Is Fungi the Futu

Building Material Production & the Construction Industry Today

Alarming human **population growth** rates resulted in **increase** of annual **consumption** of agricultural products & waste

Demand for **construction** today has intensified and has led to **HIGH** levels of **Carbon Dioxide emissions** globally.

Low-Energy Intensive Bio-Based Solutions derived from **Renewable Resources** need to be developed.

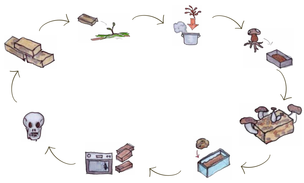
Mycelium-Based Composite material is favourable to meet this fast paced demand.

Aims

Research the **feasibility** of a mycelium bio-composite (MBC) as a potential structural **load-bearing material** in the form of a brick.

Evaluate **mechanical** & **environmental performance** of mycelium based bricks with or without bamboo reinforcement.

Lifecycle of a Mycelium Based Composite Material

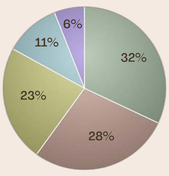


"Annual Construction & Demolition waste has increased by 70%, from 2.01 Billion Tons in 2016 to 3.4 Billion Tons in 2050"

A search for renewable and recycled alternative materials is a necessity

- Mycelium-Based Composite: The Future Sustainable Biomaterial, 2022

Global CO_2 Emissions by Sector



Industry · Building Material & Construction · Other · Transportation · Building Operations

Objectives

Desktop Research and Analysis

- Research Case Studies that have used Mycelium as a primary building material.

Manufacturing Process

- Cultivate mycelium, using 3 Fungi Species on 2 ligno-cellulosic substrates while adding 2 natural reinforcement materials to separate bricks.
- Construct Brick formwork moulds.

Physical Testing

- Test the density of mycelium bio-composite moulded brick.

Mechanical Characterisation

- Test the mycelium bio-composite bricks under applied crushing loads.
- A comparative study will be carried out to see whether a reinforcement increases its structural properties.

Medium Analysis for Mould forms

- Carry out an in depth analysis on the effects of using cardboard for moulding brick forms.

Life Cycle Assessment (LCA)

- Carry out a Cradle to Gate LCA on a mycelium based composite material.

A manual assessment on the Environmental Impact of this material will be carried out as per ISO 14040 - 14044 & EN 15804 Standards.

"Steel and Concrete account for 11% of Global Carbon Emissions"

- Global Status Report for Buildings & Construction, 2019

Yet over 70% of the world live in concrete structures

- Lorna Robinson, Curious Earth, 2022

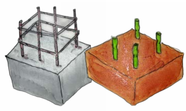
Eliminating the excessive use of these materials could potentially cut 23% of Carbon Emissions

Motivation

Reduce & Recycle

Greener Building Industry

Reduce Landfill



Natural material

Mycelium's Favourable Properties

Fire

Water Absorption

Thermal & Acoustic

Mechanical

Mycelium Bio-Composite Application

Synthetic Planar Material: Plastic and sheets

Low Density Objects: Synthetic foam

Biomedical Application: Chitin

Acoustic & Thermal Insulation

Semi-Structural Material: Furniture

Manufacturing Process

Timeline Of Process

1. Source Mushroom Growing Kits
- Research on past review papers to find common mushroom species done on mycelium growth
- Contact mushroom harvesting professionals

2. Cultivate Mushrooms
- Follow instructions to begin cultivation process

3. Wait for mycelium to produce
- Leave in an optimum environment; humid & dark

4. Source Substrate materials
- Saw Dust - Woodwork Workshop in Linenhall
- Coffee Grounds - Costa / Starbucks

5. Source Reinforcement materials
- Bamboo - Local Garden shop

6. Source Brick mould material
- Recycled Packaging cardboard - local business SyncIT

1. Manufacturing Process

CULTIVATING MUSHROOMS

'The Garden Shop' donated 3 Growing Kits in order for me to start initial testing

Phase 1 - Receiving Growing Kits

Eryngii

Blue Oyster

Shiitake

Phase 2 - Activating mycelium growth

Eryngii

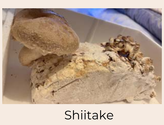
Blue Oyster

Shiitake

Phase 3 - Mycelium production visible

Eryngii

Blue Oyster



Shiitake

"6 million tonnes of coffee grounds are sent to landfill annually"

World Economic Forum - Masterson, 2021

Future problem shows 1.5 million Wax-Coated Cardboard boxes are sent to landfill

-Prokesch , 2019

Consumption of cardboard to increase from 3.7kg to 5.4kg by 2030 per-capita

Mechanical Testing

COMPRESSION TEST

Compressive Strength:
The capacity of a material to withstand loads tending to reduce its size

Importance of Compressive Strength

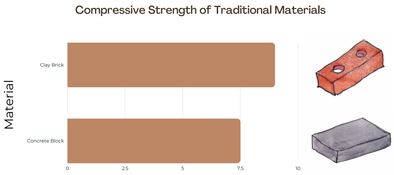
- Vital to **understand compressive strength** and how it will impact the structure.
- Buildings / structures subject to **numerous loads** that push them into the ground (Vertical Loads).
- Important to know **strengths of materials** used.
- **Loads** broken down into **3 categories**;

Dead Loads
- Weight of the structure itself

Live Loads
- Weight of people, furniture or vehicles passing through - not fixed

Environment Loads
- Weather - Wind, Rain, Snow, Earthquakes

Compressive Strength of Traditional Materials



Eryngii Mushroom

- Placed in **water** for **30 mins** to activate
- The substrate was left in its box in its growing environment for 2 weeks - Hot Press
- 1 week: Eryngii Mushrooms developed

Blue Oyster Mushroom

- Substrate left until fully covered in mycelium growth
- Incisions made in plastic bag and watered with **250ml**
- The substrate was left in its box in its growing environment for 2 weeks - **Hot Press**

Shiitake Mushroom

- Substrate submerged in **water for 24 hours**
- The substrate was left in its box in its growing environment for 2 weeks - Hot Press

7. Manufacturing Process

FORMWORK MAKING

Creating a standard brick sized: 225mm X 102.5mm X 65mm
mould from easily available and recycled materials: Recycled Cardboard

- Printed out a cuboid outline to brick dimensions to trace on material
- Cut this shape out of recycled cardboard and stuck together with tape

Prepare

Mould Cut

Mould put Together

19. Compression Test

Hydraulic Press

Part 1.

Part 2.

Part 3.

Part 4.

Testing Procedure

COMPRESSION TEST

Part 1.
- The Mycelium sample placed on **Hydraulic Press** base pressure plate.
- Placed on their **side**.
- Hydraulic Press set up with unit set to **Kilonewtons** (Kn).
- The **pressure plate** set to **10 Kn**.

Part 2 & 3.
- **Pressure Plate lowered** on to sample.
- Sample begins to **deflect**.
- Software notes **force** applied at each **deflection**.

Part 4.
- Sample reaches **max strength** & **breaks**.
- Software stops recording forces.

Calculation for Compressive Strength:

$$F = \frac{N}{mm^2}$$

F = Compressive Strength
N = Mass
mm^2 = Cross Section Area

9. Manufacturing Process

SUBSTRATE PREPARATION
SCALDING PROCESS

Lignocellulosic Substrate Material:
Natural resource from stems and roots of trees / woody plants.
Consists of fibrous tissue and carbon, which is the main food source for mycelium.

Preparing lignocellulosic Substrate samples
- Using a large cooking pot.
- Place substrate inside and saturate in water.
- Boil water and substrate at 210°C for 1 hour.
- *Boiling over 210°C kills all organisms possible.*
- Allow substrate to cool before using in testing.

No Preparation of Substrate required - Already fine - no chopping was required

SAWDUST SUBSTRATE

Recycled SawDust

Before

During

After

COFFEE GROUNDS SUBSTRATE

Recycled Coffee pods

Before

During

After

Form Medium Analysis

CARDBOARD

Physical Analysis

- Material prior to filling of material was notably **sturdy** in good condition.
- Days later the material was examined.
- The cardboard began to **warp** with **edges bulging** outward in the middle.
- Due to moisture within the substrate and humidity - the cardboard was weakening and soft to touch
- Corrugated cardboard **layers** were **separating**

Mould before sample is placed inside

Mould form days of sample placed inside

Visual Analysis

- Mycelium could be seen **digesting** the face of the **cardboard** material.
- Parts of the mycelium brick sample **bounded** to the mould.
- **Lack** of **compressed forces** from the cardboard on the growing sample led to **loose pieces** of substrate.
- Not a fully bound brick form as a result.
- The **Blue Oyster** network colonised the cardboard at a **greater scale** over the Eryngii and Shiitake root networks.

Eryngii

Mycelium colonised in groups sparse across parts of the cardboard

Blue Oyster

Mycelium colonised the whole surface of the cardboard

ure Rival to Structural Traditional B

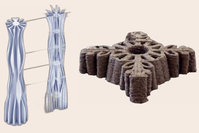
Mycelium Composite Case Study

The Tree Column & The Tree Pavilion - Blast Studio

- 3D printed
- Mushroom specie: ***Pleurotus djamor: Pink Oyster***
- Substrate Mix: Used Paper Coffee cups
- 2m Tall Tree trunk like structure
- Goal: to build cities out of produced waste

- Custom made cold extruder designed to push mixture through 3D printer
- Separate **modules** printed
- Each component carried a **different form** consisting of folds and curves
- 3D printing eliminates process required for mould formwork

- **Coffee cups** shredded and boiled in water to sterilize
- Created a **pulp mixture** that mycelium was added into
- A natural Blue pigment added colour to create A Blue Column - a separate case study



- Modules stacked to create column & fused together through mycelium growing
- Inspired by Cacti ability to capture moisture - folds create pockets for moisture for mycelium's growth
- Left for 4 weeks to grow then dried to terminate Fungus

The MycoTree - Hebel

- **Self supporting** Structure - works in compression only
- Mushroom specie: ***Ganoderma lucidum***
- Substrate Mix: **Sugarcane & Cassava root**
- **Density**: 440 kg/m³
- **Compressive Strength**: 0.61 MPa
- 3m Tall Tree like structure
- Follows a Polyhedral form

Consists of:

- 4x4m Bamboo Grid to represent a floor/ceiling
- 600mm Mycelium components
- Connections at ends of mycelium are **Bamboo plates** with dowels
- Structure fixed to Bamboo grid by slit-and-slot joints made from bamboo

- Each node point consists of 4 mycelium components
- Node points are at 400mm centres
- Mycelium components angled to be greater than 30°
- Mycelium moulds made from readily available, easy-to-recycle sheet materials - with teeth & slit joints

What is Mycelium?

Bio-Composite Material:
Composed of a resin and a reinforcement of natural fibres.
Low environment impact, recyclable & biodegradable.

Root network system of a fruiting body / fungal species.
Fine, thread-like structure called **Hyphae.**
Grows quickly and have a large surface area.
Thrive in **moisture** rich environments.
Binds substrate together giving a dense material.

Saprophyte:
Fungi that lives on dead or decaying organic matter

Functions of Mycelium Structure

Rhizoids

- Collection of Rhizoids are called **Hyphae.**
- **Grow Vertically** into the Substrate in which it is growing on.
- Acts as an **anchor** for the structure and is the location of **food absorption.**

Food Digestion

The process for digestion occurs **externally.**

- An **Enzyme** is secreted into the substrate.
- The Enzyme **breaks down** this substrate into a smaller product such a **glucose.**
- The Hyphae **absorb** the smaller products back by Diffusion

Stolon

- Grow **horizontally** on the **surface** Substrate in which it is growing on.
- Allows the fungi to colonise a the substrates surface rapidly.

Sporangiophore

- **Grow upward** away from the Substrate in which it is growing on.
- Acts as the **reproduction "organ"** for fungi

Fungi Study

Pleurotus eryngii - Eryngii Mushroom

- Known as the '**King Oyster Mushroom**'
- Naturally grown on the roots of **hardwood** trees

Pleurotus ostreatus - Blue Oyster Mushroom

- Grown in **high CO_2** Environments
- Requires Fresh air exchange
- Grows vigorously on **Malt Yeast Agar**
- Fruits in clusters on **living/dead hardwood** substrates

Lentinula edodes - Shiitake Mushroom

- One of the most common cultivated mushrooms
- Can grow in elevated CO_2 Environments
- Grows vigorously on **Malt Yeast Agar**
- Fluctuating temperature and humidity levels don't hinder its growth
- Fruits in large knots on **dead hardwood** substrates

"Decrease Greenhouse Gases by 80-95%"
by utilising organic wastes & use of mycelium based composites
Sharma, Sumbria, Innovative Infrastructure Review, 2022

7. Cut out mould from Cardboard

- Cut cuboid to standard brick dimension - 215x100x65mm

8. Create Brick mould

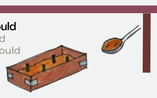
- Stick mould together

9. Prepare Substrate for Sterilization

- Scalding the substrate
- Boil water at 100°C and add to substrate
- Boil at 200°C for 1 hour

10. Add Substrate to mould

- Add substrate into mould
- Add reinforcement to mould



11. Inoculate Mycelium to mould

- Using a scalpel cut sample from mushroom growing kit and add to substrate mix in mould

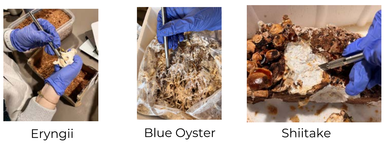
12. Measure Moisture Content

- Record moisture using Azuno Moisture Meter of brick sample

10. Manufacturing Process

INOCULATING MYCELIUM

- Cutting mycelium samples from mushroom growing kits for brick samples



Eryngii | Blue Oyster | Shiitake

- Inoculating premade moulds with substrate and mycelium

Eryngii | Blue Oyster

- Selected Mycelium Species with Substrate 1: SawDust

Eryngii | Blue Oyster

- Selected Mycelium Species with Substrate 1: **SawDust** with reinforcement: **Bamboo**

Eryngii | Blue Oyster

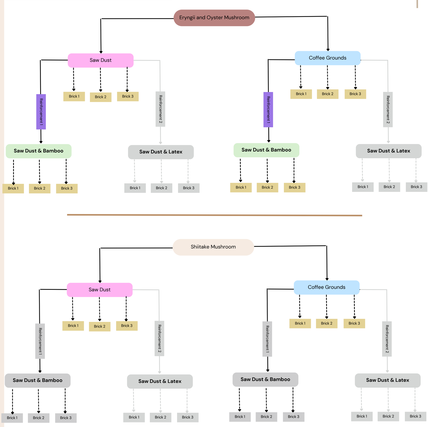
- Selected Mycelium Species with Substrate 2: **Coffee Grounds** with reinforcement: **Bamboo**

Eryngii | Blue Oyster

- Wrapping the samples in cling film to maintain humidity and prevent contamination

Sample Size Chart

TOTAL NO. OF BRICK SAMPLES MADE

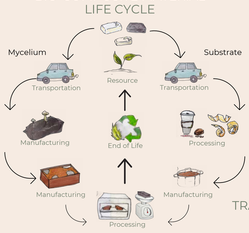


- **Total** of **24 Samples** were produced
- Initially 54 Samples were aimed to be produced
- Causes of reduced sample production: Contamination & illness

Life Cycle Assessment

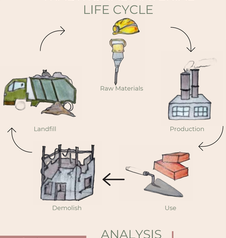
EMBODIED CARBON DURING MANUFACTURING

BIO-COMPOSITE MATERIAL LIFE CYCLE



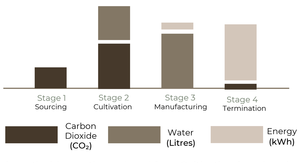
- No CO_2 emissions.
- Little energy required for the production.
- Resources are recycled.
- Biodegradable.

TRADITIONAL MATERIAL LIFE CYCLE



- Green House Gases and CO_2 emissions.
- Lots of energy required.
- Lots of waste.
- Landfill.

OUTPUTS AT EACH STAGE OF MBC PRODUCTION



- Carbon Dioxide mostly produced from Cultivating from burning of oil for a warm growing environment.
- Water usage highest for sterilizing substrates.
- Electricity input most highest for Terminating

Outputs from Manufacturing

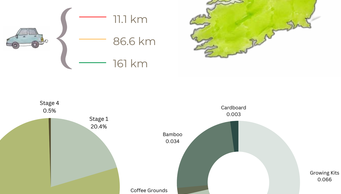
FOSSIL FUELS WATER ELECTRICITY

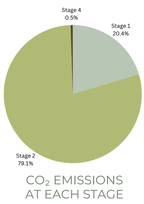
Results were calculated as follows:

$$\frac{\text{(Litres used x 100)}}{\text{km Travelled}} = \text{Fuel Consumption}$$

CO_2 = Litres used x CO_2 per Litre

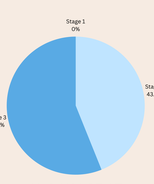
1 Litre of Diesel = 2.68kg CO_2
1 Litre of Petrol = 2.31kg CO_2



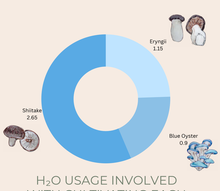


CO_2 EMISSIONS AT EACH STAGE
(Percentage)

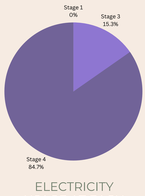
CO_2 EMISSIONS INVOLVED WITH TRANSPORT FOR SOURCING MATERIALS
(Tonnes)



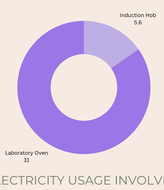
H_2O USAGE AT EACH STAGE
(Percentage)



H_2O USAGE INVOLVED WITH CULTIVATING EACH MUSHROOM SPECIES
(Litres)



ELECTRICITY USAGE AT EACH STAGE
(Percentage)

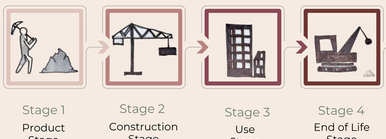


ELECTRICITY USAGE INVOLVED WITH STERILIZING & TERMINATION FOR SOURCING MATERIALS
(Kilowatts per Hour)

Life Cycle Assessment / Environmental Product Declaration

ANALYSIS

- Providing Data about the environmental impacts of a product.
- Standards EN 15804.
- **Stage 1** will be focused on.

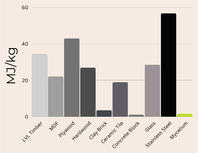


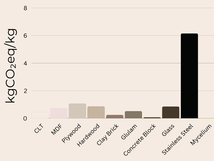
Stage 1 Product Stage | Stage 2 Construction Stage | Stage 3 Use Stage | Stage 4 End of Life Stage

Embodied Carbon & Energy

LCA ANALYSIS

Embodied Carbon:
The amount of carbon emitted during the construction of a building





Embodied Energy:
All the energy that is used to produce a material or product

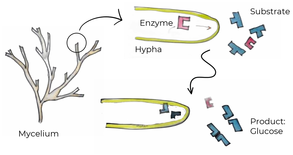
uilding Material

"By 2050 Global CO_2 emissions aim to be Net Zero"
- IEA Global Energy Review, 2021

"Years of warnings about the impact of Climate Change have become a Reality"
- Inger Andersen, Executive Director of UNEP

Reinforcement Study

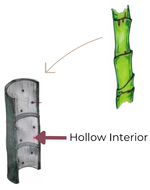
Natural Binding Reinforcement

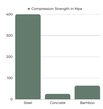


- Secretes its **own natural binder** - Enzyme.
- **Binds** substrate together.
- Replace toxic products with **carbon sequestration** products.

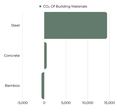
Bamboo

- **Fast growing** and versatile **grass** - Can grow up to 1 meter a day.
- **Accumulates Carbon** and locks it in for its lifespan.
- **Hollow** and thin characteristics give extreme **tensile resistance.**
- Developed to **withstand wind forces** - making a light but tension-resistant material.
- Superior to Timber and reinforcement Steel.

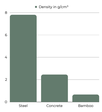




Compression Strength



CO_2 footprint of Building Materials



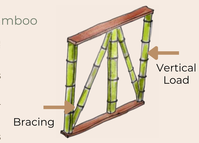
Density

Decay in Bamboo

- **Termite** - Attracted to Starch - Break down cellulose
- **Beetle** - Attracted to Starch - Lay eggs leaving exit holes
- **Rot** - Over 20% moisture content in Bamboo leads to rot

Mechanical Strength of Bamboo

- Horizontal Loads carried using **Bracing**
- Continuous vertical elements for load path
- Elements **tied** together for **robustness**
- **Compression Force** at its highest when loaded on **direction of bamboo fibers**

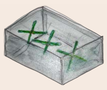


Structural Bamboo Wall System

Bamboo Reinforcement layout in a brick mould

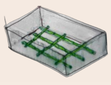
Option 1

- Single pieces placed vertically in direction of the fibres of the bamboo and compressive load - Strongest mechanical qualities



Option 2

- Single pieces placed to mimic bracing can enhance stability and rigidity to the form



Option 3

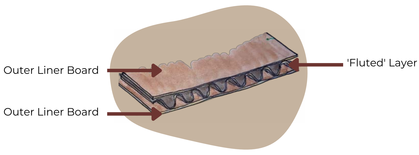
- Single pieces horizontally laid in perpendicular pattern add tensile strength

Cardboard Study

Single Wall Corrugated Cardboard

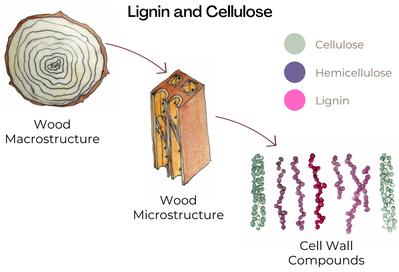
- Derived from fast grown **Pine trees**
- Trees are debarked and **chipped** before production
- Material is mechanically **pulped** and produced into cardboard
- Wood chips forced against a revolving stone sprayed with water - Lignin is not removed

Structure of Corrugated Cardboard



- **Fluted** pattern adds **strength** to the material
- A water and starch based **adhesive** is applied to the flute tips
- A heat and steam forms a gel which bonds the layers together

Lignin and Cellulose



- **White-rot Fungi** degrades lignocellulosic materials.
- Lignin is a form of structural materials that form cell walls - 3D form is rigid.
- **Fungi** are the **only organism** with the ability to **breakdown lignin.**
- Fungi release lignin and hydrocarbon enzymes to degrade the form.

13. Wrap Brick in Cling Film

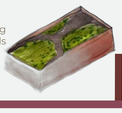
- Wrap Brick in cling film to keep humidity and prevent contaminants

14. Mycelium Growth

- White fibers on surface show mycelium growth active

15. Mycelium Growth

- Green Mould forming on Coffee Grounds based Brick



16. Termination of Mycelium

- Drying out the brick samples to kill Fungi from continued growth
- Performed in an Laboratory oven at 70°C
- Ensure no dampness in brick

17. Brick Samples ready for Application

- After termination brick samples are ready for further testing

18. Physical Testing

- Weigh Brick sample on Scientific scale

19. Mechanical Testing - Compression

- Compression tests carried out in Bolton Street on Industrial Testing Machine

16. End of Manufacturing Process

TERMINATION

- In a laboratory, the oven is **preheated to 70°C**
- A **thermometer** is placed inside to ensure conditions are reached and **maintained**
- One brick sample was used first;
  - The **cling film** wrap is **removed**
  - The brick is placed on a tray inside
  - Left for **3 hours**
- The following bricks followed procedure set out
- Left for **5 hours** to ensure the bricks were **dried**
- The oven door was opened at **40 minute intervals** - allow **moisture escape**

Maintaining Termination

MOISTURE

- Loose **Calcium Chloride** Gel Beads were placed inside a container with dried brick samples
- The **container** was closed and **sealed**
- Ensured **no moisture** was **absorbed** back into the samples before further testing

17. Physical Testing

Results after Termination

Physical Testing

CALCULATING MOISTURE CONTENT

- Water content affected **density** result - Substrate higher water content initially after scalding process
- Substrate moisture over **40%** after sterilizing - too high for construction material

Results were also calculated as follows:

$$\text{Moisture Content \%} = \frac{\text{(Wet Mass - Dry Mass)}}{\text{Dry Mass}}$$

18. Physical Testing

CALCULATING DENSITY

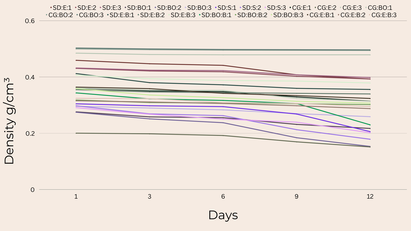
- Volume was calculated by multiplying the mould Length x Width x Height
- Initial weight of bricks were recorded
- Throughout the growth period the weight was recorded every 3 days

Results were calculated as follows:

$$\rho = \frac{m}{v}$$

ρ = Density
m = Mass
v = Volume

DENSITY OF BRICK SAMPLES



- **NOTE:** The mass of empty moulds were weighed before adding samples

Objectives Concluded

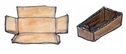
DISCUSSION

Desktop Research and Analysis

- **Case Studies** using mycelium bio-composite materials in abstract ways were **analysed.**
- Fungi **species** studied.
- **'The MycoTree'** inspired the direction to look into **mycelium structurally.**

Manufacturing Process

Cultivate Fungi



Formwork

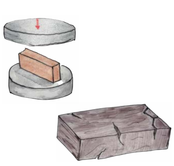
- **Fruiting bodies** were produced from all 3 Fungi.
- **Contamination** occurred in Shiitake.
- **Health & Safety** crucial dealing with Fungi.
- All moulds were produced to standard brick dimension from recycled cardboard.

Physical Testing

Density & Moisture Content

- **Density** of brick samples recorded.
- **Moisture Content** greater than **40%** for **coffee grounds** samples - **high density** throughout colonising.
- Moisture Content **3%** - **Blue Oyster and Saw Dust.**
- End material **lightweight.**

Mechanical Characterisation



- ISO 4012 - Standard testing to be done on cube.
- Brick samples do not comply with ISO 4012.
- Compression test concluded with negative results. - Low compressive strengths.
- Bamboo reinforcement showed no enhancement
- MBC brick can not be used structurally.

Cardboard Medium Analysis

- Reason for brick forms **failed.**
- **Oyster mushroom digested material.**
- Material **deteriorated** after few days.
- **Rigidity** became **warped.**
- Fungi **partially bonded** to material - short colonising period.
- End forms were **frail** with loose material.

Life Cycle Assessment (LCA)

Cradle to Gate

- LCA limited - no Software available for MBC materials.
- CO_2 emissions highest from Diesel fuel vehicles.
- 56.1% of water consumption was for sterilising substrates.
- Blue Oyster used the least water - 0.9L
- Terminating the fungi consumed the most electricity - 31kWh - 84%

Findings & Precautions

HEALTH & SAFETY

Gloves

Mask

Infected Lungs

- New set of **Surgical gloves** prevent **cross contamination** of fungi species.
- Failure to wear a proper mask / mask at all resulted in **inhaling** of fungi **spores** causing chest infections, long term cough and allergy infection in respiratory system.

Limitations

DISCUSSION

- No information on the Life Cycle Assessment for Mycelium Based composites.
- Lack of research into the mechanical properties - Not yet publicly available.

"Annual harvested Bamboo increased from 75 tons to 100 tons in 2 years"

Rate & quantity of bamboo production is rapid. Anaerobic digestion of material better solution to landfill

- Carbon Footprint Assessment of a Novel Bio-Based Composite for Building Insulation, 2022

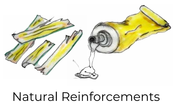
Future Work

DISCUSSION

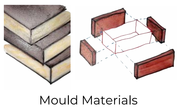
Laboratory Environment

- **Controlled Environment** required for optimum cultivation results.
- Improves rate of growth and quantity of mycelium production

- Introduce a **natural latex glue** into the samples.
- Use **bamboo** in the form of **shaved** layers.



Natural Reinforcements



Mould Materials

- **MDF** as primary mould.
- **Cardboard** as secondary form
- MDF compresses form together
- Keeping cardboard **reduces landfill**

- MBC's show promising characteristics & performance.
- Need for producing a full LCA on the material.
- Bio-degradable at its End of Life.
- Little to no waste produce.

LCA - Cradle to Grave

Cara Molloy
C19473046
Year 4, Architectural Technology, TUDublin, College of Engineering and the Built Environment

Is Fungi the Future Rival to Structural Traditional Building Material

Building Material Production & the Construction Industry Today

Alarming human **population growth** rates resulted in **increase** of annual **consumption** of agricultural products & waste

Demand for **construction** today has intensified and has led to **HIGH** levels of **Carbon Dioxide emissions** globally.

Low-Energy Intensive Bio-Based Solutions derived from **Renewable Resources** need to be developed.

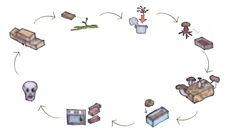
Mycelium-Based Composite material is favourable to meet this fast paced demand.

Aims

Research the **feasibility** of a mycelium bio-composite (MBC) as a potential structural **load-bearing material** in the form of a brick.

Evaluate **mechanical & environmental performance** of mycelium based bricks with or without bamboo reinforcement.

Lifecycle of a Mycelium Based Composite Material

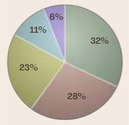


"Annual Construction & Demolition waste has increased by 70%, from 2.01 Billion Tons in 2016 to 3.4 Billion Tons in 2050"

A search for renewable and recycled alternative materials is a necessity

Mycelium-Based Composite: The Future Sustainable Biomaterial, 2022

Global CO_2 Emissions by Sector



Industry | Building Material & Construction | Other | Transportation | Building Operations

Objectives

Desktop Research and Analysis

- Research Case Studies that have used Mycelium as a primary building material.

Manufacturing Process

- Cultivate mycelium, using 3 Fungi Species on 2 ligno-cellulosic substrates while adding 2 natural reinforcement materials to separate bricks.
- Construct Brick formwork moulds.

Physical Testing

- Test the density of mycelium bio-composite moulded brick.

Mechanical Characterisation

- Test the mycelium bio-composite bricks under applied crushing loads.
- A comparative study will be carried out to see whether a reinforcement increases its structural properties.

Medium Analysis for Mould forms

- Carry out an in depth analysis on the effects of using cardboard for moulding brick forms.

Life Cycle Assessment (LCA)

- Carry out a Cradle to Gate LCA on a mycelium based composite material.

A manual assessment on the Environmental Impact of this material will be carried out as per ISO 14040 - 14044 & EN 15804 Standards.

"Steel and Concrete account for 11% of Global Carbon Emissions"

Global Status Report for Buildings & Construction, 2019

Yet over 70% of the world live in concrete structures

Laima Rekmeen, Curious Earth, 2022

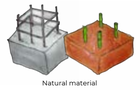
Eliminating the excessive use of these materials could potentially cut 23% of Carbon Emissions

Motivation

Reduce & Recycle

Greener Building Industry

Reduce Landfill



Natural material

Mycelium's Favourable Properties

Fire

Water Absorption

Thermal & Acoustic

Mechanical

Mycelium Bio-Composite Application

Synthetic Planar Material: Plastic and sheets | Low Density Objects: Synthetic foam | Biomedical Application: Chitin | Acoustic & Thermal Insulation | Semi-Structural Material: Furniture

Mycelium Composite Case Study

The Tree Column & The Tree Pavilion - Blast Studio

- 3D printed
- Mushroom specie: *Pleurotus djamor*: *Pink Oyster*
- Substrate Mix: Used Paper Coffee cups
- 2m Tall Tree trunk like Structure
- Goal: to build cities out of produced waste

- Custom made cold extruder designed to push mixture through 3D printer
- Separate **modules** printed
- Each component carried a **different form** consisting of folds and curves
- 3D printing eliminates process required for mould formwork

- **Coffee cups** shredded and boiled in water to sterilize
- Created a **pulp mixture** that mycelium was added into
- A natural Blue pigment added colour to create A Blue Column - a separate case study

- Modules stacked to create column & fused together through mycelium growing
- Inspired by Cacti ability to capture moisture - folds create pockets for moisture for mycelium's growth
- Left for 4 weeks to grow then dried to terminate Fungus

The MycoTree - Hebel

- **Self supporting** Structure - works in compression only
- Mushroom specie: *Ganoderma lucidum*
- Substrate Mix: **Sugarcane & Cassava root**
- **Density**: 440 kg/m³
- **Compressive Strength**: 0.61 MPa
- 3m Tall Tree like structure
- Follows a Polyhedral form

Consists of:

- 4x4m Bamboo Grid to represent a floor/ceiling
- 600mm Mycelium components
- Connections at ends of mycelium are **Bamboo plates** with dowels
- Structure fixed to Bamboo grid by slit-and-slot joints made from bamboo

- Each node point consists of 4 mycelium components
- Node points are at 400mm centres
- Mycelium components angled to be greater than 30°
- Mycelium moulds made from readily available, easy-to-recycle sheet materials - with teeth & slit joints

What is Mycelium?

Bio-Composite Material:

Composed of a resin and a reinforcement of natural fibres.
Low environment impact, recyclable & biodegradable.

Root network system of a fruiting body / fungal species.
Fine, thread-like structure called **Hyphae.**
Grows quickly and have a large surface area.
Thrive in **moisture** rich environments.
Binds substrate together giving a dense material.

Saprophyte:

Fungi that lives on dead or decaying organic matter

Functions of Mycelium Structure

Rhizoids

- Collection of Rhizoids are called **Hyphae**.
- **Grow Vertically** into the Substrate in which it is growing on.
- Acts as an **anchor** for the structure and is the location of **food absorption.**

Food Digestion

The process for digestion occurs **externally.**

- An **Enzyme** is secreted into the substrate.
- The Enzyme **breaks down** this substrate into a smaller product such a **glucose.**
- The Hyphae **absorb** the smaller products back by Diffusion

Stolon

- Grow **horizontally** on the **surface** Substrate in which it is growing on.
- Allows the fungi to colonise a the substrates surface rapidly.

Sporangiophore

- Grow upward away from the Substrate in which it is growing on.
- Acts as the **reproduction "organ"** for fungi

Fungi Study

Pleurotus eryngii - Eryngii Mushroom

- Known as the **'King Oyster Mushroom'**
- Naturally grown on the roots of **hardwood** trees

Pleurotus ostreatus - Blue Oyster Mushroom

- Grown in **high CO_2** Environments
- Requires Fresh air exchange
- Grows vigorously on **Malt Yeast Agar**
- Fruits in clusters on **living/dead hardwood** substrates

Lentinula edodes - Shiitake Mushroom

- One of the most common cultivated mushrooms
- Can grow in elevated CO_2 Environments
- Grows vigorously on **Malt Yeast Agar**
- Fluctuating temperature and humidity levels don't hinder its growth
- Fruits in large knots on **dead hardwood** substrates

"By 2050 Global CO_2 emissions aim to be Net Zero"

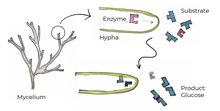
- IEA Global Energy Review, 2021

"Years of warnings about the impact of Climate Change have become a Reality"

- Inger Andersen, Executive Director of UNEP

Reinforcement Study

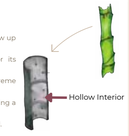
Natural Binding Reinforcement

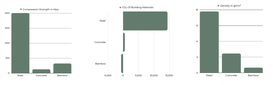


- Secretes its **own natural binder** - Enzyme.
- **Binds** substrate together.
- Replace toxic products with **carbon sequestration** products.

Bamboo

- **Fast growing** and versatile **grass** - Can grow up to 1 meter a day.
- **Accumulates Carbon** and locks it in for its lifespan.
- Hollow and thin characteristics give extreme **tensile resistance.**
- Developed to **withstand wind forces** - making a light but tension-resistant material.
- Superior to Timber and reinforcement Steel.





"Decrease Greenhouse Gases by 80-95%"

by utilising organic wastes & use of mycelium based composites

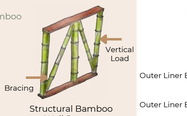
Sharma, Sumbria, Innovative Infrastructure Review, 2022

Decay in Bamboo

- **Termite** - Attracted to Starch - Break down cellulose
- **Beetle** - Attracted to Starch - Lay eggs leaving exit holes
- **Rot** - Over 20% moisture content in Bamboo leads to rot

Mechanical Strength of Bamboo

- Horizontal Loads carried using **Bracing**
- Continuous vertical elements for load path
- Elements **tied** together for robustness
- **Compression** Force at its highest when loaded on direction of bamboo fibers



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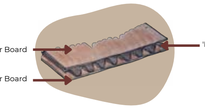

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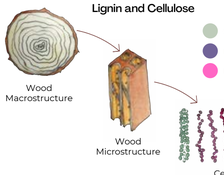

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Manufacturing Process

Timeline Of Process

1. Source Mushroom Growing Kits
- Research on past review papers to find common mushroom species done on mycelium growth
- Contact mushroom harvesting professionals

2. Cultivate Mushrooms
- Follow instructions to begin cultivation process

3. Wait for mycelium to produce
- Leave in an optimum environment; humid & dark

4. Source Substrate materials
- Saw Dust - Woodwork Workshop in Linenhall
- Coffee Grounds - Costa / Starbucks

5. Source Reinforcement materials
- Bamboo - Local Garden shop

6. Source Brick mould material
- Recycled Packaging cardboard - local business SyncIT

7. Cut out mould from Cardboard
- Cut cuboid to standard brick dimension - 215x100x65mm

8. Create Brick mould
- Stick mould together

9. Prepare Substrate for Sterilization
- Scalding the substrate
- Boil water at 100°C and add to substrate
- Boil at 200°C for 1 hour

10. Add Substrate to mould
- Add substrate into mould
- Add reinforcement to mould

11. Inoculate Mycelium to mould
- Using a scalpel cut sample from mushroom growing kit and add to substrate mix in mould

12. Measure Moisture Content
- Record moisture using Azuno Moisture Meter of brick sample

13. Wrap Brick in Cling Film
- Wrap Brick in cling film to keep humidity and prevent contaminants

14. Mycelium Growth
- White fibers on surface show mycelium growth active

15. Mycelium Growth
- Green Mould forming on Coffee Grounds based Brick

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1. Manufacturing Process

CULTIVATING MUSHROOMS

'The Garden Shop' donated 3 Growing Kits in order for me to start initial testing

Phase 1 - Receiving Growing Kits

Eryngii | Blue Oyster | Shiitake

Phase 2 - Activating mycelium growth

Eryngii | Blue Oyster | Shiitake

Phase 3 - Mycelium production visible

Eryngii | Blue Oyster | Shiitake

"6 million tonnes of coffee grounds are sent to landfill annually"

World Economic Forum - Masterson, 2021

Future problem shows 1.5 million Wax-Coated Cardboard boxes are sent to landfill

-Prokesch , 2019

Consumption of cardboard to increase from 3.7kg to 5.4kg by 2030 per-capita

Mechanical Testing

COMPRESSION TEST

Compressive Strength:

The capacity of a material to withstand loads tending to reduce its size

Importance of Compressive Strength

- Vital to **understand compressive strength** and how it will impact the structure.
- Buildings / structures subject to **numerous loads** that push them into the ground (Vertical Loads).
- Important to know **strengths of materials** used.
- **Loads** broken down into **3 categories;**

Dead Loads
- Weight of the structure itself

Live Loads
- Weight of people, furniture or vehicles passing through - not fixed

Environment Loads
- Weather - Wind, Rain, Snow, Earthquakes

Compressive Strength of Traditional Materials

1. Manufacturing Process

CULTIVATING MUSHROOMS

Eryngii Mushroom
- Placed in **water** for **30 mins** to activate
- The substrate was left in its box in its growing environment for 2 weeks - Hot Press
- 1 week: Eryngii Mushrooms developed

Blue Oyster Mushroom
- Substrate left until fully covered in mycelium growth
- Incisions made in plastic bag and watered with **250ml**
- The substrate was left in its box in its growing environment for 2 weeks - **Hot Press**

Shiitake Mushroom
- Substrate submerged in **water for 24 hours**
- The substrate was left in its box in its growing environment for 2 weeks - Hot Press

7. Manufacturing Process

FORMWORK MAKING

Creating a standard brick sized: 225mm X 102.5mm X 65mm mould from easily available and recycled materials: Recycled Cardboard
- Printed out a cuboid outline to brick dimensions to trace on material
- Cut this shape out of recycled cardboard and stuck together with tape

Prepare | Mould Cut | Mould put Together

19. Compression Test

Hydraulic Press

Testing Procedure

COMPRESSION TEST

Part 1.
- The Mycelium sample placed on **Hydraulic Press** base pressure plate.
- Placed on their **side.**
- Hydraulic Press set up with unit set to **Kilonewtons** (Kn).
- The **pressure plate** set to **10 Kn.**

Part 2 & 3.
- **Pressure Plate lowered** on to sample.
- Sample begins to **deflect.**
- Software notes **force** applied at each **deflection.**

Part 4.
- Sample reaches **max strength** & **breaks.**
- Software stops recording forces.

Calculation for Compressive Strength:

$$F = \frac{N}{mm^2}$$

F = Compressive Strength
N = Mass
mm^2 = Cross Section Area

9. Manufacturing Process

SUBSTRATE PREPARATION
SCALDING PROCESS

Lignocellulosic Substrate Material:

Natural resource from stems and roots of trees / woody plants.
Consists of fibrous tissue and carbon, which is the main food source for mycelium.

Preparing lignocellulosic Substrate samples
- Using a large cooking pot.
- Place substrate inside and saturate in water.
- Boil water and substrate at 210°C for 1 hour.
- *Boiling over 210°C kills all organisms possible.*
- Allow substrate to cool before using in testing.

No Preparation of Substrate required - Already fine - no chopping was required

SAWDUST SUBSTRATE

Recycled SawDust | Before | During | After

COFFEE GROUNDS SUBSTRATE

Recycled Coffee pods | Before | During | After

Form Medium Analysis

CARDBOARD

Physical Analysis

- Material prior to filling of material was notably **sturdy** in good condition.
- Days later the material was examined.
- The cardboard began to **warp** with **edges bulging** outward in the middle.
- Due to moisture within the substrate and humidity - the cardboard was weakening and soft to touch
- Corrugated cardboard **layers** were **separating**

Mould before sample is placed inside | Mould form days of sample placed inside

Visual Analysis

- Mycelium could be seen **digesting** the face of the **cardboard** material.
- Parts of the mycelium brick sample **bounded** to the mould.
- **Lack** of **compressed forces** from the cardboard on the growing sample led to **loose pieces** of substrate.
- Not a fully bound brick form as a result.
- The **Blue Oyster** network colonised the cardboard at a **greater scale** over the Eryngii and Shiitake root networks.

Eryngii | Mycelium colonised in groups sparse across parts of the cardboard

Blue Oyster | Mycelium colonised the whole surface of the cardboard

10. Manufacturing Process

INOCULATING MYCELIUM

- Cutting mycelium samples from mushroom growing kits for brick samples

Eryngii | Blue Oyster | Shiitake

- Inoculating premade moulds with substrate and mycelium

Eryngii | Blue Oyster

- Selected Mycelium Species with Substrate 1: SawDust

Eryngii | Blue Oyster

Life Cycle Assessment

EMBODIED CARBON DURING MANUFACTURING

BIO-COMPOSITE MATERIAL LIFE CYCLE

- No CO_2 emissions.
- Little **energy** required for the **production.**
- Resources are **recycled.**
- **Biodegradable.**

TRADITIONAL MATERIAL LIFE CYCLE

- Green House Gases and CO_2 emissions.
- Lots of energy required.
- Lots of waste.
- Landfill.

FOSSIL FUELS
WATER
ELECTRICITY

Life Cycle Assessment / Environmental Product Declaration

ANALYSIS

- Providing Data about the environmental impacts of a product.
- Standards EN 15804.
- Stage 1 will be focused on.

Stage 1 Product Stage | Stage 2 Construction Stage | Stage 3 Use Stage | Stage 4 End of Life Stage

OUTPUTS AT EACH STAGE OF MBC PRODUCTION

- Carbon Dioxide mostly produced from Cultivating from burning of oil for a warm growing environment.
- Water usage highest for sterilizing substrates.
- Electricity input most highest for Terminating

Outputs from Manufacturing

Results were calculated as follows:

$$\frac{\text{(Litres used x 100)}}{\text{km Travelled}} = \text{Fuel Consumption}$$

CO_2 = Litres used x CO_2 per Litre

1 Litre of Diesel = 2.68kg CO_2
1 Litre of Petrol = 2.31kg CO_2

CO_2 EMISSIONS AT EACH STAGE
(Percentage)

CO_2 EMISSIONS INVOLVED WITH TRANSPORT FOR SOURCING MATERIALS
(Tonnes)

- Selected Mycelium Species with Substrate 2: Coffee Grounds with reinforcement: Bamboo

Eryngii | Blue Oyster

- Wrapping the samples in cling film to maintain humidity and prevent contamination

- Selected Mycelium Species with Substrate 1: SawDust

Eryngii | Blue Oyster

Sample Size Chart

TOTAL NO. OF BRICK SAMPLES MADE

- Total of **24 Samples** were produced
- Initially 54 Samples were aimed to be produced
- Causes of reduced sample production: Contamination & illness

Embodied Carbon & Energy

LCA ANALYSIS

Embodied Carbon:

The amount of carbon emitted during the construction of a building

Embodied Energy:

All the energy that is used to produce a material or product

16. End of Manufacturing Process

TERMINATION

- In a laboratory, the oven is **preheated to 70°C**
- A **thermometer** is placed inside to ensure conditions are reached and **maintained**
- One brick sample was used first;
  - The **cling film** wrap is removed
  - The brick is placed on a tray inside
  - Left for **3 hours**
- The following bricks followed procedure set out
- Left for **5 hours** to ensure the bricks were **dried**
- The oven door was opened at **40 minute intervals** - allow **moisture** escape

Maintaining Termination

MOISTURE

- Loose **Calcium Chloride** Gel Beads were placed inside a container with dried brick samples
- The **container** was closed and **sealed**
- Ensured **no moisture** was **absorbed** back into the samples before further testing

17. Physical Testing

Results after Termination

Physical Testing

CALCULATING MOISTURE CONTENT

- Water content affected **density** result - Substrate higher water content initially after scalding process
- Substrate moisture over **40%** after sterilizing - too high for construction material

Results were also calculated as follows:

$$\text{Moisture Content \%} = \frac{\text{(Wet Mass - Dry Mass)}}{\text{Dry Mass}}$$

18. Physical Testing

CALCULATING DENSITY

- Volume was calculated by multiplying the mould Length x Width x Height
- Initial weight of bricks were recorded
- Throughout the growth period the weight was recorded every 3 days

Results were calculated as follows:

$$\rho = \frac{m}{v}$$

ρ = Density
m = Mass
v = Volume

DENSITY OF BRICK SAMPLES

- **NOTE:** The mass of empty moulds were weighed before adding samples

"Annual harvested Bamboo increased from 75 tons to 100 tons in 2 years"

Rate & quantity of bamboo production is rapid. Anaerobic digestion of material better solution to landfill

- Carbon Footprint Assessment of a Novel Bio-Based Composite for Building Insulation, 2022

Objectives Concluded

DISCUSSION

Desktop Research and Analysis

- **Case Studies** using mycelium bio-composite materials in abstract ways were **analysed.**
- Fungi **species** studied.
- **'The MycoTree'** inspired the direction to look into **mycelium structurally.**

Manufacturing Process

- **Fruiting bodies** were produced from all 3 Fungi.
- **Contamination** occurred in Shiitake.
- **Health & Safety** crucial dealing with Fungi.
- All moulds were produced to standard brick dimension from recycled cardboard.

Physical Testing

- **Density** of brick samples recorded.
- **Moisture Content** greater than **40%** for **coffee grounds** samples - **high density** throughout colonising.
- Moisture Content **3%** - **Blue Oyster** and **Saw Dust.**
- End material **lightweight.**

Mechanical Characterisation

- ISO 4012 - Standard testing to be done on cube.
- Brick samples do not comply with ISO 4012.
- Compression test concluded with negative results. - Low compressive strengths.
- Bamboo reinforcement showed no enhancement
- MBC brick can not be used structurally.

Findings & Precautions

HEALTH & SAFETY

- New set of **Surgical gloves** prevent **cross contamination** of fungi species.
- Failure to wear a proper mask / mask at all resulted in **inhaling** of fungi **spores** causing chest infections, long term cough and allergy infection in respiratory system.

Limitations

DISCUSSION

- No information on the Life Cycle Assessment for Mycelium Based composites.
- Lack of research into the mechanical properties - Not yet publicly available.

- MBCs show promising characteristics & performance
- Need for producing a full LCA on the material.
- Bio-degradable at its End of Life.
- Little to no waste produce.

Cardboard Medium Analysis

- Reason for brick forms **failed.**
- **Oyster mushroom digested material.**
- Material **deteriorated** after few days.
- **Rigidity** became **warped.**
- Fungi **partially bonded** to material - short colonising period.
- End forms were **frail** with loose material.

Life Cycle Assessment (LCA)

- LCA limited - no Software available for MBC materials.
- CO_2 emissions highest from Diesel fuel vehicles.
- 56.1% of water consumption was for sterilising substrates.
- Blue Oyster used the least water - 0.9L
- Terminating the fungi consumed the most electricity - 31kWh - 84%

Future Work

DISCUSSION

- **Controlled** Environment required for optimum cultivation results.
- Improves rate of growth and quantity of mycelium production

- Introduce a **natural latex glue** into the samples.
- Use **bamboo** in the form of **shaved** layers.

- MDF as primary mould.
- **Cardboard** as secondary form
- MDF compresses form together
- Keeping cardboard **reduces landfill**

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