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Innovative Materials : The Role of Hybrid Materials in Construction

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Dedication

To my parents, Osman and Mariam For your unconditional love, guidance, and sacrifice, which have illuminated my path.

To my family and friends all over the world, Your unwavering support and overwhelming generosity have been my stronghold. Your belief in me has been the wind beneath my wings.

And to those who inspired my work, Though you may never leaf through these pages, your spirit has left an indelible mark upon them.

Acknowledgement

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Talking about my journey, Milan has impacted me deeply, so far to say that it has been a truly life-changing experience. In the past two years, Politecnico di Milano has never been only about my master's course, but I got the chance to attend an extraordinary learning experience, explore a new culture and make many good friends from several spots around the world.

In the end, I would like to acknowledge the appreciation I have for my family, and friends who give me unconditional support. This thesis would not have been possible to do without their constant support and push.

Abstract

The manufacturing of traditional construction materials uses important levels of nonrenewable fossil fuels and creates high levels of carbon emissions, which can have negative impacts on the surrounding environment. This thesis delves extensively into the literature on the transition from traditional to bio-based building materials and examines the crucial question of sustainability in the construction industry. It demonstrates how using bio-based materials can have a significant positive influence on the environment, lower carbon footprints, increase performance and cost-effectiveness, and improve overall performance. The research identified mycelium as the most innovative bio-based material through case studies analysis performed in the construction industry. Additionally, the thesis investigate the concept of hybrid materials and proposes a hybrid materials matrix as a strategy to balance sustainability with performance requirements in construction, highlighting the potential for integrated materials solutions.

Astratto

La produzione di materiali da costruzione tradizionali impiega livelli significativi di combustibili fossili non rinnovabili e genera elevate emissioni di carbonio, che possono avere impatti negativi sull'ambiente circostante. Questa tesi approfondisce la letteratura sulla transizione da materiali da costruzione tradizionali a materiali basati su risorse biologiche, esaminando la questione cruciale della sostenibilità nell'industria delle costruzioni. Dimostra come l'uso di materiali bio-based possa influire positivamente sull'ambiente, ridurre le impronte carboniche, migliorare le prestazioni e la convenienza economica, e ottimizzare le prestazioni complessive. La ricerca ha identificato il micelio come il materiale bio-based più innovativo attraverso analisi di casi di studio nel settore delle costruzioni. Inoltre, la tesi indaga il concetto di materiali ibridi e propone una matrice di materiali ibridi come strategia per equilibrare sostenibilità e requisiti di prestazione nella costruzione, evidenziando il potenziale per soluzioni integrate di materiali.

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CHAPTER 01: INTRODUCTION

1.1 Introduction

As one of the primary consumers of environmental resources, the building industry faces unprecedented challenges in needing to reduce the environmental impact of current consumption practices. This applies to both the construction of the built environment and resource consumption during its occupation and use. The growing demands of fast increasing population expansion and urbanization can outweigh any benefits that result from little improvements to current processes. In view of this significant social issue, it is important to investigate strategies that call for a paradigm change in the sourcing, processing, and assembly of materials to address the scope of these issues in a way that is truly sustainable and even provides value.

The world is currently facing the threat of a major environmental disaster, and the construction industry plays an important role in the current condition. The construction industry must implement significant changes to establish sustainable practices and promote a circular economy. The construction industry's environmental impact is mostly attributable to the manufacturing and consumption of non-renewable materials. Hence, it is imperative that the construction industry take steps to minimize the consumption of non-renewable building materials (Girometta,2019). resulting in reduced CO_2 emissions by exploring environmentally friendly, renewable alternatives. According to the United Nations, the construction industry is responsible for 38% of global CO_2 emissions due to energy consumption, and material extraction, processing, and discharge have the greatest environmental impacts in this industry ("United Nations Environment Program. 2020 Global Status Report for Buildings and Construction: Towards a Zero-Emission, Efficient and Resilient Buildings and Construction Sector" 2022). The growing need to adopt sustainable practices in the construction industry has resulted in an increased need for sustainable building materials. In response, there has been a shift in focus towards the development and use of novel biomaterials that support the principles of the circular economy throughout their life cycle (Almpani-Lekka ,2021). This approach assures that the entire procedure, from the processing of raw materials through final disposal or recycling, reduces waste and environmental effects.

Bio-based construction materials are sustainable and affect social wellbeing positively. It can be rapidly replenished by photosynthesis every day. It has been observed that this pragmatic material is the unsurpassed alternative not only due to the reduction of the carbon and energy emissions but also because it provides thermal comfort with less energy consumption for the functioning of the buildings to replace the conventional materials. The usage of plant-based building materials is an augmentation towards an eco-friendly, sustainable, and effective multifunctional materials.

Bio-based material resources are renewable and thereby they gain fundamental advances over mineral-and fossil-based resources. "40%of global raw material is expended by the building industry. 50% of CO2 releases into the atmosphere come from the construction sector," reports abio-construction expert, Paolo Ronchetti.(*ISOBIO,2020)*

1.2 Research questions

"We need to design for the future, not just for today, and that means using materials that will not only reduce our environmental footprint but will also create a positive impact." Architect William McDonough (McDonough & Braungart, 2010)

- How are bio-based materials driving innovation in the construction industry?

"hybrid materials can offer superior performance while reducing the environmental impact of construction." Professor Dr. Michael Braungart. (McDonough & Braungart, 2010)

- what are the measurable impacts of hybrids on reducing environmental footprints? And can hybrid materials provide a sustainable and durable solution in this context?

1.3 Research objectives

The main objectives of the research are to examine the application of bio-based building materials and assess the environmental impact of transition from traditional to bio-based and hybrid building materials. Specifically, this study aims to:

1- Evaluating the environmental benefits of bio-based construction materials, particularly in terms of carbon emission reduction.
2- Identifying innovative bio-based materials, with a focus on mycelium, through case study analysis in the construction industry.
3- Proposing a hybrid materials matrix that integrates traditional and bio-based materials to enhance sustainability, strength, and different properties in construction projects.

1.4 Research Structure

The First Chapter introduces the thesis by discussing the main challenges that the building sector must overcome to reduce its environmental effect in the face of increasing urbanization and population expansion. It makes the case for a paradigm change in the procurement, processing, and assembly of materials in favor of sustainable methods. It highlights how the building sector plays a significant role in the world's CO_2 emissions and how the move to bio-based building materials would assist the concepts of the circular economy and promote sustainable development. In the second chapter provides a comprehensive review of existing literature on the use of bio-based materials in construction. It starts with an overview of why bio-based materials are important for sustainable building, highlighting their advantages over traditional materials and their potential to completely transform the construction industry. The discussion focuses on sustainability and the bioeconomy, looking at international and EU policies that encourage the use of bio-based resources. The chapter provides an objective perspective on the use of these materials in construction by critically analyzing their effects on the environment, highlighting life cycle assessment and carbon footprint analysis, and acknowledging their limitations. In the third chapter, the thesis delves into the concept of innovation in the construction industry, spotlighting bio-based materials, with a specific focus on mycelium. It provides a comprehensive examination of mycelium-based materials, covering their introduction, growth processes, properties, and the concept of material hybridization. Through detailed case studies, the chapter showcases the practical applications and potential of mycelium in construction, illustrating its role as a game-changer in achieving sustainable and innovative building solutions. In Chapter 4, the topic of hybrid materials is explored, underlining its critical role in creating a more environmentally friendly future. These materials represent the highest level of innovation, providing improved performance, durability, and a significantly smaller environmental impact. They are an innovative combination of traditional and bio-based materials. This chapter explains how combining different material properties can result in innovative composites with enhanced properties including higher strength, moisture resistance, and thermal insulation through the systematic method of the hybrid materials matrix. The chapter particularly highlights how the matrix may encourage the creation of materials that support a circular economy in the building industry while also satisfying the changing requirements of energy efficiency and sustainable development. The chapter offers an extensive overview of the potential for these materials to change the industry and ensure a sustainable and resilient built environment by presenting examples and strategies for developing these hybrid composites.

CHAPTER 02: LITERATURE REVIEW

2.1 Overview of Bio-Based Materials in Construction

What is bio-based materials ?

Biobased materials are products primarily composed of substances obtained from living items (biomass), which can occur naturally or be synthesized. It can also refer to products produced by procedures that use biomass. By following specific criteria, various common substances including paper, wood, and leather can be classified as biobased materials. However, in most cases, this term is used to describe modern materials that have undergone more thorough processing. Biomass-derived materials include a range of substances, such as bulk chemicals, platform chemicals, solvents, polymers, and bio composites.(some materials may fall under more than one category). The various methods of transforming biomass components into products and fuels with increased worth can be generically categorized as either biochemical or thermochemical. Furthermore, biotechnological procedures that primarily depend on plant breeding, fermentation, and traditional enzyme isolation are also employed (Curran, M. A.2010). Biobased materials are being recognized as possibly more environmentally friendly compared to their petroleum-derived counterparts. However, the statement is currently subjected to thorough examination. Continuously, innovative biobased materials are being introduced into the market, which could bring the possibility to traditional materials. The potential for their application in both current and innovative products is just starting to be explored.

The concept of the circular economy is frequently linked to biobased materials due to their inherent nature of promoting closed-loop systems and the creation of shorter cycles. Unlike fossil fuels, which have lifecycles that span millions of years, biobased materials have far shorter lifecycles, often ranging from a single growth season to around 100 years, such as the lifespan of a tree. Biobased materials can be classified into two main categories: Conventional and Emerging. Traditional biobased products and materials are made of organic material derived from animals or plants and contain the ability to breakdown on their own over time.

On the other hand, bio renewables and emerging biobased materials are frequently the focus of research and development and represent a significant portion of the innovation. These substances are obtained through biorefining methods or produced from substances that have biological origins. Although these substances may not completely decompose, they are capable of being partially "regrown." An instance of this is the refining process used for sugar beets, which yields lactic acid, polylactic acid (PLA), and sugar beets for use in plastics. (2014) Material District.

The definition of biobased materials by the European Union (ECS) as "materials derived from biomass" (European Committee for Standardization, 2014) provides a comprehensive operational framework. It is relevant to note, however, that the term "biobased" does not automatically mean "biodegradable," or does it guarantee that the product is integrated into a circular lifecycle of a long time (Prieto, 2016; Kawashima, Yagi, & Kojima, 2019). Additionally, the term "fixed mixing ratio" isn't related to composite materials. Therefore, an agreement on the definition is required to explain and manage expectations when entering this subject. Among all the benefits recognized by biobased materials in light of the current climate and environmental crisis is the fact that they are derived from renewable sources (Bekkering,2021).

The construction industry is a key contributor to the current situation, which places the entire world at risk of a huge environmental disaster. For the construction sector to adopt sustainable practices and advance a circular economy, major changes must be made. The production and use of non-renewable resources are primarily responsible for the environmental effects of the building sector. Thus, it is essential that the building sector take action to reduce the use of non-renewable building materials (Girometta, 2019), which will lower CO2 emissions through the exploration of renewable, ecologically friendly alternatives. The extraction, processing, and recycling of materials have the biggest environmental effects in the construction industry, which accounts for 38% of global CO2 emissions due to energy consumption ("United Nations Environment Programme. 2020 Global Status Report for Buildings and Construction: Sustainable building materials are becoming more and more necessary as the construction industry faces pressure to use sustainable practices. As a result, attention is turning to the creation and application of innovative biomaterials that uphold the circular economy's concepts over the course of their lifetime (Almpani-Lekka, 2021).This method confirms that waste and environmental effects are minimized throughout the process, from raw material processing to ultimate disposal or recycling.

2.1.1 Why build with biomaterials

Innovation in material science and construction industry products consistently offers fresh perspectives and opportunities. So, what is the most practical and sustainable course of action when technology allows humans to create nearly whatever they can imagine, and the natural world is screaming out for less environmental impact and less use of natural resources? As the world's population continues to expand rapidly, there is an increasing demand for homes and other built environments that can accommodate these growing populations. It would be simple to argue that rather than destroying our environment, we should develop new methods to utilize the resources at our disposal, create more with less, and discover new ways to utilize our experiences and abilities. Seen in this manner, we can think about the built environment and natural ecosystems and examine how new approaches to design and construction could help us advance and improve. The hereby provided initial study views hybridization as a concept and bio-based building material science, considering things like material qualities and modification as well as the design and performance of material combinations and systems. It is based on current engineering science and technology. The anticipated outcomes include a vision for the innovation of fictitious or hypothetical building items that can alter the eco-balance and improve construction efficiency. (Falk, A. 2015)

Bio architecture is being returned as an alternative for other building methods in line with the current trend of producing sustainable structures and raising environmental awareness. Bio-based materials have become highly after in a variety of applications, including building and interior and exterior design, among others, because of their special qualities and natural beauty. Because biomaterials are renewable and circle us, they have a minimal environmental impact, which is their primary benefit. Biomaterials allow for quick installation and prefabrication. They provide for significant design freedom and the construction of multistory buildings because of their advantageous weight-to-load-bearing capacity ratio (Sandak, 2019).

2.1.2 Comparison between bio based and traditional materials

One of the key characteristics that makes bio-based materials different from traditional is their availability and scalability. Because they come from renewable resources like plants and agricultural waste, bio-based materials are more environmentally friendly and sustainable than traditional materials. This is especially true when comparing them to traditional materials. Several variables, including climate, soil quality, and farming techniques, can affect feedstock abundance, which in turn affects the availability of bio-based materials. Additionally, certain bio-based materials may only be found in geographic areas. Also, the ability of bio-based materials to be produced on a big scale to satisfy expanding worldwide demand is referred to as their scalability.

Furthermore, there can be variations in the functioning and performance of bio-based and traditional materials. For instance, bio-based construction materials may differ in their thermal resistance or structural integrity when compared to traditional materials like concrete or steel, and bio-based materials may have distinct mechanical properties from their synthetic equivalents. Cost-effectiveness is another area where bio-based and traditional materials differ (Alioua et al., 2019). Bio-based materials are more promising than traditional materials in a variety of industries due to their potential to provide both economic and environmental benefits, albeit their cost-effectiveness is dependent on several factors. Because obtaining and processing renewable resources is more expensive than producing traditional materials, bio-based materials are frequently still more expensive to make. But these barriers are rapidly being broken down by technological improvements and the growing desire for sustainable alternatives (Siracusa & Blanco, 2020). Even though bio-based materials are more expensive, less readily available, and perform worse than standard materials, research is gradually removing these obstacles. Since bio-based products might not yet match all requirements imposed by traditional materials, issues like application and quality assurance are noteworthy. But these worries are being addressed by developments in engineered goods and bio-composites. A more sustainable building sector will require adjustments to supply chains, infrastructure, and manufacturing procedures in addition to the shift to bio-based materials. (Mouton et al., 2023)

Category	Bio-based Materials	Traditional Materials
Source of Raw Materials	Derived from renewable resources (living or once-living organisms) including plants, fungi, and bacteria. Examples: wood, bamboo, hemp, straw bales, bio plastics.	Typically sourced from non-renewable resources. Examples: concrete, steel, glass, petrochemical plastics
Environmental Impact	Lower environmental impact, renewable, biodegradable, smaller carbon footprint. Production requires less energy and may absorb CO2.	Higher environmental impact, energy-intensive production, non-renewable, non-biodegradable. Contribute significantly to carbon emissions.
Durability and Strength	Varied durability and strength. Innovations like engineered wood and treated natural fibers are narrowing this gap.	Known for strength and durability. Widely used in structural applications. Materials like steel and concrete define the construction industry.
Cost and Availability	Can be more cost-effective, especially with local materials. Some advanced materials can be more expensive due to limited production.	Well-established supply chains, widely available, and often cost-effective. Prices can fluctuate due to market and geopolitical factors.
Building Performance and Application	Excel in thermal insulation and moisture regulation. May require more maintenance and protection against elements.	Provide robust structural support and fire resistance, require less maintenance. May contribute to higher energy costs for heating and cooling.
Regulatory and Industry Standards	Face challenges in standardization and certification. Building codes and standards are often tailored towards traditional materials.	Have well-established standards and are widely recognized in building codes, making them the default choice in many projects.
Sustainability and Circular Economy	Align well with sustainability and the circular economy. Can often be recycled or composted at end-of-life cycle.	Recycling and reuse can be challenging. Often end up as waste in landfills at the end of their lifecycle.

Table 2. 1 Comparison between bio-based materials and traditional materials (elaborated by author)

2.1.3 Benefits of Bio-Based Materials in Construction

“ Biobased materials are considered as a promising resource for buildings in the twenty-first century due to their sustainability and versatility. They can be produced locally, with minimum transportation costs and in an ecological manner”(Sandak et al 2019)

The building industry has a significant influence on worldwide resource consumption and environmental effect. Traditional building materials, such concrete and steel, are linked to significant energy usage, carbon emissions, and degradation of resources. Considering the growing need for environmentally sustainable construction methods, bio-based materials have emerged as alternatives.

Products made of bio-based building materials have the advantage of having a much lower carbon footprint than concrete, steel, or glass (Tellnes et al. 2017). Compared to other building materials, wood has less of an environmental impact since trees store carbon in their wood tissue and absorb it from the atmosphere. As a result, biomaterials are now seen as a good replacement for a few traditional construction techniques, receiving the titles "building materials of the twenty-first century" and "timber a new concrete." Biomaterials replace emissions from other materials because they are highly effective at storing carbon. But in contrast to traditional building materials, biomaterials have some characteristics that are still poorly understood and challenging to regulate. For example, natural fabrics have the ability to bind moisture up to 40% of their dry weight, depending on the air quality outside. Then, in some architectural structures, these fibers can serve as absorbers of moisture or humidity or as buffers. Nonetheless, components composed of hygroscopic materials have different hygro-thermal stability depending on their capacity to bind moisture.

stability of humidity and temperature is a significant limitation in specific applications, including thermal insulation, hydro civil engineering, cladding, and decking. The hygroscopic characteristics of any bio-based material are the primary cause of both shrinkage and swelling, which in turn lead to dimensional distortions. The correlation between the relative humidity (RH) and equilibrium moisture content (EMC) of a material is commonly shown by an absorption equilibrium diagram (Willems 2014; Brischke 2017). During the drying process, the moisture content gradually decreases until all the free water has completely evaporated. However, the bound water remains in the material. The term used to describe this state is known as the fiber saturation point (FSP). (Sandak ,2019).

One significant benefit of utilizing biomaterials is their unique natural properties and connection with deactivating human physiology. Modern trends in architectural design are shifting away from a single focus on optimizing basic environmental factors, like air temperature and humidity, towards more comprehensive approaches that promote health and well-being. Biophilic design is a contemporary approach that revives a centuries-old method of mixing natural elements into built environments, recognizing the links between humans and the natural world. Biophilic design is an architectural approach that promotes sustainability by fostering a reconnection between individuals and the natural world. It prioritizes human well-being over green building concepts that promote environmental responsibility and effective use of sustainable resources. Utilizing bio-based construction materials can have a positive impact on the individuals living in those environments (Kotradyová, Kalináková, 2014). have reported significant advantages of natural materials in terms of human health, childhood development, health care, learning, work efficiency, and productivity. It is important to note that industrial transformation, post-processing, and alterations can greatly influence how humans perceive the "naturalness" of materials (Burnard et al. 2017).

2.2 Bioeconomy and Sustainability

In the current economic system, fossil fuels (petroleum/oil, natural gas, coal) are utilized for a variety of purposes, including the production of energy, chemicals, polymers, textiles, and other everyday materials. Global material consumption continues to rise, particularly for energy production (Abas et al., 2015). According to estimates, the global population will continue to rise steadily in the foreseeable future, resulting in a significant and ongoing depletion of natural resources (United Nations, 2017). It is essential to understand that fossil fuels are nonrenewable resources and that their utilization contributes to environmental issues including habitat damage, extinction of wildlife, and climate change. To transform our current economy, policymakers, academic institutions, and businesses across the globe have devised innovative sustainable strategies and solutions, including eco-design and green chemistry (D'Amato et al., 2017) and circular green and bio economy. To ensure biodiversity and environmental preservation, bioeconomy refers to an economic system that generates food, energy, and other bio-based products and services from renewable natural resources such as forests, animals, crops, and microorganisms. It is regarded as a revolution in our economic development (Fig. 2.1), which generates new employment, economic expansion, and innovation while decreasing our reliance on fossil fuels. (European Commission, 2018a)

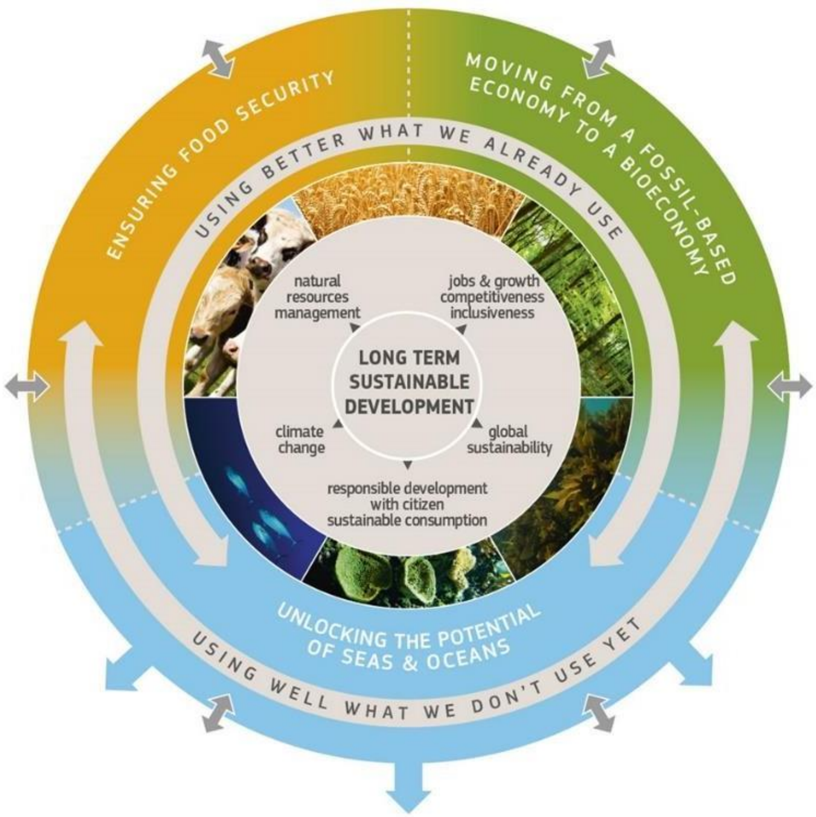


Figure 2. 1 Representation of the bioeconomy concept (European Commission, 2018b).

The goal of bioeconomy is to combat climate change directly. For instance, by substituting wood for fossil fuels, greenhouse gas emissions can be reduced. Forests are essential to our time and have been steadily increasing since 2010. Crucially, it produced over €2.2 trillion in values added in the European Union, creating 18.2 million jobs for the labor force in only one year (Ronzon et al., 2017).

The purpose of the bioeconomy is to maximize economic prosperity, quality of life, and expansion by utilizing natural resources. In the years before 1970, economists viewed the environment only as a means of obtaining resources. They only recognized environmental issues as a result of market failure and as a constraint on economic growth (Turner et al., 2013). The European Commission has made significant efforts to promote the notion of bioeconomy and its potential by encouraging the use of biotechnology in the market and the substitution of fossil resources with bio-based resources (Birner, 2017). During the early 2000s, there was a notable increase in investments in industries focused on innovation and high technology. In recent years, the EU has made a concerted effort to convert life science knowledge into innovative, environmentally friendly, efficient, and competitive products. This highlights the significance of this concept and Europe's position as a global leader in this domain. In 2007, research and companies in various industries, including biotechnology, bioenergy, crop production, and biomedicine, recognized the crucial role of biotechnology in using crops as a renewable resource to produce biofuel, biochemicals, and biopolymers (Lewandowski, 2017). Hence, the advancements in bioeconomy have been evident in the rise of scholarly articles, as well as in economic and governmental approaches, such as the European bioeconomy strategy of 2012.

2.2.1 Bioeconomy strategies in EU and worldwide

At the beginning of 2018, almost 50 countries were pursuing bioeconomy development in their policy strategies. Based on the country's degree of development, resources, and political system, these strategies are used throughout North and South America, Europe, Russia, Asia, Australia, and Africa (Fig. 2.2). To enhance the value of bio-based products, industrialized nations may support their bioeconomy by offering subsidies for bio-based research and development. In developing countries, bioeconomy initiatives are seen as having a great deal of promise to support sustainable economic development. Applying a strategy can also go forward along one or more transformation paths, such as replacing fossil fuels, increasing productivity in the primary sector, creating new and expanded uses for biomass, and applying low bulk and high value applications. In all the nations with objectives towards bioeconomic development, the bioeconomy has emerged as a strategic political objective (Dietz et al., 2018).

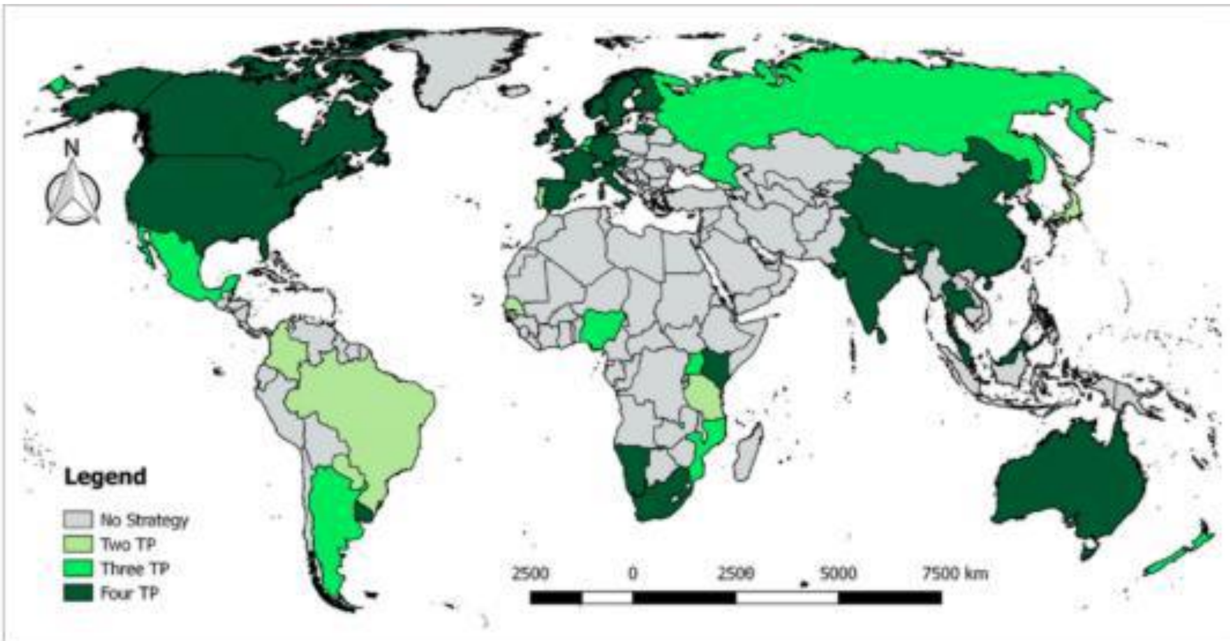


Figure 2. 2 Bioeconomy strategies around the world (Dietz et al., 2018).

In 2012, the United States and Europe were the first to introduce bioeconomy strategies. In order to retain Europe's competitiveness, assure food security, manage natural resources sustainably, decrease reliance on non-renewable resources, mitigate climate change, and create jobs, the European Bioeconomy strategy was designed in that year and revisited in 2018. 2018 saw the European Union concentrate its strategy on the circular bioeconomy, which is the bioeconomy's shift from producing virgin to secondary materials by using wastes, co-products, and leftover resources. This ensures the most efficient use of natural resources.(European Commission, 2012).

The goal of this strategy was the improvement of the sustainable use of renewable resources keeping the idea of the previous strategy. To achieve this goal three key objectives and related concrete actions were defined. Scaling up and strengthening the Biobased sector ,deploying bio economies around Europe through the development of a strategic agenda aimed at the distribution of bio-based products and sustainable agricultural food and Protecting the ecosystem and understanding the ecological limitation of the bioeconomy providing guidance and promoting good practices on how to operate as well as implementing an EU-wide monitoring system and the first countries in Europe adopting bioeconomy strategies were the Nordic countries such as Finland and Norway, followed by Germany, Austria, France, United Kingdom and Italy. (European Commission, 2018a).

2.2.2 Biobased resources: biomass as a core of Bioeconomy

Biomass refers to the number of products, waste, and residual materials that can be broken down by natural processes. This includes organic matter derived from the growth of land vegetation through photosynthesis (Vassilev et al., 2010). Due to its widespread availability globally, biomass, namely lignocellulosic feedstock, is considered the most optimal source of polysaccharides and lignin for the manufacturing of bioproducts on a large. Lignocellulosic feedstock includes a wide range of materials, including both food and non-food crops, as well as agroforestry residue and trash. The production of bioproducts traditionally relied on food crops like sugarcane, corn, and rapeseed, known as first-generation feedstock. However, concerns about the extensive use of land for energy and oil crops instead of food crops have led to a growing emphasis on the use of second-generation feedstock.

Non-food crops (non-food plant biomass) and lignocellulosic wastes (agroforestry leftovers and processing) are examples of second-generation feedstock. woody crops grown in short rotation are examples of non-food terrestrial biomass. Woody crops are also known as "short rotation woody crops" because they grow more quickly—for example, in four to five years. Hard woods like willow, poplar, black locust, and eucalyptus are superior to long-term woody crops (12 years) in terms of weed control and sustainability. Land use competition persists since using this feedstock does not eliminate issues with land usage at the expense of other crops (Popa, 2018). Soon, a solution to this problem could be to integrate the pulp and paper production industries with the production of other bio-based products, using its side streams or by-products. This would be possible if we consider that these industries extract only 47% of the potential value from lignocellulosic materials (Chakraborty et al., 2019).

Furthermore, the bioeconomy sector makes significant use of agroforestry residues and processing, which includes secondary forestry refuse and primary forest residues. Forest activities, including but not limited to harvesting, shaping, weeding, trimming, and pruning, produce forestry residues. These items are of little economic worth. Leaves, stems, branches, and needles comprise these residues. Secondary forestry residues include byproducts of industrial processes, including sawdust, sludge, veneer, and cutting, which occur during the manufacturing of products like furniture, panels, pulp, and paper. Starting from this feedstock, biorefinery represents a sustainable process and cost-effective conversion of it into several bioproducts such as chemicals and materials, as well as bioenergy such as biofuel, power or heat (Cherubini, 2010)

As previously mentioned, bioeconomy products consist of an extensive range of substances, materials, compounds, and chemicals. An illustration of the main products obtained from the forest sector entirely is presented in (Fig. 2.3) , which symbolizes the bioeconomy pyramid as described by Toppinen et al. (2018). This pyramid has been constructed with six tiers, each of which reflects an individual item. Particularly, the items positioned at the bottom show low value addition and require a substantial amount of biomass for production. Going up the pyramid, the value added to the products decreases while the amount of biomass required for their production increases.

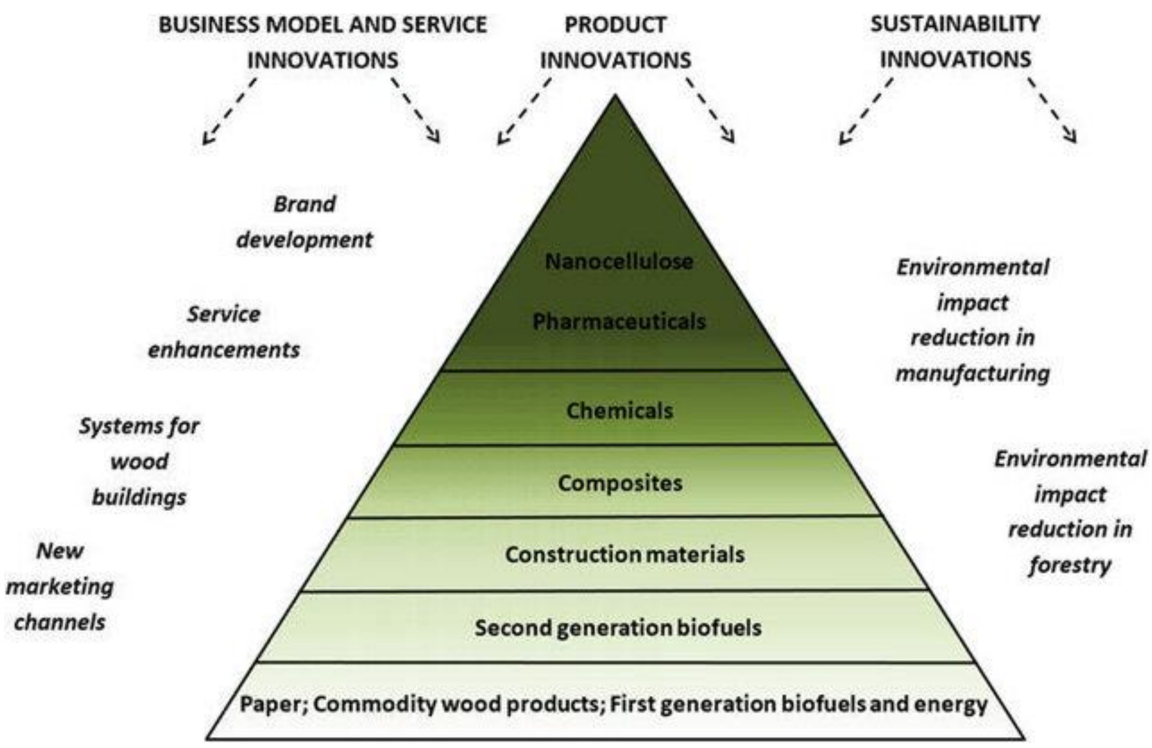


Figure 2. 3 Representation of bioeconomy pyramid (Toppinen et al., 2018a)

For example, starting from the bottom there are Paper, commodity wood products, first generation biofuels and energy. This level contains products that are widely used globally, e.g. paper or commodity wood products such as tables, chairs, cabinets, as well as first generation fuels (i.e. fuel derived from first generation feedstock.) The second level includes second generation biofuel which in turn includes biofuel for transportation and bioenergy in terms of heat and power. Such categories include several products such as bioethanol, biodiesel, biogas. Building materials, which are the third stage, have significance to the bioeconomy. They can be of many different kinds, including furniture, boards, panels, and structural structures. To make construction more ecologically friendly, policymakers now days support the use of wood in public procurement for the building industry (Toppinen et al., 2018b). Composites, the fourth level, are materials made of wood that have been combined with other materials to enhance their qualities. Wood-plastic composites, or materials composed of plastic components mixed with wood particles, are one example. Combining wood fiber with bio polylactic acid, bioplastic, or polypropylene is a common example. These wood-plastic composites replace neat plastic products and solid wood products, and they are used mainly for some parts of automotive interior but also in the building sector e.g. for decking . The last three levels include chemicals, pharmaceuticals and nanocellulose and they represent the most added value in the market inside this bioeconomy pyramid representation. (Beigbeder et al., 2019).

2.2.3 Biobased Product Positioning with Circular Economy and Bioeconomy

The concept of bioeconomy is being accepted by various stakeholders globally to address sustainability challenges and enhance social, environmental, and economic conditions in keeping with the United Nations Sustainable Development Goals. In recent years, there has been a connection and integration between the concept of bioeconomy and circular economy in both scientific literature and policymaking (Carus and Dammer, 2018). The term "bioeconomy" refers to the use of biological resources and processes to produce goods, services, and energy. The Organization for Economic Co-operation and Development (OECD) defines biotechnology as a sector that makes a substantial contribution to the overall economic output. The European Commission (EC) defines biotechnology as the process of utilizing renewable biological resources and converting them, along with waste streams, into products that have added value, such as food, feed, biobased products, and bioenergy. BE enhances CE by generating, transforming, and utilizing natural resources.

The concept of the "circular economy," or CE, takes consideration of both the technical and biological nutrition cycles. Practically speaking, it's still unclear how the biological and technical cycles differ from one another. For instance, the range of products made of biomaterials, such as wood, or abiotic materials derived from metals are described as having a unique right to exist within biological cycles (biocycles). However, it is important to acknowledge the significant possibility of these bioproducts/biomaterials being involved in technical processes (Corrado and Sala 2018). Additionally Circular economy is inspired by the circularity of material and energy in nature, where everything is recycled: plants adsorb light, leaves grow, animals eat plans, the soil is enriched with their waste, and from the soil seed sprouts ready for the new cycle. So, there is no waste and everything is reused. The circular economy promotes using waste as a raw material. In addition, this economy is based on reducing, sharing, leasing, repairing, reusing, refurbishing, and recycling in an (almost) closed loop, which aims to retain the physical characteristic and value of re-used products, materials, and raw material as much as possible (Korhonen et al., 2018).

Furthermore, the low carbon economy (LCE) is focused on addressing climate change; in this context, "carbon" often refers to emissions of carbon dioxide (CO2), which are the primary cause of climate change (Venkata Mohan 2020b). One important component of LCE is the use of renewable resources. The green economy (GE) encompasses the CE, LCE, BE, and BBE (Fig. 2.4). In its most basic form, green economy (GE) refers to a resource-efficient, low-carbon, and socially inclusive economy (Kardung et al., 2019). The sustainability of a product is also influenced by the energy that it contains during its life cycle. BE wants to have low-carbon fuels, materials, chemicals, and energy since its main goal is to achieve sustainability within the decarbonization framework. Consequently, attribution of low-carbon materials, chemicals, fuels, and energy is required for biobased goods with suitable tolls. Developing biobased CE will be largely dependent on the use of biorefinery systems and biogenic wastes as feedstocks (Dahiya et al. 2018).

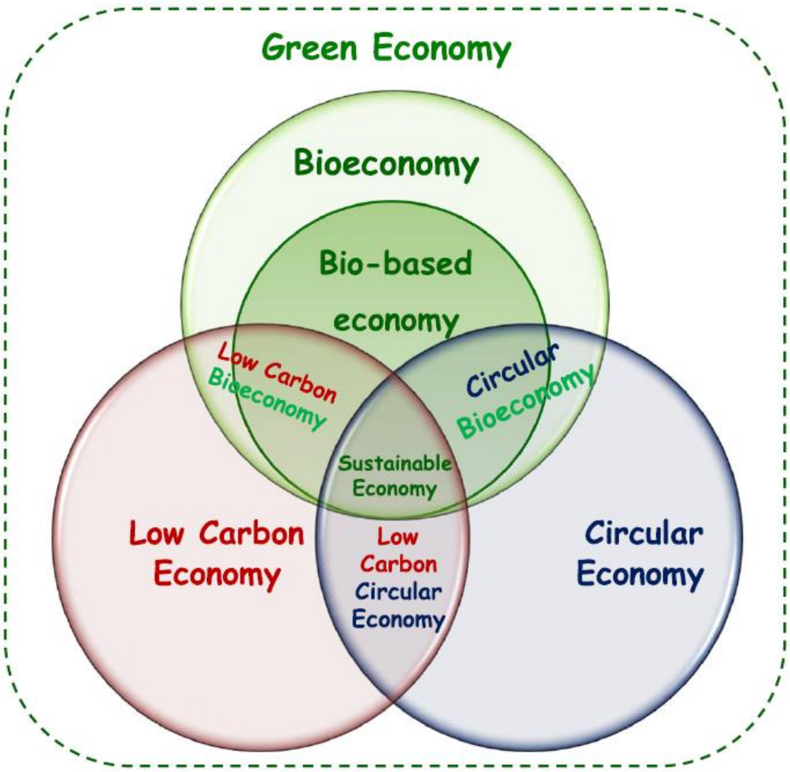


Figure 2. 4 Venn diagram depicting various economies in green economy (adapted from Kardung and Wesseler 2019)

In particular, the two concepts are closely related to each other, so that they can be defined as complementary. For example, they both share the same area of intervention as food, biomass, and products of biological origin. Furthermore, they share some common concepts such as sustainability, the chain approach, biorefinery and cascading use of biomass. Finally, both converge towards innovation and research, environmental and economic problems, and societal transition to sustainability (European Environmental Agency, 2018).

The term "BBE" refers to the utilization and processing of all natural and renewable resources (EU Publications, Bio-Based Economy in Europe 2011). To differentiate, the production of biomass/feedstock is handled by BE, whereas the manufacture of food and feed, biobased products, biomaterials, biorefineries, bioenergy, or biofuels uses the biobased feedstock handled by BBE either fully or partially (Kardung and Wesseler 2019).

The green economy placed greater focus on the connection between reducing poverty and saving the environment. That the practice "results in improved human well-being and social equity, while significantly reducing environmental risks and ecological scarcities" was defined by the United Nations Environmental Program (UNEP) in 2011. A green economy can be defined as low-carbon, resource-efficient, and socially inclusive in its most basic form (United Nations Environment Program, 2011,p.1). All the three concepts, bioeconomy, circular economy, and green economy are based on the three pillars of sustainability, even though with different priorities and solutions. For example, on the economic dimension all the three concepts aim to improve economic sustainability through the implementation of different strategies. On the environmental dimension, bio and circular economy propose which resources should be used and how. Finally, all the three concepts focus more on the economic and environmental aspects than on the social ones. In terms of scientific research, bioeconomy is most popular in Europe and in the United States, circular economy has a strong dominance in China, and green economy is more evenly distributed worldwide (D'Amato et al., 2017).

2.3 Environmental Impact and Sustainability

Bio-based construction materials are environmentally friendly and have a good impact on social well-being. It can be quickly reconstructed through the process of photosynthesis daily. This pragmatic material has been shown to be the best solution for several reasons. Firstly, it significantly reduces carbon and energy emissions. Additionally, it offers thermal comfort while consuming less energy compared to traditional materials. This makes it an excellent choice for building construction. The utilization of plant-based construction materials contributes to the development of environmentally friendly, sustainable, and efficient multifunctional materials. Bio-based material resources have the advantage of renewability, which gives them a basic edge over mineral and fossil-based resources. Approximately 40% of the world's raw materials are consumed by the construction industry. According to Paolo Ronchetti, a specialist in abio-construction, the construction sector is responsible for 50% of CO_2 emissions into the atmosphere. The source of this information is the ISOBIO report from 2020.

2.3.1 Life cycle Assessment (LCA)

Life Cycle Assessment (LCA) is an environmental management tool, and its main goal is to assess the environmental impacts of products, industrial processes, or human activities along the whole life cycle, from raw material extraction through production and to utilization and waste management (Fig. 2.5). By identifying the main environmental impacts, LCA enables us to enhance processes or products. Another name for it is a "from the cradle to the grave" assessment. This methodology evaluates effects that are both direct and indirect. Indirect effects are those that are connected to the operations of secondary processes or organizations, such as the transportation of raw materials (or finished goods) and the ensuing emission of exhaust gas. Direct affects are those that are directly tied to the products or process activities. Because LCA can be used to a wide range of industries, including plastics, personal care products, mining and oil extraction, construction materials, and many more, it is widely acknowledged and utilized as a strategic tool in many businesses. Now, the method is mostly utilized to evaluate the possible environmental effects of bio-based products to assist the growth of the bioeconomy (Weiss et al., 2012).

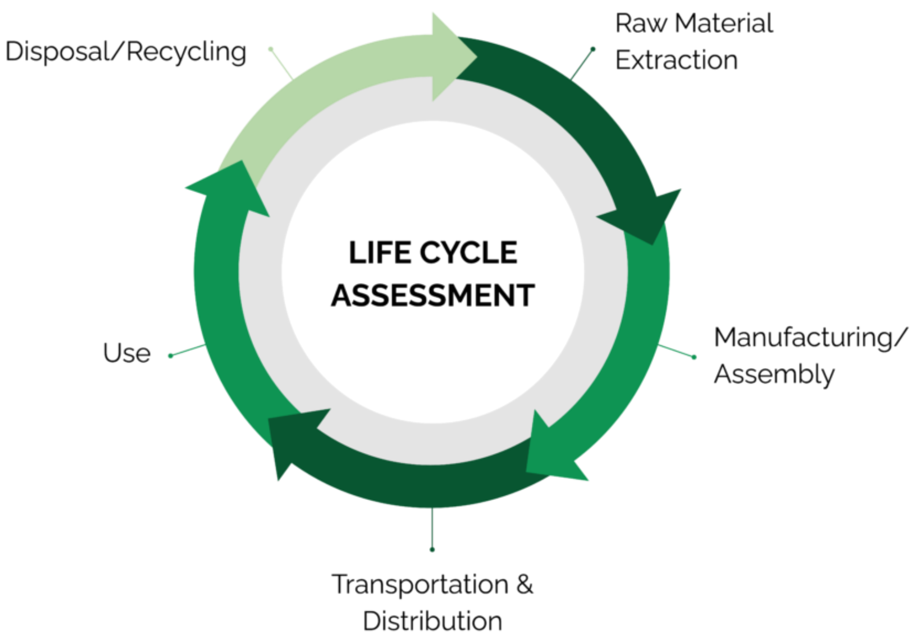


Figure 2. 5 Scope of analysis of life cycle assessments: from raw material extraction to end of life.

The framework of LCA was designed to Organization (ISO) with reference to the ISO Standard 14040 with four distinct methodological steps, namely, (a) goal and scope definition, (b) inventory analysis, (c) impact assessment, and (d) interpretation (ISO Standard 14040; (Brusseau 2019).

Life cycle of bio-based materials

The claimed advantages of utilizing renewable resources in comparison to non-renewable materials are supported by strong evidence when the complete life cycle of materials is considered. The life cycle of renewable materials can achieve closed-loop systems, resulting in the closure of both biological and technical metabolism. (Fig. 2.6)

The life cycle assessment (LCA) is an objective assessment of the environmental effects of materials and products across their entire life cycle, including their use, disposal, and potential reuse. This method has been created to assess and measure the environmental impact linked to the manufacturing, utilization, and disposal of a product (Hill 2011). Moreover, the Life Cycle Assessment (LCA) allows for the evaluation and comparison of the ecological consequences of various products (Sandak, 2019).

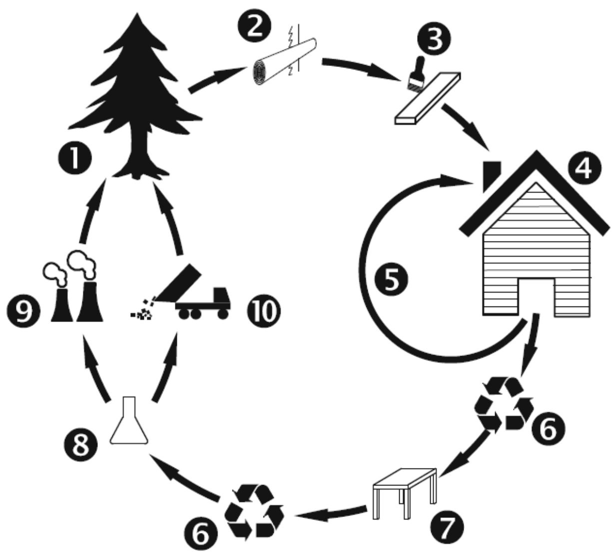


Figure 2. 6 The life cycle of the renewable materials

(1) harvesting, (2) primary processing, (3) secondary processing ,(4) use phase ,(5) reuse, (6) recycling ,(7) second use phase, (8) cascading to tertiary use, (9) energy generation , (10) landfilling , closing the biological technical metabolism

LCA Methodology

The most common methodologies to classify, characterize, and normalize environmental effects are focused on the following environmental impact indicators: acidification, eutrophication, , thinning of the ozone layer, various types of ecotoxicity, air contaminants, resource usage and greenhouse gas emissions.

The LCA analysis is performed by establishing the objective and scope of the analysis, which includes the system boundaries and the functional unit. The system boundary for comparing materials is defined as "cradle to gate," which means the comparison is limited to the materials' life cycle until they are put in a structure. This analysis assesses the environmental impacts starting from the production of a specific product in a factory until its departure from the facility. This refers to modules A1-A3 as defined in the European Standard EN 15804 (2012).

Life Cycle Assessment (LCA) accuracy is enhanced during this phase of the product life cycle since it needs few assumptions and straightforward data collection. A product with negligible environmental impact, as assessed by a full analysis from production to delivery, may require extensive maintenance during use or have a major environmental impact when it is retired. The full life cycle must be considered to fully understand and realize product selection's impact on the environment (Fig. 2.7). (Sandak 2019).

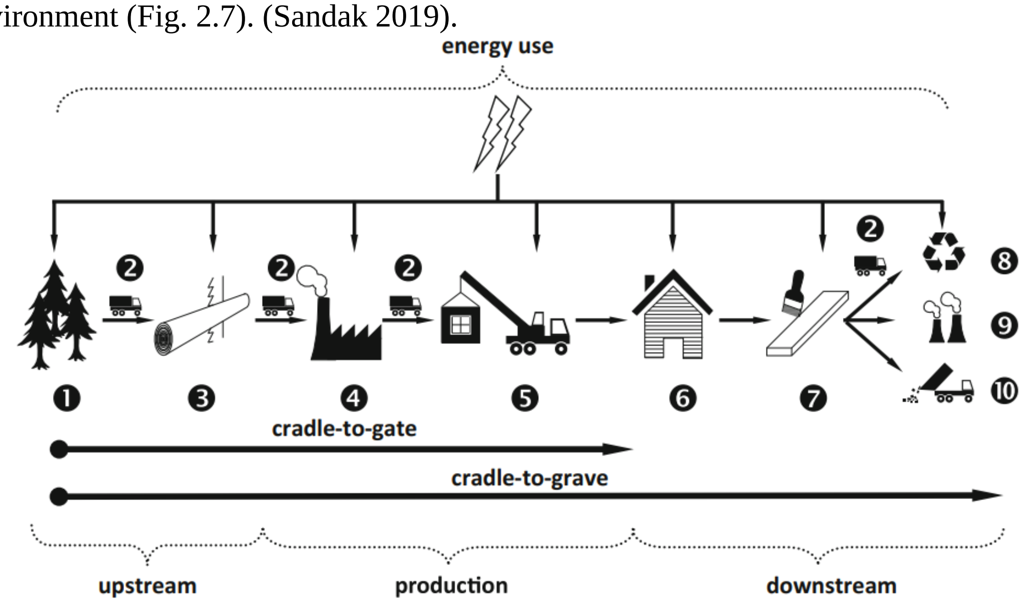


Figure 2. 7 Cradle to gate and cradle to grave concept as the LCA system boundaries

(1) harvest of raw material ,(2) transport,(3) primary processing ,(4) secondary processing ,(5) construction/assembling ,(6) use phase , (7) maintenance , (8) recycling/reuse, (9) energy generation .(10) landfill

2.3.2 Carbon Footprint

As per the 2021 Global Status Report for Buildings and Construction, the constructed surroundings account for 37 percent of the carbon dioxide (CO_2) present in the Earth's atmosphere. This proportion can be disaggregated into the many sectors within the field. Carbon dioxide (CO_2) is released during every phase of a building's lifespan. The construction process of a building releases carbon dioxide (CO_2) into the atmosphere, which includes the emissions from material production, transportation, and actual construction activities. Even when the construction is over, the structure continues to release CO_2 during its operation.(Hamilton et al. 2021). To reduce excessive CO_2 emissions, it is important to give priority to sustainability in the design process for both reconstructions and new building projects. The World Green Building Council is dedicated to enhancing the building and construction industry through its Whole Life Carbon Vision. This vision outlines the objectives that need to be achieved by the years 2030 and 2050. By the year 2030, it will be mandatory for all newly constructed buildings to have a net zero operational carbon footprint. Additionally, infrastructure and renovations must achieve a minimum of 40 percent reduction in embodied carbon, with a strong focus on reducing carbon emissions at the initial stages. By the year 2050, all newly constructed buildings, infrastructure, and renovations will have a carbon footprint of zero in terms of the materials used, while both new and existing buildings and renovations must have zero carbon emissions in terms of their operational activities (World Green Building Council, 2024).

When discussing the carbon footprint of bio-based materials, it's essential to highlight their integral role in the Earth's carbon cycle, where they interact with and influence carbon storage and release processes. These materials, derived from living organisms, absorb CO_2 from the atmosphere through photosynthesis, thereby contributing to carbon sequestration. Through photosynthesis, plants convert CO_2 into sugars to build roots, stems, and leaves, allowing bio-based materials to act as carbon sinks by storing carbon that would otherwise contribute to atmospheric CO_2 levels. By including bio-based content in products, specifically renewable plant-based materials, we can keep previously absorbed carbon from re-entering the atmosphere. And by doing so, we also significantly reduce the carbon footprint of those products since carbon footprint is measured as the greenhouse gas (GHG) emissions, like carbon dioxide, that are emitted into the air to make a product (Fifth Assessment Report — IPCC, n.d.).

2.4 Limitations of Bio-Based Materials in Construction

Bio-based materials are considered less safe than steel and masonry due to their combustibility. Their combustibility imposes limitations on their utilization as a construction material, mostly due to building laws in most countries, particularly in the case of taller and larger structures (Sandak, 2019). Exploring the domain of bio-based materials in building reveals a range of issues and constraints that require attention:

1. Limited availability: Bio-based materials could have limited availability relative to traditional construction materials, particularly in specific geographical areas. Possible causes for this phenomenon include constraints in production capacity, poor facilities for getting and using bio-based products, and limited supply chains (Keena et al., 2022).

2. Building codes and regulations: Presently, building standards and regulations often place limitations on the utilization of bio-based materials in the construction industry. The purpose of these codes and regulations is to guarantee safety and performance requirements. However, they may not always consider the distinctive qualities and characteristics of bio-based products. The existing norms and regulations may lack recognition or sufficient consideration of the performance characteristics and fire safety standards related to bio-based materials(Jones, 2017).

3.Lack of standardization and testing: Bio-based materials currently lack defined testing techniques and performance requirements (Bardage, 2017).Designers and builders may have challenges in evaluating the quality and performance of bio-based materials, as well as in making comparisons with conventional alternatives(Jones, 2017).

4. Uncertainty in long-term durability: There is currently limited knowledge regarding the extended durability and effectiveness of bio-based materials under different environmental conditions. The absence of predictability and assurance regarding the durability of bio-based

materials might provide a challenge for construction professionals when it comes to carefully choosing and using these materials.

5. fire resistance and degradability : Because bio-based materials are naturally less fire resistant, they require specific coatings and fire-resistant chemicals. Furthermore, because of the way they are built, they degrade more quickly, requiring replacement more frequently.

CHAPTER 03: INNOVATIVE BIO-BASED MATERIALS

3.1 What is innovation in construction ?

Innovation is change and being transparent to improve products, processes, and services. Whether it´s from incorporating new ideas into already established systems, or completely transforming how something is done, innovation is the key to solving the challenges many companies are faced with today. Innovation in construction refers to the introduction of new methods, materials, technologies, or processes that significantly improve building practices. It encompasses advancements that enhance efficiency, sustainability, and cost-effectiveness, as well as the adoption of digital technologies like Building Information Modeling (BIM), modular construction, 3D printing, and smart building solutions. Innovations also include the use of sustainable and eco-friendly materials, efficient construction techniques, and involves the continuous evolution and improvement of processes and practices to meet the demands of a rapidly changing world.

Bio-based building materials are a significant innovation in the construction industry, providing a sustainable substitute for traditional building materials. Products such as bamboo, hempcrete, and mycelium composites are made from renewable biological resources. By lowering carbon footprints and improving energy efficiency, their usage in construction not only promotes environmental sustainability but also creates new opportunities for architectural design and building techniques. The use of bio-based materials is in step with the worldwide increase of more environmentally friendly and sustainably constructed structures.

3.2 Innovative bio-based materials 2023

Sugarecrete

Sugarcete the aim of the sugarcrete project of the university of east London (UEL) is to develop ultra-low carbon building components using sugarcane bio-waste, allowing the storage of biogenic carbon from fast-growing plants in construction materials as an effective strategy to delay carbon emissions.

CornWall: from corn to wall

Stone cycling and circular matters developed a joint product-Cornwall to accelerate the spread of biobased building materials. Cornwall is a wall finishing materials crafted from plants-based biomass.it is sourced primarily from the cores of regional (Western Europe) corn cobs

Wood foam

LIGNEW wood foam is suitable as a core materials for new hybrid materials, for ecological lightweight – construction applications. Construction work for a production plant in Germany will commence shortly.

Algae- Dutch design week

German designer Lena vogel investigates new methods for growing microalgae.3D printing clay creates a special surface on which the algae can attach and grow. A columnar, an object has been created with which algae cultivation can be integrated into different spaces and environment without major, invasive interventions.

Mycosonic panel – Dutch deign week 2023

It a sound absorbing acoustic panel By combining biodegradable industrial waste materials like sawdust and natural sheep wool with fungi an effective noise reducing composite was created

Seawood materials

Is a series of fiberboards made from brown seaweed, developed by Rotterdam based company blue blocks. Seaweed is 100 present natural and compostable materials that can be used as building materials for interior and acoustic wall

Building on mycelium

the biobased building professorship of CoEBBE, investigated how mycelium bio-composite can be used for the construction sector

3.3 Mycelium

3.3.1 Introduction to Mycelium

Mycelium is the vegetative part of a fungus and can be found underground or on the surface. It occurs along the life cycle of fungi. The life cycle begins when a fruiting body, or mushroom, releases spores around it. If proper moisture and nutritional needs are met, these spores germinate and grow into hyphae and combine to form mycelium. The mycelium can eventually form a hyphal knot which grows into primordium, or pinhead. Finally, the pinhead will grow into a mushroom. After the mushroom has matured, the cycle repeats itself. The length of this process may vary depending on the species (Rachel Zoller,2015).

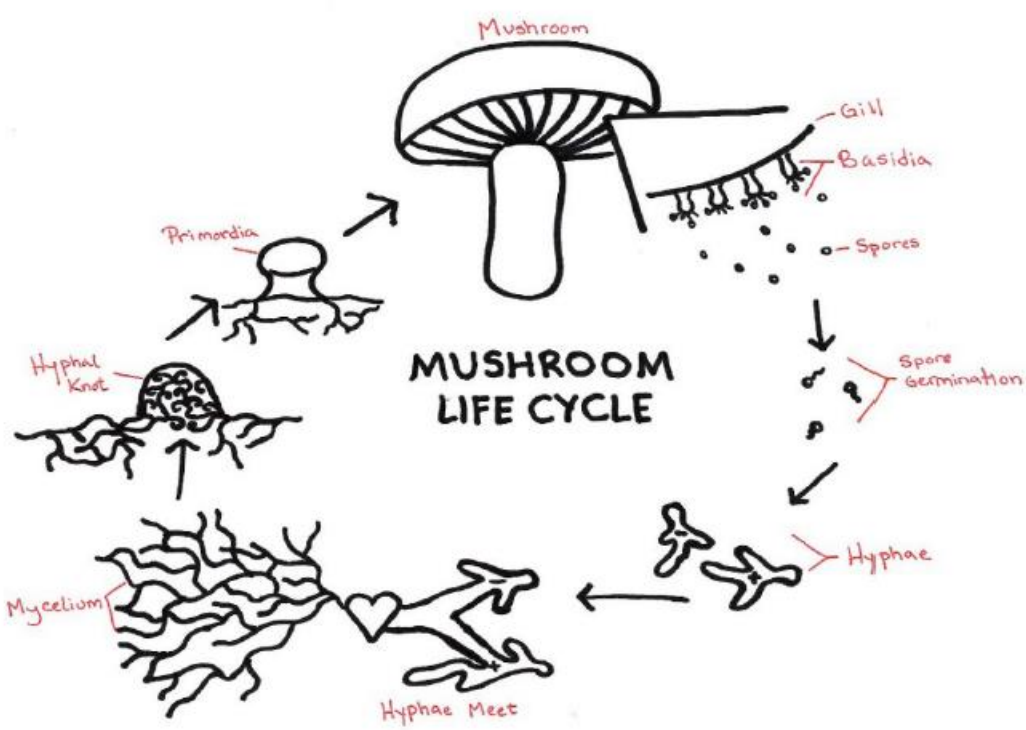


Figure 3. 1 Mushroom Life Cycle

Fungi are classified as microorganisms with several distinctions. Fungi are characterized by being unable to perform photosynthesis due to the absence of chlorophyll, which means they do not depend on sunlight to produce food. (sharp.1978). This material is a naturally occurring glue that can bind together both organic and synthetic byproducts through self-assembly. Mycelium can break down cellulose found in waste materials and convert it into chitin, which is the same substance that makes up the hard outer layer of insect shells (Haneef, et al., 2017). As the organism expands, it extends its branches, resulting in the development of hyphae that connect and bind the material together, forming a solid mass.

When used in architecture, this material possesses a range of characteristics. Mycelium has been transformed into bricks and insulating blocks. The main advantage of this material in construction is its capacity to provide insulation against sound, vibration, and heat loss. Additionally, it can support various compressive loads and can be easily molded into many shapes and forms. The utilization of a completely natural procedure and substance allows for the embodied energy of this construction material is precisely equal at zero, as described in Scientific American (2019). Applying biomimicry in buildings offers significant benefits in waste management. Later, we shall observe that certain materials that utilize waste as their raw materials have determined that mycelium offers the most extensive range of applications in the field of construction.

3.3.2 Growth Process Analysis

Condition of growth

The environment is characterized by darkness, low temperature, high moisture, and humidity. The temperature is maintained at an average of 21° C. The humidity and temperature are carefully controlled within a range of 24 to 30 ° C.-Limited access to sunlight-Organic or artificial waste. The mycelium's development duration varies from a few days to several weeks, contingent upon the species and the supplied conditions.

Composting and pasteurization

Compost is used initially in the cultivation process to establish a fertile medium for the mycelium to occupy. To facilitate aerobic fermentation, it is necessary to include a mixture of moisture, oxygen, nitrogen, carbohydrates, and gypsum into the straw and manure blend. An uninterrupted airflow is crucial to ensure the delivery of inputs and the removal of outputs from the materials.

Spawning

After the mycelium spores become embedded in the substrate, they start growth in several directions, adopting a structure like thin, microscopic hyphae, like the root system, while absorbing resources during their development.

Mycelium

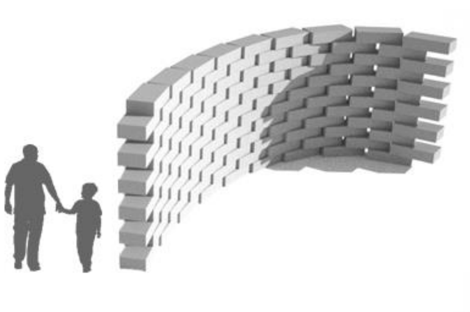
When the hyphae has eaten all its substrate, it slows down its growth to get ready for the next step. After the mycelium has grown, the new material is heated to kill the mushrooms and leave a stable, organic base for growth. At this point, mycelium is most useful for building because the materials can be used instead of ones that are bad for the environment.

Mushroom

If the mycelium is not heated at the previous stage , the micro- organism continue to develop, eventually sprouting mushrooms. Once the mushrooms have grown large enough for commercial sale , they are harvested from the mycelium. Mushrooms can continue to sprout mushroom for several harvest before the yield begin to drop off.

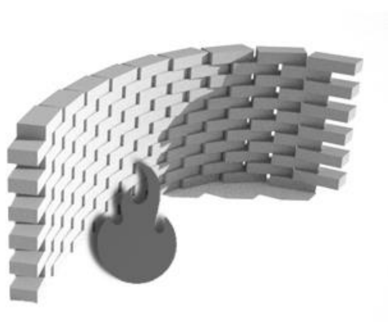
3.3.3 Materials Properties

Organic material



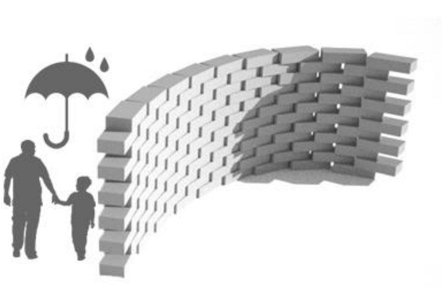
The advantages of using mycelium as a construction material relate to the interaction between humans and the constructed environment. Extended exposure to structures with insufficient indoor air quality can have serious effects on the well-being of occupants. Therefore, architects must consider the use of organic and naturally occurring materials, as they promote better health for the users. Mycelium does not contain any volatile organic compounds that can contribute to health problems.

Class A fire rating



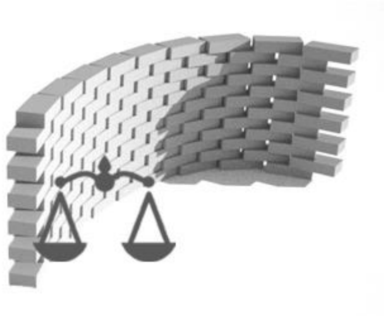
The fire resistance of mycelium-based materials, especially when they achieve a Class A grade, which represents the maximum level of fire protection, increases their appeal as construction materials. This classification shows that mycelium-based products do not possess enzymatic properties, thus preventing the fire from spreading.

Water resistance



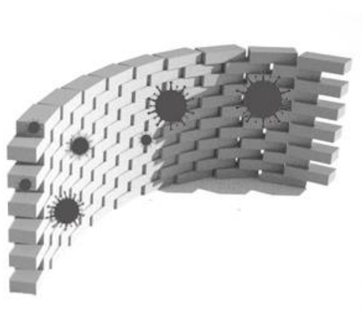
The water-resistant properties of mycelium make it suitable for both internal and exterior applications. While it possesses insulating properties, its water resistance reduces with time. If in contact with the ground, it will develop mold within a few months and gradually degrade over time. This is advantageous because when the material is disposed of it will release its nutrients back into the surrounding ecology.

Variable Strength



Mycelium functions as an adhesive, binding together the various substances it absorbs. Hence, the potency of the mycelium brick can be modified based on the substrate it is mixed with. Sawdust, straw, and inorganic components like aluminum cans possess diverse qualities that can impact the strength of the mycelium brick. Hence, many materials can get the required strength necessary for their intended use. Also, mycelium can be cultivated into any desired form or dimension, enhancing its versatility and attractiveness to designers. It currently possesses a rating of 30 psi, whereas concrete exhibits a compression strength of 4000 psi. When comparing the strength of mycelium with concrete based on weight, mycelium is significantly more robust (Bonnefin, 2018).

Mold Resistance



Mycelium can support the growth of mold. Like its water resistance, it will not develop mold under ideal conditions. Still, like other substances, if the criteria aren't stuck with greatest precision, the material will not function at its maximum capacity and will begin to degrade. degrading in terms of its structural integrity and resistance to mold. This degradation not only impacts the performance of the material but also facilitates the growth of mold, which presents health risks and compromises the structural integrity of the building.

3.3.4 Material Hybridization

The use of Mycelium in material hybridization within the construction sector signifies a novel strategy that combines the different features of mycelium with traditional and contemporary building materials. The objective of this hybridization is to develop construction materials that are both sustainable and eco-friendly, while still being highly efficient. This will help to minimize the negative effects on the environment and has the potential to revolutionize current building methods.

Process of Material Hybridization

The process of hybridizing materials by mycelium commences with its cultivation. This procedure entails cultivating the mycelium on organic substrates, typically consisting of sawdust or diverse types of agricultural waste. This substrate not only facilitates the growth of the mycelium but also enhances its overall structural characteristics. Once the mycelium has sufficiently grown and colonized the substrate, the next step involves combining it with other complementary materials. These materials, which can vary based on the desired properties of the final product, often include hemp, bamboo, or recycled wood fibers. The choice of these materials is critical as they play a significant role in enhancing the structural integrity and durability of the resulting composite. After the mycelium has been integrated with these additional materials, the hybrid composite is then ready to be molded. This molding process is adaptable, allowing for the creation of a diverse range of shapes and forms suited to different applications. The use of mycelium-based materials has the advantage of versatility in shaping. After the molding stage, the composite is subjected to a curing procedure. This stage is essential since it entails the process of removing moisture and hardening the material, thereby establishing its ultimate shape and durability. The process of curing enhances the stability of the composite, rendering it appropriate for practical applications. The outcome is a substance that not only includes the distinctive characteristics of mycelium but also gains advantages from the enhanced durability and toughness provided by the other components integrated into the hybrid. The outcome of this method yields a durable, effective, and potentially groundbreaking substance that is perfect for a range of uses, especially within the construction sector.

Applications in Construction

Mycelium-based materials are gaining a specialized position in the building industry, mostly because of their environmentally friendly nature and adaptability. Insulation panels are a significant application of these materials. These panels made from mycelium have shown significant effectiveness in providing insulation for both temperature and sound, making them a widely favored option in green building initiatives. Their natural insulating characteristics not only promote energy efficiency but also augment the comfort of indoor spaces.

In addition to insulation, there is a rising interest in extending the application of mycelium to more structural functions in the field of construction. Current research is mostly aimed at improving the load-bearing capacity of mycelium. Mycelium has the potential to be utilized in diverse structural components by enhancing its structural strength and resilience. This advancement has the potential to completely transform the process of constructing structures by providing a sustainable substitute for traditionalbuilding materials. Mycelium composites are

increasingly being utilized in the fields of interior design and furniture manufacturing. The utilization of these composite materials for the creation of eco-friendly furniture and interior fixtures is a promising and innovative domain. These uses not only enhance the visual appeal of a space but also align with objectives related to environmental sustainability. Mycelium composite furniture and fixtures possess durability, biodegradability, and the ability to be customized to suit diverse tastes and preferences.

3.4 Case studies of Mycelium in construction

VENICE ARCHITECTURE BIENNALE: IN VIVO AT THE BELGIAN PAVILION(2023)

Designer : Bento & Vinciane Despret with the collaboration of Corentin Mahieu

Concept : the installation focus on exploring the intersection of biology, ecology, and architecture through the innovative use of mycelium as a sustainable building material. the designer use natural, living materials, experimenting with the installation of panels of mycelium in a spectacular wooden structure (12m long x 6m wide x 6m high) and resting on a floor of raw earth from excavated soil. This provides an opportunity for visitors to experience the sensory, tactile, acoustic, and poetic characteristics of mycelium and the structure has been designed to be specifically dismantled. The curators used mycelium, wood and earth stemming from the urban area of Brussels with a view to an ultra-local, sustainable supply. Referring to the circular economy and sustainable principles, the structure has been designed to be specifically dismantled. (*Belgian Pavilion | in Vivo*, n.d.)

Figure 3. 2 In vivo strecture by Ugo Carmeni

Environmental impact :

- Reduction in Carbon Footprint: Using mycelium directly contributes to a reduction in carbon emissions typically associated with the production and transportation of traditional building materials. Mycelium grows quickly, requires minimal energy and resources to cultivate, and can be grown locally, reducing transportation needs. This local sourcing strategy, as applied by the project, further minimizes carbon emissions related to logistics.
- Sustainable Resource Use : Mycelium represents a shift towards more sustainable resource use in construction. It is renewable, biodegradable, and can be cultivated on agricultural waste, thereby not only reducing waste but also repurposing it into valuable construction material. This aligns with the principles of a circular economy by creating a loop where materials are reused and recycled, reducing the need for virgin resource extraction, and minimizing waste.
- Energy Efficiency and Insulation: Mycelium-based materials have shown promising properties in terms of insulation and energy efficiency. This means buildings constructed with mycelium panels may require less energy for heating and cooling, further reducing the environmental footprint of the structures over their lifetime.
- Water Use and Pollution : The cultivation of mycelium for construction materials typically requires less water compared to traditional construction materials like concrete and steel. Additionally, the natural materials used are less likely to contribute to pollution during their lifecycle, from production to disposal, compared to synthetic materials.
- Promotion of Green Urban Spaces :By showcasing the potential for mycelium in urban areas, like Brussels, the project also advocates for greener, more sustainable urban development. Integrating living materials into urban architecture can improve air quality, reduce urban heat island effects, and enhance the overall quality of life for city dwellers.

In Conclusion The "In Vivo" case study showcases the potential of mycelium as a sustainable hybrid construction material, significantly reducing the environmental impact of building. It tackles key issues like carbon emissions, resource depletion, and pollution, pointing towards a sustainable architectural future. This project highlights the use of local resources and the circular economy, promoting a shift towards more sustainable building practices.

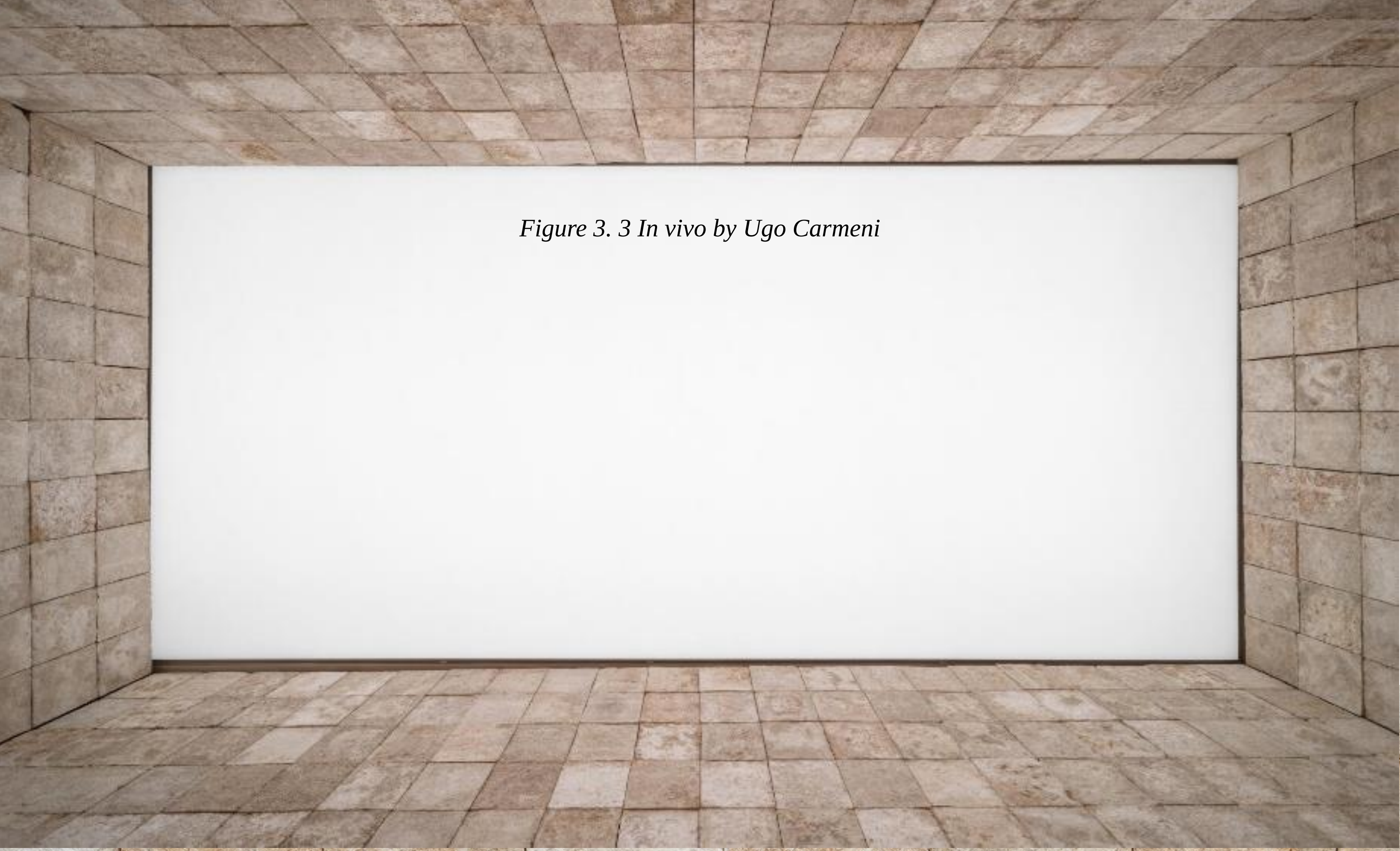


Figure 3. 3 In vivo by Ugo Carmeni

Figure 3. 4 In Vivo: Experimenting with mycelium and raw earth by Ugo Carmeni

MYCO-TEMPLE (2021)

Designer : Côme Di Meglio

Concept : Spirituality and sustainable innovation converge in Côme Di Meglio's transformative living sanctuary MycoTemple. This five-meter-wide domed structure harnesses the power of mycelium to grow temples, sheltering a space for physical and spiritual transformation. While the organism forms the structure's primary construction material, a hand-carved wooden structure is hidden within, revealed only as the mycelium gradually biodegrades over time and returns to fertilize the soil from which it came. (Di Megli, 2023)

Environmental impact :

- Sustainable Material Use: Mycelium is used as the primary construction material for the dome structure. Mycelium is a fungal network that can grow and form structures, making it a sustainable and renewable resource. It is also biodegradable, which means it will naturally break down over time without leaving a lasting environmental footprint.

Figure 3. 5 MycoTemple in a pine grove facing the Mediterranean by Gian-Battista

- Low-Tech and Low-Impact Production: The project emphasizes a low-tech approach to mycelium cultivation, which typically requires fewer resources and energy compared to traditional construction methods. The use of repurposed industrial waste, particularly sawdust, as a substrate for mycelium growth reduces waste and repurposes materials that might otherwise be discarded.
- Localized Production: The entire mycelium cultivation process, from inception to completion, took place in the artist's studio in Marseille. This localized production reduces the need for transportation and associated emissions, contributing to a lower carbon footprint.
- Biodegradable Structure: One of the most significant environmental benefits of this project is that the mycelium-based structure is designed to biodegrade over time. As the mycelium gradually breaks down, it returns nutrients to the soil, demonstrating a closed-loop and regenerative approach to architecture.
- Promoting Sustainable Innovation: Myco-Temple represents an innovative approach to sustainable architecture and material use. By showcasing the potential of mycelium and biodegradable structures, it encourages further exploration and adoption of eco-friendly materials and construction techniques within the design and construction industries.
- Spiritual Connection to Nature: The project's concept of spirituality and its connection to the natural world aligns with an environmental consciousness. It fosters a sense of reverence for nature and highlights the importance of sustainable practices in design and construction.

While the Myco-Temple project presents several positive environmental aspects, it's essential to consider the long-term durability and functionality of mycelium-based structures, the project exemplifies a commitment to sustainable and eco-friendly design principles, offering a creative and thought-provoking exploration of the intersection between architecture, spirituality, and environmental responsibility

Figure 3. 6 Assembly process | still image from movie © Alexandre Zimmermann

Figure 3. 7 Five-meter-wide domed structure harnesses the power of mycelium to grow temples by Gian-Battista

MYX SAIL / FLOOR (2023)

"My inspiration comes from observing the mushroom's natural role as a recycling agent, breaking down plant matter into soil." Jonas Edvard

Designer: Jonas Edvard

Concept: The project presents an architectural concept that is deeply rooted in sustainability, material innovation, and environmental sensitivity. It showcases how design can lead the way in reducing the ecological footprint of the built environment, fostering a closer connection between human habitats and the natural world.it is a sound-absorbing panels allows for flexibility in architectural and interior applications, ranging from office partitions to residential room dividers. The inherent properties of mycelium, combined with hemp and willow, provide a unique blend of rigidity and flexibility, enabling the creation of structures that are both functional and visually appealing. (*Jonas Edvard Crafts Sound-absorbing Panel From Mushroom Mycelium, Hemp, and Willow*, 2024)

Figure 3. 8 MYX SAIL sound-absorbing screen

Environmental impact :

- Sustainable Material Use: The project employs mushroom mycelium, hemp, and willow, all of which are renewable, biodegradable, and have a low environmental impact compared to traditional building materials. This choice promotes the use of materials that contribute to carbon sequestration, are readily available, and require minimal processing.
- Carbon Footprint Reduction: By harnessing the natural properties of mycelium and plant fibers, the project minimizes energy consumption throughout the production process. Mycelium grows in a pre-designed mold without the need for high energy inputs, leading to a significantly lower carbon footprint compared to the manufacturing of traditional acoustic panels.
- Waste Reduction: Mycelium acts as a natural recycling agent, transforming agricultural byproducts into valuable construction materials. This process exemplifies a circular economy, where waste is minimized, and materials are reused, reducing the overall waste generated by the building industry.
- -Improved Indoor Environment: Beyond its sound-absorbing qualities, the use of natural materials contributes to healthier indoor air quality. Synthetic materials often emit volatile organic compounds (VOCs), whereas mycelium-based products do not, thereby enhancing the environmental quality of interior spaces.

Figure 3. 9 MYX SAIL

Three different construction projects that use mycelium as a principal material are compared in Table (3.1). While showcasing mycelium's potential in sustainable construction, each case study additionally highlights some of its limitations.

Name of the project	Materials used (Virgin Mycelium / composite mycelium)	Type of Construction	Positive points	Negative points
IN VIVO at the Belgian Pavilion (2023)	Composite Mycelium	Exhibition/Conceptual	great compressive strength, biodegradable, improved moisture resistance and reducing waste	not be on long-term structural capabilities, Potential limitations in availability and scalability for larger constructions
MYCO-TEMPLE (2021)	Virgin Mycelium	Temporary Structure	Low production costs- Sustainable materials	Lower compressive strength, limiting structural applications, High sensitivity to water damage, affecting durability
MYX Project (SAIL / FLOOR, 2023)	Composite Mycelium	Experimental	Light weight, higher resistance to moisture and it is good sound absorption Enhanced Indoor Air Quality	As an indoor structure, specific negative impacts are not highlighted

Table 3. 1 Comparison between the case studies (elaborated by author)

There are several interesting case studies that highlight the unique relationship between material science and architectural design that can be discovered in the developing topic of mycelium-based construction. We analyze the features and results of three different projects using a comparison perspective to determine greater implications and possibilities of mycelium in the building industry.

An inspiring example of the creative uses of composite mycelium is the IN VIVO exhibit in the Belgian Pavilion (2023). Given this material's exceptional compressive strength, it looks encouraging that organic matter could eventually be manufactured to meet or even better traditional building materials. Furthermore, the present drive for environmentally friendly and sustainable design is aligned with its biodegradability. Concerns about the material's long-term structural abilities and the scalability of mycelium growing, however, become apparent as we move closer to the reality of permanent buildings. An example of sustainability in temporary architectural applications is the MYCO-TEMPLE (2021). The industry's goal of reduced production costs while keeping sustainability is highlighted using virgin mycelium. However, the decreased compressive strength and sensitivity to moisture provide an issue. Although the material is attractive from a sustainability and economic point of view, its application is limited due to limitations in its durability and structure. These limitations highlight the need for creating composites or treatments that could strengthen the material's durability without losing its environmental advantages. In the last case study The MYX Project (SAIL / FLOOR, 2023) lies at an intersection of practical application and experimental design. The project is innovative because of its lightweight structure and use of sound absorption to improve interior air quality—features that are highly valued in architectural design.

In conclusion, each case highlights various applications of mycelium, ranging from structural to experiential. Several advantages are provided by the MYX Project's achieved acoustic benefits, virgin mycelium's economic and environmental efficiency, and composite mycelium's compressive strength. On the other hand, challenges including the durability of structural integrity, water sensitivity, and the requirement for comprehensive impact assessments still need to be resolved. The combination of these case studies not only highlights the creative application of mycelium in building, but it also advances discussion about how to improve this biomaterial for sustainable development in the built environment.

CHAPTER 04: HYBRID MATERIALS

4.1 Hybrid Materials

4.1.1 Definitions of Hybrid

In simple terms, the concept of hybrid can be characterized as an combination of diverse elements, resulting in improved features compared to the individual components. This term resembles the dictionary definition of a composite, which refers to something that is constructed by combining multiple pieces or elements. The intended advantage of hybrid concepts is the ability to customize the qualities of the final product to achieve synergistic effects (Falk, A., 201).

Throughout history, there have been instances where projects were completed, and goods were created that can be classified as hybrids based on the previous definitions. However, hybridization can be identified at various levels. On a micro scale, this may be seen through the composition of materials, where particles, fibers, and chips are transformed into novel products or combined with other elements like cement, concrete, or plastics. Product scale involves the utilization of components that consist of a single material in various shapes or states. For example, an I-beam may have flanges made of structural lumber and a web made of fiberboard. Additionally, multiple materials may be combined in these components. Macro-scale hybrids refer to systems that involve the combination of several building goods, structural elements, components, or structural systems working together. From a process standpoint, the term "hybrid" can be used to describe situations when construction processes utilize several systems and prefabrication logics in combination (Falk & Wålinder, 2015).

A hybrid material can be defined as a substance that consists of two distinct components mixed at the molecular level. Typically, one of these substances is of inorganic origin while the other is organic. A more elaborate description differentiates the potential interactions that connect the inorganic and organic species. Class I hybrid materials are characterized by the presence of weak interactions between the two phases, such as van der Waals forces, hydrogen bonding, or weak electrostatic interactions. Class II hybrid materials exhibit significant chemical bonding between their components. It is evident that there is a gradual shift between weak and strong contacts due to the progressive change in the strength of chemical interactions (Kickelbick, 2007).

Hybrid materials are materials that possess the combined properties of two or more monolithic materials, or of one material and empty space. The materials include fiber and particle composites, foams and lattices, sandwiches, as well as nearly all natural materials. (Ashby, Bréchet ,2003) propose the consideration of two more dimensions: shape and scale. A hybrid material is a composite formed by combining two or more materials in a certain geometry and scale to best serve a particular technical function (Kromm et al., 2002)
Hybrid materials are nanocomposites consisting of at least one element, either organic or inorganic, with a distinct length at the nano scale. (Judeinstein and Sanchez, 1996).

My own definition : The definition of a hybrid material lacks a universally agreed-upon construct, but generally refers to a composite structure combining different elements. These elements synergize to enhance the final product's properties, with applications ranging from micro to macro scales. Examples include material compositions, chemical interactions at the molecular level, and combinations of building products or structural elements. Hybrid materials aim for improved performance and functionality by strategically blending diverse components, reflecting an evolving and interdisciplinary field.

4.1.2 Bridging the Gap

The concept of bridging the gap involves the examination and advancement of materials that combine the qualities of both bio-based and traditional materials. Materials have a crucial role in multiple industries, such as construction, manufacturing, and packaging. Historically, materials have been obtained from fossil fuels, which are finite and have a negative impact on the environment. Nevertheless, because of the increasing acknowledgment of the necessity for sustainability and the limited accessibility of fossil fuels, there has been a transition towards the utilization of bio-based materials. The grey area between bio-based and traditional materials refers to a range of options and approaches that lie between these two categories. These options and approaches may include materials that have both bio-based and traditional components, materials that are partially bio-based but still rely on some fossil resources, we could say the approach to bridging this gap is through the development of hybrid materials that combine the best properties of bio-based and traditional materials. By combining the renewable and environmentally friendly aspects of bio-based materials with the familiarity and established performance of traditional materials, hybrid materials offer a promising solution for sustainable construction and manufacturing.

These hybrid materials can be modified to lessen their negative effects on the environment while still meeting certain performance standards including strength, durability, and thermal qualities. Bridging the gap between bio-based and traditional materials also requires the incorporation of bio-based materials into current supply chains and construction techniques. or bio-based materials that go through a lot of processing that could reduce their environmental benefits.

It is necessary to carefully assess these materials' environmental impact and sustainability in this gray area. It is important to give considerable thought to the complicated and complex gray area that exists between bio-based and traditional materials. In this gray region, it's critical to weigh the trade-offs and potential effects of the materials. A substance might, for instance, be partially bio-based, which means it has both non-renewable and renewable components. Comparing this to traditional materials might have some environmental benefits, but there might be limits to how sustainable it is overall. Additionally, there can be production-related factors to consider, like waste creation and energy consumption, in the gray area between bio-based and traditional materials.

Since these options and approaches may have varying degrees of sustainability and environmental impact, it is vital to choose materials that are truly sustainable and have little environmental impact throughout the course of their existence. Paleari (2024).

Hybrid materials can be thought of as a "nuance of grey" that exists between traditional and bio-based materials. This viewpoint emphasizes how hybrid materials can combine the greatest aspects of both worlds with their versatility and adaptability. They function as a middleman in the following ways:

- Combining Origins: Bio-based elements (such as natural fibers or biopolymers) can be combined with traditional materials (such as metals or synthetic plastics) to create hybrid composites. This combination makes it possible to create materials that combine the strength, durability, and other desired qualities of traditional materials with the renewable and environmentally benign qualities of bio-based materials.

- Environmental Impact : Hybrids have the potential to have a smaller environmental impact than pure traditional materials because they combine traditional and bio-based components. For example, adding natural fibers to plastic composites might increase their biodegradability and lessen their dependency on resources derived from petroleum.
- Performance Optimization Hybrid materials can be intentionally designed to fulfill specified performance requirements by combining the characteristics of bio-based and tradiional materials. This may entail boosting the mechanical robustness of a bio-based material by adding traditional fibers or improving the biodegradability of a traditional material through the addition of bio-based additives.
- Innovation and Sustainability: The development of hybrid materials signifies a new methodology in the field of material science, with a specific emphasis on sustainability. The statement indicates a transition towards manufacturing and developing products in a manner that is more aware of the environment. This involves combining natural and synthetic materials to minimize the ecological footprint without compromising performance.
- Application-Specific Design: Hybrid materials can provide a customized solution in situations when neither fully bio-based nor traditional materials fulfill all the necessary criteria. Hybrids can offer an ideal balance in industries like automotive or aerospace, where weight, strength, and environmental factors are of utmost importance.

As shown in (Fig.4.1) appears to be a conceptual diagram related to " Hybrid Materials". It uses a tree metaphor to categorize various properties of these materials. Each leaf represents a different property, such as thermal conductivity, electrical conductivity, thermo-sensitivity, fire retardancy, corrosion resistance, mechanical properties, and optical properties. It is used to illustrate the range of characteristics that materials engineers consider when designing and using hybrid materials. Each property can have a significant impact on the functionality and application of the material in various industries.

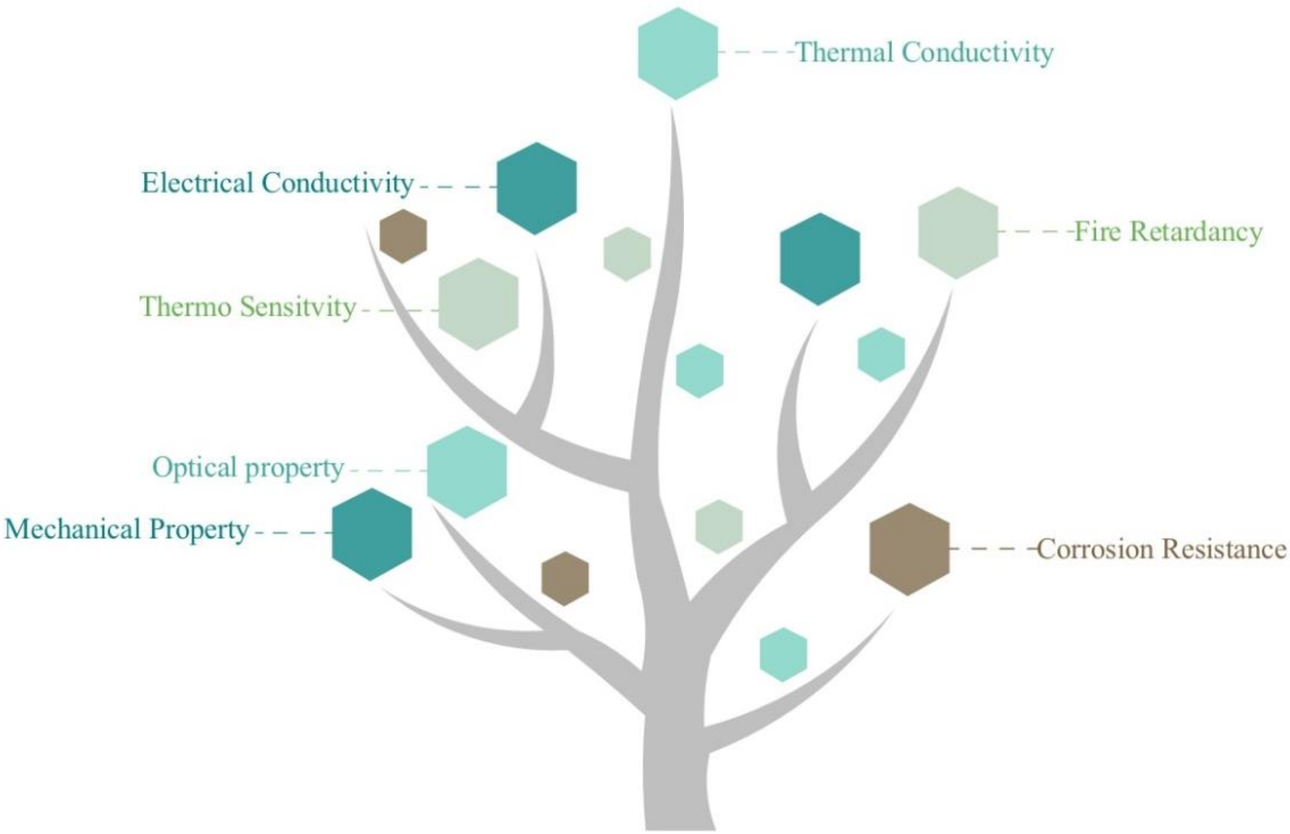


Figure 4. 1 Properties of hybrid materials

4.2 Comparative Analysis of Innovative Hybrid materials

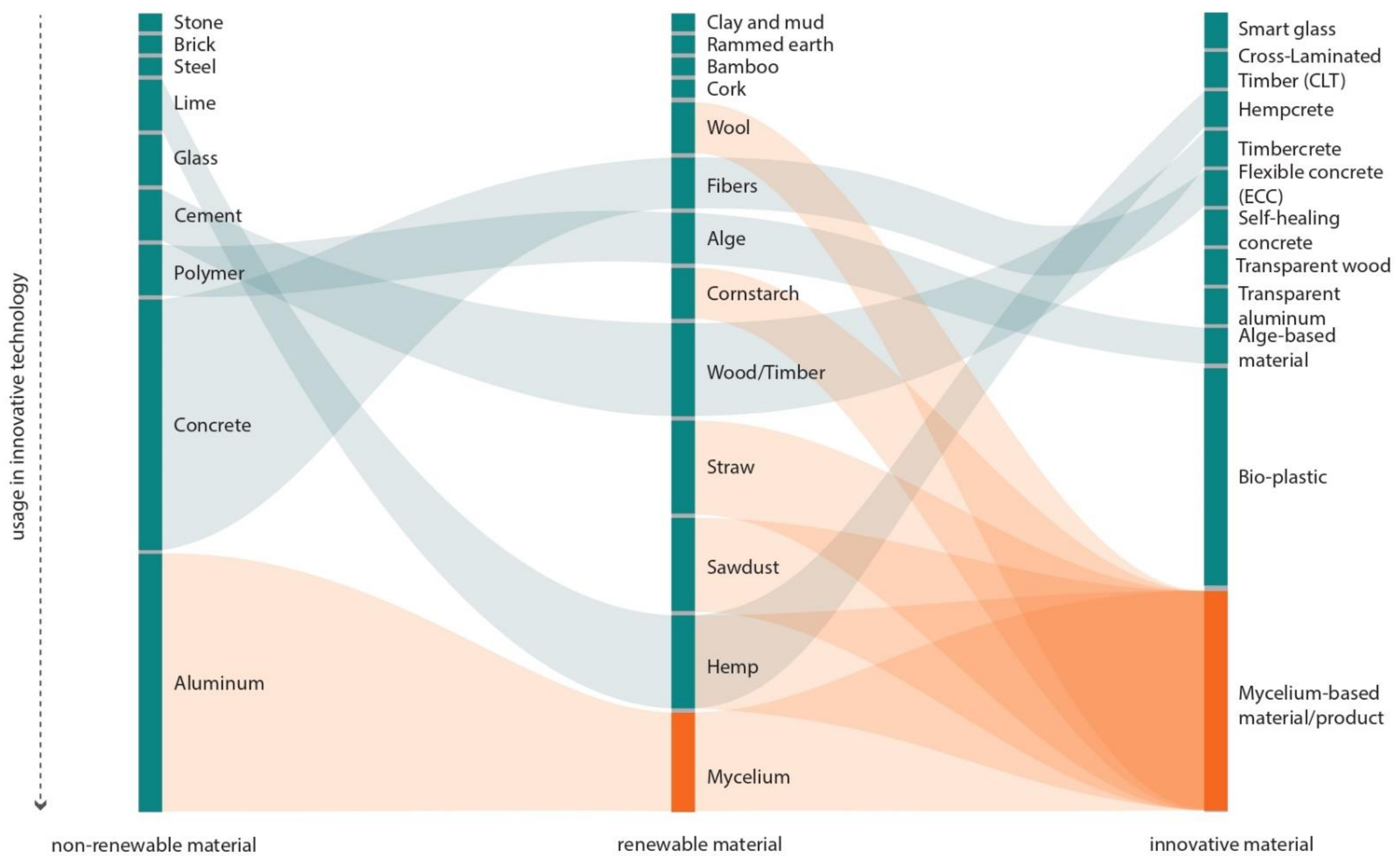


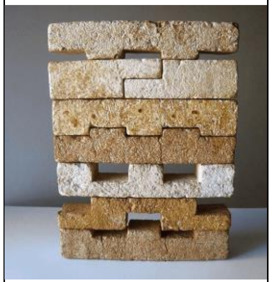
Figure 4. 2 Classification of innovative hybrid material

The scheme shown in (Fig. 4.2) provides a comprehensive list of building innovative materials categorized into non-renewable, renewable, and innovative materials. Non-renewable materials include stone, brick, steel, lime, glass, cement, polymer, and aluminum. Renewable materials encompass hemp, mycelium, clay, mud, rammed earth, bamboo, cork, wool, fibers, algae, cornstarch, wood/timber, straw, and sawdust. Innovative materials classified according to usage in innovative technologies. consist of smart glass, cross-laminated timber (CLT), hempcrete, timbercrete, flexible concrete (ECC), self-healing concrete, transparent wood, transparent aluminum, algae-based material, bioplastic, and mycelium-based material/product.

In construction technologies the Innovative materials as those that are emerging at the forefront of construction technology due to their unique properties and applications. These materials often arise from a combination of renewable and non-renewable resources. Also, it could arise from renewable materials combined together, integrating the benefits of both to address the current demands of sustainability and performance.

Mycelium-based products are highly remarkable in the scheme. Mycelium can be cultivated within molds to produce diverse structures and combinations. Once dehydrated, it transforms into a lightweight, strong, and organic insulating material. It serves as an important instance of an innovative material that combines renewable and non-renewable resources. This technique is not only ecologically benefits but also equal in mechanical qualities to typical construction materials. Furthermore, due to their organic nature, they also enhance indoor air quality and possess a smaller carbon footprint in comparison to most traditional construction materials. In the construction industry's shift towards more environmentally friendly and sustainable practices, mycelium-based materials are becoming increasingly popular due to their minimal ecological footprint and ability to be composted at the end of their lifespan. This not only reduces waste but also fosters a circular economy within the industry.

4.3 Case Studies of hybrid materials

Case studies	Uses	Type of material	Size	Manufacture /designer	Result
Mushroom bricks 	Construction bricks	Cultivated from resources (mycelium and straw waste)	Custom	Ecovative , USA	High fire resistance /insulation properties/ high Water resistance / Strength to weight ratio
Mycoform 	Construction bricks	Cultivated mushroom mycelium, paper waste and discarded aluminum	Custom	Terreform ONE,USA	High fire resistance /insulation properties/ high Water resistance/ Strength to weight ratio
Mycotecture 	Insulation bricks	Cultivated mycelium, sawdust	Custom	Philip Ross, mycoworks. USA	Fire resistance /High insulation properties/Water resistance/ Strength to weight ratio
Pulp Faction 	Architectural components	Bio fabrication and digital computation of Mycelium, woodchip, cellulose, clay, water	Custom	bio–Digital Matter, Sweden	Biodegradable do not rely on the extraction of finite resources or energy-intensive production.

Mogu floor 	Tiles	Fungal Fermentation (Mycelium and agro-industrial residues). And bio-fabrication	Custom	Mogu , Italy	Reduced energy consumption, stable, safe, durable, and biodegradable
Mogu Acoustic 	Acoustic panel	Mycelium and low-value, residual materials	Custom	Mogu , Italy	Sound absorbing , Reduced energy consumption, stable, safe, durable, and biodegradable
Bio-Fold 	Furniture	Mycelium, Agricultural waste, and bio resin	Custom	By Katya Bryskina, SPACE 10, Tomás Clavijo Made in Denmark	Sustainable furniture fabrication
MycoTree 	Installation as structural systems	3D modelling program (mycelium with food mix that includes sawdust and sugarcane)	Custom	architect Dirk Hebel and engineer Philippe Block. In Seoul Biennale of Architecture and Urbanism 2017 in Seoul, Korea	Structural column reducing both the energy and time, organic and they act to reverse carbon emissions through the absorption of carbon

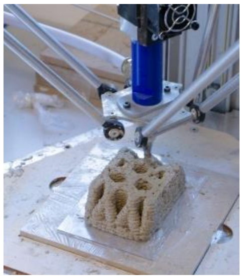
The Growing Pavilion 	Pavilion	Wood, mycelium, residual flows from the agricultural sector, bulrush (cattail), cotton	Custom	Biobased Creations in Netherland	sturdy, light weight, fire-retardant, water-repellent, acoustic top sheets
Terraforma 	Component	3D printing through Liquid Deposition Modeling from Mycelium, Clay, Sawdust, Flour, Xanthan gum, Water	Custom	Lorenzo Silvestri , Italy	preserve the material's biodegradability and the potential for reuse earlier in the production process
MycoSonic 	Installation panel	Mycelium-based, sawdust and sheep wool	Custom	By Richa Saini in Dutch Design Week 2023	Sound absorbing acoustic panel
Braunschweig state theater stage 	Theater Stage	Fungal mycelium and elephant grass fibers	Custom	Researcher from the fraunhofer WKI with the partner Protohaus GmbH	Potential for using in construction industry

Table 4. 1 Hybrid materials case studies

Table (4.1) outlines several case studies of innovative hybrid materials, including their uses, type of material, size, manufacture/designer, and results. The first case study focuses on mushroom bricks used for construction, cultivated from mycelium and straw waste, with high fire resistance, insulation properties, water resistance, and strength to weight ratio. The second case study, Mycoform, also involves construction bricks, but they are cultivated from mushroom mycelium, paper waste, and discarded aluminum, with similar properties to the mushroom bricks. The third case study, Mycotecture, features insulation bricks made from cultivated mycelium and sawdust, with fire resistance, insulation properties, water resistance, and strength to weight ratio. These materials are custom-sized and manufactured by different designers/companies, such as Ecovative, Terreform ONE, and Philip Ross.

Furthermore, the table explores additional hybrid materials such as Pulp Faction, Mogu floor, Mogu Acoustic, and Bio-Fold, which are used for architectural components, tiles, acoustic panels, and furniture. These materials are fabricated from various combinations of mycelium, woodchip, cellulose, clay, water, agricultural waste, and bio resin, with attributes like biodegradability, reduced energy consumption, stability, safety, durability, and sound absorption. also presents projects like MycoTree, The Growing Pavilion, Terraforma, and MycoSonic, which involve the installation of structural systems, pavilions, and 3D modeling programs using materials like mycelium, wood, agricultural residues, bulrush, cotton, clay, sawdust, flour, xanthan gum, and sheep wool. These projects are custom-made and designed by architects and engineers from various countries, aiming for sustainability, reduced energy consumption, and carbon absorption.

The hybrid materials mentioned in the case studies contribute to sustainability and environmental impact in several ways. Firstly, they are biodegradable and do not rely on the extraction of finite resources or energy-intensive production methods. This reduces the environmental footprint of their production and disposal. Additionally, these materials are designed to reduce energy consumption during their manufacturing process, making them more environmentally friendly. They also possess properties such as stability, safety, and durability, which contribute to their long-term use and reduce the need for frequent replacements, further reducing environmental impact.

Furthermore, the materials have attributes such as fire resistance, insulation properties, water resistance, and strength to weight ratio, making them suitable for various applications in construction and furniture fabrication. Their use in structural systems, pavilions, acoustic panels, and furniture contributes to sustainable architecture and design. Additionally, some of these materials have the potential to reverse carbon emissions through the absorption of carbon, further enhancing their environmental impact.

Overall, the hybrid materials mentioned in the case studies offer a range of sustainable and environmentally friendly properties, making them valuable contributors to sustainable design and construction practices.

4.4 Hybrid materials matrix

Global demand for high-performance, environmentally friendly buildings is driving the construction industry to look for more creative ways to address these issues. Creating and using hybrid material matrices is one such innovative strategy. This idea is in line with the more general objectives of reducing the impact on the environment and improving the use of built environments, in addition to promising to completely transform the way we think about building materials.

A hybrid materials matrix is a structured approach that facilitates the systematic exploration and combination of different materials to create new composites with enhanced properties and functionalities. This matrix essentially functions as a conceptual framework that enables engineers and architects to analyze possible material combinations and estimate the synergistic results of such combinations. The goal of the matrix is to create hybrid materials that have better properties such as strength, durability, thermal insulation, or environmental sustainability by combining various materials, each of which has certain advantages and disadvantages.

The significance of a hybrid materials matrix in the construction industry cannot be overstated. Traditional construction materials, while reliable and familiar, often fall short in meeting the evolving demands for energy efficiency, carbon neutrality, and environmental resilience. The hybrid materials matrix addresses these gaps by offering a pathway to innovate and tailor materials that can better adapt to and integrate with modern construction requirements. For instance, by combining lightweight materials with high-strength substances, the matrix can yield composites that are both structurally robust and energy-efficient. The hybrid materials matrix not only opens avenues for utilizing renewable and bio-based materials but also encourages the recycling and repurposing of existing materials, thus contributing to a circular economy in construction.

The hybrid materials matrix is a paradigm change toward sustainability, efficiency, and adaptation in the building sector, not merely a tool for material innovation. Through an organized examination of the wide range of material combinations which includes the incorporation of bio-based materials like mycelium the matrix opens the door to the creation of building materials that are not only more environmentally friendly but also more functional and high-performing. This strategy not only supports the global sustainability agenda but also gives the construction sector the tools it needs to create a future that is stronger and more sustainable. Creating a matrix for possible hybrid bio-based materials in construction involves exploring and categorizing various combinations of biological or renewable materials with traditional construction substances. This approach aims to innovate and enhance the existing materials used in the construction industry, focusing on sustainability, performance, and environmental impact. The hybrid materials matrix acts as a strategic tool to systematically identify and develop materials that combine the beneficial properties of bio-based and traditional materials, leading to advancements in construction technologies.

4.4.1 Steps to Create a Hybrid Materials Matrix for Bio-Based Materials in Construction:

1- Identify Bio-Based Materials: Make a list of materials that are biodegradable, renewable, or have less of an impact on the environment than traditional materials. Examples include mycelium (the roots of fungi), cellulose (found in wood or plants), lignin, bamboo, hemp, and biopolymers.

2- Determine Traditional Materials: Determine whether traditional materials for construction could be improved by combining them with bio-based materials. Concrete, steel, glass, and plastics.

3- Define Desired Properties: Specify the properties you aim to improve or achieve in the construction materials through hybridization. This could include increased strength, durability, thermal insulation, moisture resistance, fire retardancy, or reduced environmental impact.

4- Design the Matrix Structure: Create a matrix with bio-based materials on one axis and the desired properties or traditional materials on the other. This setup allows for easy visualization of potential hybrid combinations.

5- Fill in the Matrix: For each cell, speculate on how combining the bio-based material with the traditional material could potentially meet the desired property.

6- Evaluate and Experiment: Theoretical combinations should be evaluated for feasibility, practicality in construction applications, and environmental impact. Experimental research and development are essential to test the properties and performance of proposed hybrid materials.

4.4.2 Example of a Simplified Matrix for Hybrid Materials in Construction

Table (4.2) Comparison of Traditional and Bio-Based Building Materials Properties offers a thorough comparison of the most used traditional and bio-based building materials across several aspects.

Property	**Traditional materials**						**Bio based materials**				
	Concrete	Steel	Aluminum	Gypsum Board	Fiber glass	Polystyrene Foam	Wood	Mycelium	Bamboo	Algae	Hemp
Mechanical strength	High	Very High	High	Low	Medium	Low	Medium	Low	High	low	Low
Durability	High	High	Medium	Medium	High	Low	High	Medium	High	low	Medium
Thermal Insulation	Low	Low	Low	High	High	Very High	Low	High	Low	High	High
Environmental Impact	Medium	Low	Low	Medium	Medium	Low	High	Very High	High	High	Very High
Cost effectiveness	Low	High	High	Low	Medium	Low	Medium	High	Low	Medium	Medium
Sustainability	Low	Low	Medium	Low	Medium	Very Low	High	Very High	High	High	Very High

Table 4. 2 Comparison of Traditional and Bio-Based Building Materials Properties

The matrix compared key properties of each material to understand where bio-based materials might supplement or enhance traditional materials. When it comes to building materials, traditional materials like concrete, steel, and aluminum are recognized for their strong mechanical properties; steel and aluminum are recognized for their extremely high strengths. However, bio-based materials with a wide range of mechanical strengths, like hemp, bamboo, and mycelium, stand out for their outstanding strength. Both traditional and bio-based categories include a wide range of durability, from low to high levels. Among the traditional materials, steel and concrete are highly valued for their durability, while bamboo gets high marks for its exceptional toughness when compared to other bio-based materials. For Traditional materials, except for fiberglass and gypsum board, which offer medium to high insulation, typically provide lower thermal insulation when compared to bio-based materials. On the other hand, bio-based materials with excellent thermal insulation characteristics, such as hemp, algae, and mycelium, are known to have the potential to be used in more energy-efficient building designs. The environmental impact of various materials also varies; bio-based materials, like wood, mycelium, bamboo, algae, and hemp, show high to very high impacts, whereas traditional materials range from low to medium impacts. This highlights how important sustainable production and sourcing methods are to reducing the impact on the environment.

There is a wide range of cost effectiveness for both traditional and biobased materials. Traditional materials like aluminum and steel are known for being affordable, which may be due to their easy availability and simple manufacturing processes. Even if they might be more expensive, bio-based materials like mycelium have a considerable positive influence on the environment and sustainability, suggesting long-term savings and benefits. On the sustainability scale, bio-based materials—such as wood, mycelium, bamboo, algae, and hemp—are valued for their high to very high sustainability, while traditional materials are typically rated lower. This highlights the benefits to the environment of using bio-based materials in construction projects, encouraging a more environmentally responsible and sustainable method of construction. These insights provide a foundational understanding for the development of a new table focusing on matrix hybrid materials. Such a table could delve into the synergistic combinations of traditional and bio-based materials, aiming to optimize characteristics like strength, durability, insulation, and environmental impact.

Construction application	Traditional materials	Hybrid Materials				
		Bambo	**Hemp**	**Mycelium**	**Algae**	**Wood**
Foundation and Structure	**Concrete** High compressive strength, versatility	**Bamboo-reinforced concrete** improved strength and sustainability	**Hempcrete** Enhanced concrete tensile strength and crack resistance	**Mycelium concrete composite** Lightweight and improved thermal performance	**Algae-infused concrete** Improved carbon capture and green aesthetics	**Wood-infused concrete** Enhanced durability and natural aesthetics
	Steel High tensile strength, durability, versatility	**Bamboo-steel composite** increase environmental resistance and reduce weight.	**Hemp fiber reinforced steel** Increased tensile strength of steel structures	**Mycelium-infused steel** Corrosion resistance improvement through mycelium-based coatings	**Algae-based coatings for steel** Corrosion resistance and sustainability	**Wood veneer steel reinforcement** Improved strength
	Aluminum thermal and electrical conductivity lightweight, High strength-to-weight ratio, corrosion-resistant	**Bamboo-Aluminum Composite** lightweight and corrosion-resistant	**Hemp Fiber Reinforced Aluminum** enhance the tensile strength and lower environmental footprint	**Mycelium-Infused Aluminum** improved corrosion resistance	**Algae-Based Coatings for Aluminum** reducing the carbon footprint	**Wood-aluminum composite** Enhanced stiffness

Insulation	**Polystyrene foam** lightweight, insulation properties, moisture resistance, compressive strength, sound insulation, versatility, and cost-effectiveness	**Polystyrene foam with bamboo fibers** Increased strength and reduced environmental impact	**Hemp-filled polyethylene composites** Improvement of Thermal insulation	**Mycelium fillers in polystyrene foam** Biodegradability improvement	**Algae-infused foam** Carbon capture and insulation	**Wood chip fillers in foam** Improved insulation and sustainability
	Fiberglass High strength-to-weight ratio, design flexibility	**fiberglass with bamboo fibers** Durability and sustainability improvement	**Hemp fiberglass composites** Enhanced mechanical properties and reduced environmental impact	**Mycelium-enhanced fiberglass** Fire retardancy and mechanical strength increase	**Algae-based resins in fiberglass** Sustainability and performance	**Wood pulp-reinforced fiberglass** Strength and eco-friendliness
Interior Walls And Ceilings	**Gypsum boards** fire resistance, sound insulation, durability, versatility, moisture resistance, thermal properties	**Bamboo fiber-reinforced gypsum boards** High-strength gypsum boards reinforced with bamboo fibers	**Gypsum boards reinforced with hemp** better impact resistance and sound insulation	**Mycelium-gypsum composites** Improved indoor air quality and moisture regulation	**Algae-infused gypsum boards** Improved air quality and moisture control	**Wood fiber-reinforced gypsum boards** Durability and natural aesthetic

Table 4. 3 Possible hybrid materials matrix

A comprehensive evaluation of hybrid bio-based materials created for construction applications—foundation and structure, insulation, and interior walls and ceilings is provided in table (4.3). Hybrid materials that combine bamboo, hemp, mycelium, algae, and wood are contrasted with traditional materials including concrete, steel, aluminum, polystyrene foam, fiberglass, and gypsum boards. Every material goes through extensive testing to see whether it can match or exceed the performance of traditional materials while supporting environmentally friendly and sustainable building methods. Because of their strength and adaptability, classic materials like steel and aluminum are needed for foundation and structure. To improve their properties, they are currently being creatively combined with bio-based materials. The possibility of hemp fiber-reinforced steel and bamboo-steel composites to increase environmental resistance and decrease weight without reducing tensile strength is studied. Mycelium-infused aluminum is being studied for its corrosion resistance and reduced environmental impact, while bamboo-aluminum composites provide a lighter, more corrosion-resistant option. The goal of these bio-based improvements is to minimize the negative environmental effects of traditional materials while maximizing their natural strengths.

Moving on to insulation, it becomes clear that this material is critical for maintaining a building's comfort and energy efficiency. The table shows a move away from traditional polystyrene foam and toward alternatives that are blended with natural fibers, including bamboo and wood chips, which have better sustainability characteristics in addition to better insulation properties. Fiberglass composites enhanced with mycelium and filled with hemp offer better thermal insulation and less environmental impact. Fiberglass with algae-based resins offers a new way to insulate that combines outstanding insulating qualities with carbon capture.

Lastly, The table concludes by examining interior walls and ceilings, where traditional gypsum boards are common because of their ability to resist fire and effectively insulate sound. The study aims to enhance the mechanical strength and environmental sustainability of gypsum boards by integrating bamboo fibers. Improved moisture control and durability are offered by wood fiber-reinforced gypsum boards, while mycelium-gypsum composites promise better air quality and sound regulation. These hybrid materials combine environmentally responsible production and the lifespan processes with a focus toward improving the functional performance of interior finishes. This study on hybrid bio-based materials shows that the building sector has a revolutionary future. The materials covered show how innovation and sustainability may combine in a way that promotes architectural integrity and material performance while maintaining environmental responsibility.

(Fig 4.3, 4.4) are the result of previous comparative studies and provides a thorough reference for evaluating the suitability of hybrid materials in relation to many construction characteristics and properties.

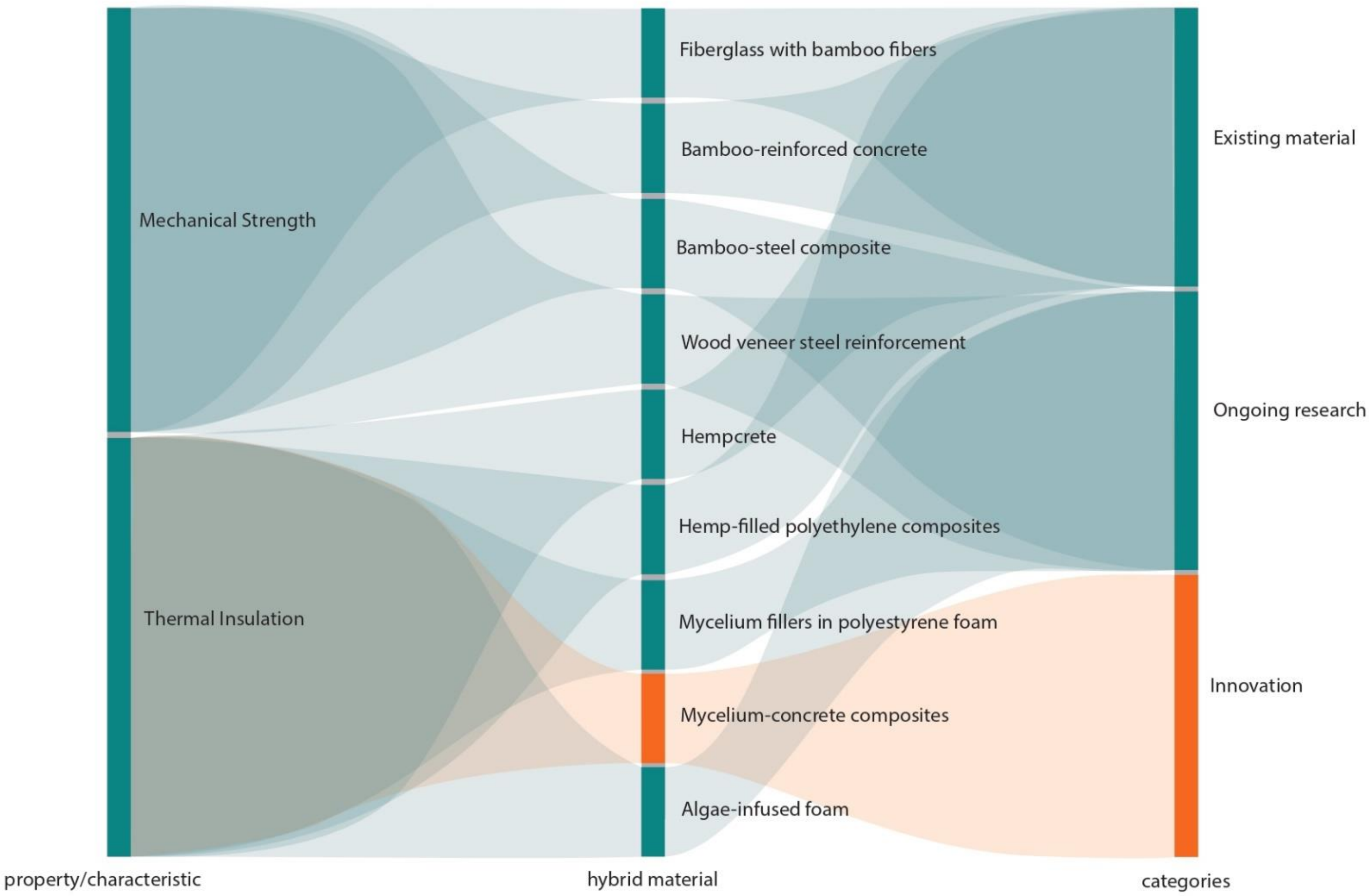


Figure 4. 3 Matrix of Possible strength and insulation Properties Matching

This scheme above provides a thorough analysis of innovative hybrid materials used in the construction industry, highlighting two essential performance criteria: mechanical strength and thermal insulation. Bamboo-steel composites and wood veneer steel reinforcement, which focus on the unique tensile strength and flexibility of bamboo and wood, are among the best examples of mechanical strength, which is essential for the structural integrity of structures. By providing the appropriate support and load-bearing capability, these materials could reduce the amount of traditional steel needed and thus reduce the total weight of the structure and they are presently being investigated and may be in various stages of development. For both energy efficiency and occupant comfort, thermal insulation is necessary. Better insulating materials that help control a building's temperature include hempcrete and mycelium concrete composites. The potential for bio-based insulators that not only control temperature inside but also enhance a building's energy efficiency is expanded by hemp-filled polyethylene composites and foam infused with algae.

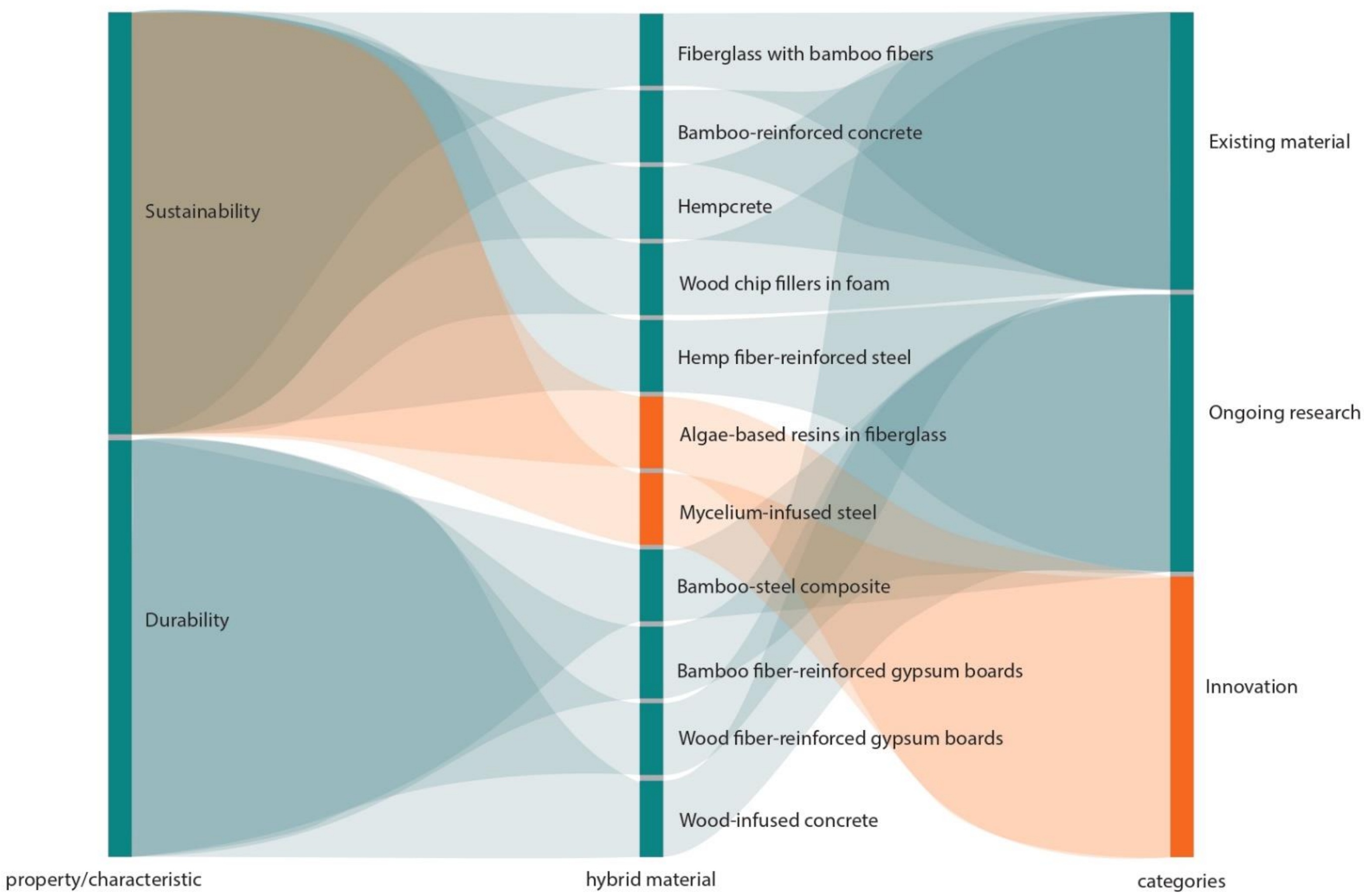


Figure 4. 4 Matrix of Possible sustainability and durability Properties Matching

This scheme provides a thorough analysis of innovative hybrid materials used in the construction industry, highlighting how well they meet two essential performance criteria: durability and sustainability. Sustainability is addressed through materials such as bamboo-reinforced concrete and hempcrete, which replace non-renewable resources with fast-growing, carbon-sequestering natural fibers but those hybrid had been classified as existing materials they are already used in construction. An emerging trend in construction materials is the use of wood chips and mycelium-infused steel fillers in foam which is classified as innovative materials. These materials improve the environmental impact of traditional construction materials through using the waste products of the timber industry and biological processes, respectively. In place of synthetic resins, algae-based resins in fiberglass provide a renewable option that could reduce dependence on fossil fuels and the greenhouse gas emissions connected with their production and it classified as innovative hybrid materials.

Durability is enhanced with the integration of bamboo and wood fibers into gypsum boards and concrete, resulting in materials that can withstand the test of time and reduce the need for maintenance or replacement for example wood infused concrete, bamboo steel composite and wood fiber reinforced gypsum board all these materials are presently being investigated and may be in various stages of development. Bamboo fiber-reinforced gypsum boards, for instance, show promise in extending the lifespan of interior finishes and it is currently in commercial use.

CHAPTER 04: CONCLUSION

4.1 Reflections

In conclusion, the development of technology in building materials offers a significant chance to improve the sustainability and resilience of our built environments. The integration of bio-based materials with traditional substrates has been carefully studied in this thesis, and the results show promise for enhancing the characteristics of traditional building materials. The study of these hybrid materials has overcome challenging challenges and produced critical knowledge about these composites' transformational potential.

The findings of this research illuminate the threshold of a transformative era in the construction industry, one that is ready to balance the two requirements for high performance and environmental sustainability. Through using all the different characteristics of both traditional and bio-based materials, the research suggests that the introduction of these innovative hybrids may start more durable, effective, and environmentally conscious construction methods, thus driving the field of green construction towards achieving and far exceeding global sustainability standards. Driven by an intense attraction with the interaction between traditional and bio-based materials, this research has only just started to highlight the wide range of opportunities that these pairings present. The variety of potential applications and effects provides great ground for future study aimed at clarifying the long-term environmental footprints of these materials and going deeper into their lifecycle impacts.

4.2 Future Development

This thesis's foundational work is only the first step toward a thorough understanding of hybrid construction materials. It is expected that in the future, studies would focus more on the hybrid materials matrix and carry out laboratory experiments to examine and clarify their characteristics. Additionally, there will be an excellent opportunity to investigate how emerging technologies like hybrid materials that adapt to their surroundings and advanced 3D printing method can be included into the development of even more creative and environmentally friendly building practices. It is hoped that further research will build upon this work, expanding the boundaries of sustainable construction technology for future generations.

List of Figures and Tables

Abbreviations

RH	Relative Humidity
ASTM	American Society for Testing and Materials
ISO	The International Organization for Standardization
LCA	Life Cycle Assessment
BE	Bio Economy
OECD	Organization for Economic Co-operation and Development
EC	European Commission
CE	Circular Economy
BBE	Bio-Based Economy
LCE	Low Carbon Economy
UNEP	United Nations Environmental Program
SETAC	Society of Environmental Toxicology and Chemistry
GE	Green Economy

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