Fundamental Studies for Designing Insulation Panels from Wood Shavings and Filamentous Fungi

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The production of environmentally friendly thermal insulation boards is important for the building industry to reduce its environmental impact. The primary objective of this study was to test the feasibility of producing wood-based insulation panels as well as to use fungi as a binding agent and to explore whether a bio-based composite could be a viable alternative to the standard traditional foam insulation board and more expensive wood fibreboards (mainly available in European markets). Experiments were conducted to determine which combinations of wood fibers from selected northern tree species, wood decay fungi, and growth conditions were most suitable for panel making. The results showed that under the determined optimal growth conditions, *Polyporus arcularius* and *Trametes suaveolens* on birch wood shavings provided the best combination. Outcomes from initial physical screening tests, particularly thermal conductivity, suggested that these panels had a comparable performance to traditional insulation material.

Keywords: Thermal insulation; Wood fiber; Sustainable building material; Filamentous fungi

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INTRODUCTION

One of the great challenges imposed by humans on our environment is the management of the production of a large amount of synthetic materials that are neither recyclable nor reusable, lack an adequate recycling infrastructure, or that have a very energy-intensive recycling process (Hammond *et al*. 2011; Symons 2011). For such materials, recycling is often avoided altogether. In addition, many synthetic materials used routinely in daily activities take a long time to naturally decompose. For example, polystyrene, a petroleum-based synthetic thermal insulation material used in large amounts in the construction industry, has a substantial negative impact on the environment (Lambert and Wagner 2016; Kornei 2017) and is not biodegradable (Suwanmanee *et al.* 2012). As a society, the reduction of the amount of synthetic materials produced and the development of more environmentally friendly alternatives should be a major consideration.

In some European and Asian countries, particularly Austria, France, Germany, and Japan, more environmentally benign materials do exist, *i.e.*, wood fiber-based thermal insulation (Sekino *et al*. 2005; Euring *et al.* 2015). However, the initial investment for production facilities is typically high, and therefore these materials are mostly absent in North America, even though the base material is available in abundance. Wood fiber-based thermal insulation is an intriguing alternative if a cost-efficient method for designing an environmentally friendly binding agent can be developed.

The largely natural growth of filamentous fungi could serve as this new method. The growing body of a filamentous fungus involved in wood decay is composed of millions of thin tubular-like structures called hyphae (Schmidt and Czeschlik 2006). In nature, hyphae grow and branch repeatedly, colonize a substrate to initiate decomposition processes and, by branching repeatedly, create a dense mass called a mycelium. Similarly, when working under laboratory conditions and using an inoculated substrate, such as saw dust or small wood chips and shavings, large numbers of hyphae can spread three-dimensionally to build the mycelium. During this process, several questions arise. For example, does the mycelium effectively and sufficiently penetrate the substrate to function as a binding agent to hold the substrate particles together? Furthermore, because the tube-like hyphal structures generate air pockets with diameters from 2 to 10 μm, it was hypothesized that they would increase the thermal resistance of the resulting material.

A characteristic of mycelial growth that is of utmost importance for both academic communities and commercial application is its ability to add value to agricultural and industrial waste and create an environmentally friendly composite material (Jones *et al*. 2018). Currently, several companies and universities are exploring the development and use of biofiber-fungi composite materials. Companies, such as Ecovative and MycoWorks, are developing and producing products like benches, chairs, and packing material by growing mycelium in certain forms (Holt *et al*. 2012; Abhijith *et al*. 2018). The University of British Columbia has installed benches on their campus created entirely from mycelium on alder sawdust (Dahmen 2017). Other universities are exploring the fire properties of this new biocomposite material (Jones *et al*. 2018) alongside its acoustic building insulation properties (Pelletier *et al*. 2013).

In this study, the novel use of fungi and wood shavings in thermal insulation applications for building envelopes was examined. The materials tested are based on the mycelium of several wood-decaying Basidiomycetes grown on sawdust and wood shavings. The wood-based substrate provides nutrients for the fungi and a base structure; in return, the fungi provide a low cost and environmentally friendly binding agent throughout the wood fiber to form a usable insulation material.

To better understand these biomaterials and determine how to optimize protocols to grow fungi on sawdust material, different species of fungi and types of wood substrate under defined conditions were screened to achieve a dense material composite of wood-mycelium. Both deciduous and coniferous woods were tested as substrates because those wood shavings are a renewable resource and a by-product of the forest industry in the Pacific Northwest region of North America. This study is the first to examine the potential of a fungi-wood substrate for thermal insulation panels. The authors focused their investigation on investigating various fungi cultures, moisture levels, nutrient solutions, sizes of sawdust and wood chips, and types of wood substrate to establish the combinations best suited for the intended purpose of developing insulation panels.

EXPERIMENTAL

Materials

Fungal strains

Nine wood-degrading fungi species were selected from cultures obtained from a fungal collection established by Dr. Leonard Hutchison (Faculty of Natural Resources Management, Lakehead University, Thunder Bay, Ontario, Canada). Cultures included

five brown rot and four white rot fungi (Table 1). One additional fungal species, *Pleurotus ostreatus* (also a white rot fungus) was regrown from an oyster mushroom growing kit. Brown rot fungi degrade mainly cellulose and hemicellulose, while white rot fungi degrade all of the main compounds in wood, including hemicellulose, cellulose, and lignin (Lundell *et al*. 2014).

Table 1. Fungal Species and Their Functional Guild

Taxa and Binomial Name	Common Name and Functional Guild
Fomitopsis pinicola (Sw.) P. Karst.	Red belted conk, brown cubical rot (Ginns 2017)
Gloeophyllum sepiarium (Fr.) P. Karst.	Rusty gill polypore, brown rot (Ginns 2017)
Laetiporus sulphureus (Bull.:Fr.) Murrill	Chicken-of-the-woods, brown cubical rot (Gilbertson and Ryvarden 1986)
Phaeolus schweinitzii (Fr.) Pilát	Dyer's conk, brown cubical rot (Ginns 2017)
Piptoporus betulinus (Bull) P. Karst.	Birch conk, brown rot (Ginns 2017)
Pleurotus ostreatus (Jacq. ex Fr.) P. Kumm.	Oyster mushroom, white rot (Trudell and Ammirati 2009)
Polyporus arcularius (Batsch) Fr.	Spring polypore, white rot (Ginns 2017)
Trametes pubescens (Schumach.) Pilát	Pubescent *Trametes* or Samtige Tramete, white rot (Ginns 2017)
Trametes suaveolens (L.) Fr.	Fragrant bracket fungus, white rot (Ginns 2017)
Trichaptum abietinum (Dicks.) Ryvarden	Violet-pored bracket, white rot (Ginns 2017)

Culture media

The cultures were grown on 2% malt extract agar (20 g malt extract, 1 g yeast extract, 15 g agar, and 1 L water) at 21 °C in an incubator and then moved to a fridge and stored at 4 °C until further use.

Wood substrate

Five different wood species (Table 2) were tested as substrate for growing the fungal cultures: hardwoods included paper birch (*Betula papyrifera*) and aspen (*Populus tremuloides*) while softwoods included lodgepole pine (*Pinus contorta*), subalpine fir (*Abies lasiocarpa*), and white spruce (*Picea glauca*). The wood originated from the Pacific Northwest region of North America and was kiln-dried and not treated with any chemicals. Some birch wood pieces had small amounts of bark, which was incorporated into the sawdust; other wood species did not have any bark included in the sawdust. The tree species chosen grow naturally in this region of North America and the coniferous species are commercially processed in regional sawmills; abundant sawdust from these tree species is, therefore, available in regional sawmills and could be used as a substrate resource. The deciduous species are currently not commercially harvested but potentially available in large amounts.

Table 2. Wood Species Used as Substrate

Species Latin Binomial	Tree Type (Common Name)
Betula papyrifera	Birch (Paper Birch)
Populus tremuloides	Aspen (Trembling Aspen)
Picea glauca	Spruce (White Spruce)
Pinus contorta	Pine (Lodgepole Pine)
Abies lasiocarpa	Fir (Subalpine Fir)

The wood substrate was cut to different sawdust sizes, ranging from 1 mm to 20 mm in diameter. The smallest particles (approximately 1 mm) were produced with a band saw, at a slow feed rate of approximately 50 mm/s (Fig. 1). The middle-size (2 mm to 10 mm) sawdust particles were produced with a jointer with a helical blade at a manual feed of about 50 mm/s. The largest (5 mm to 30 mm) sawdust particles (Fig. 2) were produced on a wood lathe with a roughing gauge at 1800 rpm. The sawdust was sterilized at 121 °C for 30 min; nutrient solution, consisting of peptone, malt extract, and yeast, was incorporated to moisten the mixture and supplement it.

Fig. 1. Band saw used for sawdust production

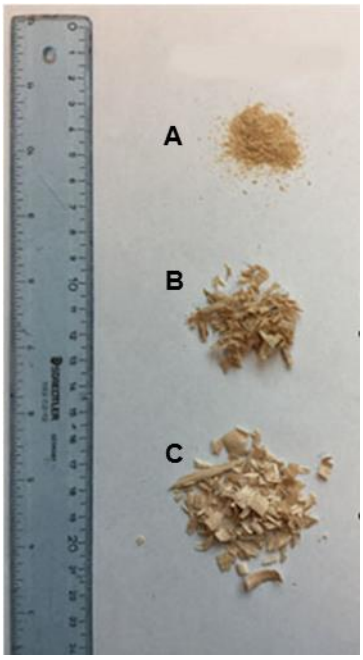

Fig. 2. Sawdust sizes: A- circa 1 mm, B- 2 to 10 mm, and C- 5 to 30 mm

Methods

Moisture content of substrate

The desired moisture content mc_d (BC Ministry of Agriculture and Food 1998) was calculated using a moisture equation (Eq. 1) and, hence an equation was derived to determine the required moisture needed (Eq. 2). The moisture content of water, mc_{H2O}, 100%, and the moisture content of dry sawdust, mc_{sd}, 6%, was determined with an Extech Dual Moisture Meter Pro MO265 (Extech Instruments, Inc., Boston, MA, USA) moisture meter. The target moisture content, mc_d, was 45% for petri dish trial 1 and 65% for petri dish trials 2 and 3. The 45% moisture content were considered to be a reasonable number on the lower end of humidity. The 65% is below the saturation point of the wood fibers, and higher values were considered too wet (Stamets 2005). The *x* represents the mass ratio of water to sawdust. When *x* is multiplied by the dry sawdust mass, it provides the mass of water required to add to the dry sawdust (Eq. 3). The moisture content was determined according to Eq. 1,

$$mc_d = \frac{m_{sd} * mc_{sd} + m_{H2O} * mc_{H2O}}{m_{sd} + m_{H2O}} \quad (1)$$

where mc_d is the desired moisture content (%), m_{sd} is the mass of sawdust (g), mc_{sd} is the moisture content of sawdust (which was 6% for the wood samples used), m_{H2O} is the mass

of added water (g), V_{H2O} is the volume of added water (mL), and mc_{H2O} is the moisture content of water (100%),

$$\frac{m_{H2O}}{m_{sd}} = \frac{mc_{sd} - mc_{d}}{mc_{d} - mc_{H2O}} \quad (2)$$

$$x = \frac{mc_{sd} - mc_{d}}{mc_{d} - mc_{H2O}} \quad (3)$$

where $= \frac{m_{H2O}}{m_{sd}}$.

Therefore, $x * m_{sd} = m_{H2O} = V_{H2O}$ with the assumption that 1 mL of nutrient solution is equal to 1 g (BC Ministry of Agriculture and Food 1998).

Petri dish trials

To determine the best fungi/host combinations and their optimal growing conditions, Trials 1, 2, and 3 were performed in standard laboratory petri dishes (100 mm diameter x 15 mm thickness) at 21 °C in an incubator. Each petri dish was filled with 3.5 g of wet sawdust. The sawdust was then inoculated with five agar plugs, each 7 mm in diameter, obtained from a fresh culture of the given fungal species. All assessments of growth were obtained visually.

Fig. 3. Petri dish trials in process

Trial 1 compared the fungal growth on the different types of sawdust. Fungi (all but *P. ostreatus*, as it was unavailable) were grown on a mixture of the smallest and middle sawdust sizes (ratio 1:1). Those two types of saw dust were selected for the first trial because faster growth of the fungi was expected on a larger surface area given by the small sizes of particles. All wood types had a 45% moisture content. The sawdust was supplemented with nutrient solution #1 (2 g peptone, 2 g malt extract, and 0.2 g yeast extract per L (Hendriks and Zeeman 2009; Shao *et al.* 2016)). Malt extract, peptone, and yeast extract were chosen as supplements because they add essential nutrients, such as nitrogen, phosphorus, and vitamins for fungal growth. Prior to inoculation of the substrates, the fungal cultures were grown on malt extract agar.

Trial 2 used the sawdust at a higher moisture content (65%) and a mixture of all sawdust particles (ratio 1:1:1). In this trial larger saw dust particles were added because a lack of structural integrity already had been observed with the first trial. Larger fiber sizes would add to the stability of the specimen. Four different wood species were used, including spruce, fir, birch, and aspen, and the mixtures were supplemented with nutrient

solution #2 (3 g peptone, 3 g malt extract, and 0.3 g yeast extract per L). Trial 3 compared the growth with different concentrations of the nutrient solutions. Ionised water free of nutrients and nutrient solution #3 (4 g peptone, 4 g malt extract, and 0.4 g yeast extract per L) were used. The same sawdust mixture, sawdust types, and moisture content as in Trial 2 were used.

Jar trials

The birch sawdust mixture gave the best results in the petri dish trials; therefore, the authors used it for cultivation in 1-L glass jars, incubated at 21 °C. A total of 40 autoclaved 1-L jars were filled with different quantities of birch sawdust to verify which weight might provide panels with a thickness close to 25 mm, comparable to standard panels available on the current market. The amounts of wet sawdust (autoclaved sawdust mixed with nutrient solution) used per jar were 500 g, 320 g, 300 g, and 240 g (Table 4). The jars of sawdust were inoculated with one of the following four fungi: *P. arcularius*, *T. pubescens*, *T. suaveolens*, and *P. ostreatus*. These were the fastest and most reliable growing fungal cultures from the petri dish trials. The sawdust mixture in each jar was inoculated with three different levels of six agar plugs (a total of 18 plugs per jar, Fig. 4). The jars consisted of a mixed sawdust substrate (60% middle size, 30% large size, and 10% small size) with a moisture content of 65%. The nutrient solution consisted of 3 g peptone, 3 g malt extract, and 0.3 g yeast extract per L. The jar lids were closed loosely to minimize moisture loss but to allow air exchange; as aerobic organisms, wood fungi produce CO_2, water, and energy through respiration and therefore need oxygen (Hendriks and Zeeman 2009). A total of 20 jars were filled (five jars per fungi species with different amounts of weights).

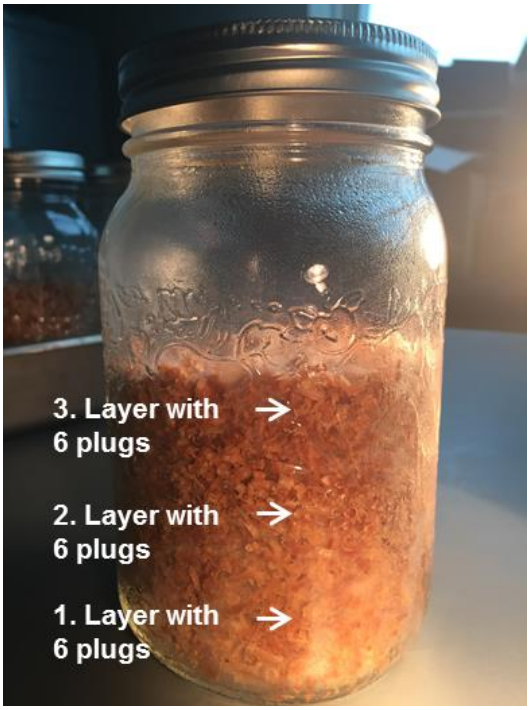

Fig. 4. One-litre jar filled with inoculated sawdust mixture (ca. 160 g); arrows indicate 1st, 2nd, and 3rd layer, approximate level, 6 plugs per level

Panel production

After 21 days of incubation, the inoculated sawdust was manually mixed and transferred to a rectangular plastic mold or to an aluminum tray to achieve the 20 cm × 20 cm panel dimensions with a thickness between 2 cm and 3 cm. The contents of one jar were transferred in one mold and distributed within the panel mold. In total, 13 panels were produced.

The panels were allowed to incubate at 23 °C in a growth chamber for an additional 21 d. Afterwards, each panel form was visually assessed for fungal growth (Table 5) and subsequently baked at 140 °C for 120 min in an industrial oven (Fig. 5) to ensure that the fungi were killed and that no fungal activity remained.

Fig. 5. Panels after baking in oven

Physical panel testing

After baking, the samples were weighed. At this point no humidity was present. The panels were stored at 20 °C in a room with approximately 30 to 35% relative air humidity for 4 weeks. Next, the physical properties testing began. The panels were reweighed and the haptic properties were examined. Additionally, the stability and rigidity of the panels were tested through lifting and slightly bending them and by pressing and pulling them. Finally, the panel thicknesses were measured and the thermal conductivities of the panels were tested using a Thermtest HFM Rapid-K 300 (Thermtest, Inc., Fredericton, Canada). The standard ASTM C518-17 (2017) was applied. The steady state thermal transmission properties were examined by applying a temperature difference of 30K, 10 °C on the cold side and 40 °C on the warm side. The heat flow meter did take between 68 and 89 min (average 76 min) to establish the thermal transmission for each sample.

RESULTS AND DISCUSSION

Petri Dish Trials

The main findings are summarized in Table 3. In general, the white rot fungal cultures (*e.g.*, *P. arcularius*, *T. suaveolens*, and *T. pubescens*) grew faster and denser than the brown rot cultures determined through visual assessment (Fig. 6 and 7). From a host standpoint, all three sawdusts supported some fungal growth. However, the most abundant growth was found with birch, followed by aspen, spruce, and fir. The most reliable and promising combinations were *P. arcularius* and *T. suaveolens* on birch substrate. The moisture content in Trial 1 (45%) was not sufficient, as the dishes started to dry out after approximately 2 weeks. Alternatively, the higher moisture content (65%) used in Trials 2

and 3 was adequate (just below the saturation point) and proved to be more successful. A mixture of finer and larger sawdust sizes appeared to be a more suitable mixture than the small particles or larger particles alone. The optimal nutrient concentration that supported the best fungi growth, speed, and density, was the solution tested in Trial 2, containing 3 g peptone, 3 g malt extract, and 0.3 g yeast extract per L (Table 3, Table 8).

Table 3. Visual Assessment of Fungal Growth in Petri Dishes on Sawdust Substrate for Five Wood Species (Trials 1 and 2)

Species	Birch		Aspen		Pine		Spruce		Fir	
	1	2	1	2	1	2	1	2	1	2
P. betulinus	**	*	/	/	*	na	**	*	/	*
L. sulphureus	*	/	/	/	*	na	*	*	*	*
F. pinicola	*	*	/	***	*	na	*	*	***	**
G. sepiarium	/	/	/	/	/	na	**	/	**	/
P. schweinitzii	/	/	/	/	*	na	/	/	*	/
P. arcularius	***	****	**	****	**	na	***	****	***	***
T. pubescens	**	****	/	**	**	na	***	**	**	**
T. suaveolens	**	***	/	**	***	na	***	**	***	**
T. abietinum	/	/	/	/	/	na	/	/	*	/
P. ostreatus	na	**	na	/	na	na	na	*	na	*

Note: / = no visible sign of growth or only growth on plugs; * = growth until the edge of dish but transparent, mycelium spots on edge; ** = some clear visible mycelium spots on surface of sawdust; *** = at least half of the plate was covered with dense mycelium, some visible mycelium on bottom of dish; **** = surface of plate was covered with dense mycelium, denser mycelium also on bottom of dish**;** na = not available for Trial 1; 1 = Trial 1, nutrient solution #1, moisture content 45%; and 2 = Trial 2, nutrient solution #2, moisture content 65%

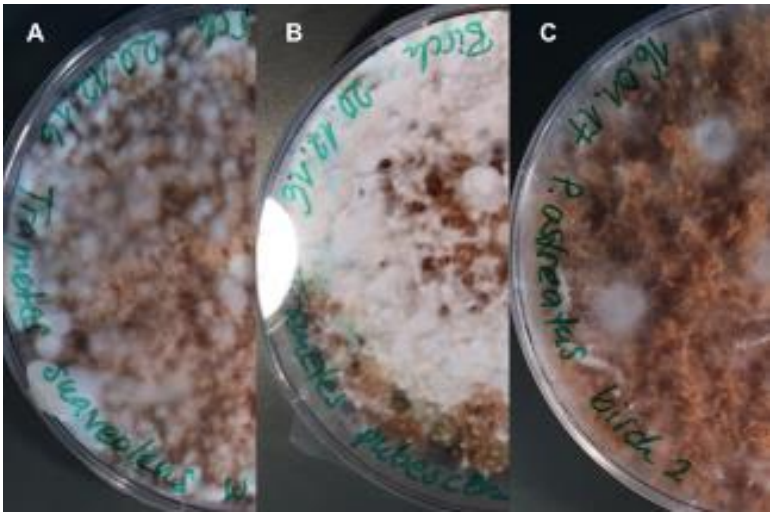

Fig. 6. Top view of petri dishes and the mycelium grown on birch after 35 days; A – *T. suaveolens*, B – *T. pubescens*, and C – *P. ostreatus*

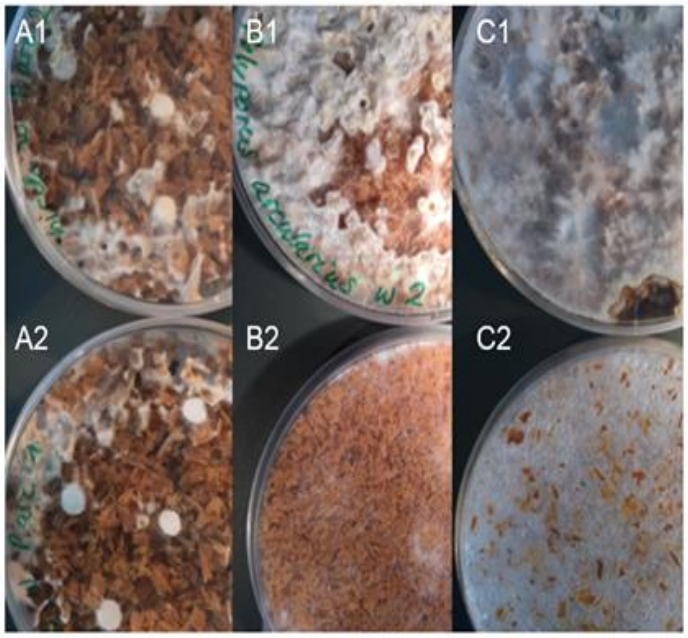

Fig. 7. *P. arcularius* on birch sawdust after 35 days in petri dish; A1 and A2: top and bottom views of growth without nutrients; B1 and B2: top and bottom views of growth with nutrient solution #1 (2 g peptone, 2 g malt extract, and 0.2 g yeast extract per liter); and C1 and C2: top and bottom views of growth with nutrient solution #2 (3 g peptone, 3 g malt extract, and 0.3 g yeast extract per L)

Jar Trials

After 3 weeks of incubation, the visual assessment of fungal growth on birch substrate (20 jars) revealed that the most consistent growth was from *P. arcularius* and *T. suaveolens*.

Fig. 8. Inoculated birch sawdust jars after 3 weeks of incubation

All of the jars with *P. arcularius* exhibited strong growth and were considered for the next step: panel production. Similar growth trends were noted for *T. suaveolens*, except for the 500 g jars, which became contaminated and were, therefore excluded from panel

production. *T. pubescens* showed medium growth in the three trials (less than half of the jar was filled with mycelium and, in one case, no visible growth). *P. ostreatus* exhibited inconsistent results (2 instances of minimal growth, 1 instance of no visible growth, and 1 instance of moderate growth, which was used for one panel). Overall two out of the 20 jars (10%) were contaminated and discounted.

Table 4. Assessment of Fungal Growth in 20 1-L Jars on Birch Sawdust Substrate with Different Weight Trials

Fungi Species	Weight (g)	Growth	Contamination	Into Panels	Panel # (Used in Table 5)
P. arcularius	500	****	No	Yes	11
	320	****	No	Yes	1
	320	****	No	Yes	2
	300	***	No	Yes	7
	240	**	No	Yes	8
T. suaveolens	500	***	Yes	No	-
	320	***	No	Yes	3
	320	***	No	Yes	4
	300	****	No	Yes	6
	240	***	No	Yes	10
T. pubescens	500	**	No	Yes	13
	320	/	No	No	-
	320	/	No	No	-
	300	**	No	Yes	12
	240	**	No	Yes	9
P. ostreatus	500	*	Yes	No	-
	320	*	No	No	-
	320	*	No	No	-
	300	**	No	Yes	5
	240	/	No	No	-

Note: Weight (g): wet sawdust mixture weight per jar, /: no growth, *: small signs of growth, **: less than half of the jar filled with visual fungal growth, ***: over half of the jar filled with visual fungi growth, and ****: all of the sawdust covered with visual fungal growth

Physical Panel Testing

The ranking of the haptic properties is based on how easily the panels can be removed from the mold and handled. Refer to Table 5 for the range (0 for "no bonding" to +++++ for "very good bonding and flexibility when handled"). The values for thermal conductivity ranged between 0.051 and 0.055 W/mK and were approximately 30% higher

than the most common thermal insulation materials, such as mineral fiber, polystyrene, or wood fiber panels, used in construction today. However, further reduction of thermal conductivity by adjusting fiber size and fungi growth might be possible. The values were consistent; only one sample achieved an approximately 10% lower conductivity. This particular sample also had the highest flexibility amongst all samples. All samples were weighed after drying through autoclaving for 120 min at 140 °C. After 4 weeks of storing at a room temperature of 21°C and an average room humidity of 30% to 35%, the panel weights consistently increased throughout all samples by an average of 5.9%.

Table 5. Panel Measurement Results

Panel No.	*Species*	Growth	Thickness of Panel (mm)	Haptic Properties	Thermal Conductivity (W/mK)	Dry Weight (g)	Weight After 28 d (g)
1	*P. arcularius*	****	26	++++	0.055	110	117
2	*P. arcularius*	****	26	++++	0.055	105	108
3	*T. suaveolens*	*	27	+	-	-	-
4	*T. suaveolens*	*	25	+	-	-	-
5	*P. ostreatus*	**	25	+	-	-	-
6	*T. suaveolens*	**	25	++	0.055	80	86
7	*P. arcularius*	***	26	+++	0.055	100	106
8	*P. arcularius*	***	22	+	-	-	-
9	*T. pubescens*	**	22	++	0.055	96	102
10	*T. suaveolens*	***	23	+++++	0.051	68	72
11	*P. arcularius*	****	27	++++	0.055	129	137
12	*P. ostreatus*	*	25	0	-	-	-
13	*P. ostreatus*	/	28	0	-	-	-

Growth column key: /: no growth, *: few signs of growth, **: less than half of the panels were covered with visual fungi growth, ***: over half of the panels were covered with visual fungi growth, ****: the sawdust was completely covered with visual fungi growth;
Haptic Properties column key: 0: no bonding; +: some bonding but fell apart when lifted; ++: some bonding but brittle; +++: good bonding with some brittleness; ++++: very good bonding with some brittleness; +++++: very good bonding and flexible when handled; and -: not tested

Petri Dish Trials Discussion

Based on a qualitative visual assessment of fungal growth, it was determined that a mixture of smaller and larger sawdust particle size performed better than a substrate of only small particles or large particles. It was hypothesized that small sawdust particles would be easier to penetrate by the fungal mycelium and would support good fungal growth. However, air spaces can be lost because the particles are so small, resulting in fewer gaps, creating anaerobic areas (Stamets 2005). Larger fibres increased the structural performance of the panels. However, the moisture of the substrate in the petri dish trials was also an important factor as growth of the fungal cultures was faster and denser at 65% moisture content (Trial 2) compared to 45% (Trial 1). Because the white rot fungal cultures (*P. arcularius*, *T. pubescens*, *T. suaveolens*, and *P. ostreatus*) grew faster and denser under the given conditions, they were selected for the third trial in which the fungi were grown on all remaining wood species.

The growth on petri plates with ionized water and without nutrients was minimal compared to the growth on petri dishes with nutrients. Initially, there was some visible fungal growth from the plugs but, without the addition of nutrients, fungi did not grow

quickly and did not produce visible, dense mycelium on the plates. This suggested that under laboratory conditions, some nutrients need to be added to the substrate to ensure better growth of the fungal cultures on sawdust substrates.

Jar Trials

The petri dish trials showed four promising fungal species. However, the jar trials reduced this number to two fungal species: *P. arcularius* and *T. suaveolens*. The higher substrate volume and lower surface/air ratio afforded by the jars compared to the petri dishes were more advantageous to the growth of these two species, compared to *T. pubescens* and *P. ostreatus*. The wood species were not examined at the cellular level and, therefore, it was not possible for the authors to explain the different growth patterns on different wood species.

Physical Panel Testing

Out of the 13 panels produced, only five were stable and rigid enough to be hypothetically used as insulation panels in construction. In several panels, the fungi did not bond (*via* mycelial growth) the sawdust particles sufficiently to obtain a useable rigidity and consistency. Most panels were fragile and brittle; four panels bonded well but retained brittleness. Only panel #10 (*T. suaveolens*) bonded well and was, in addition, also flexible.

The results of the tested thermal conductivities were promising, exhibiting values between 0.051 W/mK and 0.055 W/mK. These values are approximately 30% higher than other established insulation products such as expanded polystyrene (EPS), mineral fiber, and wood fiber boards (Kim 2012). Panel #10 also performed best in the thermal conductivity category. *P. arcularius* on birch performed quite consistently; 4 out of 5 panels achieved at least good bonding with some brittleness or very good bonding with some brittleness. *T. suaveolens* on birch did not perform consistently; 3 out of 4 samples performed poorly while one achieved the best results overall, both in haptic performance and in thermal conductivity.

As the panel samples were relatively small and thin, and the fiber sizes were also relatively small, and the panel samples reached their moisture equilibrium after only a few weeks. The measured 5.9% humidity content of the samples correlates well with several moisture content calculation methods (Hendriks and Zeeman 2009).

The traditional standard foam insulation boards and current wood fiber insulation boards available on the market are manufactured using fairly costly processes. Compared to those products, the cost of manufacturing as well as the initial and recurrent embodied energy of this alternative production of insulation boards can be considerably lower. The primary non-renewable energy content of a thermal insulation made from EPS covering 1 m^2 with a thermal conductivity of 0.333 W/(m^2K), equivalent to 100mm thickness is 295.5 MJ. Given the simple production requirements of fungi-based materials, it can reasonably be assumed that the embodied energy for the same area but larger thickness (160 mm), due to the higher thermal conductivity, is around 60 MJ. This number is an estimation based on the assumption that waste materials of the saw mill industry can be used but it does include energy for drying and mechanical processing . (Austrian Institute for Building and Ecology 2009).

CONCLUSIONS

1. The best fungal growth was achieved on sawdust derived from birch. The other tested softwood and hardwood species did not perform as well.
2. In all trials, the fungi *P. arcularius* and *T. suaveolens* produced the fastest, densest, and most reliable growth.
3. Thermal testing was conducted according to ASTM C518-17 (2017), and thermal conductivities between 0.051 W/mK and 0.055 W/mK were achieved. This is approximately 30% higher than commonly used insulation products.
4. Overall, this study indicated that mycelium-based boards are indeed a promising option that could provide a unique alternative compared to the traditional foam-based insulation boards and to current wood fiber insulation boards available on the market.

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