SUSTAINABLE STRUCTURAL PROTOTYPE USING BAMBOO-BASED SUBSTRATE MYCELIUM COMPOSITE

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Abstract. The paper introduces the initial finding of Pleurotus ostreatus (PO) mycelium growing on the Phyllostachys makinoi (PM) bamboo substrate and taking advantage of mycelium composite's elevated compressive strength, lightweight, and thermal insulation properties; this study proposes a structural module system for a barrel vault structure. This research investigated 5:1, 2:1, and 1:1 bamboo-fiber and bamboo-powder mixtures with 5% $C_6H_{12}O_6$ and 65% water growing in a 25°C controlled environment. Due to the powder form of the PM substate, PO mycelium has easy access to the pentosan inside the substrate. As a result, the 1:1 ratio mixture has a higher growing rate than the 5:1 and 2:1 mixture. The experiment also indicates that the mycelium composite wall thickness shall be less than 40 mm for optimal PO mycelium growth when using PM substrate.

Keywords. Biodegradable materials; Bamboo Fiber; Mycelium Bamboo Substrates; Large-scale Mycelium Composite Materials; Degradable Structural Prototype.

1. Introduction

According to the Taiwanese Central Weather Bureau's recent report, Taiwan has experienced a 0.87 °C rising temperature in the past 30 years (Hsu & Chen., 2002). It is expected to be warmer in the foreseeable future. To prevent the irreversible rising temperature threshold of 1.5°C, the global community commits to decreasing CO_2, CH_2O, and other Volatile Organic Compounds (TVOC) emissions. Thus, strategically reducing building energy consumption is crucial to achieving Carbon Neutrality and Net Zero emissions in the upcoming decades. The Energy White Paper published in 2020 by the Federal Taiwanese government establishes the national strategy for reducing building energy, which can be categorized primarily into indoor lighting, building mechanical systems, and building thermal envelopes (AmCham Taiwan, 2020). The former two categories have a well-researched body of works and commercially viable products (MOEA Taiwan, 2008). However, the building's thermal envelope material relies mainly on petroleum-based sources to produce thermal barrier products (Yang, 2013). Such material is not only toxic in the production process but

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lacks biodegradability, and it will create a large amount of TVOC while burning (ABRI Taiwan, 2010). Hence, researchers worldwide have been looking for alternative materials, including one of the most promising materials, mycelium composite.

Mycelium composite has gained recognition over the years as a potentially sustainable material and has often been experimented with as an alternative insulation (Zhang, et al., 2022). In addition, several commercially viable indoor acoustic boards and packaging stuffing products are made from mycelium composite. The mechanical properties of mycelium composites are an ongoing topic. Researchers have consistently demonstrated that mycelium composites have lower thermal conductivity than the traditional insulation panel and perform better in compressive strength than tensile (Alaneme et al., 2023).

At present, it is known that there are a great deal of experiments and designs that have been conducted on this new material (Fig. 1). With the special organic fiber form of mycelium, non-conducting feature, and excellent structural strength after high-temperature baking. Ecovative, a mycelium technology company, uses fungal mycelium to develop sound insulation bricks, insulation panels, and compost packaging materials; Hy-Fi, which MoMA's PS1 exhibited is an organic mycelium tower built of mycelium bricks; MycoTree, designed by Felix Heisel and others, was exhibited at the Seoul Biennale in 2017, which is a spatially branched structure composed of load-bearing mycelium groups (Fig. 2).

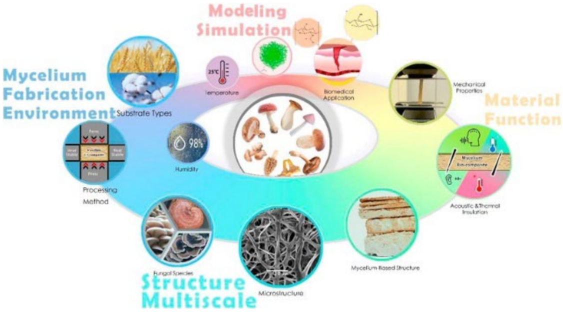


Figure 1. The Mycelium Studies (image credit: Holt et al., 2012; Pelletier et al., 2013; Jones et al., 2017; Nawawi et al., 2020)


(A) (B) (C)

Figure 2. (A)Pressing of the biological bricks (image credit: Courtesy of Arup / ArchDaily - Reproduction, 2020), (B)Hy-Fi Pavilion (image credit: ©Andrew Nunes/ ArchDaily - Reproduction, 2020). (C) MycoTree (image credit: © Carlina Teteris, 2017)

The majority of existing researched mycelium substrates are mostly sawdust and hemp. These substrate materials have been proven to have thermal and structure efficiencies on par with existing petroleum-based thermal installations. However, these substrate source materials are hard to come by in tropical environments like Taiwan and southeast Asia.

The local name Mengzong bamboo (Phyllostachys edulis) is endemic to Taiwan. It can sequester 47.36 metric tons of carbon per hectare per year, about 7.45 to 14.9 metric tons for regular wood forests (Yang, 2021, pp. 16-17). Bamboo can be harvested in two to three years due to its rapid growth; hence, a tri-annual harvest is a requirement to manage the bamboo forest. If the harvest is not done regularly, it will cause an environmental burden (AFA Taiwan, 2022). However, the bamboo industry has declined due to the relatively high labor cost of harvesting and transportation fees.

In recent years, domestic research on the bamboo process has been enough of a series of technical innovations to re-examine the bamboo material's development (AFA Taiwan, 2022). The Fu Lu Shou Factory in Miaoli revives ancient methods. It uses modern machines to cut, split, soak, roll, and press bamboo into bamboo paper, as well as the raw material for joss paper. It sparks the new bamboo material application. Encouraged by the novel bamboo processing, this research focuses on growing Pleurotus ostreatus (PO) mycelium on the locally sourced Phyllostachys makinoi (PM) bamboo fiber substrate. At the same time, the potential for the PO mycelium - PM substrate as the structural component for a barrel vault is investigated and studied.

2. Material Properties

2.1. MYCELIUM SUBSTRATE

Mycelium is a vegetative growth part of a fungus. It comprises a network of thread-like hyphae with a diameter of 1-30 µm (Fricker et al., 2007; Islam et al., 2017). An inner layer of glucans typically forms a hyphae's cell wall structure, and an outer layer of proteins protects inner cell membranes. Hyphae will extend cell walls and membranes at hyphae tips to form a mycelium network structure during the growing process. (Sejian et al., 2015). The growth of a network requires organic nutrients (cellulose, tannin, cutin, lignin, various proteins, and carbohydrates) and water. The nutrients generally come from a provided substrate and growing methods (Soh et al., 2020).

Pleurotus ostreatus (PO) mycelium, the prevalent species that can be cultivated locally in Taiwan, is one of the most common edible mushrooms. In the 1990s, cultivation techniques were developed through agricultural experiments. In other countries, wheat straw or straw compost is used and then bagged or covered with plastic sheets to dig holes for mushroom cultivation (Frost and Clarke, 2006). After being introduced to Taiwan, the cultivation bag technology was used to plant mushrooms, increasing the growth speed and significantly shrinking the time while keeping the quality standard. After generations of cultivated biogenic mycelium modification, the current PO mycelium is well suited for Taiwan's climate and environmental conditions. Therefore, the yield was greatly increased.

Based on known mycelium experiments, various substrate types are suitable for mycelium growth, including rapeseed straw, beech sawdust, hemp hurd, and other agricultural wastes (Fig.3, Jones, et al., 2020). Different substrates will provide various mechanical properties, such as tensility and compressivity. The mechanical performance depends on the substrate's porosity and the mycelium's digestion (Jones, et al., 2020). The growing speed of mycelium also pivots on the nutrient-rich additives during the incubation process, including starch or other carbohydrates, to foster a friendly growing environment.

Substrate type	**Substrate**
Fibrous	Rapeseed straw
	Flax hurd
	Hemp hurd
	Wheat straw
Particulate	Beech sawdust
	Red oak sawdust
	Pine shavings
	White oak sawdust

Figure 3. Local references for comparison of carbohydrates in different bamboo species.

2.2. BAMBOO SUBSTRATE

The bamboo substrate is a less understood subject matter for culturing mycelium growth. According to Soh, et al., 2020, it has been confirmed that mycelium can grow on bamboo fiber. It suggests using 500 µm mycelium-enriched bamboo fibers in 70:30 or 60:40 ratios mixed with a 3wt% of chitosan. The compression modulus of bamboo fiber-mycelium shows 40 kPa (Fig. 4). Although the studied compression mechanical property is a subpart of the existing non-bamboo-based substrate, it shows the early possibility of using bamboo as the substrate.

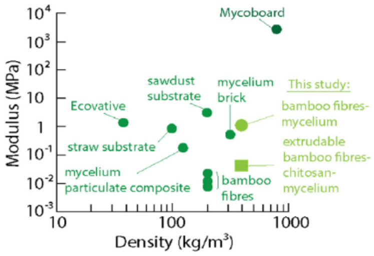
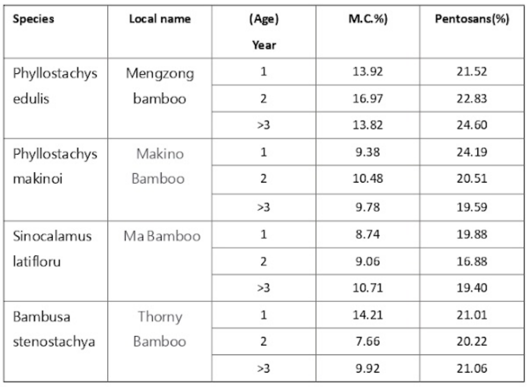


Figure 4. The relationship between density and modulus on mycelium-bound materials. (Islam, et al., 2017; Appels, et al., 2019; Elsacker, et al., 2019; Islam, et al., 2018; Wösten, et al., 2018)

Different bamboo species are made of similar chemical substances with various content percentages, including Pentose, Lignin, Holocellulose, Microcrystalline α-Cellulose, and other extractive chemicals (Ku & Chiou, 1972). Based on the prior research, high Pentosan content can foster a faster mycelium-growing environment. Besides, the one-year-old Phyllostachys makinoi (PM) bamboo has 24.19 % Pentosan content while Phyllostachys edulis has 21.52 % (Fig. 5). Therefore, this research selects

PM bamboo as the substrate to grow the PO mycelium.



Species	Local name	(Age) Year	M.C.%)	Pentosans(%)
Phyllostachys edulis	Mengzong bamboo	1	13.92	21.52
		2	16.97	22.83
		>3	13.82	24.60
Phyllostachys makinoi	Makino Bamboo	1	9.38	24.19
		2	10.48	20.51
		>3	9.78	19.59
Sinocalamus latifloru	Ma Bamboo	1	8.74	19.88
		2	9.06	16.88
		>3	10.71	19.40
Bambusa stenostachya	Thorny Bamboo	1	14.21	21.01
		2	7.66	20.22
		>3	9.92	21.06

Figure 5. Local references for comparison of carbohydrates in different bamboo species.

3. Experiments

3.1. PREPATATION OF THE MYCELIUM AND GROWTH LIMITATION

The 90mm x 180 mm cylinder container of PO mycelium was acquired from a local mushroom farming facility and has been incubated maturely for over 28 days in a controlled environment with approximate humidity of 65-75% and 24±2 °C temperature. The PO mycelium sample was removed from the initial container and placed in a sterilized environment for two days to grow on the outer layer, from which the PO mycelium culture was extracted.

A cross-section of fully grown PO mycelium was studied during the culture preparation. The cut sample was baked in the oven (DENG YNG, D9LD-DH400, Taiwan) at about 80 ° C for three days. The PO mycelium was discovered not to reach the center of the cross section. Given the incubation time and method, there is a 40 mm growth length limitation.

3.2. PREPARATION OF BAMBOO FIBER AND BAMBOO POWDER

In this experiment, a 1-year-old PM bamboo was dried in a room environment for a year and then was cut into 5mm and 10 mm bamboo strips and further dried inside the oven (DENG YNG, D9LD-DH400, Taiwan) at 80°c for three days. Then, the bamboo fiber was produced by the grinding machine (Felsted,2500A, Germany) and sieved via a #3.5 mesh screen (Fig.6. A). The bamboo powder was produced by using a DeWalt hand-held disc sander, and the particle size was less than 0.6 mm (Fig.6. B). A pH value study was carried out, determining that the bamboo fiber and bamboo powder solution are at pH 5.5. The optimal pH value for the PO mycelium to grow is pH 5.8 (Sándor, et al., 2016). It further demonstrates that PM bamboo as mycelium substrate is a viable option.

(A) (B)

Figure 6. (A)0.5cm/1cm bamboo fiber, (B) bamboo powder

3.2.1. Preparation Of Bamboo Fiber and Powder Substrates and Incubation

Bamboo mycelium studies were conducted to investigate three different PM substrates of bamboo fiber and bamboo powder ratios of 5:1, 2:1, and 1:1. First, the bamboo fiber material was completely soaked inside Reverse Osmosis (RO) water for 24 hours to ensure the fiber was hydrated. The excess water was removed and mixed with 5% glucose ($C_6H_{12}O_6$) solution as one of the nutrients. Finally, the mixed substrates were autoclaved at 121 °C for 1 hour (HY-230, Hung Yi Medical Instrument CO., LTD, Taiwan) and naturally cooled to room temperature.

Approximately 4g of the PO mycelium was extracted from the matured PO mycelium container and inoculated with each sterilized PM substrate mixture. It was placed in a sterilized container with a transparent film with four small perforations and affixed with medical microporous self-adhesive surgical tape. The incubation environment was controlled at 24±2 °C room temperature with 65%-75% humidity for ten days. Based on the ongoing experiments, the 1:1 ratio mixture has a higher growing rate than the 5:1 and 2:1 mixture (Fig. 7). The hypothesis of the faster growth is due to the powder PM substrate; PO mycelium has easy access to the pentosan chemical substances inside the substrates.

Once the current batch of the incubated PO mycelium has been thoroughly matured, another batch of PM substrate will be mixed in to increase the amount of the inoculated substrates for the mycelium composite fabrication (J.Weiler, et al .,2019, p.69-72, Heisel, F.,2017).

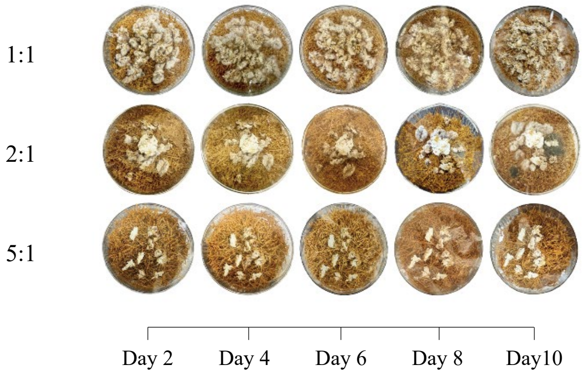


Figure 7. The growing process of different ratio combination (1:1, 2:1, 5:1)

4. Application

An arch has a compression form and characteristics. It can span a large area while resolving forces into compression (Chilton, J.,& Isler, H. et al., p.32). One fundamental principle of designing a funicular circular arch or the constant stress arch is keeping the dominant load and stress in the center zone between the two structural thicknesses (Fig. 8, Adriaenssens, S. et al., 2014, p. 46). Suppose the dominant load or other load conditions occurred near the boundary curves' edge. It will likely cause localized material overload and buckled.

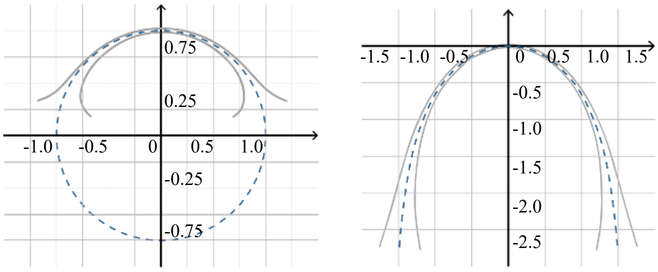
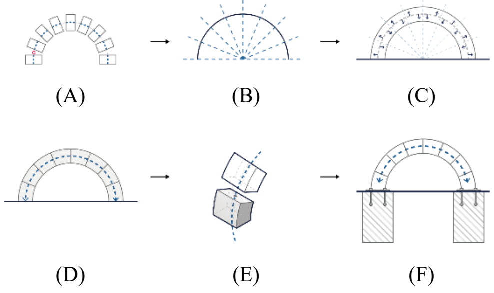


Figure 8. The central line of stress line (Adriaenssens, S. et al., 2014, p. 46)

4.1. STRUCTURAL PROTOTYPE AND DETAIL

This research proposes a series of interlocking modules to construct a mycelium barrel vault based on the funicular circular arch design principle and the established mycelium growth limitation. The proposed interlocking mechanism can connect not only the vertical unit but also the horizontal unit. One advantage of using barrel vault form is that when the arch divides evenly, each segment will be precisely the same, which is ideal for creating a modularized unit (Fig. 9. A and B). The designed module was shifted at the center line to accommodate the vertical and horizontal connections (Fig. 9. C). The dominant load is mainly concentrated in the center zone; therefore, it does not violate the funicular circular arch design principle. A post-tensioned cable system is added near the outer boundary of the mycelium barrel vault (Fig. 9. E-F) to secure the structure below. Although the interlocking unit can make out 90% of the barrel vault, the remaining 10% requires two customized edge modules to complete. As a result, three module forms are needed to complete a barrel vault (Fig.10).


(A) (B) (C)

(D) (E) (F)

Figure 9. Establishing a post-tensioned structural system

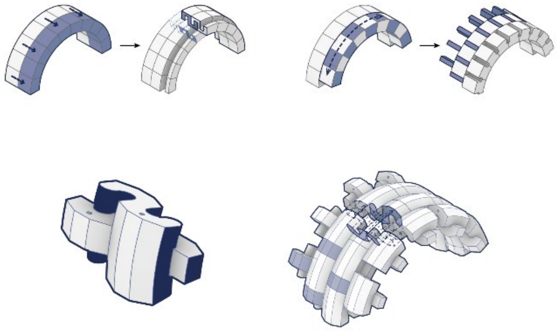


Figure 10. Final Prototype and The Form Of Arch.

A series of interlocking modules were conducted and prototyped from 3D-printed PLA to study the interlocking mechanism (Fig.11). Due to the unit's self-interlocking nature, a minimum scaffolding is required once the ground unit is secured to assemble into a stable barrel vault with the post-tension cables to further safeguard the overall structure. The proposed unit will be made of bamboo mycelium composite. Based on the initial material understanding and the known data, the module is designed to be capable of carrying the vault's weight. Yet, the module's compression strength and manufacturing accuracy still needed to be confirmed. The ongoing practical testing is still required.

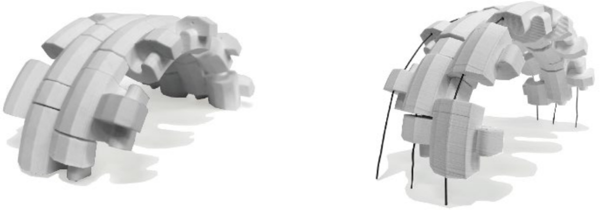


Figure 11. 3D Print Model and The Post-Tension System Structural Model

5. Discussion & Conclusion

Based on the existing mycelium composite research, this paper explored the potential of using Pleurotus ostreatus (PO) mycelium growing on the locally sourced Phyllostachys makinoi (PM) bamboo fiber and powder as the substrate. Three fiber and powder mixtures were studied: 5:1, 2:1, and 1:1. The study discovered that the 1:1 ratio mixture has a higher growth rate than the 5:1 and 2:1 mixtures. The ongoing hypothesis is that the 1:1 has more bamboo powder and that mycelium has easy access to the pentosan chemical substances. The paper demonstrates the successful cultivation and incubation of the specific ratios of PO mycelium grown on PM substrate mixtures. Further research is needed to determine the mechanical properties of PO mycelium grown on PM substrate composite.

Although the current barrel vault module is designed based on known limitations, an actual module must be produced and tested to properly determine the proposed vault design's mechanical properties. Tolerance is needed to fit each module properly. However, the joint gap will become a concern; hence, this research proposes using bio-based cetyl palmitate as the sealer. This requires further examination to provide the functionality.

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References

Adriaenssens, S., Block, B., Veenendaal, D.,& Williams, C.(2014). *Shell Structures for Architecture: Form Finding and Optimization.*

Agriculture and Food Agency, Ministry of Agriculture, R.O.C (Taiwan). (2022). *Emerging Bamboo Industry Development Plan*

Alaneme, K.K., Anaele, J.U., Oke, T.M., Kareem, S.A., Adediran, M., Ajibuwa, O.A., & Anabaranze, Y.O. (2023). Mycelium based composites: A review of their bio-fabrication procedures, material properties and potential for green building and construction applications. *Alexandria Engineering Journal.* 83, 234-250. https://doi.org/10.1016/j.aej.2023.10.012.

Almpani-Lekka, D., Pfeiffer, S., Schmidts, C. & Seo, S. (2021). A review on architecture with fungal biomaterials: the desired and the feasible. *Fungal Biology and Biotechnology, 8,* https://doi.org/10.1186/s40694-021-00124-5

AmCham Taiwan. (2020). *2020 Taiwan White Paper,* from https://amcham.com.tw/wp-content/uploads/2020/06/June-2020-Taiwan-Business-TOPICS.pdf

Architecture and Building Research Institute, Ministry of the Interior, ROC (Taiwan). (2010). *Experimental study on the emission of volatile organic compounds from recycled green building materials.*

Bhat, T., Jones, M., Kandare, E., Yuen, R., Wang, C.H., & John, S. (2018). *Composite Materials. European Conference.*

Central Weather Bureau, Taiwan. (2021). *Taiwan's Climate in 2021,* from https://www.cwa.gov.tw/Data/service/notice/download/Publish_20220628113633.pdf

Cerimi, K., Akkaya, K.C., Pohl, C., Schmidt, B., & Neubauer, P. (2019). Fungi as a source for new bio-based materials: a patent review. *Fungal Biology and Biotechnology,*6(17), https://doi.org/10.1186/s40694-019-0080-y

Chilton, J.,& Isler, H.(2000). *Heinz Isler: the engineer's contribution to contemporary architecture.*

Energy Administration, Ministry of Economic Affairs, R.O.C.(2008). *Lighting System Q&A Energy Saving Technical Manual.*

Fagan, J. (2019, March 25). *Nursing clinical brain.* OER Commons. Retrieved January 7, 2020, from https://www.oercommons.org/authoring/53029-nursing-clinical-brain/view.

Frost, D. and Clarke, A. (2006). *The use of composted woodchip as a substrate for growing varieties of edible mushrooms.*

Heisel, F., Schlesier, K., Lee, J., Rippmann, M., Saeidi, N., Javadian, A., Nugroho, A.R., Hebel, D., & Block, F. (2017). *Design of a load-bearing mycelium structure through informed structural engineering.*

Hsu, H.H., & Chen, C.T.(2002). Observed and projected climate change in Taiwan. *Meteorol Atmos Phys* 79, 87–104.https://link.springer.com/article/10.1007/s703-002-8230-x

Hu, W., Di, Q., Liang, T., Liu, J., & Zhang, J. (2022) Effects of spent mushroom substrate biochar on growth of oyster mushroom (Pleurotus ostreatus). *Environmental Technology & Innovation,* 28, 102729. https://doi.org/10.1016/j.eti.2022.102729

J.Weiler, P. Fernando, N. Siyambalapitiya, S. Kuznetsov(2019), Mycelium artifacts: Exploring shapeable and accessible biofabrication, In *DIS 2019 Companion - Companion Publication of the 2019 ACMDesigning Interactive Systems Conference 2019,* (pp. 69-72). ACM Designing Interactive Systems Conference 2019.

Jones, M., Mautner, A., Luenco, S., Bismarck, A., & John, S. (2020). Engineered mycelium composite construction materials from fungal biorefineries: A critical review. *Material and Design.*187,108397.

Ku, Y.C., & Chiou, C.H.(1972).Tests on Fiber Morphology and Chemical Composition of Important Bamboo in Taiwan. *Co-operative bulletin of Taiwan Forestry Research Institute in co-operation with The Joint Commission Onrural Reconstruction,*20.

Sándor, R., Dănuț Nicolae, M., Vasile, L., Tincuța-Marta, G., Ileana, A., (2016). *The influence of pH and the source of nitrogen on the mycelial growth of the Pleurotus ostreatus mushrooms.* Lucrări Ştiinţifice – vol. 59(2)/2016, seria Agronomie

Soh, E., Chen, Z.Y., Saeidi, N., Javadian, A., Hebel, D., & Ferrand, H.L. (2020).Development of an extrudable paste to build mycelium-bound composites. *Materials and Design*,195, 109058.

Yang, G.X.(2013). *A Study for Heat Insulating Efficiency of Aggregate Roof Heat Insulation Bricks.*

Yang, J.H. (2021). *The biology of humans at our best and worst The Bamboo Dreams in Taiwan create another green and golden generation.* HARVEST, 71(5), 16-17. https://doi.org/10.6708/harvest.202105_71(5).0003

Yang, L., & Qin, Z. (2023). Mycelium-based wood composites for lightweight and high strength by experiment and machine learning. *Cell Reports Physical Science, 4(6),.* https://doi.org/10.1016/j.xcrp.2023.101424

Yang, L., Park, D., & Qin, Z. (2021). *Material Function of Mycelium-Based Bio-Composite: A Review.* Biobased Nanomaterials: New Trends and Applications, 8(9), https://doi.org/10.3389/fmats.2021.737377.

Zhang, X., Hu, J., Fan, X., & Yu, X. (2022). Naturally grown mycelium-composite as sustainable building insulation materials. *Journal of Clear Production*, 342, 130784.