Economic assessment of mycelia-based composite in the built environment

by

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B.A., University of Cape Coast, 2020

A THESIS

submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

Department of Agricultural Economics
College of Agriculture

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2023

Approved by:

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Abstract

Resource depletion and environmental pollution are becoming worse due to rapid global population growth. Numerous conventional products have been produced to satisfy consumer demand in the building industry. However, most of these products are environmentally unfriendly, costly, and not locally accessible. In order to make headway in solving these issues, it is necessary to implement cost-effective, environmentally friendly technologies and locally accessible resources in the built environment. Mycelium-based composites are the recently introduced technology that has drawn more attention in the built environment because of their contribution to the advancement of environmentally friendly and sustainable building materials.

We assess the economic feasibility of mycelia as a competitive composite building material against traditional building materials such as concrete and lumber. The cost of building a 2000 sq ft house with each type of building material was estimated and used as the base cost of building for our analysis. The economic feasibility was analyzed based on the assumption that the difference in building cost between mycelium composite and any other material is invested at a given interest rate and the consumer price index is applied to the building cost in year t.

We found that a mycelium composite house is relatively cheaper to build compared to concrete and lumber if the mycelium price is less than \$0.83/ft^3, however, it is less durable than concrete and lumber houses. The study concludes that if the current consumer price index (inflation rate) remains the same and the interest rate is 8.50% or greater, assuming the price of mycelia is \$0.83/ft^3, then mycelia building is economically feasible and competitive as a composite building material against concrete and lumber. That is, for any given year *t*, the interest rate on investment should at least be greater than the prevailing inflation rate by 2%.

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Acknowledgements

I will first give all praise and thanks to the Almighty Allah. I would like to give thanks and gratitude to my major professor – Dr. Vincent Amanor-Boadu. It has been a great honor to be mentored by you. You have challenged me to read and learn outside my comfort zone. And you have brought the best out of me. To Dr. Bergtold Jason and Dr. Aleksan Shanoyan, thank you so much for your suggestions, guidance, and mentorship. You have always been there to listen to my challenges and provide me guidance. I would also like to thank all my fellow graduate students for helping me one way or the other. And special gratitude to Ashling Murphy, Amber Oerly, and Catherine Obiribea Ofori-Bah.

Finally, to my mom and dad, thank you so much for always being there for me when it mattered most.

Dedication

This thesis is dedicated to my family and all my mentors.

Introduction

Traditional building materials, such as cement, have been used for several centuries. These adverse impact on the environment has become increasingly evident in recent decades (Mehra et al. 2022; Eštoková, Wolfová Fabiánová and Ondová 2022). There is, therefore, an increasing need for developing natural or renewable alternatives to ameliorate these adverse effects (Zhu, Romain and Williams 2016; Koronis, Silva and Fontul 2013; Alemu, Tafesse and Mondal 2022). Attention is shifting to renewable sources of materials for the building industry`s transition to a more environmentally friendly and cost efficiency in production practices (Zhu et al. 2016; Koronis et al. 2013; Hoang, Pham and Nguyen 2021).

Increasing global population and urbanization is increasing housing needs and putting pressure on the housing construction industry (Mpakati-Gama, Wamuziri and Sloan 2012). The world population exceeded 8 billion in November 2022 (United Nations 2022) and is projected to reach 8.5 billion people in 2030, 9.7 billion in 2050, and 10.4 billion in 2100 (United Nations 2022). African nations` (especially Sub-Saharan Africa) are the most rapidly urbanizing countries globally and are also expected to have the fasted growth in their populations. They are expected to account for more than half of the projected rise in the world's population by 2050 (United Nations 2022). This will put additional pressure on already strained building resources, such as lumber and cement around the globe (Mpakati-Gama et al. 2012). The competition for building materials in the building industry and the significant negative impact of traditional building materials on the environment has made it more important for stakeholders in the industry to look for more sustainable alternative building materials (Mpakati-Gama et al. 2012) to augment or replace the conventional building stocks.

The rapid growth in urbanization has put pressure on the building industry (Ongpeng et al. 2020; Yang, Park and Qin 2021) in supplying the demands for this urban population using traditional building materials like cement, lumber, and steel (Jones et al. 2017; Pheng and Hou 2019; Madurwar, Ralegaonkar and Mandavgane 2013; Yang et al. 2021). For instance, the global urban population is rising by 200,000 people per day rapidly increasing the demand for affordable houses (Maskuriy et al. 2019). According to the United Nations, urban population reached over 50% in 2014 (Cornelia Van Empelen 2018) and predicts that 66% of the world's population will reside in urban areas by 2050 (Alemu, Tafesse and Mondal 2022). The rise in urban population will cause a significant increase in energy consumption and urban emissions through conventional building activities such as concrete production (Alemu, Tafesse and Gudetta Deressa 2022).

Cement is one of the most often utilized building materials globally compared to other materials (Yang et al. 2017). Materials made with cement are water-resistant, durable, and strong (Yang et al. 2017; Alemu, Tafesse and Gudetta Deressa 2022). However, they do not decompose, they pollute the environment, and they are costly (Alemu, Tafesse and Gudetta Deressa 2022). Production of cement accounts for 7% of all carbon dioxide emissions worldwide (Siddique et al. 2016). The building industry requires technological advancement to be sustainable and clean (Alemu, Tafesse and Gudetta Deressa 2022).

The advancement of technology in building materials is now one of the most significant in the fields of biotechnology and civil engineering (Alemu, Tafesse and Gudetta Deressa 2022). A mixture of fungus mycelium and organic substrates can be used to create sustainable building materials (Ongpeng et al. 2020; Alemu, Tafesse and Mondal 2022). Mycelium is the vegetative portion of fungus that includes hyphae, which are long, branching filaments that serve as a natural binder and are utilized to construct a web of very thick fibers that are linked to a substrate such as sawdust, straw, coffee grounds, wheat bran, or bagasse (Alemu, Tafesse and Gudetta Deressa 2022; Ongpeng et al. 2020; Alemu, Tafesse and Mondal 2022; Islam et al. 2017; Yang et al. 2021; Heisel et al. 2017; Jones et al. 2020).

Mycelium is becoming more and more sought-after as a next generation of sustainable materials because of its biodegradable, low density, and low environmental impact properties (Silverman, Cao and Cobb 2020; Attias et al. 2020; Jones et al. 2017; Jones, Bhat, Huynh, et al. 2018a; Jones, Bhat, Kandare, et al. 2018; Ongpeng et al. 2020; Sydor et al. 2022; Butu et al. 2020). Mycelium-based bio-composites can help transition away from a fossil-based economy and unfriendly climate materials (Meyer et al. 2020). Mycelium lends itself to easy recycling, making it a promising input for sustainable building (Butu et al. 2020; Alemu, Tafesse and Gudetta Deressa 2022). Mycelium-based bio composites will play a significant role in a new generations of natural, regenerative materials for the world (Silverman et al. 2020; Ongpeng et al. 2020; Sydor et al. 2022; Attias et al. 2020).

1.1 Background

Fungi are eukaryotic organisms, which also include the more well-known mushrooms and microbes like yeast and mold that exhibit enormous variation in their morphology and can grow in a wide range of habitats, including deserts and deep-sea sediments (Manan et al. 2021). Fungi inhabit their substrate using their elongated filamentous cells called hyphae, which develop into a three-dimensional intertwined network called mycelium (Manan et al. 2021). Mycelium is the vegetative part of a fungus that resides beneath the ground (Maria 2021; Søren 2018; Jiang et al. 2016). It consists of delicate root-like threads of hyphae that act as a natural glue, binding particles together to create a bio-composite material that is extremely durable and resistant to both water and fire (Søren 2018). Mycelium is grown through an apical tip development of hypha from a spore or an inoculum (Klemm et al. 2005). The hypha commences random branching after an isotropic development phase, generating fractal tree-like colonies that are randomly connected by hyphal fusion (anastomosis), resulting in a random fiber network topology, which primarily depends on environmental and nutritional conditions (Klemm et al. 2005; Islam et al. 2017; Jones, Bhat, Kandare, et al. 2018).

Mycelium composites are then made when water is driven off after colonization, and the mycelium is inactivated by drying the composite at a high temperature (>80 °C) for a period (Jiang et al. 2016). The inactivated mycelium binds together natural fiber reinforcement and nutrients as a bio composite (Jiang et al. 2016). Mycelium works as a natural self-assembling binder when it penetrates a substrate, binding a loose mixture in a monolithic shape and forming a solid composite of biopolymers, cellulose matrix, and very thick chitin reinforcement (Sydor et al. 2022). The unique attributes of fungus-mycelia thus portend enormous potential for their use in biotechnology and industry.

Mycelia alternatives have been identified as credible in the face of declining and more environmentally unfriendly resources, such as cement and lumber (Alemu, Tafesse and Mondal 2022; Jones et al. 2020). For instance, about 4.25 million tons of cement are produced globally each year, and 4.4 million tons of cement were produced in 2021 globally (National Minerals Information Center (NMIC) 2022). Approximately, one ton of carbon dioxide (CO_2) is released in the production of a ton of cement, which accounts for 7% of all carbon dioxide emissions worldwide (Siddique et al. 2016). Felling of one tree which weights a ton when standing of lumber size deprives the world of 25kg of CO_2 sequestration capacity each year forever (Ecotree 2022). Also, the supply of traditional building materials, such as cement, bricks, lumber, and steel has struggled to keep pace with an expanding global population and urbanization over the past decade, placing a significant strain on the building construction industry (Jones et al. 2017; Pheng and Hou 2019; Madurwar et al. 2013). Coupled with this is the increasing demand for food and agricultural products leading to the generation of agricultural wastes such as rice husks, sugarcane bagasse, straw, and cotton stalks (Jones et al. 2017), which can be converted into renewables with the help of mycelia for industrial purposes. The fashion industry is one of the first markets for which mycelium-based products can give a solution, as there is a consumer and market desire for alternatives to animal skins and plastics used in garments (Meyer et al. 2020).

Mycelium-based products provide significant benefits compared to conventional synthetic materials, including low cost, low density, low energy consumption, biodegradability, minimal environmental effect, and carbon sequestration (Jones et al. 2020; Haneef et al. 2017; Abhijith, Ashok and Rejeesh 2018). Mycelia-based products also satisfy structural and functional requirements such as fire resistance and acoustic and thermal insulation (Jones et al. 2020). This opens new opportunities for environmentally sustainable and renewable building materials as substitutes for conventional materials. They can also be used as semi-structural materials, including paneling, flooring, decking, and insulation panels (Islam et al. 2017; Michael 2014; Jiang et al. 2017). In addition, low-cost or costless agricultural wastes are often used as substrates such as straw, rice husks, and sawdust, which makes the cost of mycelia composites low and promote waste recycling (Pelletier et al. 2013; Jones, Bhat, Huynh, et al. 2018a; Jones et al. 2020)

Mycelium-based composites are used in product manufacturing, packaging, building, and applied arts (Maria 2021; Abhijith et al. 2018; Sydor et al. 2022). Mycelia has been employed in the industry to produce building material such as insulation, acoustic panels, and doors. In addition, mycelium is used to produce leather in a low-carbon manner for accessories such as shoes, bags, and clothes, which can be broken down and form soil after being thrown away (Woodfin 2021a)

Even though the mechanical properties of mycelium composites based on biomass are inferior to those of traditionally manufactured composites (Islam et al. 2017; Michael 2014; Jones, Bhat, Kandare, et al. 2018), the large range of substrates on which mycelium grows, along with better processing techniques have allowed their usage in several applications (e.g. furniture, decking, etc.) (Haneef et al. 2017; Pelletier et al. 2019; Mayoral González, Keller and Joachim n.d.; Jones, Bhat, Kandare, et al. 2018).

Much of the literature has pointed out the potential applications of mycelia in industry and the key properties are environmentally friendly and bio renewable. However, very little is known about the techno-economic feasibility of mycelia as a building product. It is imperative to assess the economic implications of producing mycelia-based sustainable products in large quantities to serve the ever-increasing population and meet the requirements for achieving a sustainable economy. Today, with sterilizing technology, mycelium building material continues to reduce its energy impact, and carbon sequestration is possible by using mycelium-based products (Jiang et al. 2017; Holt et al. 2012; Woodfin 2019a). Because of its environmentally friendly and low cost, people will invest in the production of mycelium-based products as a business to make money (Woodfin 2018; Woodfin 2021b; Woodfin 2019b; Ecovative 2022). Therefore, it is more important now than ever to assess the economic feasibility of producing this material in enormous quantities to meet demand.

1.2 Research Problem

Mycelium composite has a huge potential in the building industry as a sustainable building material. Economic feasibility of this environmentally friendly material has been noted from above as a key factor in encouraging investment in this product in the industry. Despite their immense potential, mycelia have not yet gained widespread recognition as a commercial resource, therefore mycelium composites remain a mostly unexplored niche industry. To fulfill the needs of an expanding population and the criteria for developing a sustainable building industry, it is essential to evaluate the economic feasibility of generating mycelia composites for buildings. The problem this research tackles is to contribute to the knowledge gap in the potential role of mycelia composite as a building material within the built environment.

1.3 Research Questions

1. Is mycelia composite an economically feasible alternative to concrete and lumber structures in the built environment? Thus, is the lower construction cost for mycelia enough to compensate for its lower life expectancy?

1.4 Objectives

The overall objective of this study is to estimate the economic feasibility of using mycelia composites as a building material for a single-family home and compare it to concrete and lumber homes. The specific objectives are:

1. Compare the base construction cost of mycelium composite home to concrete (cement block) and lumber-framed homes under different mycelium price conditions.
2. Assess the economic feasibility of mycelium as a competitive composite building material.

1.5 Overview of Methods

This study considers a single-family home of 2000 ft^2 built in a typical Midwest community in the United States for the analysis. A 2,000-square-foot house is used because it is estimated that a typical American family of three to four can live comfortably in this size of home (https://www.forbes.com/). The construction cost of each building material type (i.e., mycelium composite, concrete, and lumber) is estimated using a simple multiplication and summation model. The assessment of the economic feasibility model considers a situation where the difference in building cost between any two types of material is invested at a given interest rate and the prevailing inflation rate. The model uses the relative life expectancy between any material and mycelium composite to determine if mycelium composite is competitive over other types of building materials.

The data for the study was extracted from the literature and self-calculations. Mycelium composite data were extrapolated from the literature. Concrete and lumber framed data were mostly sourced from Forbes Home (https://www.forbes.com/). All the models were estimated and analyzed using Microsoft EXCEL.

1.6 Thesis Outline

This study is organized into five chapters. Chapter 1 has provided the background and the research plan. Chapter 2 covers the review of the extant literature. Chapter 3 covers the research methods, the model and data, and tool used. Chapter 4 presents the results of the study while the final chapter presents the summary and conclusion of the study. The recommendations for further study are also presented in that chapter.

Chapter 2 - Literature Review

The literature review outlines the existing literature supporting the research problem area and the question. It has been organized in the following subsections. Section 2.1 discusses the current state of the building industry and its contribution to greenhouse gas emissions and climate change. Section 2.2 explores how alternative materials in buildings originate and their contribution to a reduction in the carbon footprint of the industry on climate change. Section 2.3 explores the biology and botany of mycelium and why it is an effective alternative, and the economics literature on approaches to assessing the feasibility of alternative approaches and comparing them for the purpose of decision-making. Finally, Section 2.4 summarizes the literature by identifying the gaps discovered through the literature review. It then presents the study's expected contribution in filling in these gaps.

2.1 Current State of the Building Industry

The building industry uses a wide range of resources which includes materials such as gravel, clay, stone, sand, thatch, mud, cement, asphalt, mortar, gypsum, and slag; metal products such as steel, iron, pipes, and radiators; wood products such as lumber and bamboo; plastics; and other products (Piecyk, Allen and Woodburn 2021).

The building industry contributes about one third of all the negative environmental effects globally (Cornelia Van Empelen 2018). The Environmental Protection Agency (EPA) estimated that 136 million tons of building-related waste was generated in the United States in 1996, by 2003 it reached 170 million tons (US EPA 2023). In 2018, the United States produced more than 600 million tons of construction and demolition-related waste. The building industry generates around 25% of the total construction waste according to the US EPA (2023). In the European Union (EU), it is estimated that the construction industry produced 38.4 million tons of waste, around 13%

came from the construction and demolition of buildings in 2020 (Eurostat 2020). In Hong Kong building construction and demolition waste account for 42% of the total waste produced and Taiwan generates about 2.4 million tons of concrete as waste per year (Cornelia Van Empelen 2018). Also, about one third of Malaysia waste comes from the building industry (Cornelia Van Empelen 2018). The environmental impacts of this waste can be significant, as about 24% often ends up in landfills, where it takes up valuable space and contribute to greenhouse gas emissions (Osmani 2021).

According to the International Energy Agency (IEA), 38% of the world's CO_2 emissions are attributed to building construction energy-related emissions (Global Alliance for Buildings and Construction 2020). For instance, the building construction sector accounts for approximately 19% of UK CO_2 emissions (Piecyk et al. 2021). Additionally, traditional building materials like steel and concrete require a large amount of energy to produce (Yang et al. 2021), which negatively impact on our environment (Yang et al. 2021; Madurwar et al. 2013). However, mycelium has recently attracted increased interest in both academic and commercial research due to its low energy need for production, zero-byproducts, and wide range of possible applications in a building (Holt et al. 2012; Pelletier et al. 2013; Jones et al. 2017; Yang et al. 2021).

It is critical to develop ideas and technologies in the building sector that are environmentally friendly and cost effective. In this way, the more effective use and recycling of raw materials may provide significant environmental benefits, as well as create new opportunities in the building construction industry. Mycelium has been proven to be a valuable source of material for this sector (Ecovative 2022; Ecovative Design 2019; MycoWorks 2022; Robinson 2016; Yang et al. 2021; Ongpeng et al. 2020; Attias et al. 2020; Pelletier et al. 2019; Holt et al. 2012; Pelletier et al. 2013; Jones et al. 2017). For building matreial technology to advance, adapt, and raise the acceptance of such materials as a viable substitute (Ongpeng et al. 2020), there is a need to assess the economic feasibility of mycelium composite industrial products, because investing in this alternative eco-friendly product may result in a more sustainable future for the world (Ongpeng et al. 2020; Abhijith et al. 2018).

2.2 Alternative Building Materials

The availability and use of materials have always impacted building practices. The type of building materials used for building has changed over time, beginning with ancient building materials, the renaissance period, and the industrial revolution to the present (WeBuildvalue 2021).

2.2.1 Ancient Building Construction Materials

In the ancient period, traditional buildings were determined by the availability of building materials provided by nature like clay, wood, and stone (Cornelia Van Empelen 2018). Most buildings were constructed with simple wood and roofed with animal skins (WeBuildvalue 2021). These buildings provided only little weather protection during the Paleolithic era (WeBuildvalue 2021). Then, in the Neolithic period, people started to build with wood due to hostile climatic conditions (Iko 2020). At the end of the Bronze Age, around the third millennium BC, people started to use stone as a building material, the pyramids were built from heavy blocks of granite (WeBuildvalue 2021). During this period, ancient peoples also used bamboo as a building material in places where it was naturally grown and abundant (Manandhar, Kim and Kim 2019).

The Greeks used thatched roofs with overhanging eaves that were supported by dried clay bricks (Iko 2020). Once the Greeks started to use stone, which made the walls of their homes sturdy enough to hold heavier roofing materials, they began to develop roofing tiles with clay (Iko 2020).

Figure 2.1. A Thatch Roof House

Source: Iko (2020)

2.2.2 Ancient Greece to the Renaissance Period

In the second millennium BC, bricks were initially employed as a building construction material in Mesopotamia (a region in West Asia between the Tigris and Euphrates rivers). From that point on, the qualities of building materials quickly evolved. During this period, the Romans developed concrete as a new building material, alongside the high use of bricks (WeBuildvalue 2021). Bricks are made of clay that is left to dry in the hot sun (Gambrick 2022). Raw bricks were used in the first century BC until the ancient Romans began to bake them in earth kilns (Gambrick 2022), which increases their durability and strength. Then stone once again became the main building material for the most important buildings such as churches and castles during the Middle Ages (WeBuildvalue 2021).

Another transformation in the building industry happened during the Renaissance (transition from Middle Ages to modernity, i.e., 15th and 16th centuries), when brick replaced stone (Iko 2020). And since then, brick has remained a standard building material (Gambrick 2022). During this period, plaster became widely used to decorate structures and serve as a protective and bonding material (WeBuildvalue 2021).

2.2.3 The Industrial Revolution to Present Day

Another crucial period in the development of building materials was during the Industrial Revolution, which took place in the late 18th and early 19th centuries. In this period, the building situation changed radically with the introduction of industrially manufactured materials like steel, iron and concrete and alongside bricks, became the most important building materials (WeBuildvalue 2021; Cornelia Van Empelen 2018). Architects were no longer required to modify their designs to fit into the limited availability of materials (Cornelia Van Empelen 2018). These materials were widely exploited during the building boom between 1955 and 1975, with insufficient understanding of their long-term environmental consequences (Cornelia Van Empelen 2018).

During the 1980s global shortages of housing material, particularly in the lumber industry, renewed interest in bamboo as a building material (Nurdiah 2016; Erkol 2021; Manandhar et al. 2019). The 1973 energy crisis caused people to reevaluate their thinking about conventional building materials, as people became more environmentally conscious, and shifted their focus toward sustainable development (Cornelia Van Empelen 2018). People also started to develop interest in buildings and materials life cycles (Cornelia Van Empelen 2018).

Concrete

Concrete is made by mixing cement, water, and aggregates like sand and crushed stone. It is the most widely used building material worldwide, with over 10 billion tons used annually (Piecyk et al. 2021). Cement is the main ingredient used in the production of concrete. Cement is made by heating limestone to a high temperature of about 1450°C to produce lime which then combines with other materials to form clinker (Piecyk et al. 2021; Nuhu, Ladan and Muhammad 2020). Cement is a crucial component of concrete, whose production uses energy and emits carbon dioxide (Ousmane Toure et al. 2020). About 4.25 million tons of cement are produced globally each year, in 2021 alone, 4.4 million tons of cement were produced globally (National Minerals Information Center (NMIC) 2022). Approximately, every ton of cement produced releases one ton of carbon dioxide (CO_2) (Siddique et al. 2016). Concrete plays a key role in the modern building industry due to its durability, high compressive strength of about 4000 psi, and can withstand harsh climatic conditions like rainstorms and earthquakes (Alemu, Tafesse and Mondal 2022). Despite these qualities, it is non-renewable and nonbiodegradable (Alemu, Tafesse and Mondal 2022; Siddique et al. 2016).

Steel and Iron

Steel is produced primarily from iron ore with small amounts of carbon (from 0.002% to 2.1%) (Maltais et al. 2021). Steel is the third most used material in the construction industry (Torraca 2009). A ton of steel produced emits 3 tons of CO_2 (Gartner and MacPhee 2011). Over 1500 million tons of steel are produced each year, generating about 9% of the world's carbon dioxide emissions from the process and energy use (Gartner and MacPhee 2011). Steel is also highly durable (can last about 100 years), recyclable, and flexible (can bend without cracking)

(Sharma et al. 2017). Although the less-reinforced rust and fade with time (over 30 years), it is nonbiodegradable (Aghion 2018).

Bamboo

Bamboo was used in ancient times for building construction because of its natural flexibility and strength (Dhenesh Raj and Agarwal 2014; Manandhar et al. 2019). Bamboo is mostly found in Asia, Africa, and Latin America and is naturally located in tropical, subtropical, and mild temperate regions (FAO 2022). Bamboo is a natural material that is renewable, environmentally friendly, and generally accessible (Dhenesh Raj and Agarwal 2014). Bamboo is a good building material because it is strong, accessible, affordable, and simple to work with (Galmarini, Costa and Chiesi 2022).

Bamboo is very strong and can withstand up to 3656 kg/cm^2 (358.53 MPa) (Manandhar et al. 2019). According to Nurdiah (2016), bamboo has a tensile strength comparable to steel at roughly 28,000 N/m^2 (0.028 MPa). Bamboo is frequently used as a less expensive alternative to other building materials, usually in areas where it is cultivated nearby (Manandhar et al. 2019; Galmarini et al. 2022). However, bamboo can be a very expensive building material in areas where it is not produced due to factors like transportation costs (Manandhar et al. 2019). Although the natural durability of bamboo varies depending on species, a typical bamboo building material can last for 30 to 40 years (Manandhar et al. 2019).

Figure 2.2. Modern-day Bamboo House

Source: Bamboo Living (2022) (https://bambooliving.com/)

Wood

Wood has proven to be a good building material because of its durability in construction and durability in hostile environmental conditions (Ilvitskaya, Lobkov and Lobkova 2019). Using wood products for building construction purposes has led to deforestation and unexpected climate change (Alemu, Tafesse and Mondal 2022). The use of wood for building is a major factor contributing to the loss of Ethiopia's forests, according to a study by Mpakati-Gama et al. (2012). Recently, the high demand for wood for housing construction has an excessive negative environmental consequence to the world (Mpakati-Gama et al. 2012). Sequestration of 25kg of carbon is lost per year for every one ton of tree fell for lumber (Ecotree 2022). A lumber framed home can last about 100 years or more with the right wood treatment, and frequent maintenance according to Creek (2019).

In modern-day advancements in building construction, people are increasingly interested in environmentally friendly building materials that are economically feasible (WeBuildvalue 2021). To achieve this, several innovative ideas have been proposed in recent years such as mycelia (Alemu, Tafesse and Mondal 2022). Mycelia have emerged since 2007, as an alternative environmentally friendly building material (Alemu, Tafesse and Mondal 2022; Sydor et al. 2022; Attias et al. 2020; Jones et al. 2020; Jones, Bhat, Huynh, et al. 2018b; Madurwar et al. 2013; Haneef et al. 2017).

2.3 Mycelium Composite

Mycelium is the vegetative portion of a fungus, and is made up of a network of tiny, white filaments that range in diameter from 1 to 30 micrometers and extend out from a single spore into every crevice of a substrate (Yang et al. 2021; Alemu, Tafesse and Mondal 2022; Islam et al. 2017; Haneef et al. 2017). Mycelium networks grow on nutrients (Yang et al. 2021), which originate in nature from the remnants of living things like plants and animals, as well as their environmental waste (Yang et al. 2021; Swift 2018). The general process in producing mycelium composite includes:

1. Inoculate a culturing dish with mushroom spores along with enough water and nutrients. It takes between 7 to 14 days for the mycelium to fully incubate and cover the dish;
2. A sterilized growing substrate, which is made of different organic materials such as straw and rice husks, is prepared by adding a small sample of mycelium from the culturing dish to it for continued incubation; and

3. The substrate is then dried at a high temperature for several hours after it has accumulated enough mycelium to inactivate the hyphae and halt the growth process to obtain the mycelium composite.

[these steps are adopted from (Yang et al. 2021)]

2.3.1 Mycelium Composite Fabrication

2.3.1.1 Species and Substrate Types

The fungus species and substrate type used in producing mycelium composites are important in determining the quality of the mycelium products (Jiang et al. 2017; Girometta et al. 2019; Alemu, Tafesse and Mondal 2022). The main fungal species used for making mycelium composites according to the literature are ganorderma lucidum, Ganoderma sp., pleurotus ostreatus, pleurotus sp., trametes versicolor, and tramrtes sp. (Yang et al. 2021; Alemu, Tafesse and Mondal 2022; Attias et al. 2020; Sydor et al. 2022). The fungus type and carbohydrate composition of each plant material making up the substrate determine how these structural components biodegrade over time (Hori et al. 2013).

Agricultural crop waste, such as cotton, corn, wheat, hemp, kenaf, and flax residues and sawdust are often used as substrate mixtures for producing mycelium composites (Yang et al. 2021; Jiang et al. 2017; Girometta et al. 2019). Additionally, the final mycelium product qualities are directly impacted by the kind, size, and processing method of the substrate particles(Elsacker et al. 2019).

2.3.1.2 Temperature, Humidity and Water Content for Mycelium Growth

Mycelium growth may be highly impacted by temperature and humidity (Yang et al. 2021; Jiang et al. 2017). The ideal temperature for mycelium growth is room temperature (24–25 °C) (Hoa and Wang 2018). Additionally, a relatively high-humidity environment is needed for mycelium growth (Jiang et al. 2017). For instance, Jiang et al. (2017) indicated that up to 98% relative humidity is needed for mycelium growth. The water content of mycelium after natural growth is high above 60% (Elsacker et al. 2019; Yang et al. 2021) or 200% (Alemu, Tafesse and Mondal 2022). To stop the mycelium growth and deliver a strong and dependable mycelium composite, most of the water must be dried (Yang et al. 2021). The exact percentage of residual moisture in mycelium-based composite is not currently stated in the literature, however, Girometta et al. (2019) indicated that it must be sufficiently dried to stop fungal growth. The ultimate water content of the mycelium is determined by the substrate and the kind of fungus (Yang et al. 2021). For instance, Alemu, Tafesse and Mondal (2022) find that mycelium composite made from coffee husk has the highest water absorption capacity of all the substrates, while composite created from sawdust had the lowest. Also, mycelium material with a hemp pulp substrate absorbs more water than a cotton wool substrate (Yang et al. 2021).

2.3.2 Mycelium Composite Bricks

A mycelium brick is an organic building material made of fungal mycelium and waste (Cornelia Van Empelen 2018; Alemu, Tafesse and Mondal 2022). When mycelium is mixed with fibers, it can be grown into precise shapes and utilized as a very strong, water, mold, and fire-resistant building brick when dried (Cornelia Van Empelen 2018). This 100% biodegradable building material is gaining a lot of interest for the built environment (Jones et al. 2017).

Ecovative Design LLC is one of the leading companies (www.ecovative.com) in replacing conventional polystyrene-based materials with mycelium composites for protective packaging and insulation (Ecovative 2022; Alemu, Tafesse and Mondal 2022; Cornelia Van Empelen 2018). In 2013, they grew a mycelium composite by mixing mycelium and agricultural waste into a mold for 3 to 5 days to develop into a durable material (Cornelia Van Empelen 2018). Besides Ecovative

Design, a number of other companies are developing the use of mycelium bricks as a building material globally, including MycoWorks Inc. (https://www.mycoworks.com/) of Philip Ross in San Francisco, MyCoPlast, which was recently rebranded as Mogu (https://mogu.bio/) in Italy, and PT Miko Bahtera Nusantara (Mycotech) (https://www.bcorporation.net/) in Bandung, Indonesia. These businesses frequently publish cutting-edge applications and manufacturing techniques about mycelia on their websites and social media. However, the literature reveals that most academic works affiliated with the companies lack critical data about the composites and methods, possibly because of monopoly profit motives (Attias et al. 2020).

The Hy-Fi project (Figure 2.3) by the Living (http://www.thelivingnewyork.com/) is the largest building built of mycelium bricks to date, it was displayed at the MoMA PS1 in 2014 (Benjamin David 2014). Ross also produced Mycotectural Alpha (Ross 2014) with mycelium bricks in the same year (Attias et al. 2020). Rahman, Arredia, and Yassin's Kerela pavilion also build a polygon-shaped timber building that has layers of mycelium composites that do not appear to fully colonize it (Attias et al. 2020).

Although mycelium as a building material is evolving with numerous environmentally friendly features, there is still a significant uncertainty about its economic feasibility (Jones et al. 2020; Cornelia Van Empelen 2018).. Its compressive strength is between 0.1 and 0.4 MPa lower than concrete's (20 to 40 MPa), and its tensile strength is between 0.1 and 0.2 MPa. Mycelium brick is stronger than concrete relative to its weight, with mycelium brick weighing as low as 43kg/m^3 and concrete weighing 2400kg/m^3 (i.e., 60 times lighter as conventional brick) (Bonnefin 2022; Cornelia Van Empelen 2018; van der Hoeven 2020). Mycelium brick produced from sawdust composites had a maximum density and compressive strength of 280 kg/m3 and 570 kPa, respectively, with a 200% water absorption, which cost about 19.0$/m3 or 0.07-0.17$/kg (Alemu, Tafesse and Mondal 2022). However, mycelium bricks are not considered very durable yet because they cannot last over 50years in their current form (Michael 2014; Cornelia Van Empelen 2018).

Figure 2.3. Mycelium Composite Structure by the "Living"

Source: Benjamin David (2014), (http://www.thelivingnewyork.com/)

Mycelia are naturally fire resistant, can be easily molded into any shape, environmentally friendly, biodegradable, and carbon neutral (van der Hoeven 2020). Despite having excellent fire resistance, the material performs badly when it is in contact with water (Cornelia Van Empelen

2018). By soaking mycelium bricks in natural oil, it is possible to weatherproof them without compromising their fundamental composability (Cornelia Van Empelen 2018). Non-treated mycelium bricks do not degrade unless they are exposed to living organisms like those in soil and water (Cornelia Van Empelen 2018). Mycelium composites have been demonstrated to be resistant to ultraviolet radiation as well (Chan et al. 2021).

2.3.3 Mycelium Composites in Academic Literature

This section considers some of the academic research literature on mycelium-based products in industrial settings. The first scholarly work on mycelium composites was about using mycelium for packaging purposes (Holt et al. 2012). Some key material characteristics of mycelium-based composites according to the literature were compiled in a review by Jones et al. (2017). An updated discussion of material characteristics was included in a recent review by Girometta et al. (2019), along with several important findings. However, many crucial experimental details are missing from the original publications mentioned in these reviews.

Elsacker et al. (2019) and Elsacker et al. (2020) provide a synopsis of mycelium-based composites' thermal conductivity and density compared to traditional insulating materials. Meyer et al. (2020) present a white paper and highlighted the current prospects and research challenges in fungal biotech revolution for growing a circular economy. Jiang et al. (2016) and Jiang (2015) summarize a seven-step manufacturing cost model that accounts for all labor, material, and overhead expenses for a unique mycelium-based bio-composite sandwich structure.

Manan et al. (2021) present a review of the synthesis and structural structure of mycelium-based materials, the impact of different factors on the material qualities and the applications of mycelium-based products in the sectors of building, packaging, cosmetics, and medicine. Madurwar et al. (2013) highlights the application of agro-waste for a sustainable construction industry considering rapid urbanization and population increase. Sydor et al. (2022) reviewed literature mycelium-based composites usage in art, architecture, and interior design and concluded that mycelium-based composites are cheap to produce, environmentally friendly, and very artistic, while their shortcomings include unknown reliability, poor water affinity, and inadequate load capacity. Islam et al. (2017) investigate the morphology and mechanics of fungal mycelium and a novel biomaterial made from fungi's mycelium. Abhijith et al. (2018) study the present state of mycelium biotechnology for bio-renewable uses of agricultural waste and indicate the implications of mycelium-based composites for packaging and insulating applications as a long-term replacement for polystyrene. According to Scopus (2021), the most frequently cited publications on mycelium-based composite materials are Haneef et al. (2017), Islam et al. (2017), Jones et al. (2017) Holt et al. (2012), and Appels et al. (2019).

2.4 Gaps in the Literature and the Study Contribution to the Literature

With growing research interest in mycelium composites, the literature has focused on the biological processes (Jones et al. 2017; Camere and Karana 2018; Karana, Blauwhoff and EJ Hultink 2018; Attias et al. 2020). They have also evaluated mycelium composites' sustainability and durability (Camere and Karana 2018; Grimm and Wösten 2018; Geldermans, Tenpierik and Luscuere 2019). The literature has also assessed the techniques underlying composite engineering, improvement in composites characteristics, and factors affecting mycelium composite uses and applications in the construction industry (Jones et al. 2020).

Currently, there is limited publicly accessible documentation about the physical and mechanical characteristics of mycelium composites even though they are now commercially explored and used in the USA and Indonesia (Ecovative Design 2019; Jones et al. 2020).

Mycelium materials continue to be a mostly untapped niche market (Jones et al. 2020) because acceptance of mycelium as a commercial resource has lagged despite their significant promise (Jones et al. 2020). For instance, computers are packaged with mycelium foams by Dell, and IKEA has also indicated an interest in using mycelium-based packaging (Gosden 2016; Dell 2022). Philip Ross also created a "Hy-Fi" tower-pavilion (Figure 2.3) for the "MoMA's PS1" exhibition in 2014, which was constructed with only mycelium bricks together with a corn stalk substrate (Sydor et al. 2022). Ecovative design uses it for packaging, insulation etc. (Ecovative Design 2019).

There is limited or no literature on the economic feasibility of industrial uses of mycelium composites (Jones et al. 2020), which might contribute to the underutilization of mycelium composites. However, there is now growing interest by companies and corporations in the USA, Italy, India, Indonesia, Netherlands, Australia, Austria, and Switzerland (Ecovative Design 2019; Jones et al. 2020; MycoWorks 2022; Mogu 2022; Research through design 2022) to explore them. This study contributes to the literature by providing a comparative case study of the economic feasibility of industrial use of mycelium composites in the built environment.

Chapter 3 - Data and Methods

The study considered three forms of single-home construction: Mycelium composite house; Concrete house; and lumber frame house. Mycelium composite house is basically a house built with mycelium composite. It can be constructed either with mycelia bricks or poured mycelia composite (panels).

A concrete block house, also known as "cinder block" house, is built by laying prepared blocks and filling in the spaces between with mortar. Cinder block walls may cost more than poured concrete because it takes more time and is more labor-intensive to stack the cinder blocks. Cement is the main ingredient in molding and constructing a cinder block house. Cement is a binding material that helps to hold the concrete and mortar together.

A lumber frame house is built using lumber as the primary structural material. The framing of the house consists of wooden beams and posts, which support the floors, walls, and roof of the structure. The lumber used in the framing is often pressure-treated and kiln-dried to prevent rot and insects. The house is then finished with a variety of materials, such as siding and bricks to give it a finished appearance.

3.1 Model

The economic feasibility of mycelium composite in industrial use is evaluated using a single-family home of q ft^2 built in a typical Midwest community in the United States. The location is important because construction costs of building differ across the country and across regions. Additionally, the environmental conditions of the location, including seismic and fire risks, have the potential to influence regulatory costs and material costs. The analysis compares the building cost and the investment of the cost difference between a mycelium composite house with plywood molds and a cement block and a lumber framed house. The economic feasibility assessment model for construction type, i is defined as follows:

$$C_i = \gamma_i \sum_j \omega_{ij}\, q_{ij} + k_j \tag{3.1}$$

$$\frac{\delta \mathrm{C_i}}{\delta \omega_{ij}} > 0;\ \frac{\delta^2 C_i}{\delta \omega_{ij}^2} \geq 0 \tag{3.2}$$

Where C_i is the construction cost of building material i, γ_i is the technical compensation factor for the type of construction, i.e., mycelium composite, concrete, or lumber. The unit price for input j for construction type i is ω_{ij} and the quantity of input j is q_{ij}. The fixed costs associated with each construction type is k_j.

The assessment of the economic feasibility model is organized as follows. Let:

$C_0 =$ Cost of building mycelia house

$C_i =$ Cost of building using alternative material, $0 \neq i$

$V_{0i}^t =$ the cost difference between mycelia and the alternative building material

$V_{0i}^t = C_i^t - C_0^t > 0$, t=0, 1,...T

$T_0 =$ Life expectancy of mycelia house

$T_i =$ Life expectancy of alternative material house

$\frac{V_{0i}^{t'}}{C_0^t} > 1;$ = Relative number of mycelium-plywood houses

To conduct the economic assessment, assume that the difference between the cost of building type *i* versus the cost of building type *0* (the mycelium house) is invested at a given interest rate to cover replacement costs of building type *0* over the life span of building type *i*.

Therefore, let

$$V_{ij}^{t=0} = C_i^{t=0} - C_0^{t=0}$$

where $C_i^{t=0}$ is base cost of building using alternative material at time *0* and $C_0^{t=0}$ is the base cost of building mycelium house at time *0*.

Assume that the consumer price index is applied to the replacement cost of building type *0* at time *t*. Therefore,

$$C_0^t = C_0^t(1+d)^t + R_0^t(1+d)^t + L_0^t(1+d)^t$$

where R_0^t is relocation cost for residents when the new house is to be built again, L_0^t is labor cost for removing the old house and refixing fixtures, electricals etc. in the house, and *d* is the CPI (inflation rate). This is done every 15 years for the mycelium house with plywood and 20 years for the mycelium house with plexiglass. For instance, when comparing to a concrete house, the mycelium-plywood house will need to be replaced 5 times.

Therefore,

$$V_{0i}^t = V_{ij}^{t=0}(1+r)^t - C_0^t$$

where *r* is interest rate.

We define the mycelium plywood house as being an economically feasible and competitive against building material *i* at time *t* as long as $\frac{V_{0i}^{t'}}{C_0^t} > 1$, where t' = $t-1, t =$ years, $V_{0i}^{t'} =$ investment on the difference in building cost between mycelium-plywood and mycelium-plexiglass, concrete, and lumber, $C_0^t =$ mycelium-plywood building cost. For an owner of the mycelium house then this would be assessed at a time period t' that is the year prior to replacement of the mycelium plywood house. Therefore, the condition is that the value of the amount invested is greater than the replacement cost of the plywood mycelium house at time *t*. That is, there is an adequate amount of funds in the investment to cover the cost of house replacement at time *t*.

The feasibility of mycelia as a competitive composite building material is, therefore, determined by the following variables: $V_{i0}^t,\ r,\ d,\ T_i$ and T_0, $\quad \forall\ i \neq 0$

These variables are simulated to determine the boundaries for feasibility of using mycelium as a building material.

3.2 Data

3.2.1 Mycelium composite

Mycelium composite panels are made by molding and incubating (heating) it to stop the growth after the appropriate form has been achieved. The molding is done in plastic molds, which have the desired shapes to build walls, roof, and floor. Given a 2,000 sq ft house with 50ft by 40ft by 8ft, a 4ft by 8ft plastic mold (https://www.professionalplastics.com/) was used as the molds. We needed 90 pieces of panels and 90 pieces of strips for constructing the exterior walls. The strips are used to seal the ends of the panels. Considering a flat roof of 50ft by 40ft, we need 45 pieces of plastic mold and 45 pieces of strips as well. This will also be the same requirement for the floor since the floor and the roof are the same square feet. Also, plywood can be used as a mold where the mycelium combine with substrate is filled between two pieces of plywood and then left to grow and heated after growth to stop the growth. We need the same number of 4ft by 8ft pieces of plywood as the plastic mold to make the mycelium panels for the house.

After making the molds, they are filled with fully colonized mycelium with a density of 7.6 lbs/ft^3, compressive strength of 18psi, and flexural strength of 34psi that fill about 0.12ft^3. A price of $0.10 was assumed for the 0.12ft^3 mycelium from (Grow.bio n.d.) estimations. This assumption was necessary in the absence of information on industrial scale cost of mycelia panels. After the mycelium growth, then we will have 4ft by 8ft by 0.5ft mycelium composite panels for the house exterior walls, roof, and floor (i.e., 16ft^3 mycelium composite panels for the construction). Therefore, the total material cost for constructing the mycelium composite house is the mycelium panels and molds, which depends on current prices, demand, and supply dynamics. The molds will act as siding for this type of house.

After constructing the panels, they have to be bolted to the foundation with ties and bolts. We consider 10% of the total cost of the material cost as the cost of ties, bolts etc. for constructing the house. Likewise, 25% of the material cost is assumed to be the cost for labor in constructing the exterior side of the house. The total cost of construction is presented in our results section.

In estimating the mycelium-plywood mold house cost, we included relocation cost of residents for one month ($1,228.57) extrapolated from Wallender and Allen (2022). Also, we included 10% of total material cost of mycelium plywood molds house as labor cost moving stuffs from the olds and refixing them after construction.

3.2.2 Concrete (cinder blocks) house

For the concrete house, it is built with cinder blocks and cement mortar. The standard block area is 16″ x 8″ dimension and the total wall area estimated is 259,200 inches. The total number of blocks is 2,025, costing an amount of $5,063 with a per unit average cost of $2.50. The total number of bags of mortar is 61 bags, costing an average of $610. Therefore, the average total cost estimated for building the concrete house exterior walls is $5,673.

Most home builders choose affordable asphalt shingles Wallender and Allen (2022) for their roofs. The average costs for shingle roofing for a concrete block house is between $5,500 and $10,500 (Wallender and Allen 2022). The average cost of roofing a flat roof is $8,500 for a concrete house. Trusses, joists, and sill plates are constructed using 2x10s and 2x12s lumber.

For flooring, as noted by Perry and Allen (2022), it is often expensive to install a square foot of hardwood flooring relative to cement. Some of the cost components include material cost, underlayment, and labor. The average cost of concrete flooring is $7.50 per square foot (Perry and

Allen 2022) and 2000sq ft as the total quantity of area to floor. Any additional design or finish, like stenciling, staining, or engraving, can increase the final cost by $8 to $18 per square foot.

With concrete houses, there is a need for siding to protect the walls. Siding is any material used to cover the exterior walls of a building to protect the building from rain, snow, and blustery winds from seeping into the building. It also helps keep dirt, moisture, and insects away from the walls. High-quality exterior siding and weatherproofing are investments in the house's durability, much like the roof. The average cost of siding is $11,100, which includes plastering, painting etc., and labor cost is $2 per square foot (HomeGuide 2021). Also, cleanup after construction is added to the exterior components of the construction cost.

3.2.3 Lumber-framed house

We considered drywall for constructing the lumber framed house. In constructing the drywalls, roof, and floor, we need framing. The house starts to take shape during the framing phase of the building. House framing is usually referred to as the skeleton of a house that runs behind all the interior and exterior walls, supports the roof shingles, and connects the house to the foundation (Simms 2022). The main function of house framing is to support the other building components (like windows, floors, roofing components, and more) in the house.

Wood framing is considered in this study. Wood frames are relatively inexpensive and simple to build, however wood is susceptible to rot and moisture damage (Simms 2022). Sheathing for the roof and the basement are additional wood framing components. Rafters, joists, and sill plates are constructed using 2x10s and 2x12s broader materials, and the wall studs and frames around door and window openings are composed of 2x4s.The average cost of wood framing is $33,000 for the entire lumber framed house (i.e., both exterior and interior) (Abraham and Allen 2022). The house will start to take shape once the framed walls are finished with drywall. Both the interior and exterior walls of the lumber framed house are built with drywall; however, our focus is only on the exterior. On average, it will cost $4,050 to install drywall for on only the exterior wall of the lumber framed house (Abraham and Allen 2022).

Roofing involves the labor and materials involved in constructing a roof. The roof enhances the beauty of the house while shielding you and the building from the weather elements. Most home builders choose affordable asphalt shingles (Wallender and Allen 2022) for their roofs. According to Wallender and Allen (2022), the average costs for shingle roofing for the lumber framed house range from $9,200 to $11,500.

Flooring cost components include material cost, underlayment, and labor. As noted by Perry and Allen (2022), it is often expensive to install a square foot of hardwood flooring relative to cement. Therefore, on average, it costs $8 per square foot (Perry and Allen 2022) and a quantity of the floor space of 2000sq ft to construct the floor of a lumber framed house using hardwood (Perry and Allen 2022). With lumber framed house, siding and cleanup is added to the exterior components of constructing the lumber framed house.

The data for this study was sourced from various literature about building construction. The data comprised of the cost and quantities of building components of mycelium composite, concrete blocks, and lumber frame. The cost to construct a house is mostly determined by its location. Most home construction costs are labor and material-related, which are highly influenced by local supply and demand dynamics (https://www.forbes.com/). This study considers a 2,000-square-foot house because it is estimated that a typical American family of three to four can live comfortably in a 2,000-square-foot home (https://www.forbes.com/).

Table 3.1: Data Summary

Variable	Plywood Mold Mycelium	Plexiglass Mold Mycelium	Lumber	Concrete
Exterior walls	$4,912.50	$20,670.60	$16,650.00	$5,673.00
Floor	$2,456.25	$10,335.30	$16,000.00	$15,000.00
Roof	$2,456.25	$10,335.30	$9,200.00	$15,500.00
Siding	$4,000.00	$4,000.00	$11,500.00	$15,100.00
Insulation	-----	-----	$5,250.00	$8,000.00
Clean up	-----	-----	$2,600.00	$2,600.00
Total external construction cost	$59,810.62	$17,263.75	$61,200.00	$61,873.00
Life expectancy of house (years)	15	20	50	75

Notes: The total cost of plywood mold and plexiglass mold mycelium comprised of 10% of the material cost for bolts, ties, etc. and 25% of the material cost for labor. The plywood mold mycelium and plexiglass mold mycelium siding cost are assumed that the mold will also act as siding. No insulation cost because mycelium itself is an insulation material. No cleanup cost because they are built in panels.

3.3 Analytical Methods

All the equations in the model were estimated in Microsoft Excel. After estimating the cost of each home at time t, we use the sensitivity simulation model to forecast the possible outcomes given different scenarios. Simulations under alternative market conditions are used to determine the likelihood of a variety of outcomes based on specified conditions. Since the CPI is considered exogenous (i.e., is determined by market forces), we only analyzed the effects of interest rate changes on investment and mycelium price change per cubic foot. This sensitivity analysis allows us to determine under which dimensions mycelium composite as a building material is economically feasible. We also explored the interest rate level that will make mycelium composite building indifferent to concrete and lumber frame buildings from our extrapolated values. This was done using “What-if Analysis” tool in Microsoft Excel.

Chapter 4 - Results and Analysis

We present the results and the analysis in this chapter. The chapter is organized in the following sections. Section 4.1 lists the key assumptions made in the study. Section 4.2 discusses the comparative analysis of the base construction cost for each type of building material. Section 4.3 presents the sensitivity analysis of the construction cost of price changes of plexiglass and plywood. Section 4.4 assesses the economic feasibility of mycelium-plywood as a composite building material and its competitiveness against the other types of building materials. Section 4.5 analyzes the sensitivity of the preceding to interest rate, inflation rate and life expectancy changes.

4.1 Key Assumptions

Our estimations and analysis are based on some key assumptions, and these are:

1. It is assumed that the interior part of the structure is the same no matter which material is used to build. Therefore, the estimations and analysis are based on only the external structure of a house (i.e., exterior walls, roof, and floor).
2. The cost is linear but there might be some economies of scale.
3. Over time, the life expectancy of mycelium houses can be increased through technology.
4. Relocation cost was added to the mycelium plywood and plexiglass houses from year $t > 15$ to year T.
5. We also assume that the windows for all the houses have an expected lifespan of the mycelia structure (15 years), hence it is not included in the estimations.
6. Doors can also be removed and be refixed after building the new mycelium-plywood house after every 15 years. Therefore, the doors are the same for all types of houses and hence excluded from estimations.

7. Fixtures in the mycelium house will be placed at one place and can be refixed after building.
8. We also use 10% of the total construction cost of mycelium plywood house as labor cost for refixing the things in the house after building.

4.2 Comparative Analysis of Construction Cost

We estimated the basic cost of constructing a house with each type of building material using equation 3.1. The base cost is shown in Table 3.1, mycelium- plywood panels have the lowest building cost, while concrete (cement) blocks construction has the highest cost of construction. For mycelium, it is assumed that it cost $\$0.83/ft^3$ of mycelium to make the panels for the building. It cost $190.53 and $40 per unit for a 4ft x 8ft x 0.01ft of plexiglass and plywood, respectively for making the molds which are filled with the mycelium composite (https://www.professionalplastics.com/PLEXIGLASS-ACRYLICSHEET-CAST). For concrete and lumber, we used the estimations of HomeGuide (2021), Abraham and Allen (2022), and other sources in the literature.

Mycelium composite is less expensive to build compared to concrete and lumber. However, it is less durable, lasting between 15 and 20 years (Critical Concrete 2018) in contrast to the more than 75 years and 50 years for cement and lumber, respectively. However, mycelium has very good fire resistance and is lightweight, making it a suitable material for insulation and lightweight interior walls. Due to its low water resistance, mycelium bricks cannot be directly used for facades, because when they get wet and exposed to nutrients, the fungus begins to germinate again. Therefore, using the plexiglass or plywood as molds will protect the mycelium composite from direct contact with water and may also prolong its lifespan. A mycelium panel house is less costly since the mycelium composites are produced using local organic waste as a raw material as illustrated in the literature review.

The lower cost and shorter life expectancy of the mycelium composite creates the need to explore the feasibility of mycelia within a time dimension. That is, we assume the life expectancy of each material remains unchanged. The building cost of concrete and lumber are factual figures from the literature, while the building cost of mycelium-plywood and -plexiglass are extrapolated from the literature. Therefore, the sensitivity analysis will allow us to change the extrapolated parameters (i.e., mycelium price/ft3, plexiglass price, plywood price, interest rate and CPI) to assess how sensitive the results are to the different parameters.

Table 4.1: Base Price of Mycelium, Interest rate, CPI, Building Costs, and Life Expectancies

Variables	**Base values**
Price of mycelium /ft^3	$0.83
Plexiglass	$190.53
Strip plexiglass	$25.81
Plywood	$40.00
Strip plywood	$1.25
Interest rate	7.75%
CPI (inflation rate)	6.50%
Concrete house	$61,873.00
Lumber house	$61,200.00
Mycelium-Plexiglass house	$59,810.62
Mycelium-Plywood house	$17,263.75
Life Expectancy of House (Years)	
Concrete house	75
Lumber house	50
Mycelium-Plexiglass house	20
Mycelium-Plywood house	15

4.3 Sensitivity Analysis of Price Effects on Construction Cost

Different scenarios were run to test the sensitivity effects of mycelium price, plexiglass, and plywood price to assess the impact on the building cost while maintaining all others unchanged from the base case. These price changes affected mycelium-plexiglass and plywood houses building cost, and we compared the new costs to the concrete and lumber building materials house cost as well.

Scenario 1: Change in mycelium price, all other parameters unchanged. We explored the effect of the maximum price that will make mycelium composite economically feasible, holding all other base values unchanged. The base price of mycelium/ft^3 was \$0.83. That is, we explored the price of mycelium per cubic foot area that will make mycelium-plywood building be at least economically feasible and competitive against concrete and lumber. When the price of mycelium/ft^3 decreased to \$0.09 (approximately, 89.2% decrease), the mycelium composite plywood house cost decreased to \$14,347.75 (about 18.3%). Similarly, mycelium-plexiglass building cost also decreased to \$56,894.62 (approximately 4.9%). These cost changes indicate that mycelium cost has a minimal impact on the total building cost.

Table 4.2: Change in Mycelium Price, all others Unchanged.

Changing Cells:	Current values:	Mycelium Price Effect
Price of Mycelium/ft^3	\$0.83	\$0.09
Result Cells:		
Concrete	\$61,873.00	\$61,873.00
Lumber	\$61,200.00	\$61,200.00
Mycelium-Plexiglass	\$59,810.62	\$56,894.62
Mycelium-Plywood	\$17,565.07	\$14,347.75

Notes: Current Values column represents values of changing cells at time Scenario Summary Report was created. Changing cells for the scenario are highlighted in gray.

Scenario 2: Change in plexiglass cost by 25%, all others unchanged. The base price of plexiglass and strip plexiglass as shown in Table 4.2 decreased by 25% simultaneously, respectively. The outcome of this scenario is presented in Table 4.3. The decrease in the price reduces the mycelium-plexiglass house construction cost by about 22%. This indicates that if plexiglass is bought at the wholesale price level, the mycelium composite house with plexiglass building cost will be less costly than concrete and lumber but more costly than mycelium-plywood home.

Table 4.3:Change in Plexiglass Price by 25%, all others Unchanged.

Changing Cells:	Current values:	Plexiglass Price Effect
Plexiglass	$190.53	$142.90
Strip Plexiglass	$25.81	$19.36
Result Cells:		
Concrete	$61,873.00	$61,873.00
Lumber	$61,200.00	$61,200.00
Mycelium-Plexiglass	$59,810.62	$46,669.18
Mycelium-Plywood	$17,263.75	$17,263.75

Notes: Current Values column represents values of changing cells at time Scenario Summary Report was created. Changing cells for the scenario are highlighted in gray.

Scenario 3: change in plexiglass price by 30%, all others unchanged. In this scenario, the price of plexiglass and strip plexiglass both decreased further to $133.37 and $18.07 at the same time, respectively, off the base prices, while holding all other variables unchanged. The decrease in plexiglass price by 30% reduces the building cost of mycelium-plexiglass home by 26.4% as shown in Table 4.4. This shows that plexiglass cost has a significant impact on the home construction cost.

Table 4.4: Change in Plexiglass Price by 30%, all others Unchanged.

Changing Cells:	Current values	Plexiglass Price Effect
Plexiglass	$190.53	$133.37
Strip Plexiglass	$25.81	$18.07
Result Cells:		
Concrete	$61,873.00	$61,873.00
Lumber	$61,200.00	$61,200.00
Mycelium-Plexiglass	$59,810.62	$44,039.92
Mycelium-Plywood	$17,263.75	$17,263.75

Notes: Current Values column represents values of changing cells at time Scenario Summary Report was created. Changing cells for the scenario are highlighted in gray.

Scenario 4: change in plexiglass price by 36%, all others unchanged. We explored the same price changes under scenario 1 and scenario 2 except that the price decreased by 36% for both from the base price, while others are unchanged. The results of this scenario are shown in Table 4.5. The decrease in price of plexiglass and strip plexiglass by 35% decreased the mycelium-plexiglass building cost by about 30.8%. This indicates that plexiglass price has a significant impact on the building cost.

Table 4.5: Change in Plexiglass Price by 35%, all others Unchanged.

Changing Cells:	Current values:	Plexiglass Price Effect
Plexiglass	$190.53	$123.84
Strip Plexiglass	$25.81	$16.78
Result Cells:		
Concrete	$61,873.00	$61,873.00
Lumber	$61,200.00	$61,200.00
Mycelium-Plexiglass	$59,810.62	$41,410.66
Mycelium-Plywood	$17,263.75	$17,263.75

Notes: Current Values column represents values of changing cells at time Scenario Summary Report was created. Changing cells for the scenario are highlighted in gray.

Scenario 5: change in plywood price by 25%, all others unchanged. The fifth scenario decreased plywood and strip plywood prices to 25% at the same time, while all others are unchanged. The decrease in the plywood price reduces the mycelium-plywood building cost to $10,758.42 (by about 14.5%) from the base cost. And this further makes mycelium composite house with plywood cheaper than concrete and lumber house. Thus, mycelium-plywood homes are six times cheaper than concrete and lumber houses.

Table 4.6: Change in Plywood Price by 25%, all others Unchanged.

Changing Cells:	Current Values:	Plywood Price Effect
Plywood	$40.00	$30.00
Strip-Plywood	$1.25	$0.94
Result Cells:		
Concrete	$61,873.00	$61,873.00
Lumber	$61,200.00	$61,200.00
Mycelium-Plexiglass	$59,810.62	$59,810.62
Mycelium-Plywood	$17,263.75	$14,758.42

Notes: Current Values column represents values of changing cells at time Scenario Summary Report was created. Changing cells for the scenario are highlighted in gray.

Scenario 6: change in plywood price by 30%, all others unchanged. Also, we assess the effect of the same price changes under scenario 5 by decreasing the plywood and strip plywood prices from the current values by 30% simultaneously, while all others are unchanged from the base scenario. The mycelium-plywood home cost decreased by approximately 17.4% when the price of plywood decreased by 30% as shown in Table 4.7.

Table 4.7: Change in Plywood Price by 30%, all others Unchanged.

Changing Cells:	Current Values:	Plywood Price Effect
Plywood	$40.00	$28.00
Strip-Plywood	$1.25	$0.88
Result Cells:		
Concrete	$61,873.00	$61,873.00
Lumber	$61,200.00	$61,200.00
Mycelium-Plexiglass	$59,810.62	$59,810.62
Mycelium-Plywood	$17,263.75	$14,257.84

Notes: Current Values column represents values of changing cells at time Scenario Summary Report was created. Changing cells for the scenario are highlighted in gray.

Scenario 7: change in plywood price by 35%, all others unchanged. The seventh scenario decreased plywood and strip plywood price by 35% from the base price simultaneously. As expected, the decrease in price plywood and the strip plywood led to a reduction in mycelium-plywood home building cost by approximately 20.3%.

Table 4.8: Change in Plywood Price by 35%, all others Unchanged.

Changing Cells:	Current Values:	Plywood Price Effect
Plywood	$40.00	$26.00
Strip-Plywood	$1.25	$0.81
Result Cells:		
Concrete	$61,873.00	$61,873.00
Lumber	$61,200.00	$61,200.00
Mycelium-Plexiglass	$59,810.62	$59,810.62
Mycelium-Plywood	$17,263.75	$13,754.83

Notes: Current Values column represents values of changing cells at time Scenario Summary Report was created. Changing cells for the scenario are highlighted in gray.

4.4 Assessment of the Economic Feasibility of Mycelium-Plywood Composite House

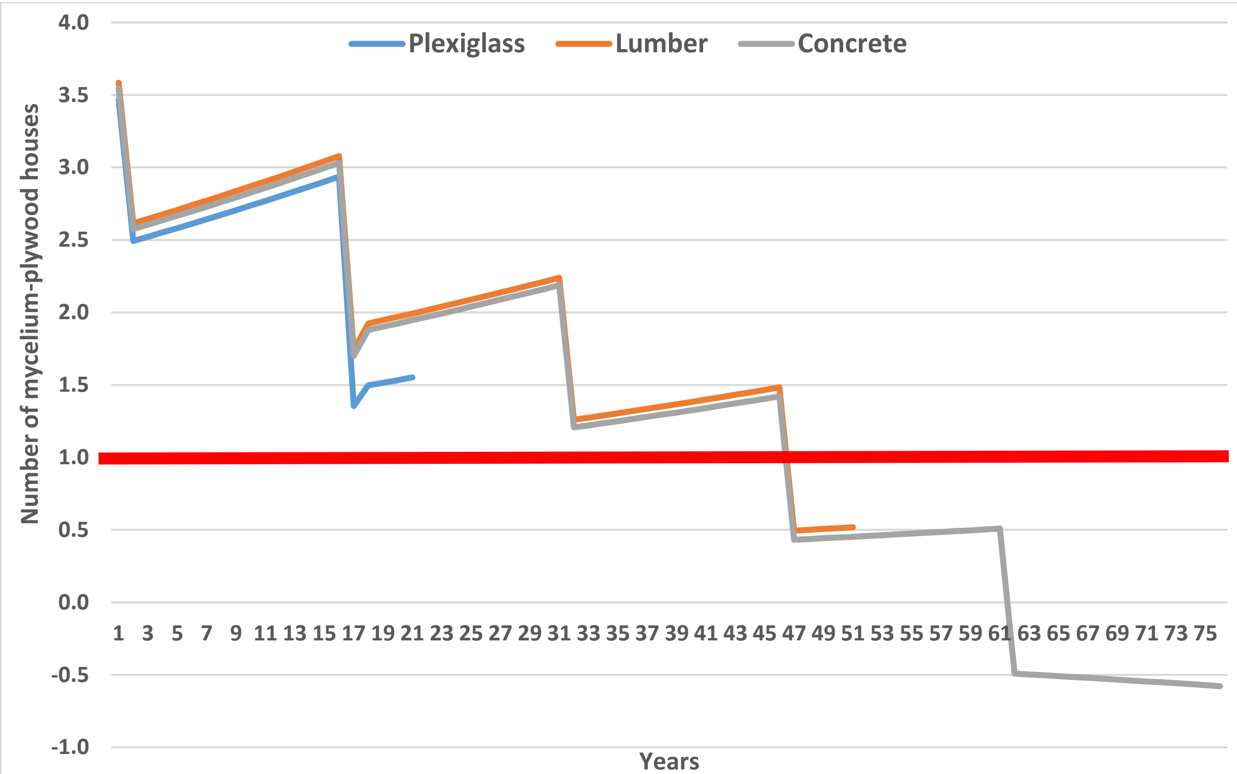
The economic feasibility of the mycelium composite is determined by its cost competitiveness against other building materials. Given that the cost of building using mycelia composite is lower than other building materials, it is assumed that the cost difference between mycelium composite and other type of building material is invested at the prevailing interest rate and the consumer price index is applied to the mycelium-plywood building cost in year *t*. Therefore, the mycelium-plywood building is economically feasible and competitive against any other building material if at the end of each material's relative life expectancy, the cost difference investment at time t minus one is greater than mycelium-plywood building cost at time *t* (i.e., if at the end of mycelium-plexiglass, concrete, and lumber life expectancy, $\frac{V_{0i}^{t'}}{C_0^t} > 1$, where t' = $t - 1$, $t =$ years, $V_{0i}^{t'} =$ investment on the difference in building cost between mycelium-plywood and mycelium-plexiglass, concrete, and lumber, $C_0^t =$ mycelium-plywood building cost). The economic feasibility of mycelium composite as a competitive building material is analyzed by using different interest rates for the investment of the cost difference between mycelium-plywood building value (cost) at each time t period and any other building material (i.e., mycelium-plexiglass, concrete, and lumber framed homes).

Using March, 2023 prime rate of 7.75% (Federal Reserve Economic Data (FRED) 2023) (https://fred.stlouisfed.org/series/DPRIME), we estimated the amount that will accrue at the end of each period of investing the cost difference between mycelium-plywood on the one hand and the other building materials (concrete, lumber framed, and mycelium-plexiglass building) on the other. The incremental cost of using mycelium-plywood material to build in the future is estimated using the 2022 consumer price index (CPI) of 6.50% (Bureau of Labor Statistics (https://www.bls.gov/)) to account for inflation for future prices. Using a straight-line depreciation, we estimated the value of the mycelium-plywood house at the end of each year and subtracted that from the inflation-adjusted mycelium-plywood building cost to get the actual value of the house at the end of each year, *t*.

From the literature, we assumed that a mycelium-plywood house is expected to last for 15 years, mycelium-plexiglass for 20 years, concrete block house 75 years, and lumber framed house 50 years. The decision is under the assumption that after every 15 years, the mycelium-plywood house is built again, and the balance is reinvested. The analysis focuses on mycelium-plywood building against concrete and lumber frame buildings.

From Figure 4.1, we can observe that at the end of the life expectancy of concrete house (75 years), concrete is below 1. This indicates that mycelium-plywood houses cannot be built again with the cost difference investment at year 75, where concrete houses will totally be deteriorated. This shows that mycelium-plywood building is economically infeasible and cannot compete against concrete homes economically. Therefore, mycelia composite as a building material is economically infeasible and not competitive against concrete at a 7.75% interest rate and a 6.50% inflation rate.

Figure 4.1: Mycelium-Plywood Building Cost Against the Value of Cost Difference Invested at a Base Prime Rate of 7.75% (Base Scenario)



Notes: Plexiglass = the difference in building cost between mycelium-plywood and mycelium-plexiglass invested/Plywood cost in year t, Concrete = the difference in building cost between mycelium-plywood and concrete invested /Plywood cost in year t, Lumber = the difference in building cost between mycelium-plywood and lumber invested /Plywood cost in year t.

Similarly, mycelium-plywood mold house is not economically feasible against lumber. Figure 4.1, lumber is less than 1 at year 50, indicating that mycelium-plywood houses cannot be built till the end of lumber frame house life expectancy (year 50). This shows that the cost difference between mycelium-plywood house and lumber frame house is less than mycelium-plywood mold house at the end of the life expectancy of lumber frame house. This indicates that mycelium-plywood building is not economically feasible and not economically competitive against lumber frame house at an interest rate of 7.75% on investment and 6.5% inflation rate.

4.5 Sensitivity Scenarios

Several scenarios (see Table 4.9) Table 4.9: Sensitivity Scenarios for Assessing the Economic Feasibilitywere run to test the sensitivity effects of interest rate on investment and mycelium price changes holding inflation rate and life expectancy unchanged since they cannot be influenced by the consumer. The base scenario of 7.75% was based off current market prime rates for banks operations loans. Assuming interest rates would rise during the life expectancy of each building material. Interest rates sensitivity was measured with an interval of 0.25% increase from the base interest rate across all alternative building materials while holding the inflation rate unchanged over the period.

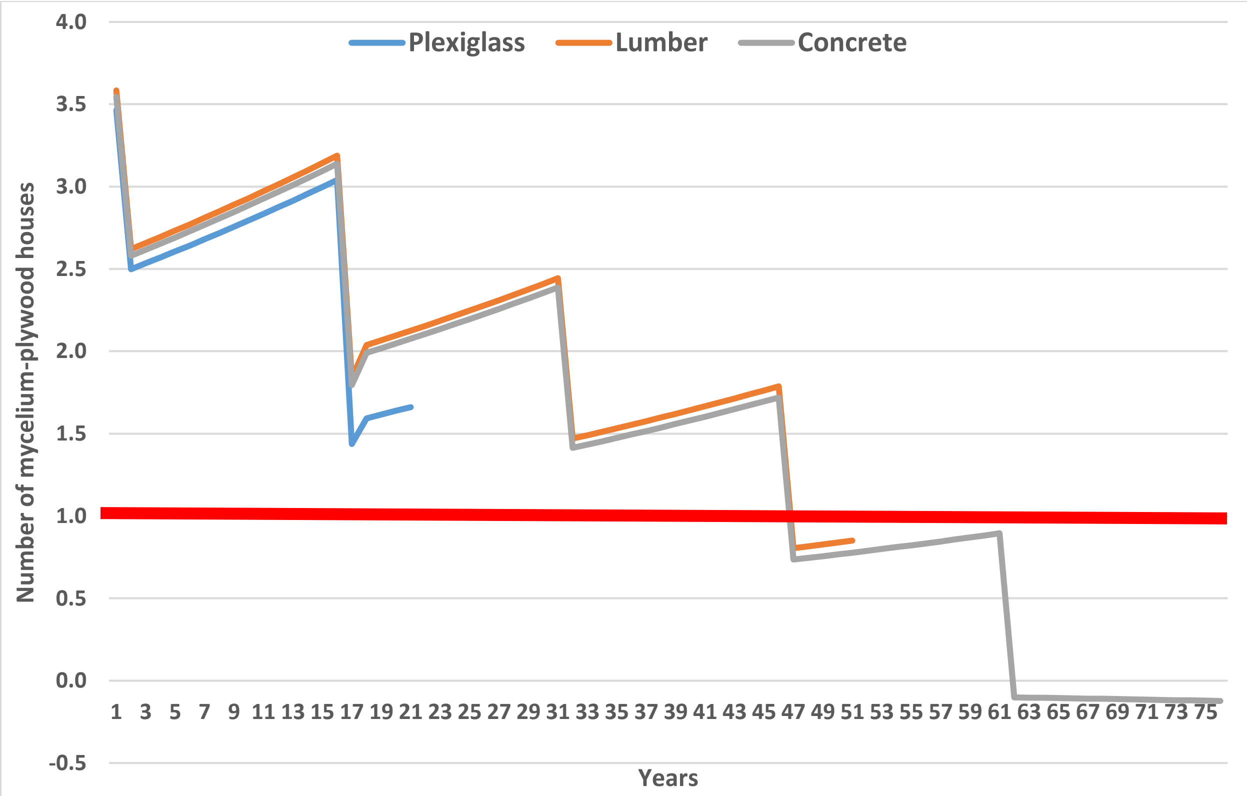
Table 4.9: Sensitivity Scenarios for Assessing the Economic Feasibility

	Base Values:	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Interest Rate	7.75%	8.00%	8.25%	8.50%	8.75%	7.75%	7.75%
CPI	6.50%	6.50%	6.50%	6.50%	6.50%	6.50%	6.50%
Mycelium Price/ft^3	$0.83	$0.83	$0.83	$0.83	$0.83	$1.17	$0.83
Mycelium-Plywood Life Expectancy	15 years	15 years	15 years	15 years	15 years	15 years	20 years

Notes: Base Values column represents values of changing cells at time Scenario Summary Report was created. Changing cells for each scenario are highlighted in gray. Any variable not included remains unchanged.

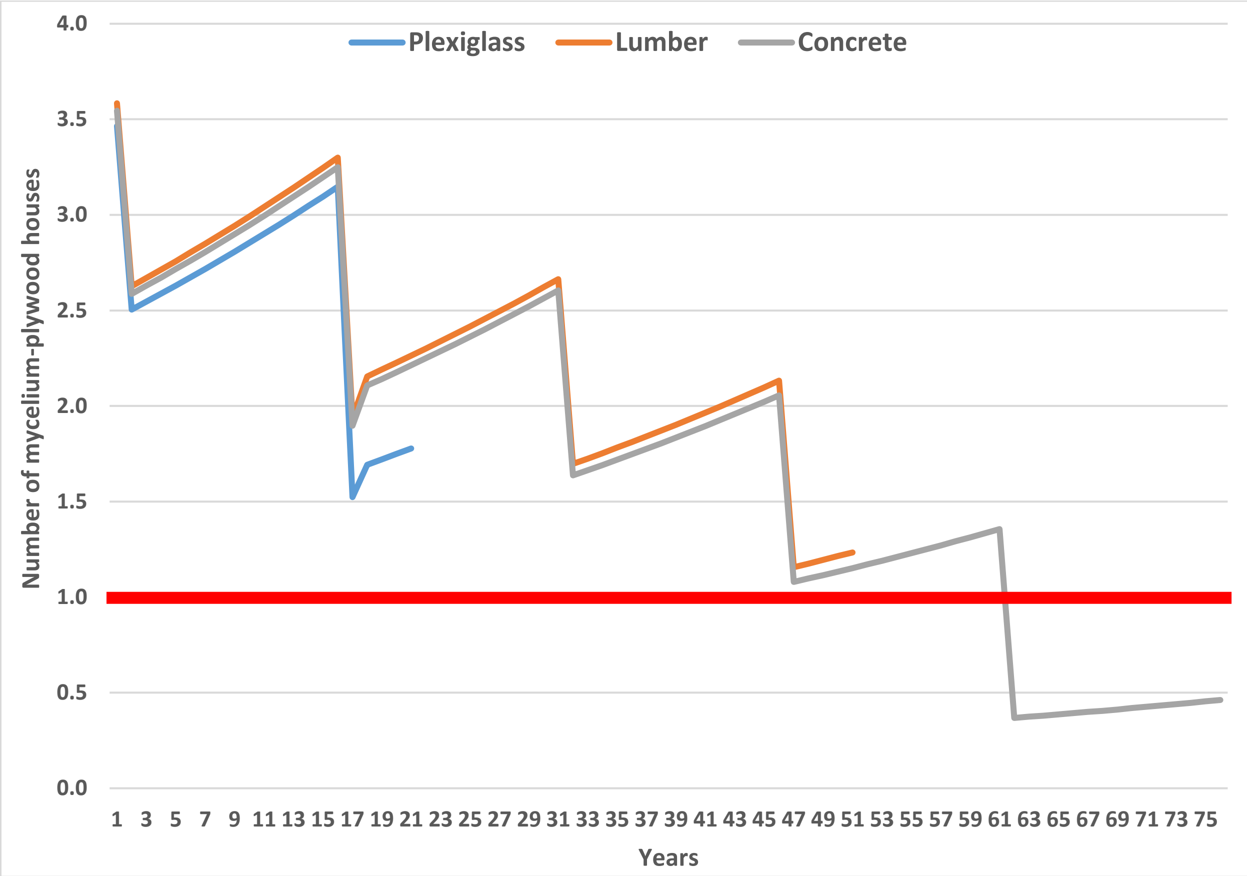
Scenario 1: Effect of change in interest rate (from 7.75% to 8.00%). The first scenario involved exploring the effect of 8.00% interest rate on the investment of the cost difference between mycelium-plywood and all the alternative building materials, while holding everything else unchanged. The investment under the base scenario is presented in Figure 4.1. If interest rate increased to 8.00%, the value of the cost difference invested at the end of each period (i.e., every 15 years) against the mycelium-plywood cost accounted for inflation and depreciation are presented in Figure 4.2. The results indicate that mycelium composite house with plywood mold is not economically feasible against concrete and lumber framed houses at an interest rate of 8.00%, since concrete and lumber are less than 1 at the end of their respective life expectancies.

Figure 4.2: Effect of Change in Interest Rate (7.75% to 8.00%)



Scenario 2: Effect of change in interest rate (from 7.75% to 8.25%). The second scenario explored the effect of an increase in interest rate from 7.75% to 8.25%, any other parameter unchanged. This scenario results are presented in ……. The results indicate that mycelium plywood houses are economically feasible and competitive against lumber. Thus, the lumber graph is greater than 1 at the end of the life expectancy of lumber house, indicating that we can build mycelium-plywood houses till the end of lumber life expectancy. On the other hand, mycelium-plywood houses are economically infeasible against concrete.

Figure 4.3: Effect of Change in Interest Rate (7.75% to 8.25%)

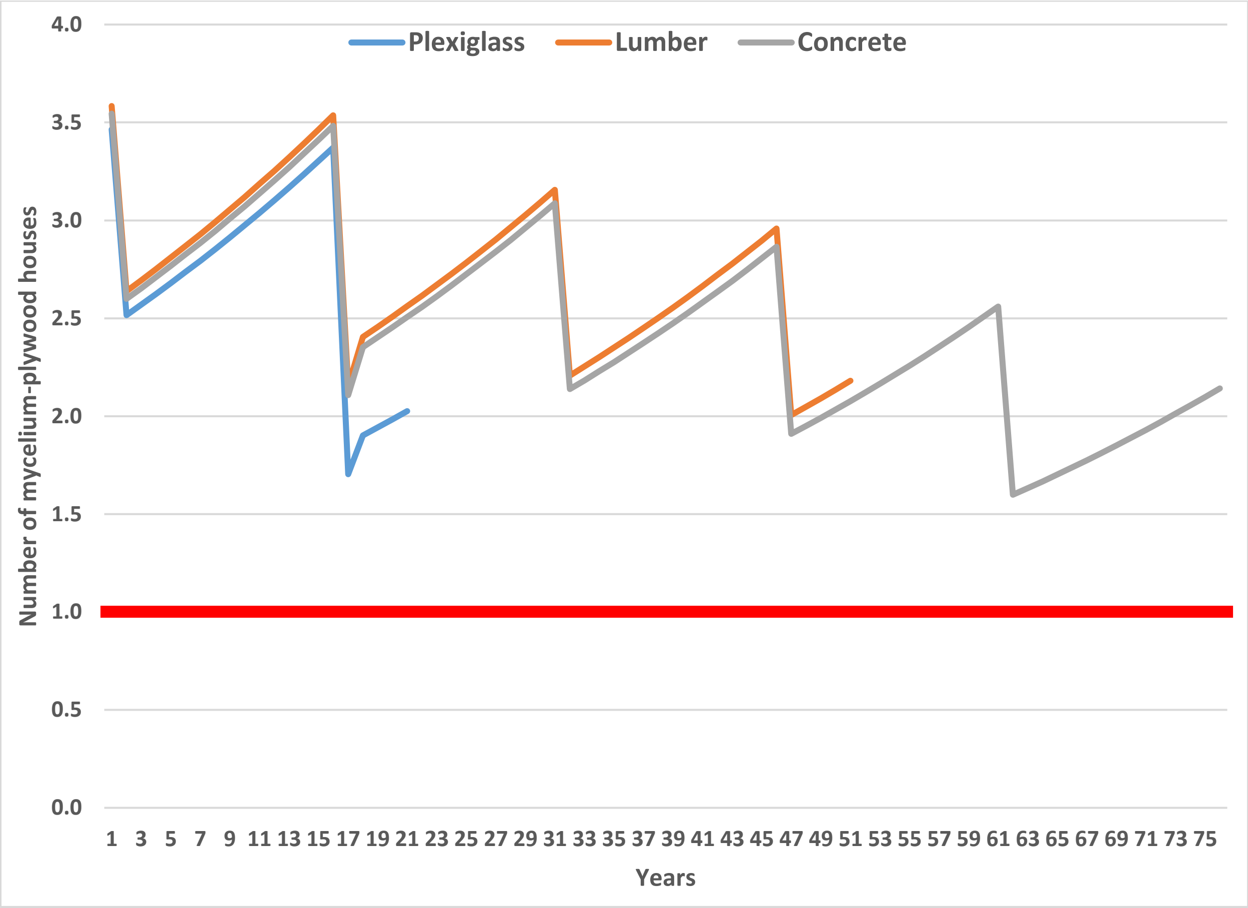


Scenario 3: Effect of change in interest rate (from 7.75% to 8.50%). The third scenario explored the effect of an increase in interest rate from 7.75% to 8.50%, any other parameter unchanged. When the interest rate on investment was increased to 8.50% on the cost difference between mycelium-plywood and the other type of building materials, the net returns on investment for concrete, and lumber were greater than mycelium-plywood cost at the end of each material life expectancy, respectively, as shown in Figure 4.4. Thus, concrete and lumber graphs are greater than 1 at year 75 and year 50, respectively. This indicates that mycelium-plywood building is economically feasible at an interest rate of 8.50% on investment and an inflation rate of 6.50% on mycelium-plywood cost and competitive as a composite building material.

Figure 4.4: Effect of Change in Interest Rate (7.75% to 8.50%)

Scenario 4: Effect of change in interest rate (from 7.75% to 8.75%). In scenario 4, we explored the effect of interest rate increased by 1% from the base interest rate of 7.75%, while any other thing is unchanged. That is, this scenario considers an interest rate of 8.75% on investment of the cost difference. The results are presented in Figure 4.5. We can build mycelium-plywood houses up to the end of lumber home life expectancy. Likewise, the cost difference between concrete and mycelium-plywood house invested at an interest rate of 8.75% over the cost of mycelium-plywood house is greater than 1 at the end of concrete life expectancy (year 75). Therefore mycelium-plywood building is economically feasible and competitive against lumber and concrete buildings at an interest rate of 8.75%.

Figure 4.5: Effect of Change in Interest Rate (7.75% to 8.75%)



Scenario 5: Maximum price of mycelium/ft^3 (from 0.83/ft^3 to 0.09/ft^3). Given that the mycelium price was extrapolated from the literature, we explored the maximum price limit that would at least make mycelium-plywood house feasible and competitively against concrete and lumber, given the base values remains unchanged. The outcome shows that the maximum price level should be \$0.09/ft^3 for mycelium-plywood buildings to be economically feasible and competitive against concrete and lumber frame buildings. This indicates that any price beyond this will make mycelium-plywood economically infeasible and non-competitive against concrete for homeowners at the base scenario values of interest rate, inflation rate, and life expectancy.

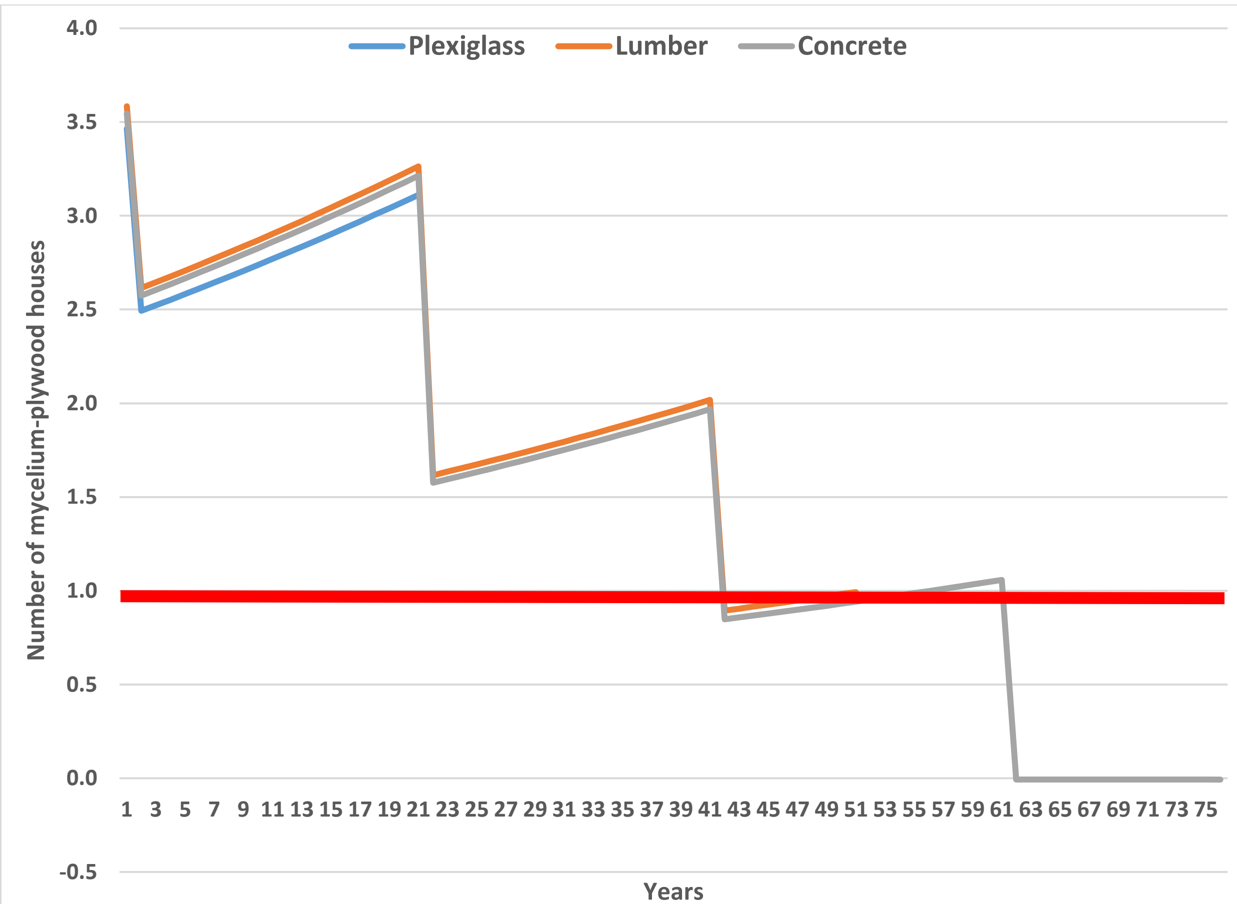
Therefore, the price of mycelium should be reduced to 0.09/ft^3 to make it economically feasible and competitive under current conditions.

Figure 4.6: Maximum Price of Mycelium ($0.83/ft3 to $0.09/ft3)

Scenario 6: Technology feasibility. We assume that technology can be improved over time and life expectancy of mycelium-plywood home would increase. Thus, we assessed a situation if the life expectancy of mycelium-plywood house increase to 20 years, all other base values unchanged (see Table 3.1, Table 4.1, and Table 4.9). The results of this scenario are presented in Figure 4.7. For concrete homes, mycelium-plywood houses are economically infeasible and not competitive as a composite building material at an interest rate of 7.75% and inflation rate of 6.50% if mycelium-plywood house life span is 20 years. However, if technology is improved (i.e.,

mycelium-plywood house life expectancy is 20 years) and interest rate increases to 8.25% the same time while inflation rate remains unchanged, then mycelium-plywood house will be economically feasible and competitive against concrete. On the other hand, mycelium-plywood is economically feasible and competitive against lumber frame house at 7.45% interest rate on investment is and 6.50% inflation rate when the life expectancy of mycelium-plywood house is increased to 20 years.

Figure 4.7: Technology Feasibility (Life Expectancy of Mycelium-Plywood House is 20 Years)



From the foregoing sensitivity scenarios, mycelium-plywood is economically feasible and competitive against concrete and lumber buildings with an interest rate of 8.50% and above and CPI of 6.50%. Assuming the 2022 inflation rate of 6.50% remains the same for the life expectancy for all building materials, interest rate must be at least 8.50% for mycelium composite to be economically feasible. Mycelium-plywood will be economically feasible and competitive against concrete and lumber whenever the interest rate on investment is about 2% more than the prevailing inflation rate for any period given the base building costs and relative life expectancy of all building materials. Also, the maximum price of mycelium should be $\$0.01/ft^3$ for mycelium-plywood to be economically feasible and competitive against concrete and lumber frame buildings.

If technology is improved that will increase the life expectancy of mycelium composite, then mycelium composite as a building material will be economically feasible and competitive against concrete and lumber building materials.

Chapter 5 - Summary, Conclusion, and Recommendation

This chapter presents the summary and conclusions of the study. It is organized in subsections as follows: Section 5.1 provides the summary of the findings of the study. Section 5.2 presents the conclusions drawn from the analyses in the study.

5.1 Summary

The purpose of the study was to assess the economic feasibility of mycelium composite as a building material. Mycelium composite is 100% biodegradable, emission free, recyclable, locally accessible that reduces transportation costs, environmentally friendly, fire resistant and a low-cost material relative to concrete and lumber.

The base building cost of mycelium-plywood house is the lowest compared to the other types of building materials when the mycelium price is at least \$0.83/ft^3. Mycelium composite with plywood molds house cost is approximately 258% and 255% lower than concrete and lumber framed buildings, respectively. However, mycelium-plywood houses are less durable (about 15 years) than all the other types of building materials. Its compressive strength of about 30 psi is nowhere comparable to concrete 4000psi.

Assuming the current interest rate on investment and inflation rate remains the same throughout the life expectancy of concrete house (75 years) which is the most durable, then mycelium composite with plywood molds is not economically feasible and competitive building material against concrete and lumber building materials. The base scenario of 7.75% interest rate and 6.50% inflation rate produced a number of mycelium-plywood houses less than one at the end of each concrete and lumber frame houses life expectancies. However, if the price of mycelium decreases to or less than \$0.09/ft^3, mycelium-plywood building will be economically feasible and competitive.

If technology can be improved to make mycelium composite house last longer than current form of composite, then mycelium house will be economically feasible and competitive building material.

Also, for mycelium composite to be economically feasible and competitive against concrete and lumber framed houses, interest rate on investment should be at least greater than the prevailing inflation rate (approximately 2%) at any given period if mycelium composite price is $\$0.83/ft^3$ or less.

5.2 Conclusions

This is a solid base analysis for mycelium structures, however there is a lot more to do.

Based on the results of the analysis of a wide range of literature data and our own extrapolated data, it indicates that mycelia as a composite building material is economically feasible on key conditions and assumptions. Since inflation rate is exogenous, interest rate on investment can always be negotiated to be at least 2% more than the prevailing inflation rate to make mycelium composite feasible and competitive against concrete and lumber building materials. The cost was the prior advantage of the mycelium composite with plywood molds over the other traditional materials.

While durability is the main concern of mycelium composite at its current state as a building material, it should not be a deterrent to potential builders because it can stay for long if it is well protected against harsh weather conditions. And since it is economically feasible at some dimensions, several mycelium composite houses can be built to offset the long durability of conventional building materials such as concrete and lumber.

Mycelium composite houses will be feasible in areas that are disaster prone areas and areas where life expectancy of houses is very low.

Also, this study can be applied in other sectors of the economy such as the packaging industry. It is an industry that companies such as Ecovative Design have started using mycelium composite for packaging to replace plastic packaging which has negative consequences on the environment.

The main limitation of this research was data on mycelia products, which were extrapolated from the literature. And since there is no known mycelium structure, we are unable determine the exact estimates and durability of this material.

5.3 Recommendation for Future Research

Concrete and lumber framed houses have been built for several years and data is available for their construction cost which we used in the study. However, mycelium houses have not been built yet, so the data on mycelium house construction were extrapolated from the literature, therefore making the estimates as possibilities and not actuals. And given that, even though mycelium composite as a building material is feasible with our analysis, people will not be willing to invest their resources in it. Therefore, we recommend that mycologists and building engineers should work together and construct a mycelium composite home that would provide us with the true estimates of the construction cost for future studies.

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