves) as the equipment is often custom-made for the production facility and no approximate costs were found in the literature.

Costs for mineral insulation were also estimated and calculations are detailed in Appendix 6 as well. Costs for a relatively small-scale production facility were estimated at 12 MCAD for a production capacity of 30 tons per hour. This high production capacity means it would take 6 minutes to produce 3000 kg of insulation, hence the standardized comparison capital expenses would be 1.2 MCAD. Mineral insulation benefits from mature industrial processes and a short turnover time, which explains the much lower cost. Nevertheless, mycelium insulation could still be cost competitive with economies of scale and by requirement lower operation expenses as energy and water requirements would be significantly lower. Still, much more in-depth techno-economical analyses and scalability studies would be required guide future work on commercializing mycelium-based construction materials.

9. Conclusion

In conclusion, the purpose of this project was to design a replacement for conventional insulation out of a mycelium composite material, which would have equivalent material properties, better overall sustainability and potential for scalability all while being suited for above grade non-combustible applications. Through the design process and optimization of raw material and grow conditions, we managed to demonstrate that our mycelium insulation prototype is capable of achieving thermal resistance properties within 4.5% of conventional rock wool insulation. It also showed the potential to reduce global warming potential by 74% compared to conventional insulation. However, this material demonstrated unusually high water vapour permeance values, opening the door for further research and refinement for this type of biological material.

However, it is important to consider the limitation of our results. As a bio-based product, its growing can induce significant variability from sample to sample and from batch to batch. This has impacts on the validity of the results while also highlighting the difficulty of producing such materials at industrial scale. The limited time constraints of our project made it unfeasible to conduct a complete life cycle assessment, limiting the evaluation of the full environmental impacts.

Despite these challenges, this project has shown the potential of mycelium-based insulation materials as an affective sustainable alternative to conventional insulation, reducing its environmental impact from production to disposal. The findings in this project provide a base line for further research in mycelium-based insulation materials as an alternative to conventional products and create a foundation for future refinement and optimization for commercial applications.

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Appendices

Appendix 1. Summer Operations Images

Figure A1. Fully colonized, brown rice spawn jar. Picture by Arthur Bégin.

Figure A2. Initial test sample, after colonization. Picture by Arthur Bégin.

Figure A3. Test samples, out of their growth molds and ready for heat treatment and dehydration. Picture by Arthur Bégin.

Figure A4. Liquid culture, only 5 days after inoculation, showing signs of growth. Picture by Arthur Bégin.

Appendix 2. Pictures and Data Documenting Growth Experiments

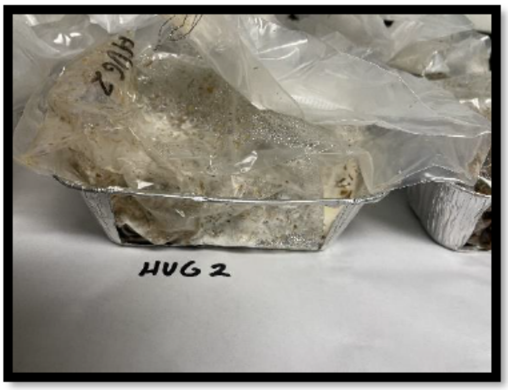

Figure A5. Example of a growth mold from growth experiment 1. Picture by Irene Tovar.

Figure A6. Growing environment during growth experiment 1 with 60 samples, heating mat at floor level, humidifier and fan at the uppermost shelf. Picture by Irene Tovar.

Figure A7. Filled growth molds at the beginning of growth experiment 2. The filter spacers are visible on the sides of each mold. The bottom tray spacers are not visible as they are covered by the substrate. The aluminum tape piece on the top face is stuck from the inside of the bag and marks the incision site that had to be cut open and taped back shut to allow for inoculation. Picture by Irene Tovar.

Figure A8. Specimen from growth experiment 2 that got ruptured by separation of the bottom tray spacer. Picture by Irene Tovar.

Table A1. Density of specimens from the first growth experiment. 5 specimens per recipe.

Recipe	Average Density (g/cm^3)	StdDev
HVC	0.139	0.011
HVG	0.164	0.013
HVM	0.131	0.009
SVC	0.260	0.048
SVG	0.186	0.036
SVM	0.130	0.017

Appendix 3. Comparison of standard and in-house Steiner Tunnel parameters

Table A2. Comparison of standard and in-house Steiner Tunnel parameters. All information for the specifications of a standard Steiner Tunnel was taken from Spensieri (2020).

Categories	Value	Standard CAN/ULC-S102	In-House (Actual)	Units	%scale (A/S)	Justification
Furnace Size	Length	7.5	0.68	m	9%	The size of the refractory brick in-house tunnel is limited to one space on the workbench in the welding workshop.
	Width	0.45	0.175	m	39%	
	Height	0.305	0.12	m	39%	
Ignition flame	Length	1.37	0.08	m	6%	Using a propane torch.
	Power	90	4.41	kW	5%	Assuming a small handheld propane torch has an average power output of 15000 BTU/h
	Type	Cloud	Direct (pencil flame)	-	-	No clean "cloud" torch was available or with conditions that we could control. Using a propane torch was more convenient.
	Angle	45	45	°	100%	Angle of the nozzle provides a 45° angle, so the tank must be kept parallel (use a level). Nozzle is pointed downward, adapted to a floor mount.
	Vertical Distance from specimen	0.5	0.03	m	6%	Proportional to flame length
	Horizontal offset from specimen edge	0.25	0	m	0%	No material to waste since limited availability. Since the flame is direct, it will still impact fully on the flat upper surface of the material.
Air	Velocity	1.2	Open to allow circulation	m/s	#VALUE!	No fan used to force air over material, but since using a propane flame and openings at each end of the furnace, plenty of air to fuel combustion
Test duration	Time	10	5	min	50%	Determined experimentally as the time to reach a flame spread plateau with oak.
Material	Mount	Top	Floor	-	-	Much easier to lay material on the floor of the furnace for testing. Following standards for ULC102.2 which is for materials that melt, deform, flooring, etc. Designed for floor mount
	Length	7.32	Variable	m	-	Approximative, combination of samples available
	Width	5.18	Variable	m	-	Using the width of the material. Since the flame is direct, the

						point of ignition is only where the propane flame impacts.
	Height	N/A	Variable	m	-	
Observation window	Window Well for turbulence and air mixing	TRUE	TRUE	-	100%	Present in CAN/ULC but the US version is smooth, so the addition of thermal bricks for turbulence is necessary.
Calibration	Red Oak FS	100	-	-	-	Only looking at flame front position curves
	Cement FS	0	-	-	-	*idem*
	Rockwool FS	0	-	-	-	*idem*

Appendix 4. Fire testing results. Data points and images for standard materials and mycelium composites

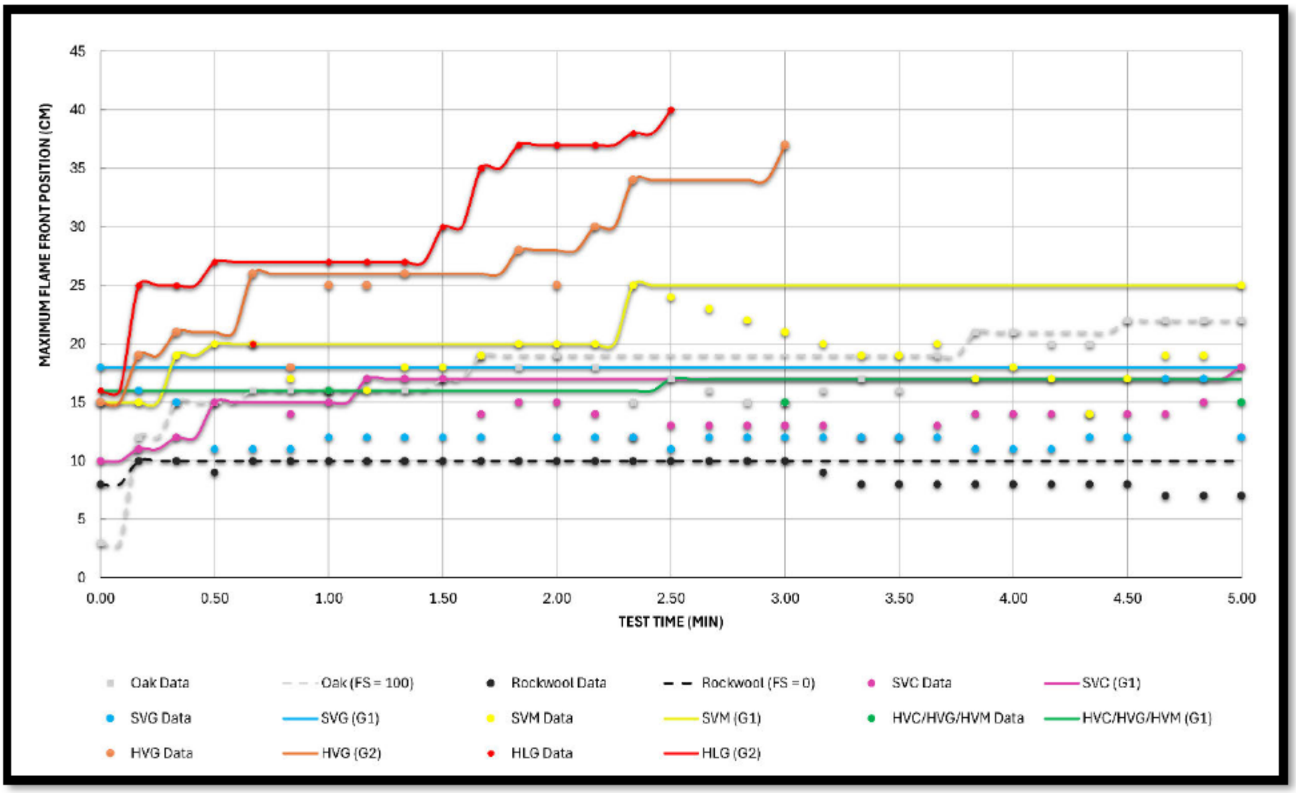

Figure A9. Data points and maximum flame front position over test time for reference materials and mycelium composite materials. Material codes refer to recipe labels defined in Table 2. (G1) and (G2) indicate the growth experiment from which specimens were obtained.

Table A3. Before and after pictures of samples tested for flame spread

Material or recipe	Before test	After test
Oak		
Rockwool	No pictures were taken	

HVG(G2)		
HLG(G2)		
HVC/HVG/ HVM(G1)		
SVC(G1)		
SVG(G1)	No pictures were taken	
SVM(G1)		

Appendix 5. Water Vapor Permeance Testing Images

Figure A10. Water vapor permeance testing setup, including containers (3), sensors, and Arduino Uno board. Picture by Arthur Bégin.

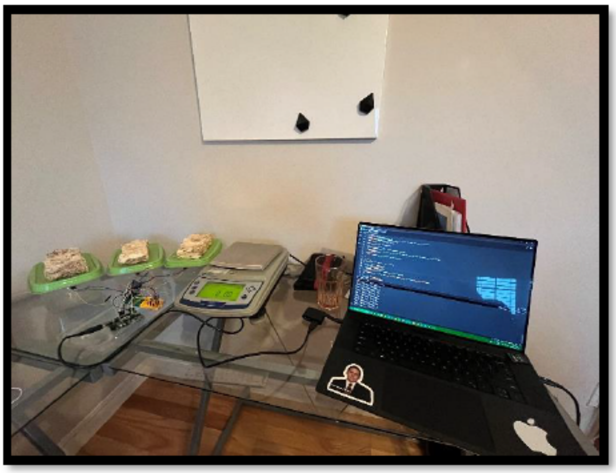

Figure A11. Water vapor permeance testing, data acquisition test directly on a computer. Picture by Arthur Bégin.

Figure A12. Water vapor permeance testing, water weighting test. Picture by Arthur Bégin.

Appendix 6. Comparison of Main Capital Expenses for Mycelium-based and Mineral-based Insulation Material Industrial Production

This cost comparison consists in identifying the manufacturing steps differing from conventional insulation and estimating associated costs. This means costs related to baling, transport, rent, etc. are omitted as they would likely be similar for any insulation product. To scale to realistic production capacity, a hypothetical production volume of 3000 kg of insulation was established as a unit of comparison between mycelium- and mineral-based insulation. This value was obtained by estimating how much insulation would be required to insulate the above-grade exterior walls with R20 insulation of an average house with 2000 sq.ft. of wall area. Assuming, mycelium and mineral insulation have similar thermal insulation properties of R4.50 per inch, it is assumed that approximately 4.5 inches of insulation thickness would be required, hence a total of 700 ft^3 or 20 m^3 of insulation volume would be required (National Research Council Canada, 2022, p. 1445). Considering mass densities of 0.164 g/cm3 for mycelium composites (see Table A1 in Appendix 2), 0.176 g/cm3 for rockwool and 0.112 g/cm3 for fiberglass, it was calculated that a rough average of 3000 kg of insulation would be required (Rockwool, n.d.; Owens Corning, 2013).

Table *A4. Estimated Capacity and Cost of Machinery for Mycelium-based Insulation Production. The maximum cost is calculated by multiplying the maximum cost estimated from the literature for the maximum capacity assumed, multiplied by the scaling factor to get a production capacity of about 3000 kg/h. When max capacity values were not available, the biggest scaling factor among other equipment was used.*

Equipment	Max Capacity	Unit	Standardized capacity (tons/h)	Scaling factor	Max Cost (CAD)	Reference
Substrate mixer	300	kg/batch	0.3	11	92,933	(Shroom Stop, n.d.)
Large-scale atmospheric steamer (for sterilizing AND curing)	20000	L/batch	3.28	2	420,000	(Rooe, n.d.)
Laminar flow hood	na	na	na	11	13,667	(Shroom Stop, n.d.)
Incubation shelving/racks	2000	sq.ft.	na	na	100,000	Fully hypothetical.
Climate control systems (temperature, humidity, CO2 levels, etc. in incubation room)	na	na	na	11	65,600	(Shroom Stop, n.d.) Mostly hypothetical.
Air filtration system (HEPA air purifiers)	na	na	na	11	3,116	(Shroom Stop, n.d.)
Continuous conveyor belt dryers or convection oven	na	na	3	1	700,000	(Direct Industry, 2024; Davron Technologies. Inc., 2024)
TOTAL CAPEX	na	na	3	1	**1,395,316**	

Note. AI chatbot (ChatGPT) was used to determine key machinery systems and find realistic cost estimates. This was confirmed by reviewing the sources used by the system.

Table *A5. Estimated Capacity and Cost of Machinery for Mineral-based Insulation Production. Since machinery is already designed for larger capacities than required, minimum capacity and costs were assumed and only scaled the final total cost value based on the minimum capacity to consider the portion dedicated to producing 3000 kg of insulation.*

Equipment	Min Capacity	Unit	Standardized capacity (tons/h)	Min Cost (CAD)
Furnace	1500	tons/d	62.5	5,000,000
Spinner	30	tons/h	30	2,000,000
Binder application system	30	tons/h	30	1,000,000
Curing ovens	30	tons/h	30	3,000,000
Dust collection and filtration systems	na	na	30	1,000,000
TOTAL CAPEX	na	na	30	**12,000,000**
TOTAL SCALED CAPEX	3	tons/6 min	na	**1,200,000**

References: (iMarc, 2024; Alfi Technologies, 2024; Hairui, 2024)

Note. AI chatbot (ChatGPT) was used to determine key machinery systems and find realistic cost estimates. This was confirmed by reviewing the sources used by the system.