Biomass and Waste-derived Sustainable Mycelium Composite Construction Materials with Enhanced Fire Safety

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Abstract

Mycelium has attracted significant academic and commercial interest due to its ability to upcycle agricultural and industrial waste products into low cost, environmentally sustainable composite materials with almost zero additional energy input. In this paper, we investigate the use of widely available agricultural and industrial waste (e.g. rice hulls and glass fines) to enhance the fire-retardant properties of mycelium-biomass composites. The results show that the inclusion of rice hulls or glass fines significantly improves the fire safety and structural integrity of these materials while maintaining their economic and environmental sustainability. The findings of this study demonstrate that mycelium composites are safer and economical alternatives to highly flammable petroleum- and natural gas-derived synthetic polymers and engineered woods for applications including insulation, furniture and panelling.

1. Introduction

The past decade has witnessed a steady rise in the use of mycelium-biomass composites as an environmentally friendly alternatives to synthetic materials derived from non-renewable sources such as petroleum and natural gas [1-3]. Mycelium is the vegetative growth of filamentous fungi and comprises of a network of filaments known as hyphae [4]. The hyphae digest and bond to the surfaces of organic material under ambient conditions without additional energy input, thereby acting as natural self-assembling glue [2]. The key incentives for the use of mycelium composites are their low cost, low environmental impact and carbon footprint, low density, reduced energy consumption and most importantly, their biodegradability [5]. Mycelium composites are as geometrically versatile as plastics and are viable for the manufacture of products with simple to complex design geometry and uniqueness. Mycelial growth digests organic feedstock irrespective of arrangement with remarkable precision with simple shapes easily achieved using basic moulds [3, 6-8]. Furthermore, the wide variety of substrates on which mycelium grows combined with advanced processing techniques makes them viable, low-cost and sustainable alternatives to many widely used, highly flammable petroleum- and natural gas-derived synthetic materials (e.g. plastics including insulation foams) and resin-based engineered woods (e.g. particleboard) [5].

Synthetic resin-based materials have been identified as the main cause of severe and fatal fire incidents worldwide [9-12] due to significant heat and the toxic fumes generated during combustion [9, 10]. Modern houses constructed from unprotected engineered woods collapse over 3 times faster than older wood-based constructions [13]. Plastic foams are often major contributors to fires involving rapid flame spread which generate high volumes of smoke and toxic gases [14] including carbon monoxide and hydrogen cyanide [15]. Many potential applications of mycelium-based composites are in high fire risk environments (e.g. packaging and building insulation). However, very little is known about the thermal degradation and fire properties of mycelium and its composites. To meet the stringent fire safety regulations in industry, it is imperative to characterize the fire properties of mycelium and mycelium composites.

This study aims to investigate the effect of different substrates on the fire reaction properties of mycelium composites. Agricultural and industrial waste materials such as rice hulls and glass fines were used as substrates to improve the sustainability of these materials and to reduce their cost. The results of this study provide the first quantitative fire safety data regarding the impact of replacing synthetic construction materials with mycelium composites.

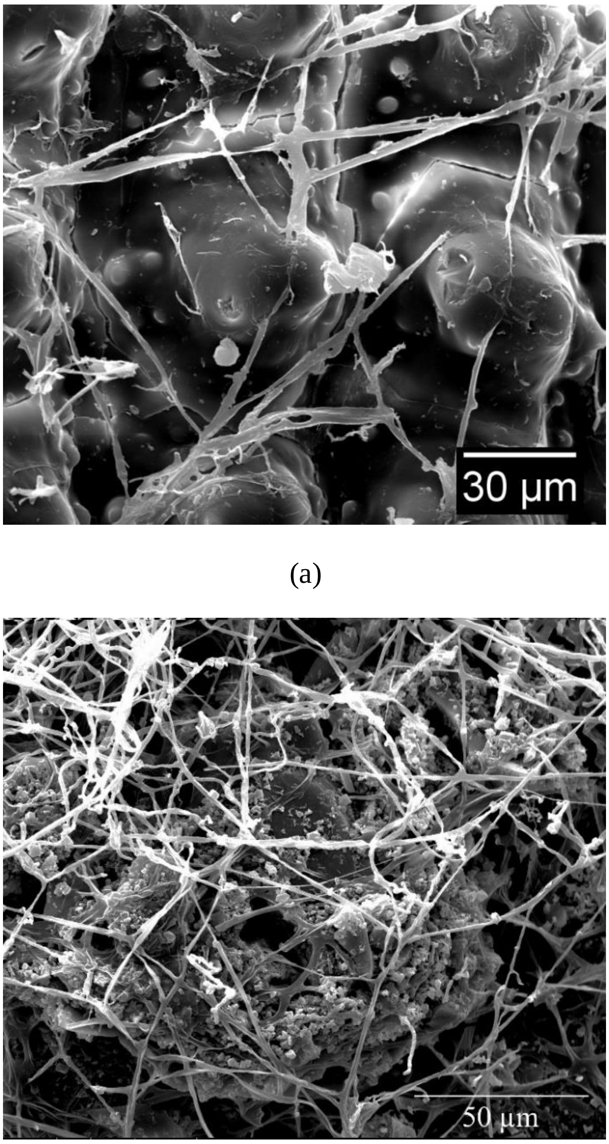
2. Materials and experimental methodology

2.1 Composite constituents

Rice hulls (CopRice, Leeton, Australia) and glass fines (The Alex Fraser Group, Melbourne, Australia) were selected as waste derived substrate materials for this study based on their local availability and cost. The common white-rot fungus *Trametes versicolor* was selected to bond these waste materials based on its growth performance [16]. The fungal inoculum was purchased from New Generation Mushroom Supplies (Melbourne, Australia) as a mycelial mass on digested wheat grain sealed in plastic bags with filter patches.

2.2 Preparation of mycelium composites

Rice hulls and glass fines were first soaked for 48 hours in type 1 Milli-Q® ultrapure water and sterilised at 121°C and 103.4 kPa for 40 minutes before use. The substrates and additives were then combined in varying ratios with *Trametes versicolor* wheat grain inoculum using a sterilised blender. The inoculated substrate was deposited into sterile plastic moulds which were sealed and incubated under standard atmospheric conditions (25°C, 50% RH) for 12 days allowing the hyphal growth to bind the substrates and additives. Following the incubation period, specimens were dried at 50°C for 48 h to completely remove adsorbed moisture and denature the fungal material. SEM images of mycelium grown on rice hulls and glass fines are shown in Figure 1.



(a)

(b)

Figure 1: SEM images of mycelium grown on (a) rice hulls and (b) glass fines.

Commercially available ClimaFoam® extruded polystyrene (XPS) foam (Knauf Insulation, Brisbane, Australia) and STRUCTAflor® YELLOWtongue® particleboard (CarterHoltHarvey Woodproducts, Melbourne, Australia) were cut to the same dimensions as the mycelium composites and used for comparison of fire reaction and fire safety properties.

2.3 Fire reaction testing

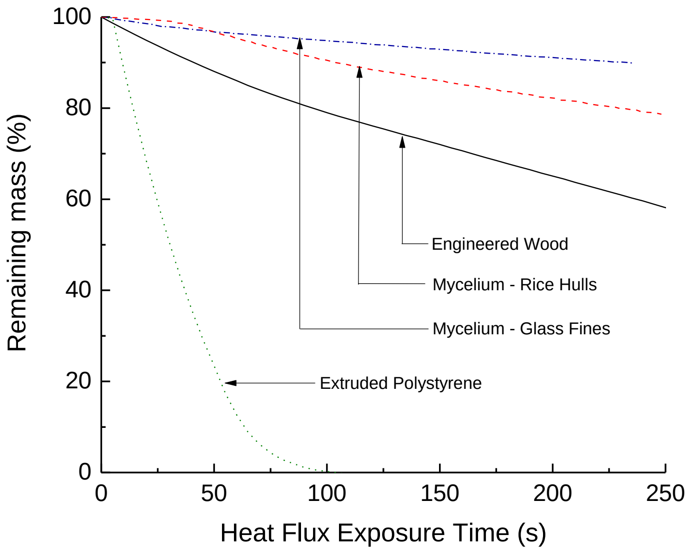
The fire reaction properties of the mycelium composites, XPS foam and particleboard were assessed using a three-cell cone calorimeter (Fire Testing Technology, UK) operated in the horizontal testing mode. All samples (100 mm long × 100 mm wide × 20 mm thick) were exposed to a constant incident thermal heat flux of 50 kW/m^2 simulating a well-developed room fire per ISO 5660 [17]. The heat-exposed specimen surface was positioned 25 mm from the cone heater. The fire reaction parameters including the time to ignition (t_{ig}), heat release rate (HRR), mass loss rate (MLR) and smoke (CO, CO_2 and soot) release were measured.

2.4 Scanning electron microscopy (SEM) and elemental analysis

Hyphal growth was examined using a FEI Quanta 200 environmental scanning electron microscope under high vacuum. Samples were removed from the surfaces of the mycelium composite dehydrated tiles, gold coated and subsequently imaged using an accelerating voltage of 30 kV and a spot size of 5. Multiple sites were imaged to ensure consistency. Elemental analysis of as-received uncoated glass fines was also completed using the attached Oxford X-Max^N 20 energy dispersive x-ray spectrometer and subsequent spectra analysis performed using AZtecEnergy EDS software.

3. Results and Discussion

The effect of heat flux exposure time on the fire reaction properties of mycelium composites, engineered wood and extruded polystyrene foam is shown in Figure 2 and Table 1. Mycelium composites had far superior fire reaction and fire safety properties to the synthetic construction materials assessed, with significantly lower heat release rates and smoke production. However, mycelium composites ignited faster than the synthetic materials assessed indicating that their surfaces reached their endothermic decomposition temperatures more rapidly than the synthetics.



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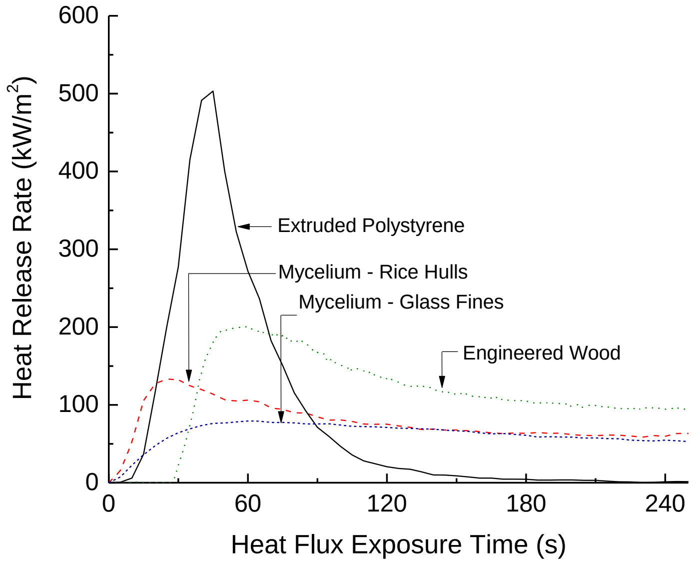

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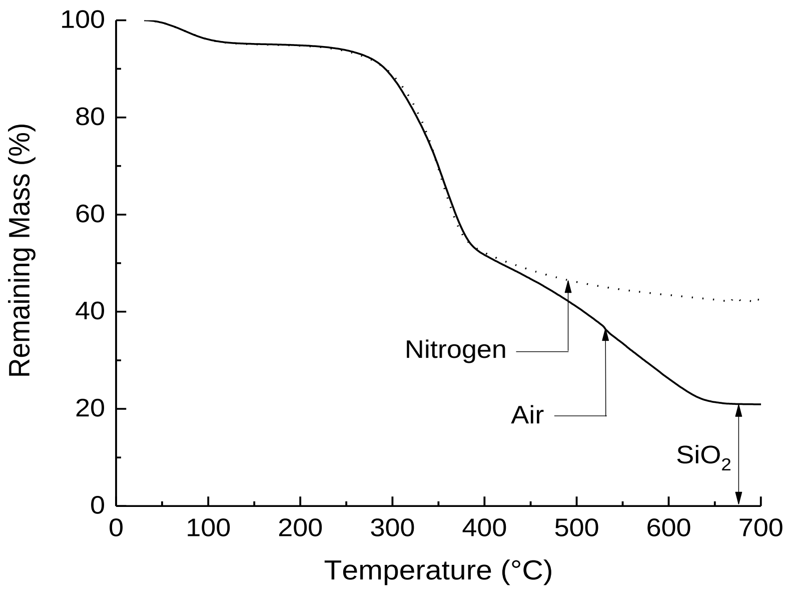
Figure 2:(a) Effect of radiant heat flux on the (a) mass loss and (b) heat release rates

The average and peak heat release rates of the mycelium composites were far lower than those of the synthetic samples, and the estimated time-to-flashover values were far higher. The most significant improvement in fire reaction and fire safety properties was associated with incorporation of significant concentrations of industrial glass waste (up to 50 wt%) which could be included in mycelium composites without adversely affecting growth. A chemical analysis revealed that glass fines comprise primarily of silica (SiO_2) and contain up to 30 wt% organic surface matters including well-documented fungal macronutrients (C, O, Mg, S, K) and micronutrients (Ca), which can be easily utilized by the fungi for growth. The addition of glass waste significantly increased the silica content of the composite materials which is known to reduce flammability and smoke yield through fuel dilution and heat sink mechanisms. It also reduced the concentration of flammable organics (e.g. cellulose) which are known to fuel combustion [18].

Table 1: Fire reaction properties obtained from cone calorimetry

Type	Sample	ρ (kg/m^3)	t_{ig} (s)	RHR_{180} (kW/m^2)	PHRR (kW/m^2)	t_{fo} (s)	TSR (m^2/m^2)	COP_{180} (g)	CO_2P_{180} (g)
Synthetic	Extruded Polystyrene (XPS)	33	9	114	503	61	1184	0.48	15.2
	Engineered Wood	689	26	134	200	173	64	0.47	30.0
Mycelium composite	75 wt% rice hulls	193	7	85	133	75	40	0.02	14.6
	25 wt% rice hulls + 50 wt% glass fines	450	7	33	85	311	0.9	0.91	6.3

The presence of rice hulls also reduced mycelium composite flammability due to the shielding effect of their significant char yield and the silica-ash layers formed on the composite surfaces. Thermogravimetric analysis and electron dispersive x-ray spectroscopy (Figure 3) revealed that rice hulls retain a significant mass (40 wt%) at 600°C comprising mainly of silica and amorphous carbon. High char yields and silica-ash layers of rice hull-based composites also reduced smoke generation due to the ability of char to impede the release of ultra-small fragments of fibre into the smoke plume [11].



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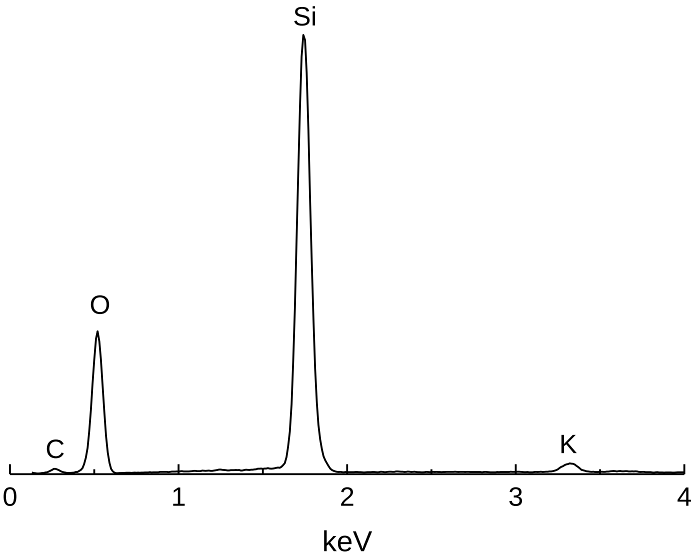

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Figure 3:(a) TGA mass loss curves for rice hulls and glass fines (b) EDS spectra of rice hull ash following heat treatment in air

Conclusion

This study has found mycelium composites to be an economical, sustainable and thermally-safer alternative to petroleum- and natural gas-derived synthetic construction materials. In particular, mycelium composites had much lower average and peak heat release rates and longer estimated time-to-flash over than the synthetic construction materials considered. They also released significantly less smoke and CO_2. Rice hulls yielded significant char and silica ash which improved fire performance, but composites containing glass fines exhibited the best fire performance due to their significantly higher silica concentrations and low combustible material content. Overall, mycelium composites were very economical and exhibited far better fire safety parameters than the traditional construction materials tested. Their widespread use in civil construction would enable better fire safety in buildings.

References

1. Y.H. Arafin and Y. Yusuf. Mycelium Fibers as New Resource for Environmental Sustainability. *Procedia Engineering*, 53: 504-508, 2013.
2. M.L. Haneef, C. Ceseracciu, I.S. Canale, J.A. Bayer, J Heredia-Guerrero, and A. Athanassiou, Advanced Materials From Fungal Mycelium: Fabrication and Tuning of Physical Properties. *Scientific Reports*, **7**: 41292, 2017.
3. G.A. Holt, G. McIntyre, D. Flagg, E. Bayer, J.D. Wanjura, and M.G. Pelletier, Fungal Mycelium and Cotton Plant Materials in the Manufacture of Biodegradable Molded Packaging Material: Evaluation Study of Select Blends of Cotton Byproducts. *Journal of Biobased Materials and Bioenergy*. 6(4):431-439, 2012.
4. M. Fricker, L. Boddy, and D. Bebber, *Biology of the Fungal Cell*. Springer Publications, 2007.
5. M. Jones, T. Huynh, C. Dekiwadia, F. Daver, and S. John. Mycelium Composites: A Review of Engineering Characteristics and Growth Kinetics. *Journal of Bionanoscience*, 11(4): 241-257, 2017.
6. L. Jiang, D. Walczyk, G. McIntyre, R. Bucinell, and G. Tudryn. Manufacturing of biocomposite sandwich structures using mycelium-bound cores and preforms. *Journal of Manufacturing Processes*, 28: 50-59, 2017.
7. L. Jiang, L., D. Walczyk, G. McIntyre, and W.K. Chan. Cost modeling and optimization of a manufacturing system for mycelium-based biocomposite parts. *Journal of Manufacturing Systems*, 41:8-20, 2016.
8. M.G. Pelletier, G.A. Holt, J.D. Wanjura, E. Bayer, and G. McIntyre. An evaluation study of mycelium based acoustic absorbers grown on agricultural by-product substrates. *Industrial Crops and Products*, 51:480-485, 2013.
9. J.H. Cho, V. Vasagar, K. Shanmuganathan, A.R. Jones, S. Nazarenko, and C.J. Ellison, Bioinspired catecholic flame retardant nanocoating for flexible polyurethane foams. *Chemistry of Materials*, 27(19): 6784-6790, 2015.
10. Z. Miao, L. Xingna, C. Zhen, W. Ji, and S. Wenhua. Experimental Study of the Heat Flux Effect on Combustion Characteristics of Commonly Exterior Thermal Insulation Materials. *Procedia Engineering*, 84: 578-585, 2014.
11. A.P. Mouritz and A.G. Gibson, *Fire properties of polymer composite materials*. Springer Science & Business Media, 2007.
12. Q. Xu, C. Jin, and Y. Jiang. Compare the flammability of two extruded polystyrene foams with micro-scale combustion calorimeter and cone calorimeter tests. *Journal of Thermal Analysis and Calorimetry*, 2017:1-8, 2017.
13. M.S. Izydorek, M.D. Samuels, P.A. Zeeveld, and J.P. Smyser. Report on structural stability of engineered lumber in fire conditions. Underwriters Laboratories, 2008.
14. H. Melville. *Fire and Cellular Polymers*, Springer, 1986.
15. A.A. Stec and T.R. Hull. Assessment of the fire toxicity of building insulation materials. *Energy and Buildings*, 43(2): 498-506, 2011.

16. M. Jones, T. Huynh, and S. John. Inherent Species Characteristic Influence and Growth Performance Assessment for Mycelium Composite Applications. *Advanced Materials Letters*, 9(1): 71-80, 2018.
17. The International Organization for Standardization, *ISO 5660-1: 2002: Heat Release, smoke production and mass loss rate–Part 1: Heat release rate (Cone calorimeter method)* Geneva, 2002.