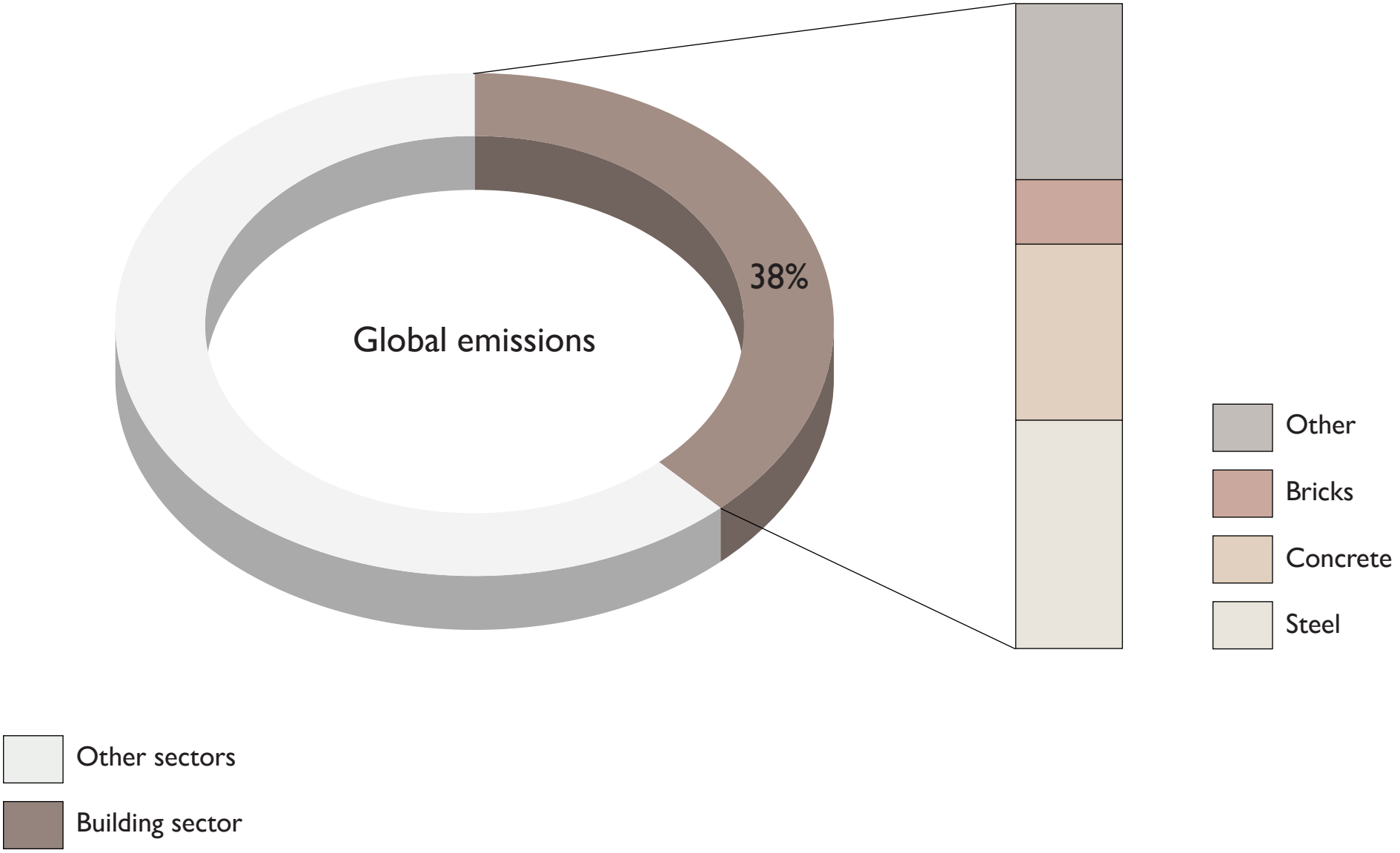
A record amount of CO2 was released into the air.

Source: https://climate.copernicus.eu/copernicus-2024-first-year-exceed-15degc-above-pre-industrial-level

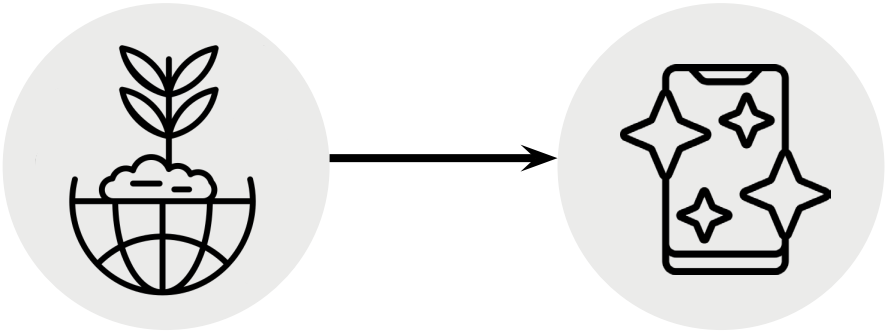

38%
Global emissions
Other
Bricks
Concrete
Steel
Other sectors
Building sector

Today's issues

Linear economy

Today's issues

Linear economy



Today's issues

Linear economy

Today's issues

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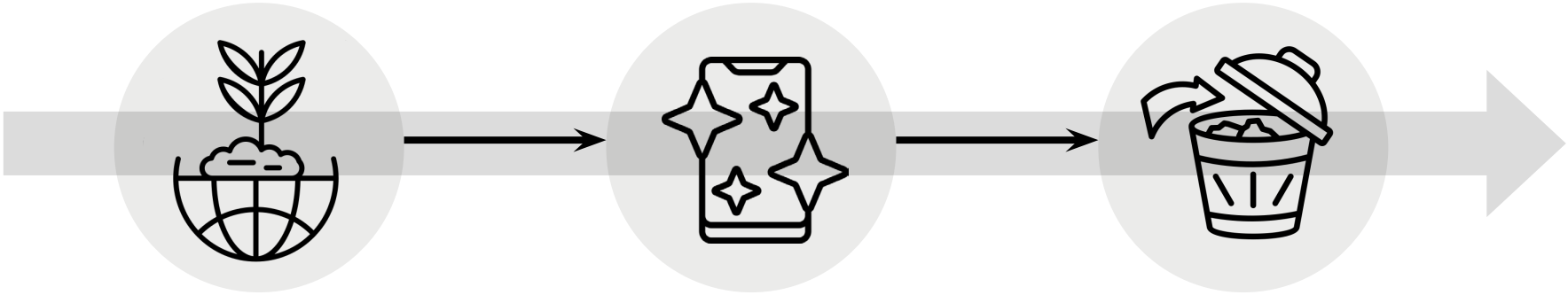
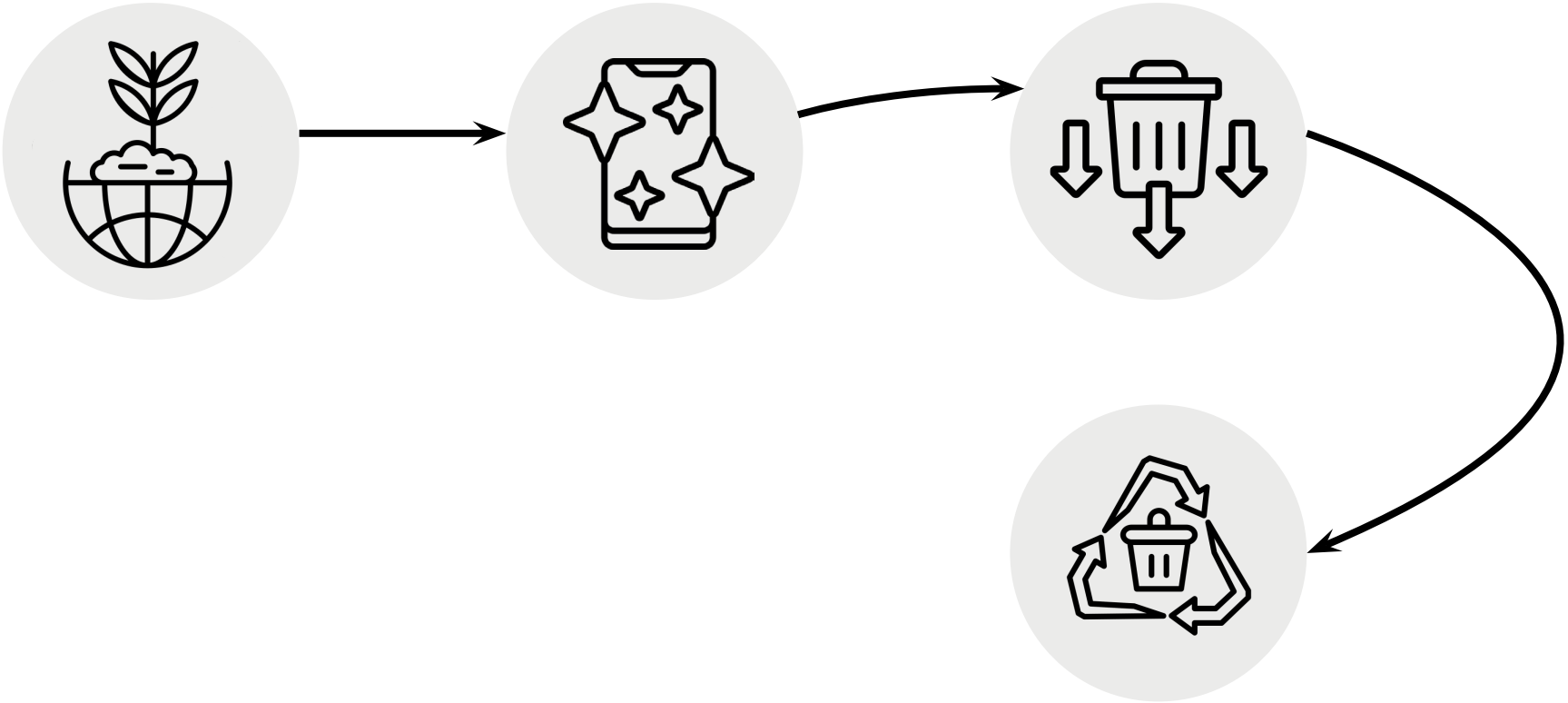
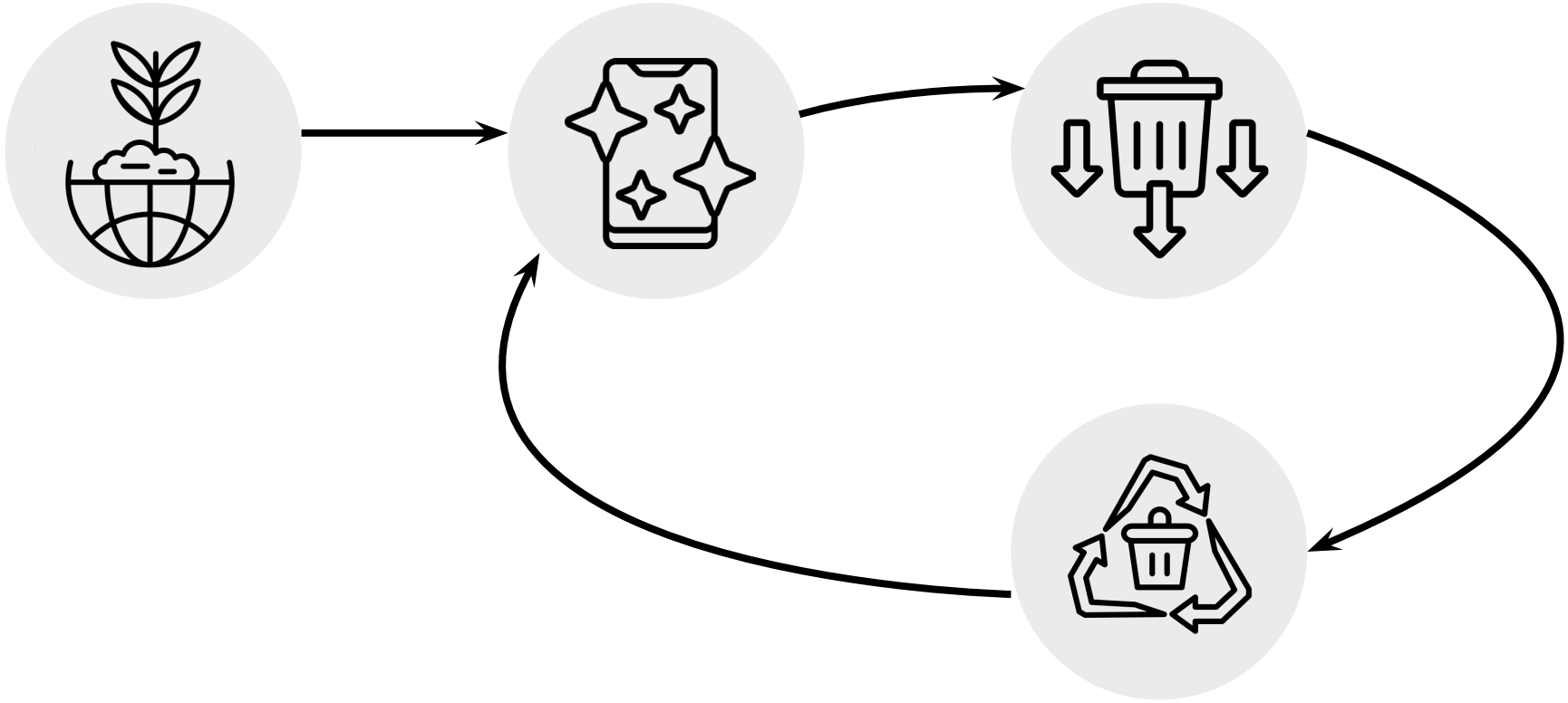
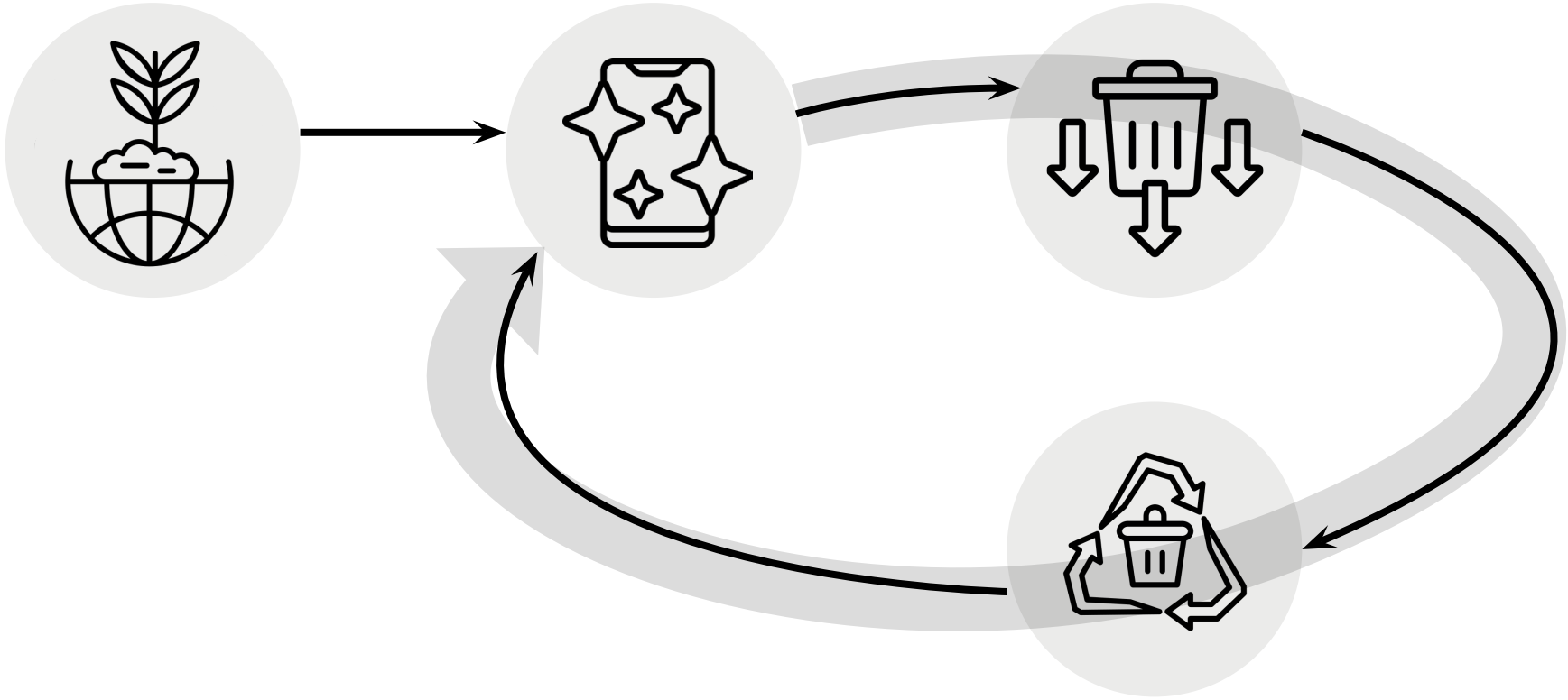


Today's issues

Linear economy

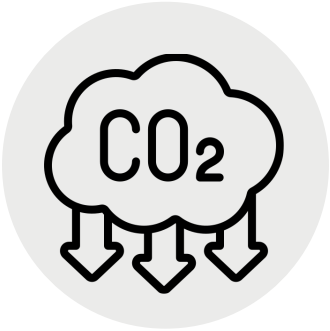


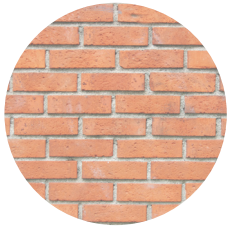


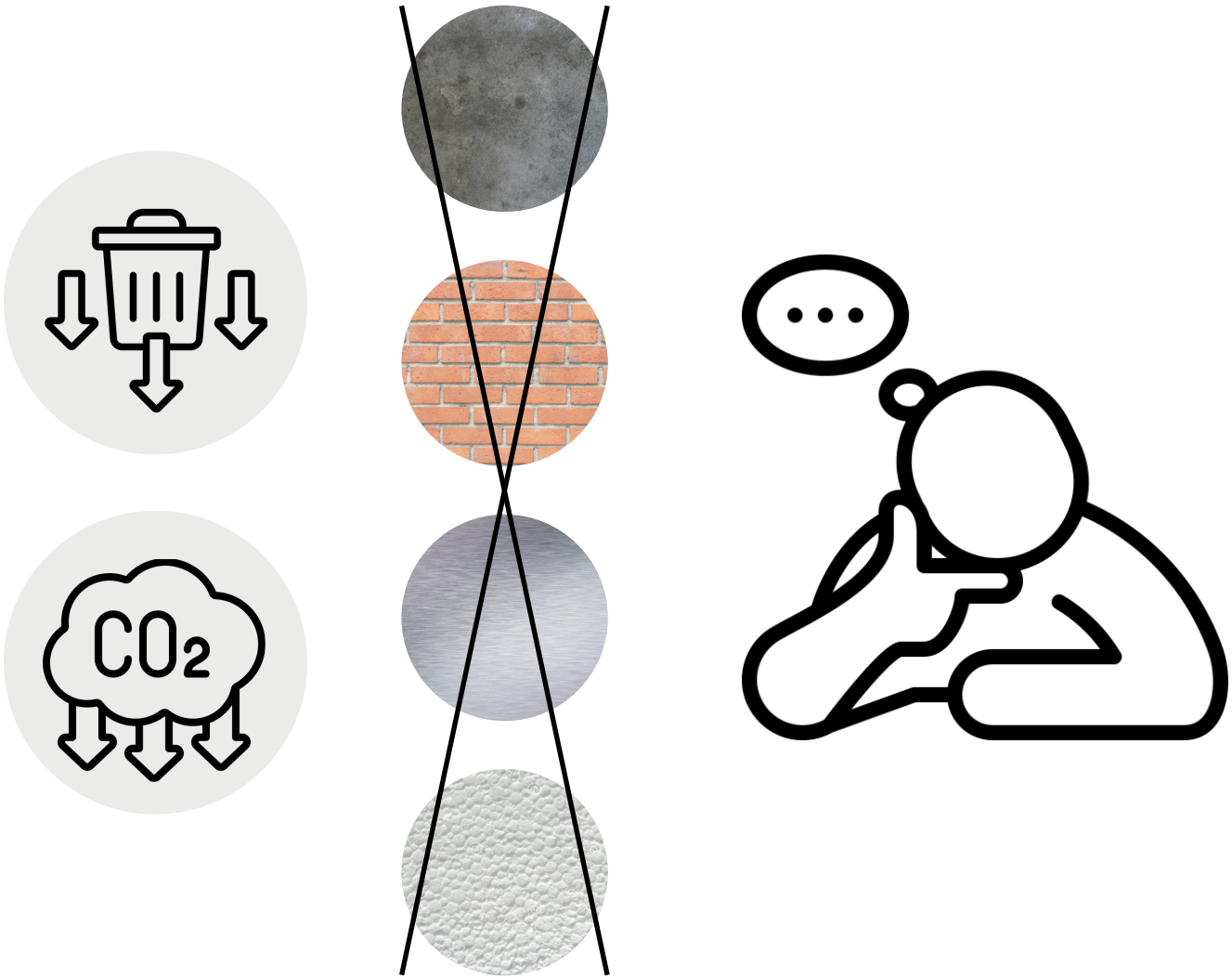


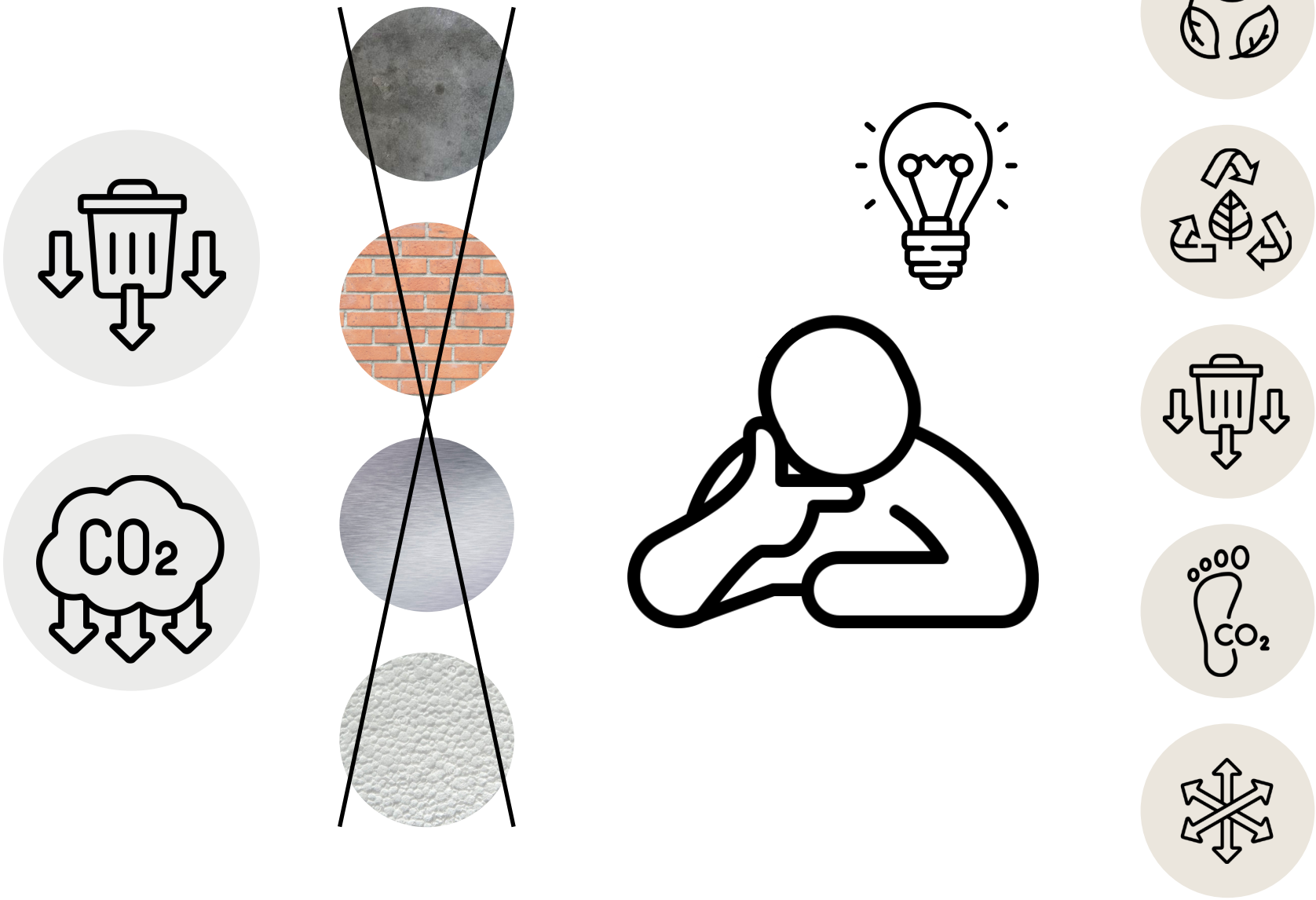
Solutions

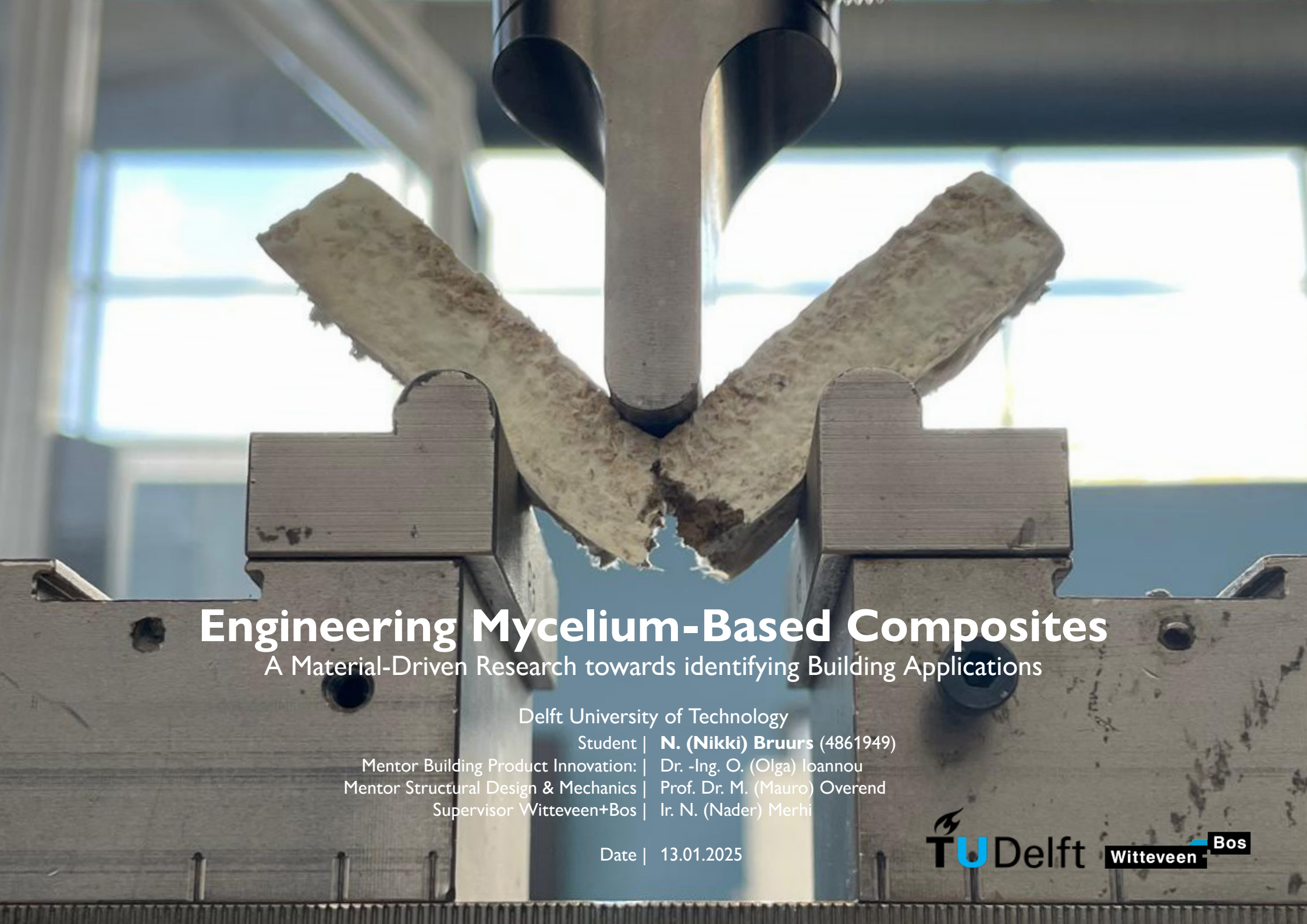
Circular economy






CO2


CO2
CO2



Engineering Mycelium-Based Composites

A Material-Driven Research towards identifying Building Applications

Delft University of Technology

Student | **N. (Nikki) Bruurs** (4861949)

Mentor Building Product Innovation: | Dr. -Ing. O. (Olga) Ioannou

Mentor Structural Design & Mechanics | Prof. Dr. M. (Mauro) Overend

Supervisor Witteveen+Bos | Ir. N. (Nader) Merhi

Date | 13.01.2025

TU Delft

Witteveen Bos

Interest

Floriade, Almere, 17.09.2022

The Growing Pavilion (left) & The Living Shelter (right)

Interest

Floriade, Almere, 17.09.2022

Mogu Acoustic panels

Contents

01 Research questions

How can **mycelium-based composites** be engineered and optimized for use as a **building element** in **internal applications**?

1. What is a mycelium-based composite?

1.1 Growing process
1.2 Applications
1.3 Advantages and disadvantages

2. What different combinations of substrate and fungal species can be used to make mycelium-based composite suitable for sustainable building elements?

2.1 Substrates
2.2 Fungal species
2.3 Optimal growing process
2.4 Mechanical properties

3. How can mycelium-based composite be designed and manufactured as a building product for internal use?

3.1 Manufacture
3.2 Design

How can **mycelium-based composites** be engineered and optimized for use as a **building element** in **internal applications**?

Literature review

1. What is a mycelium-based composite?

1.1 Growing process
1.2 Applications
1.3 Advantages and disadvantages

Experimentation

2. What different combinations of substrate and fungal species can be used to make mycelium-based composite suitable for sustainable building elements?

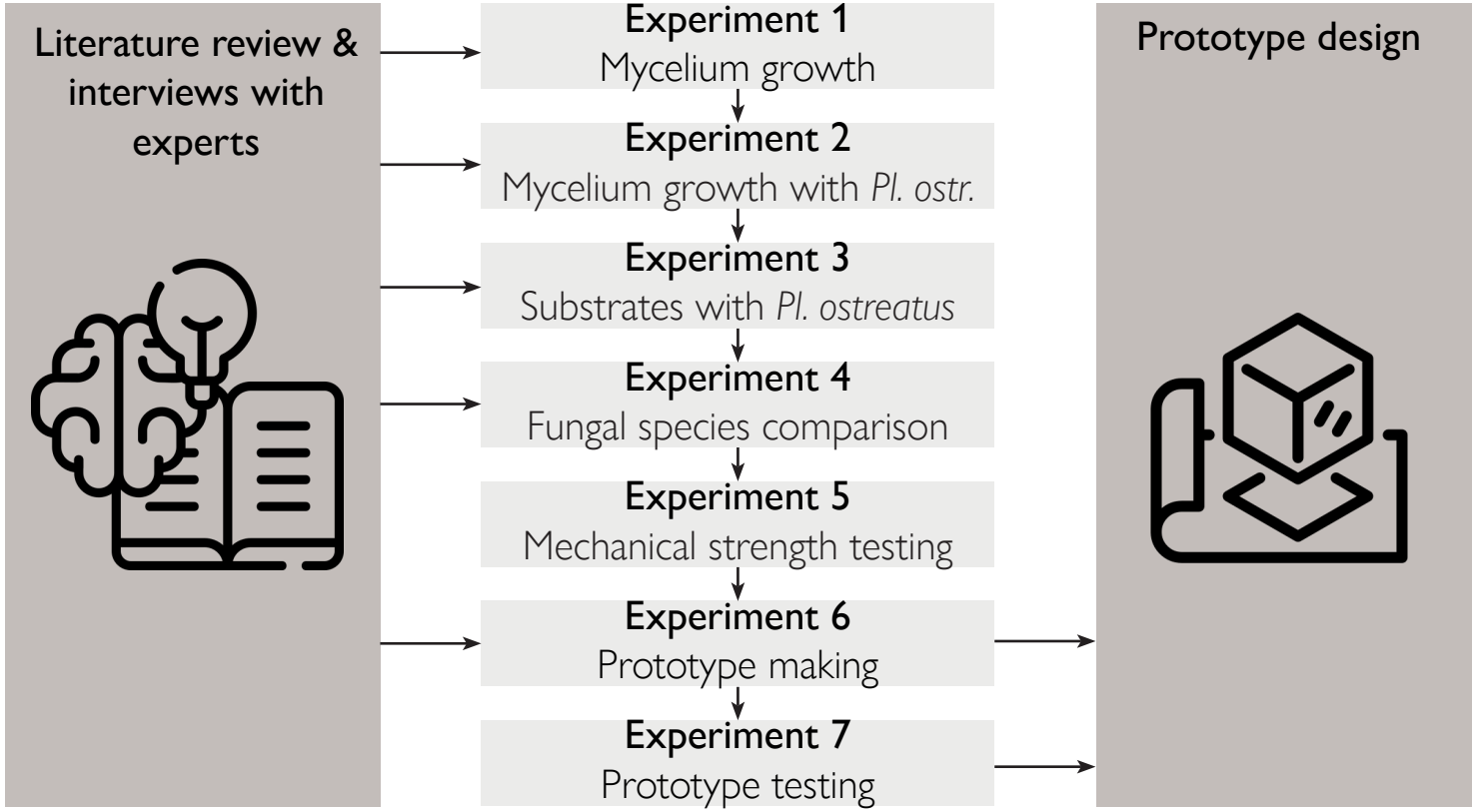
2.1 Substrates
2.2 Fungal species
2.3 Optimal growing process
2.4 Mechanical properties

Design & manufacture

3. How can mycelium-based composite be designed and manufactured as a building product for internal use?

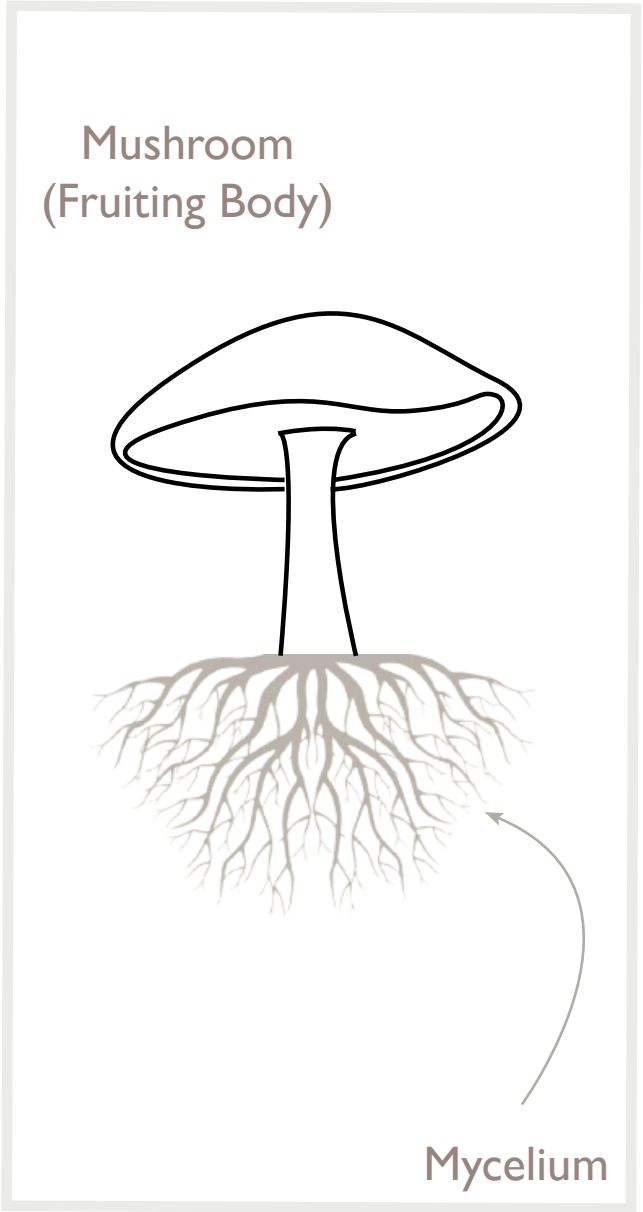
3.1 Manufacture
3.2 Design

How can **mycelium-based composites** be engineered and optimized for use as a **building element** in **internal applications**?

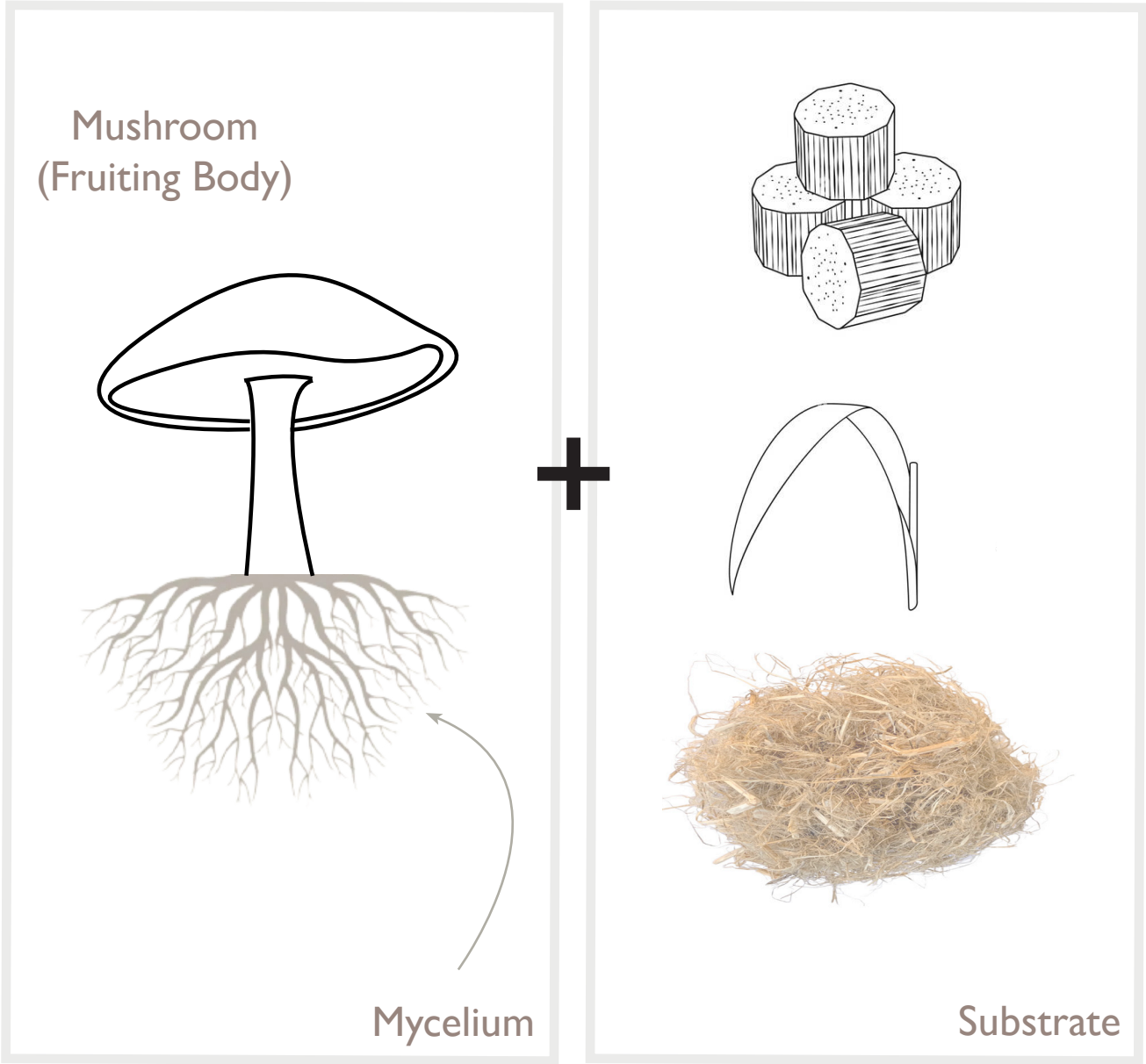


02 Background research

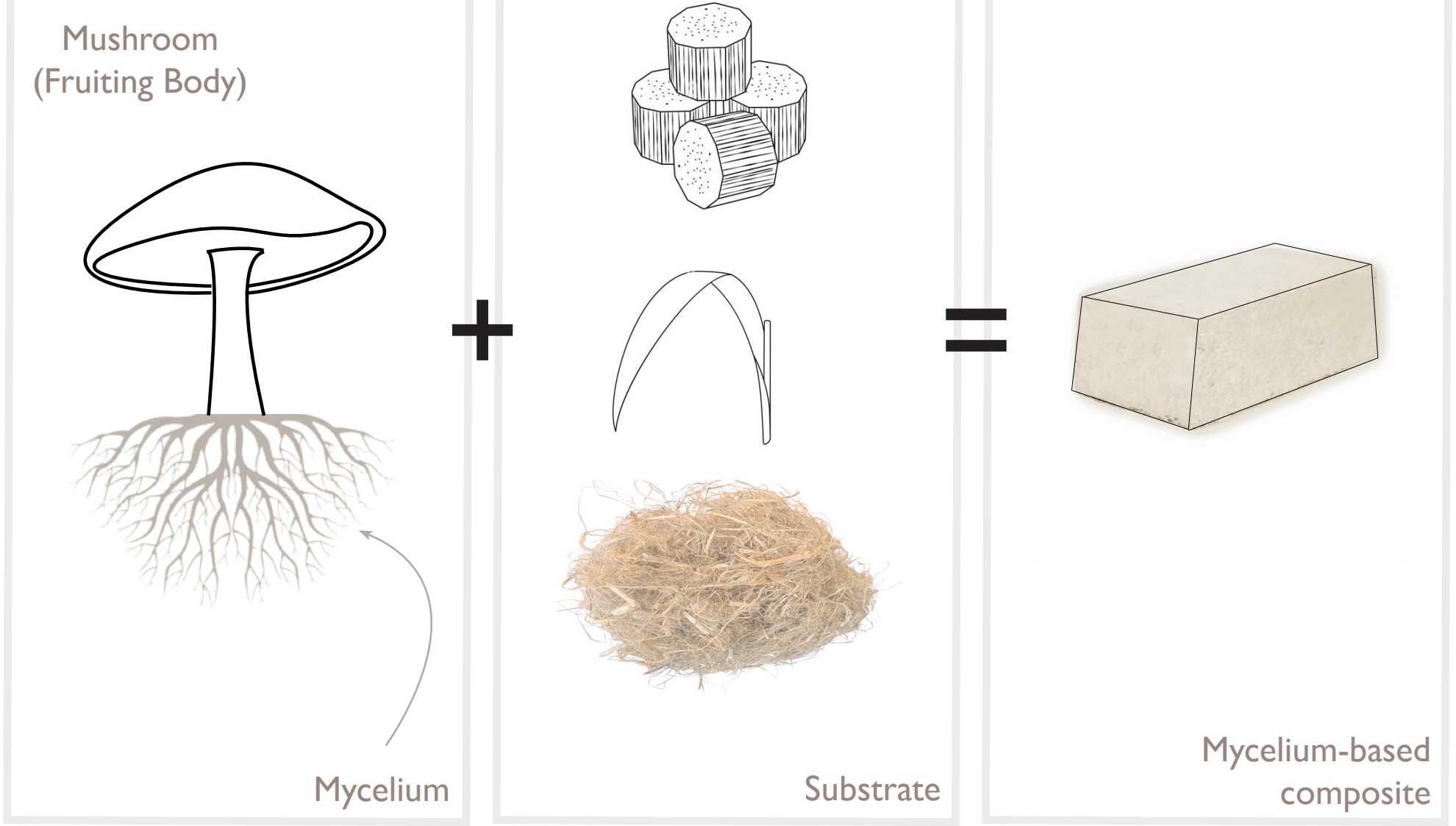
What is mycelium-based composite?



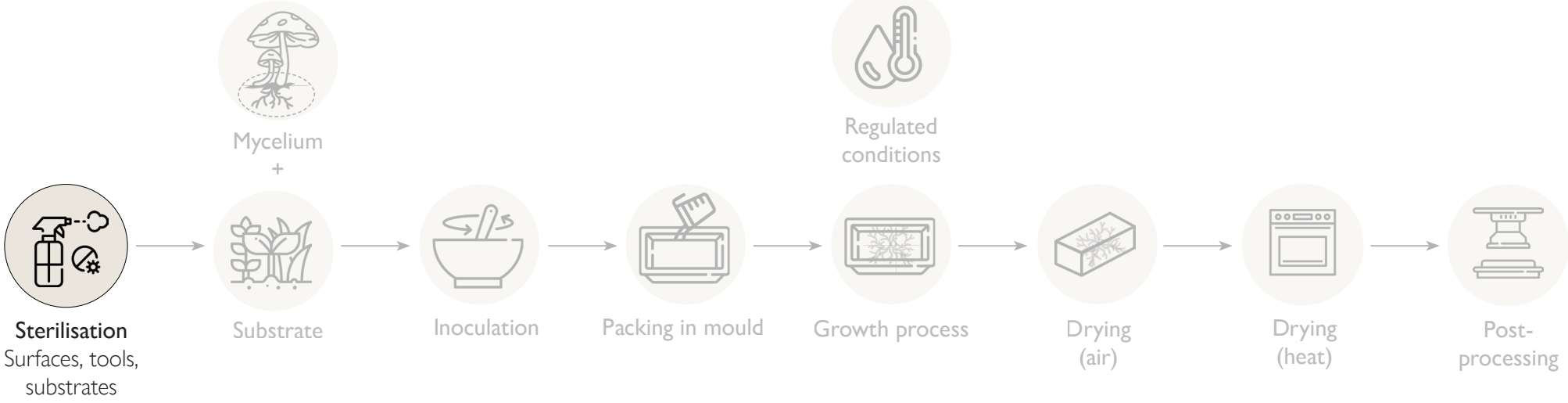
What is mycelium-based composite?

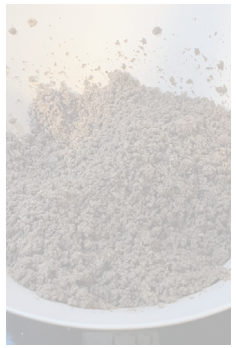


What is mycelium-based composite?



How to make mycelium-based composite?





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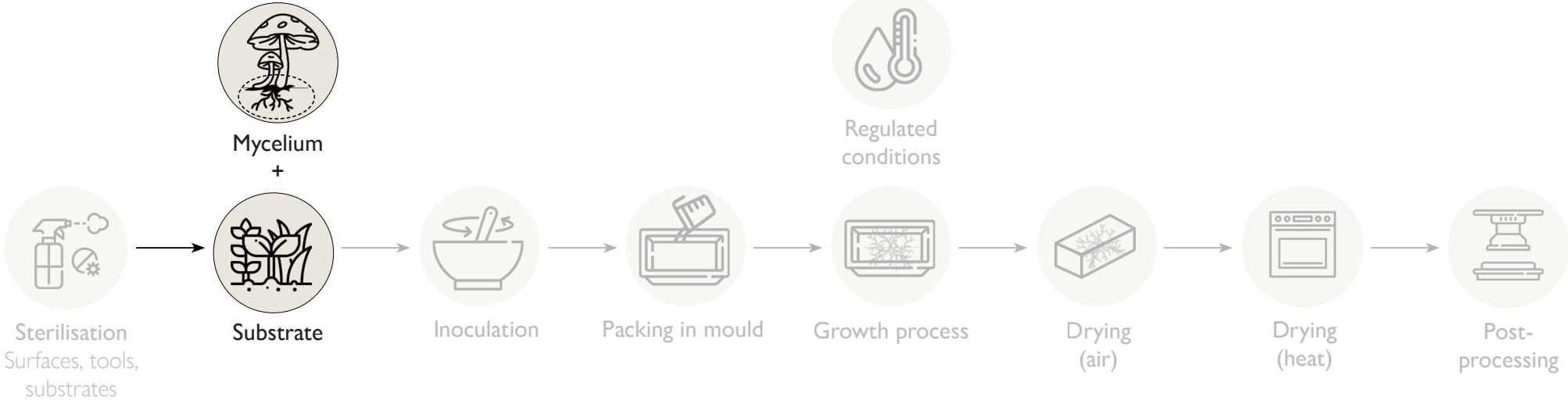

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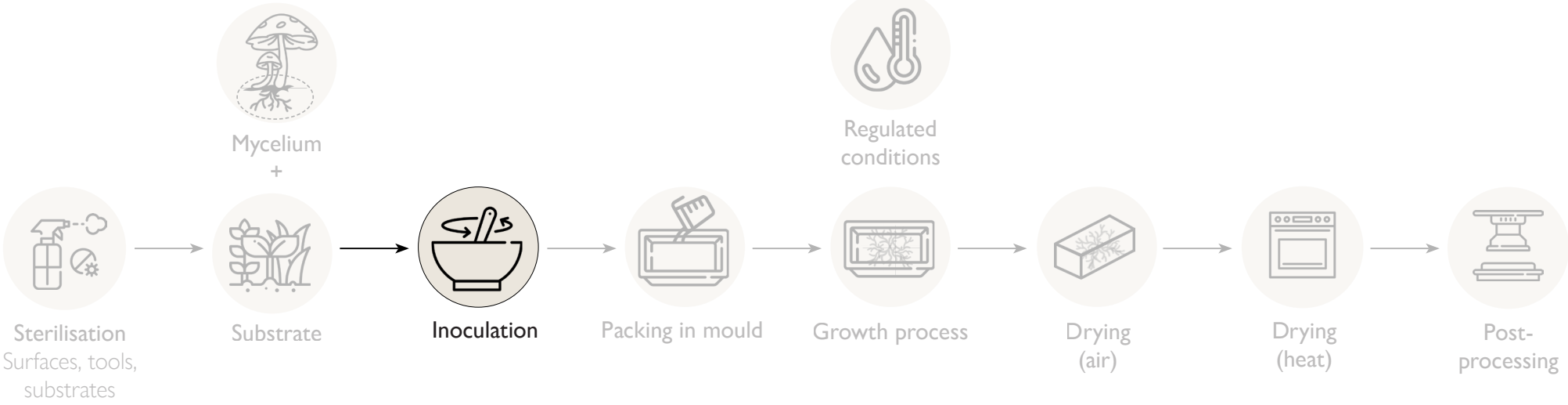
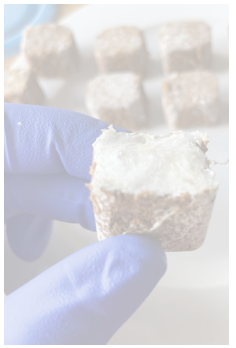
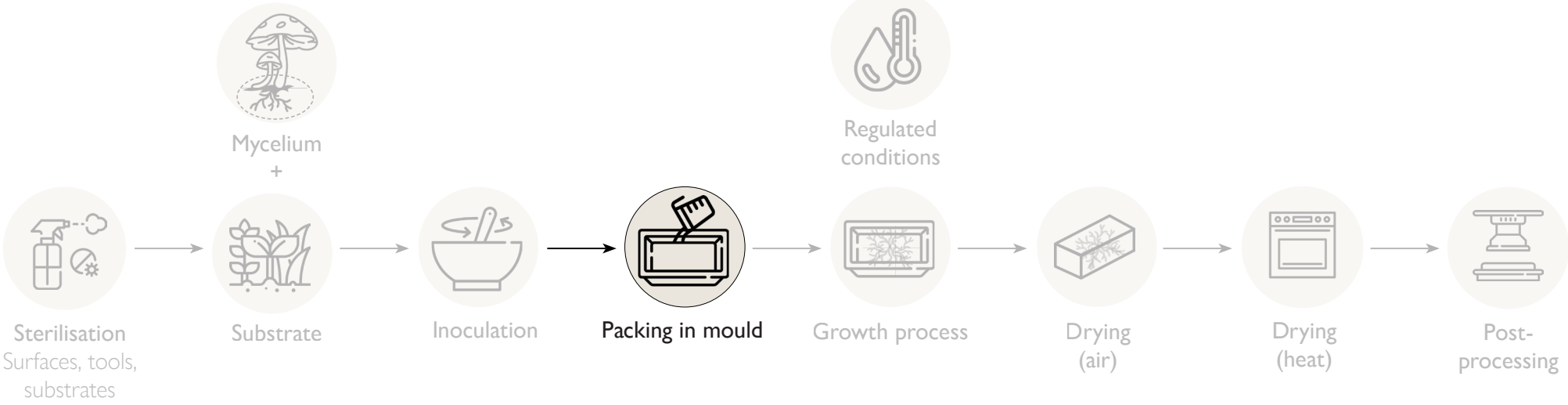




How to make mycelium-based composite?



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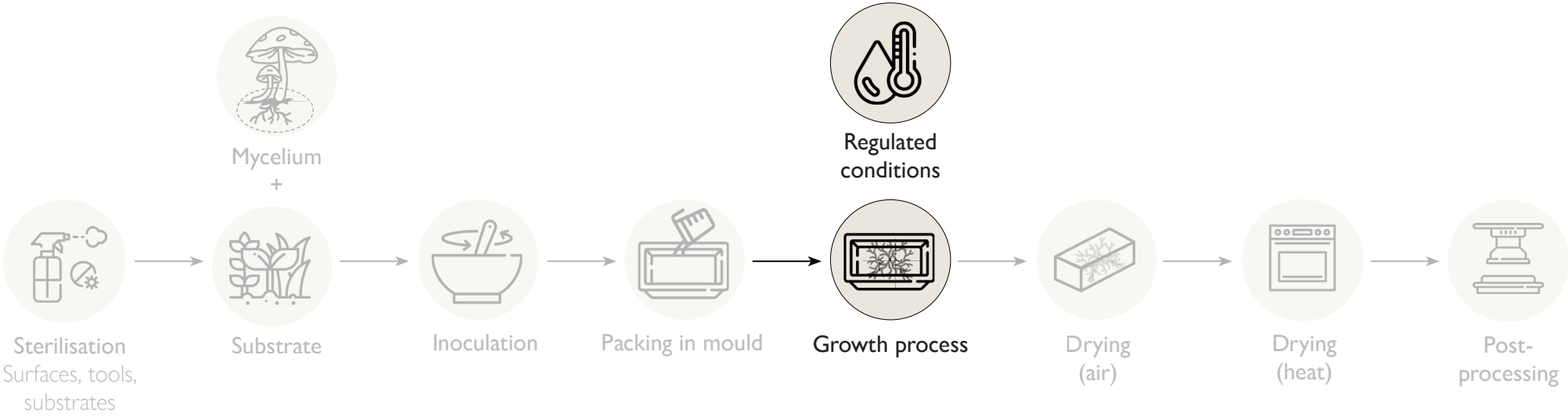

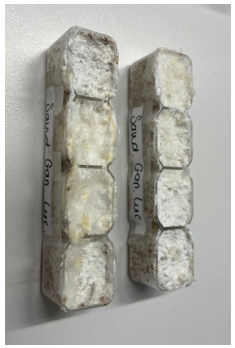

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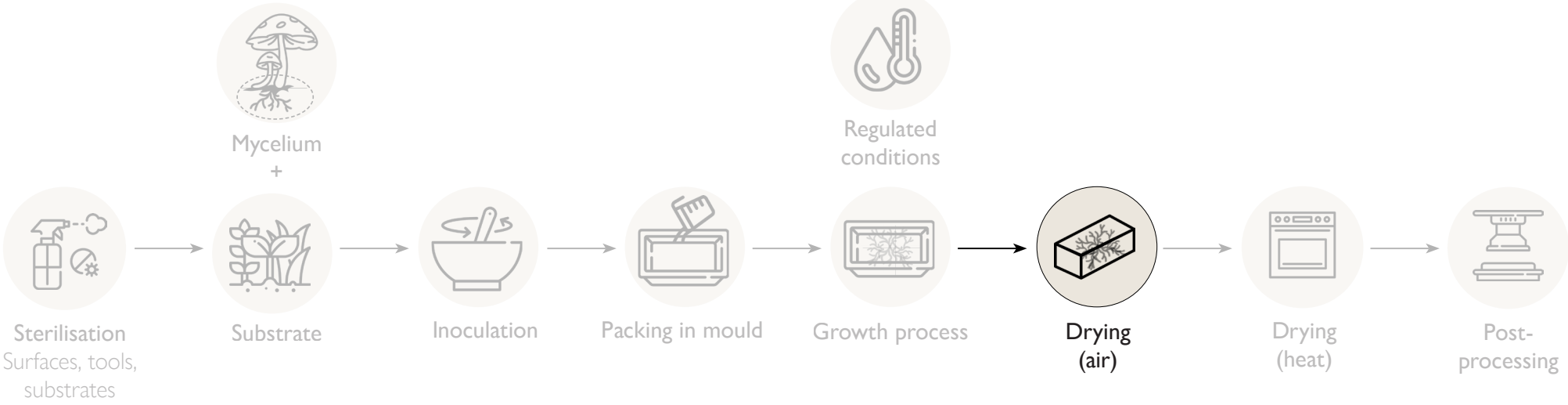

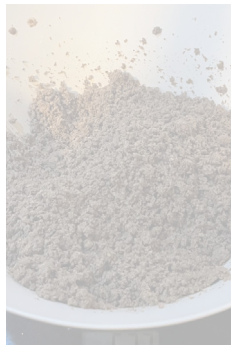

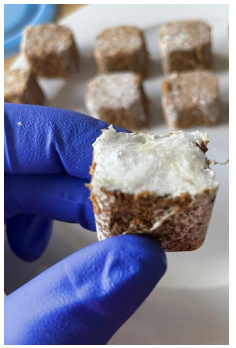

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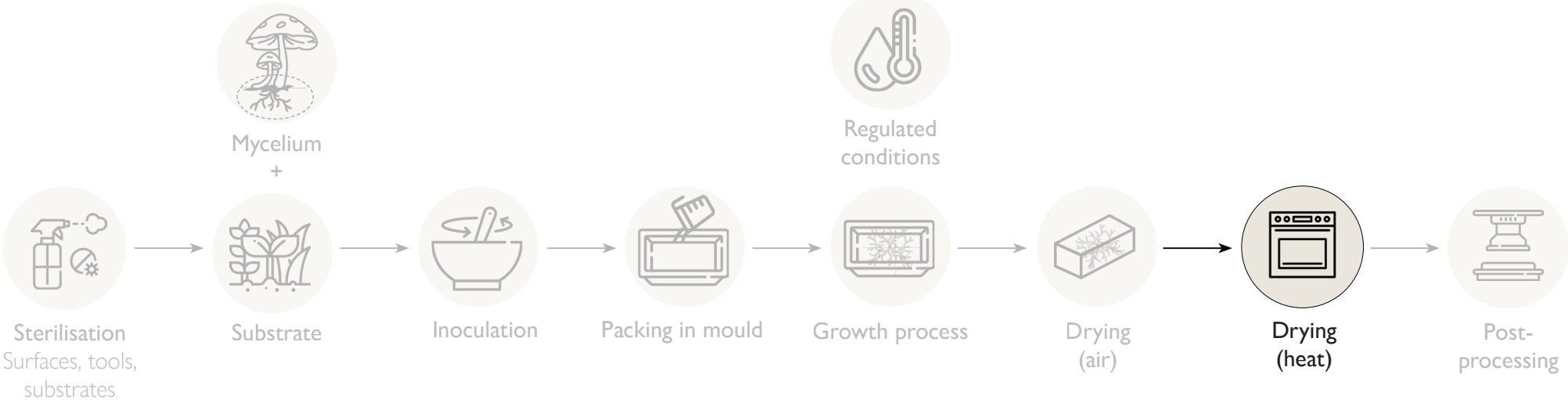

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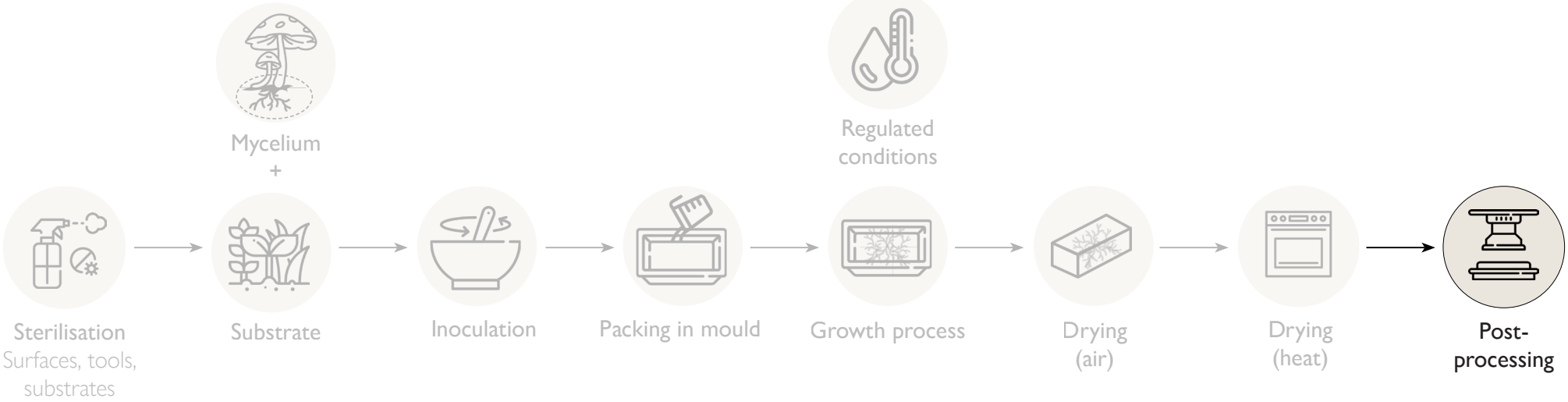

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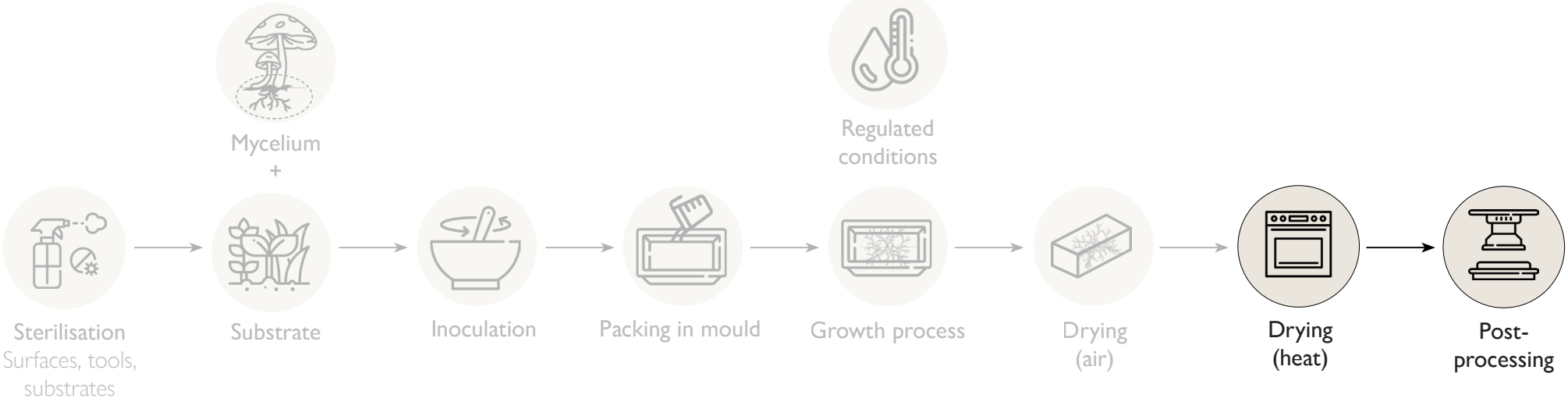
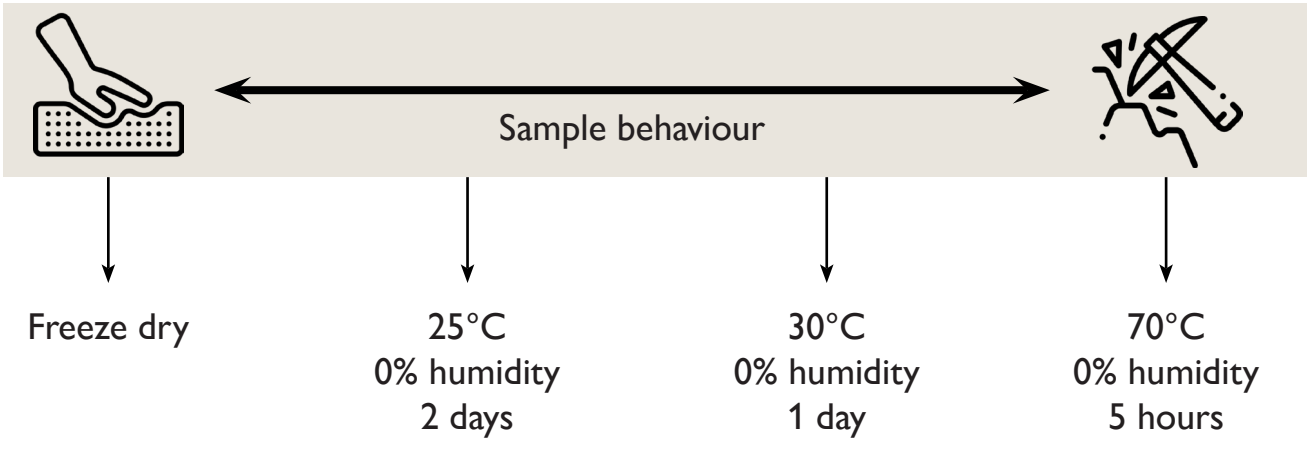
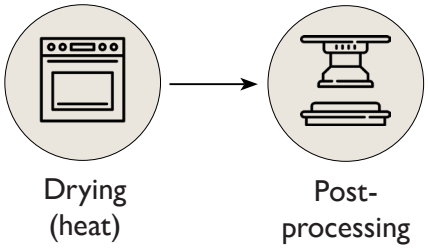


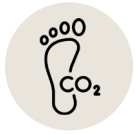
Sample behaviour





Aerospace Engineering Lab, TU Delft

Mycelium-based composite advantages


Reduce CO2 emissions by production in large scale


Easily biodegradable or compostable at the end of life


Very little waste during production


Multifunctional and versatile


100% Bio-based (mycelium + bio-based substrate)


No difficult tools or machines needed


Lightweight


Thermal and acoustic insulation values

Advantages & limitations

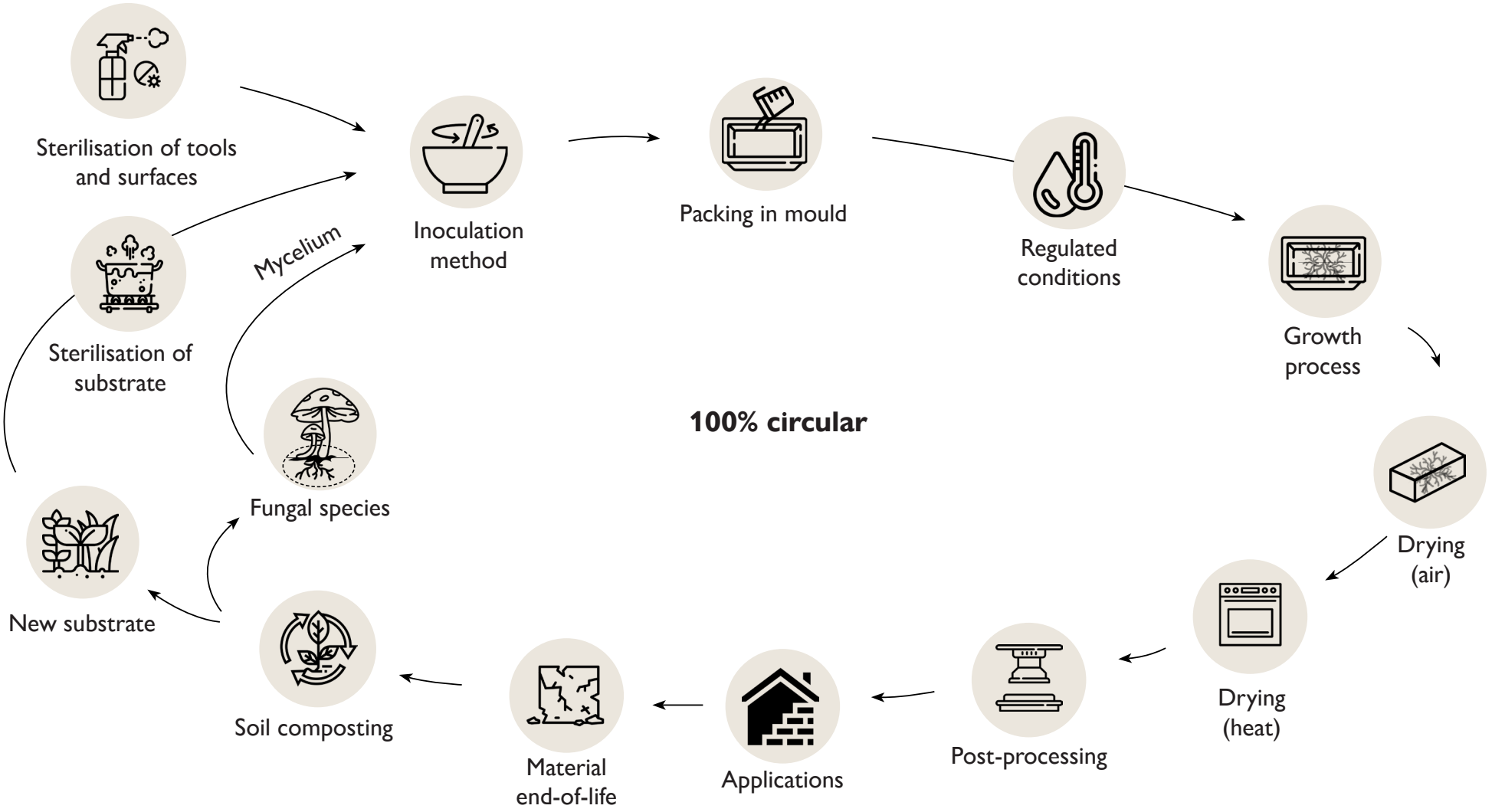
Mycelium-based composite advantages

- Reduce CO2 emissions by production in large scale
- Easily biodegradable or compostable at the end of life
- Very little waste during production
- Multifunctional and versatile
- 100% Bio-based (mycelium + bio-based substrate)
- No difficult tools or machines needed
- Lightweight
- Thermal and acoustic insulation values

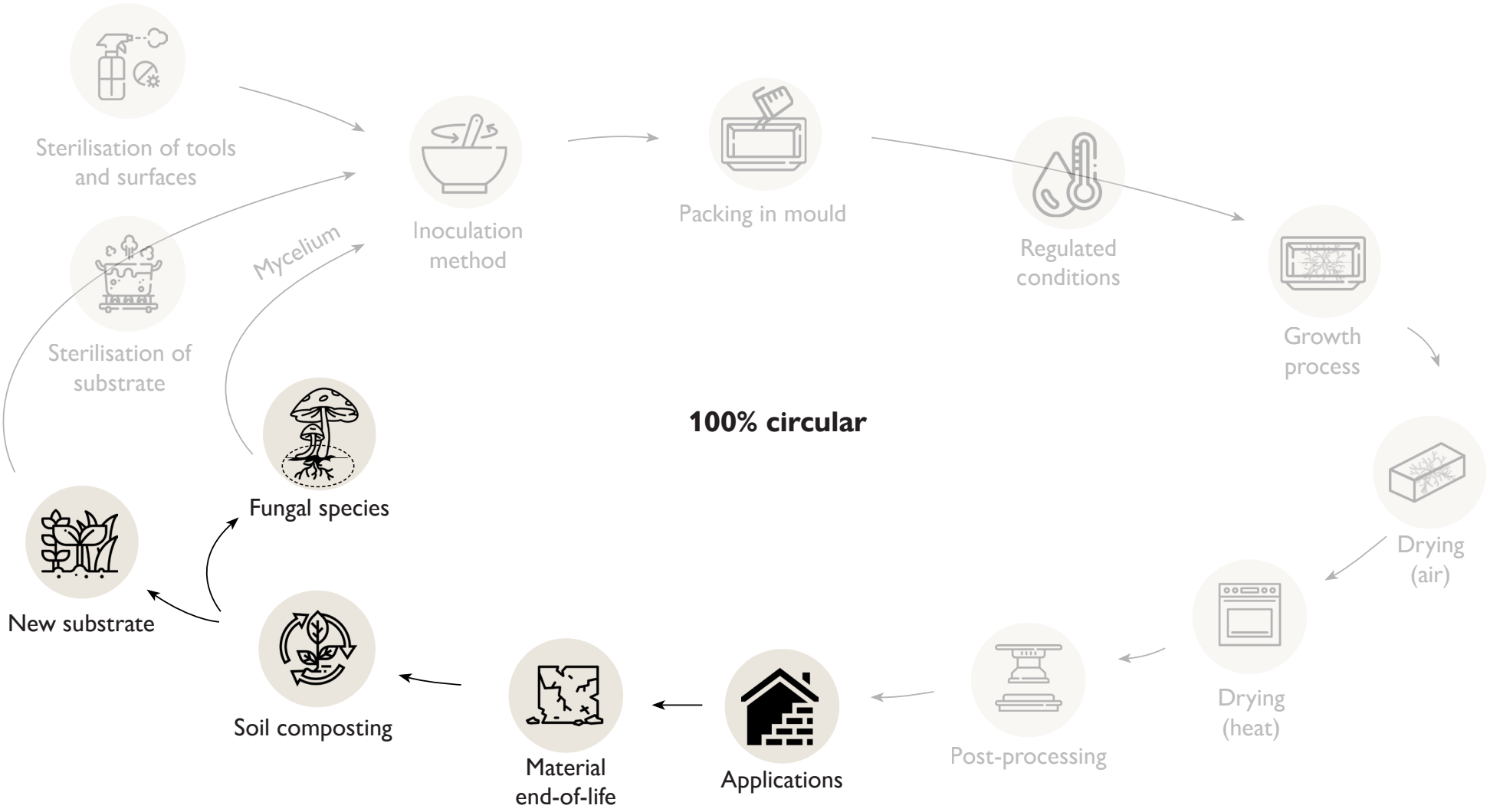
Limitations

- Low mechanical strength
- Shorter lifespan than traditional construction materials

Life cycle


Sterilisation of tools and surfaces
Sterilisation of substrate
Mycelium
Inoculation method
Packing in mould
Regulated conditions
Growth process
Drying (air)
Drying (heat)
Post-processing
Applications
Material end-of-life
Soil composting
New substrate
Fungal species
100% circular

Life cycle


Sterilisation of tools and surfaces
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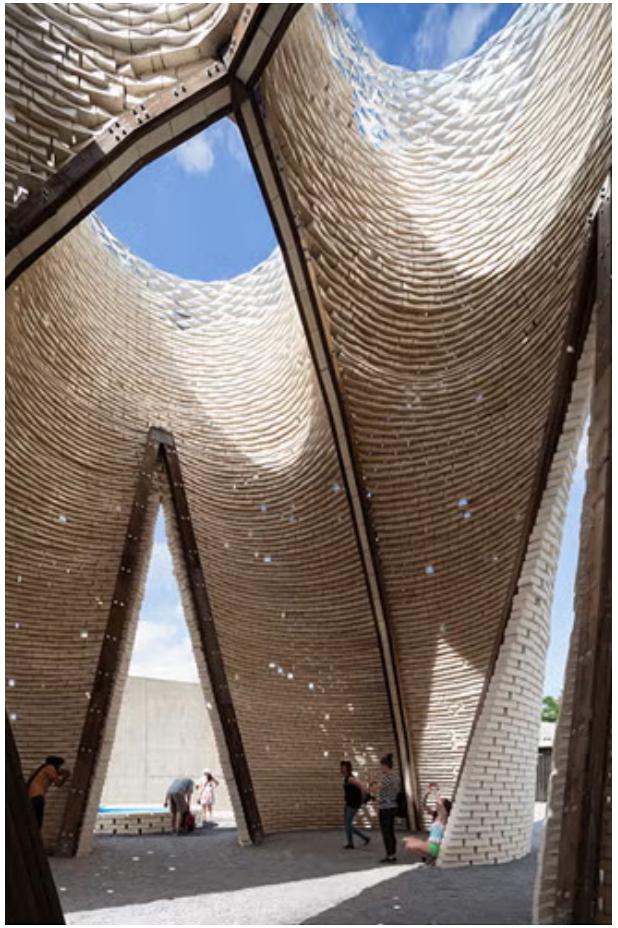
Applications
Material end-of-life
Soil composting
New substrate
Fungal species
100% circular

Hy-Fi, New York, 2014



Largest MBC building project

Mogu, 2022

The first mycelium-based product on the market

Mechanical strength comparison

		Mechanical properties			Physical properties		
	Material	**Compressive strength**	**Tensile Strength**	**Young's modulus**	**Density**	**Thermal conductivity**	**Source**
		[MPa]	[MPa]	[GPa]	[kg/m^3]	[W/mK]	
Bio-based materials	**Bamboo**	60 - 99,9	160 - 319	15,1 - 19,9	602 - 797	0,185 - 0,196	Granta EduPack 2023
	Cardboard	41 - 55	23 - 51	3 - 8,9	480 - 860	0,05 - 0,1	Granta EduPack 2023
	Cork	1 - 2	1 - 2,5	0,025 - 0,05	160 - 240	0,04	Granta EduPack 2023
	Cotton	-	360 - 660	7 - 12	1,52e3 - 1,56e^3	0,04 - 0,05	Granta EduPack 2023
	Egg shell	180 - 200	50 - 70	19 - 30	2,4e3 - 2,53e^3	-	Granta EduPack 2023
	Flax fiber	-	750 - 940	27 - 80	1,42e3 - 1,52e^3	0,04 - 0,05	Granta EduPack 2023
	Hemp	-	550 - 890	55 - 70	1,47e3 - 1,51e^3	0,04 - 0,06	Granta EduPack 2023
	Jute fiber	-	400 - 770	17 - 55	1,44e3 - 1,52e^3	0,038 - 0,046	Granta EduPack 2023
	Palm fiber	-	143 - 263	9,3 - 13,3	1,48e3 - 1,5e^3	-	Granta EduPack 2023
	Sawdust oak (l, quercus spp.)	68,2 - 83,3	133 - 162	20,6 - 25,2	850 - 1,03e3	0,07 - 0,12	Granta EduPack 2023
	Sawdust oak (t, quercus spp.)	12,8 - 15,6	7,1 - 8,7	5 - 5.58	850 - 1,03e3	0,07 - 0,12	Granta EduPack 2023
	Silk	-	340 - 720	5 - 25	1,26e3 - 1,35e^3	0,04 - 0,05	Granta EduPack 2023
	Straw bale	0,16 - 0,48	0,01 - 0,02	5e-4 - 0,002	80 - 191	0,045 - 0,065	Granta EduPack 2023
	Sugarcane fiber	-	190 - 260	17,9 - 27,1	1,22e3 - 1,28e^3	0,048 - 0,05	Granta EduPack 2023
	Wool	-	50 - 290	2,3 - 5	1,28e3 - 1,34e^3	0,038 - 0,043	Granta EduPack 2023
Building materials	**Concrete (insulating lightweight)**	0,5 - 2,8	0,1 - 0,3	0,6 - 1,53	900 - 1,4e3	0,1 - 0,7	Granta EduPack 2023
	High density concrete	30,6 - 36,6	3,1 - 3,7	40,2 - 41,6	4,9e3 - 5,5e3	1,6 - 2,5	Granta EduPack 2023
	Low alloy steel, SAE 8630, cast, quenched & tempered	827 - 914	915 - 1,01e3	196 - 204	7,81e3 - 7,84e3	42 - 48	Granta EduPack 2023
	Stainless steel, austentic, AMST CH-10, cast, water quenched	333 - 363	547 - 667	189 - 197	7,67e3 - 7,77e3	14 - 16	Granta EduPack 2023
	Timber: oak (l, quercus spp.)	68,2 - 83,3	133 - 162	20,6 - 25,2	850 - 1,03e3	0,16 - 0,2	Granta EduPack 2023
	Timber: oak (t, quercus spp.)	12,8 - 15,6	7,1 - 8,7	5 - 5.58	850 - 1,03e3	0,16 - 0,2	Granta EduPack 2023
	Mycelium-based composites	0,17 - 1,1	0,03 - 0,18	0,05e-3 - 0,29e-3*	59 - 552	0,05	(Jones et al., 2020)

Mechanical strength comparison

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	Low alloy steel, SAE 8630, cast, quenched & tempered	827 - 914	915 - 1,01e3	196 - 204	7,81e3 - 7,84e3	42 - 48	Granta EduPack 2023
	Stainless steel, austentic, AMST CH-10, cast, water quenched	333 - 363	547 - 667	189 - 197	7,67e3 - 7,77e3	14 - 16	Granta EduPack 2023
	Timber: oak (l, quercus spp.)	68,2 - 83,3	133 - 162	20,6 - 25,2	850 - 1,03e3	0,16 - 0,2	Granta EduPack 2023
	Timber: oak (t, quercus spp.)	12,8 - 15,6	7,1 - 8,7	5 - 5.58	850 - 1,03e3	0,16 - 0,2	Granta EduPack 2023
	Mycelium-based composites	0,17 - 1,1	0,03 - 0,18	0,05e-3 - 0,29e-3*	59 - 552	0,05	(Jones et al., 2020)

Literature review: Substrate & fungal species selection

Three critaria for using a substrate:

1. Enough cellulose for the fungi to feed on;
2. Mechanical strength;
3. Formability

Three critaria for using a fungal species:

1. Rate of growth;
2. Strong connections (hyphae);
3. Resistance to external mould contamination.

Substrate selection:


Loose hemp fibers


Hemp fibers mat


Corn stalk waste (corn granules)


Coffee grain waste


Cotton cloth


Jute


Oak sawdust


Flax fibres mat

Mycelium selection:

Pleurotus ostreatus

Grain Spawn

Ganoderma lucidum

Hedelcomposite

03 Experiments

Experiment 1
Mycelium growth

↓

Experiment 2
Mycelium growth with *Pl. ostr.*

↓

Experiment 3
Substrates with *Pl. ostreatus*

↓

Experiment 4
Fungal species comparison

↓

Experiment 5
Mechanical strength testing

↓

Experiment 6
Prototype making

↓

Experiment 7
Prototype testing

Experiment 1
Mycelium growth

Experiment 1 | Mycelium growth

Better understanding

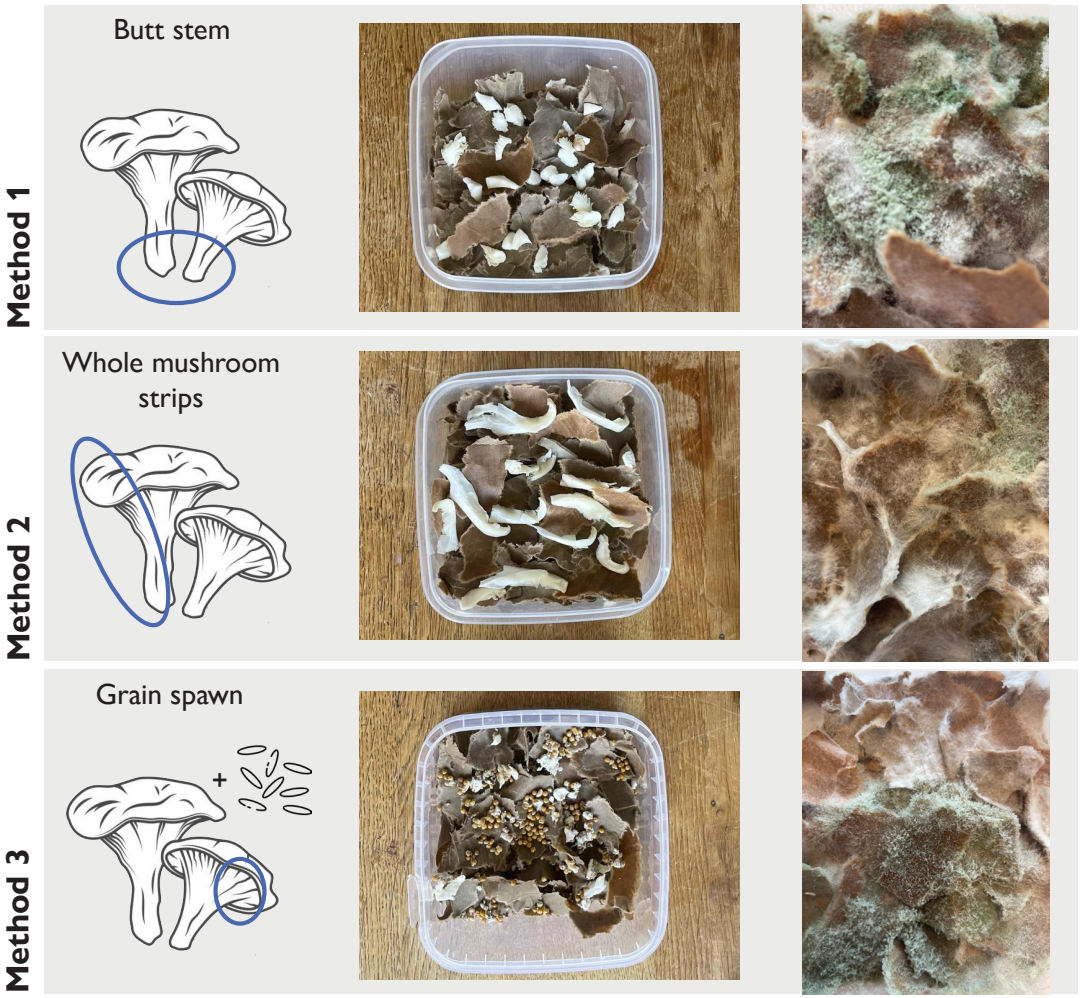





Experiment 2
Growth with 3 methods

Experiment 2 | Growth with 3 methods

Pleurotus ostreatus on cardboard



Experiment 3
Substrate testing

Experiment 3 | Substrate testing

Pleurotus ostreatus


Hemp fiber mat


Cotton


Coffee grains


Hemp fiber particles


Flax fiber mat


Jute


Corn granules

Oak sawdust (soaked)

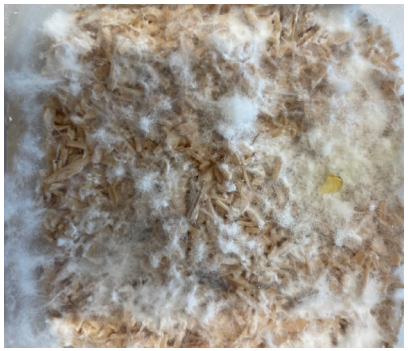
Experiment 3 | Substrate testing

Pleurotus ostreatus


Hemp fiber mat


Cotton


Coffee grains


Hemp fiber particles


Flax fiber mat

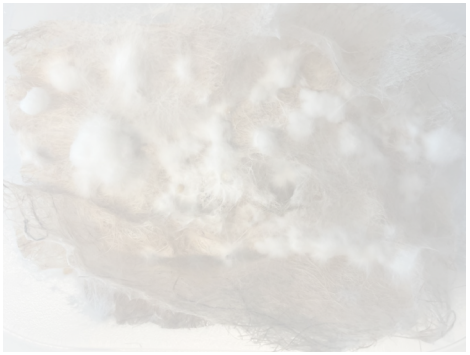

Jute


Corn granules


Oak sawdust (soaked)

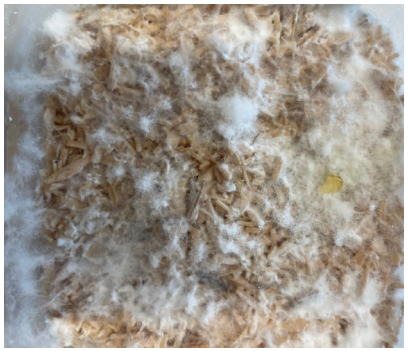
Experiment 3 | Substrate testing

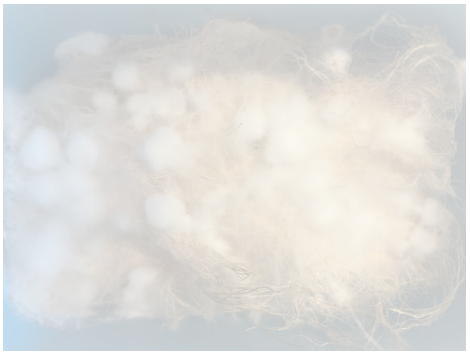
Pleurotus ostreatus


Hemp fiber mat


Cotton


Coffee grains


Hemp fiber particles


Flax fiber mat


Jute


Corn granules


Oak sawdust (soaked)

Experiment 4
Fungal species comparison

1 Mycelium growth

2 Mycelium growth with *Pl. ostreatus*

3 Substrates with *Pl. ostreatus*

4 Fungal species comparison

5 Mechanical strength testing

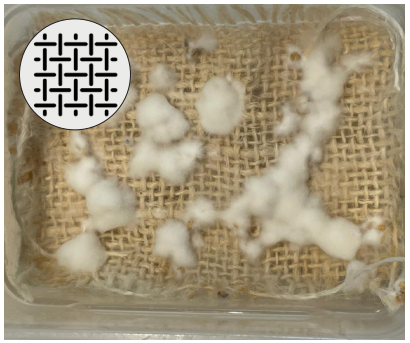
6 Prototype making

7 Prototype testing

Hemp fiber particles

Oak sawdust (soaked)

Cotton



Jute

Experiment 4 | Fungal species comparison

Pleurotus ostreatus vs. Ganoderma lucidum

1 Mycelium growth

2 Mycelium growth with *Pl. ostreatus*

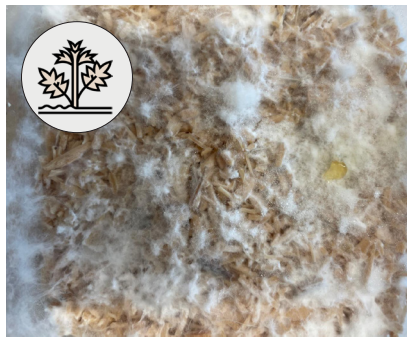
3 Substrates with *Pl. ostreatus*

4 Fungal species comparison

5 Mechanical strength testing

6 Prototype making

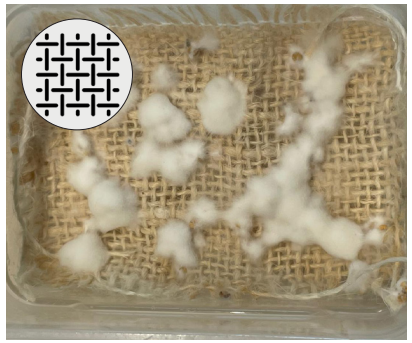
7 Prototype testing



Hemp fiber particles

Oak sawdust (soaked)

Cotton



Jute

Experiment 4 | Fungal species comparison

Pleurotus ostreatus vs. Ganoderma lucidum

Pleurotus ostreatus

Ganoderma lucidum

1 Mycelium growth

2 Mycelium growth with *Pl. ostreatus*

3 Substrates with *Pl. ostreatus*

4 Fungal species comparison

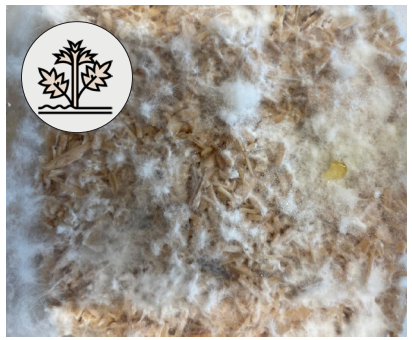
5 Mechanical strength testing

6 Prototype making

7 Prototype testing

Experiment 4 | Fungal species comparison

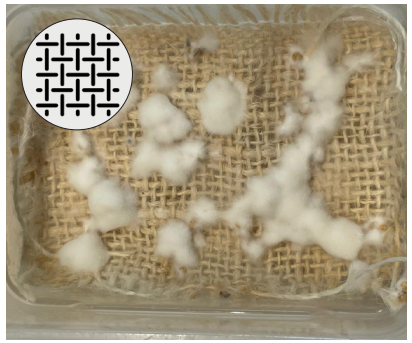
Pleurotus ostreatus vs. Ganoderma lucidum



Hemp fiber particles

Oak sawdust (soaked)

Cotton



Jute

Pleurotus ostreatus

Ganoderma lucidum

1 Mycelium growth

2 Mycelium growth with *Pl. ostreatus*

3 Substrates with *Pl. ostreatus*

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7 Prototype testing

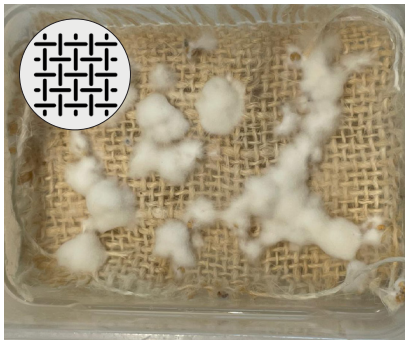
Experiment 4 | Fungal species comparison

Pleurotus ostreatus vs. Ganoderma lucidum

Hemp fiber particles

Oak sawdust (soaked)

Cotton



Jute

Pleurotus ostreatus

Ganoderma lucidum

1 Mycelium growth

2 Mycelium growth with *Pl. ostreatus*

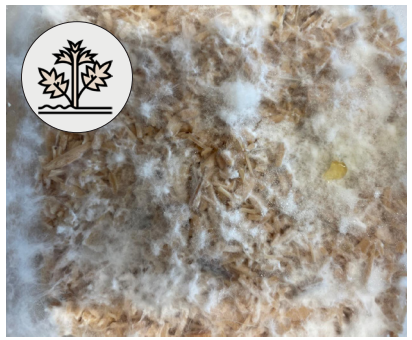
3 Substrates with *Pl. ostreatus*

4 Fungal species comparison

5 Mechanical strength testing

6 Prototype making

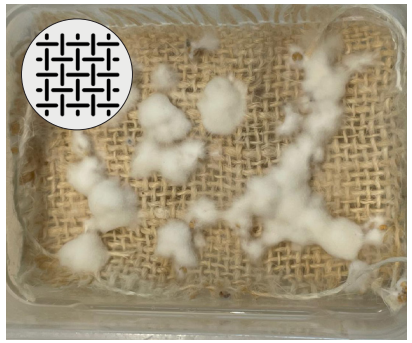
7 Prototype testing



Hemp fiber particles

Oak sawdust (soaked)

Cotton



Jute

Experiment 4 | Fungal species comparison

Pleurotus ostreatus vs. Ganoderma lucidum

Pleurotus ostreatus

Three criteria for using fungal species

1. Rate of growth:
Consistent and fast growing rate;

2. Strong connections (hyphae):
Will be examined in the following chapter;

3. Resistance to external mould contamination:
Acceptable level of resistance.

Ganoderma lucidum

Three criteria for using fungal species

1. Rate of growth;
Not consistent, but accelerated growth in the later stages.

2. Strong connections (hyphae);
Will be examined in the following chapter, but existing literature indicates that it has strong hyphae.

3. Resistance to external mould contamination.
Acceptable level of resistance.

1 Mycelium growth

2 Mycelium growth with *Pl. ostreatus*

3 Substrates with *Pl. ostreatus*

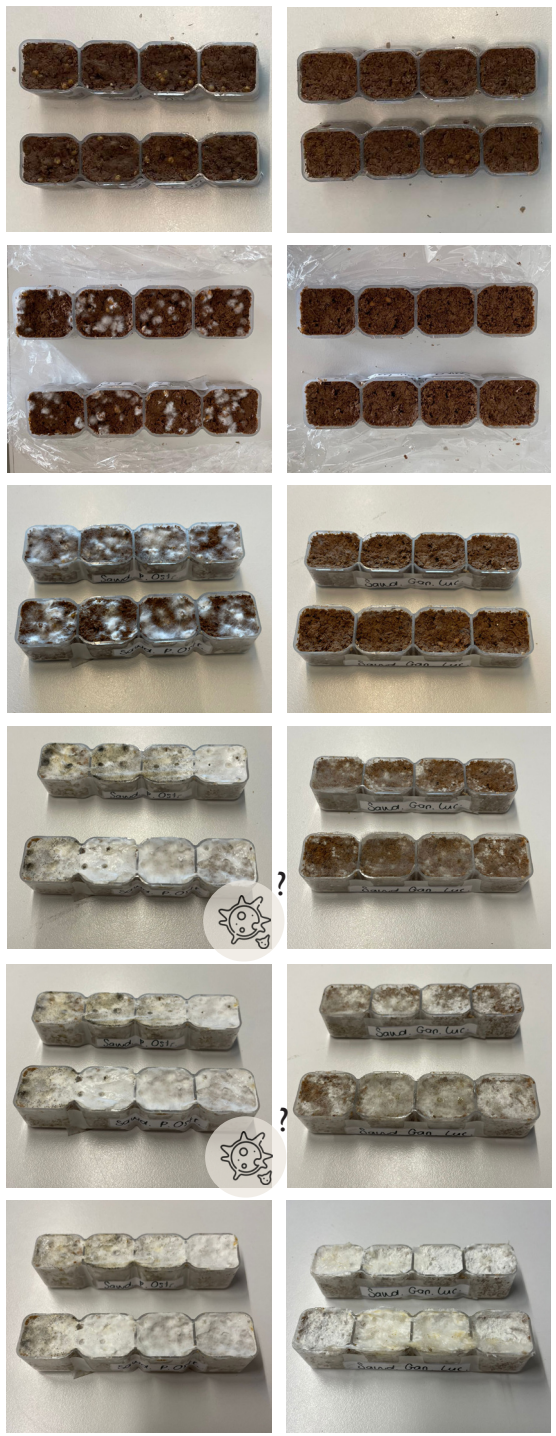
4 Fungal species comparison

5 Mechanical strength testing

6 Prototype making

7 Prototype testing

Sawdust



Experiment 4 | Fungal species comparison

Pleurotus ostreatus vs. Ganoderma lucidum

Pleurotus ostreatus

Three criteria for using fungal species

1. Rate of growth:
Consistent and fast growing rate; ✓

2. Strong connections (hyphae):
Will be examined in the following chapter; ?

3. Resistance to external mould contamination:
Acceptable level of resistance. ✓

Ganoderma lucidum

Three criteria for using fungal species

1. Rate of growth;
Not consistent, but accelerated growth in the later stages. ✓

2. Strong connections (hyphae);
Will be examined in the following chapter, but existing literature indicates that it has strong hyphae. ?

3. Resistance to external mould contamination.
Acceptable level of resistance. ✓

1 Mycelium growth

2 Mycelium growth with *Pl. ostreatus*

3 Substrates with *Pl. ostreatus*

4 Fungal species comparison

5 Mechanical strength testing

6 Prototype making

7 Prototype testing

Hemp

	Pleurotus ostreatus	*Ganoderma lucidum*
Day 1		
Day 3		
Day 5		
Day 8		 ?
Day 10		 ?
Day 12		

Experiment 4 | Fungal species comparison

Pleurotus ostreatus vs. Ganoderma lucidum

Pleurotus ostreatus

Three criteria for using fungal species

1. Rate of growth:
Consistent and fast growing rate; ✓

2. Strong connections (hyphae):
Will be examined in the following chapter; ?

3. Resistance to external mould contamination:
Acceptable level of resistance. ✓

Ganoderma lucidum

Three criteria for using fungal species

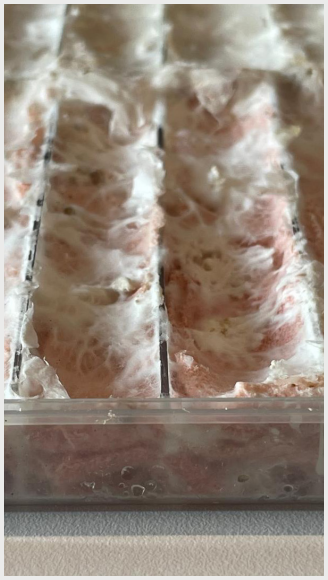
1. Rate of growth;
Not consistent, but accelerated growth in the later stages. ✓

2. Strong connections (hyphae);
Will be examined in the following chapter, but existing literature indicates that it has strong hyphae. ?

3. Resistance to external mould contamination.
Acceptable level of resistance. ✓

Fungal species comparison

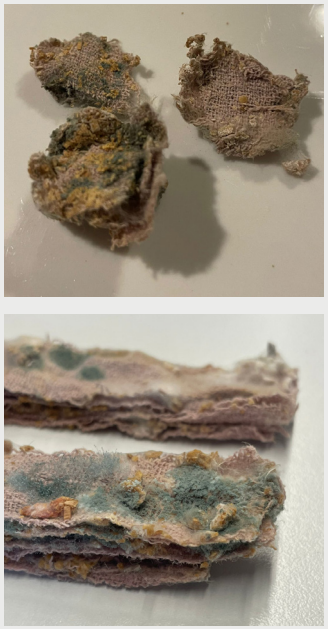
Pleurotus ostreatus vs. Ganoderma lucidum



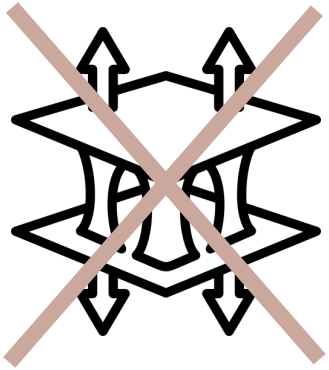
Cotton + *Pleurotus ostreatus*

Jute + *Pleurotus ostreatus*

Cotton + *Ganoderma lucidum*

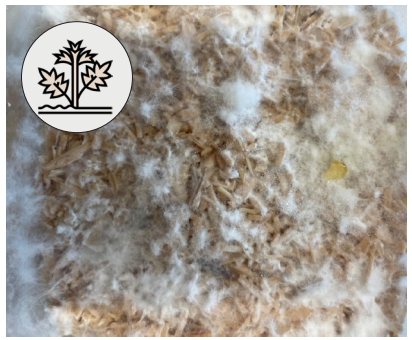


Jute + *Ganoderma lucidum*



Fungal species comparison

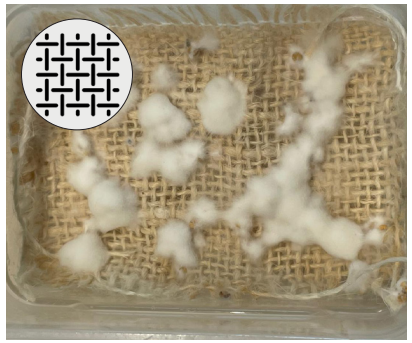
Pleurotus ostreatus vs. Ganoderma lucidum



Hemp fiber particles

Oak sawdust (soaked)

Cotton



Jute

Pleurotus ostreatus

Ganoderma lucidum

Fungal species comparison

Pleurotus ostreatus vs. Ganoderma lucidum

Hemp fiber particles

Oak sawdust (soaked)

Cotton

Jute

Pleurotus ostreatus

Ganoderma lucidum

Fungal species comparison

Pleurotus ostreatus vs. Ganoderma lucidum

Hemp fiber particles

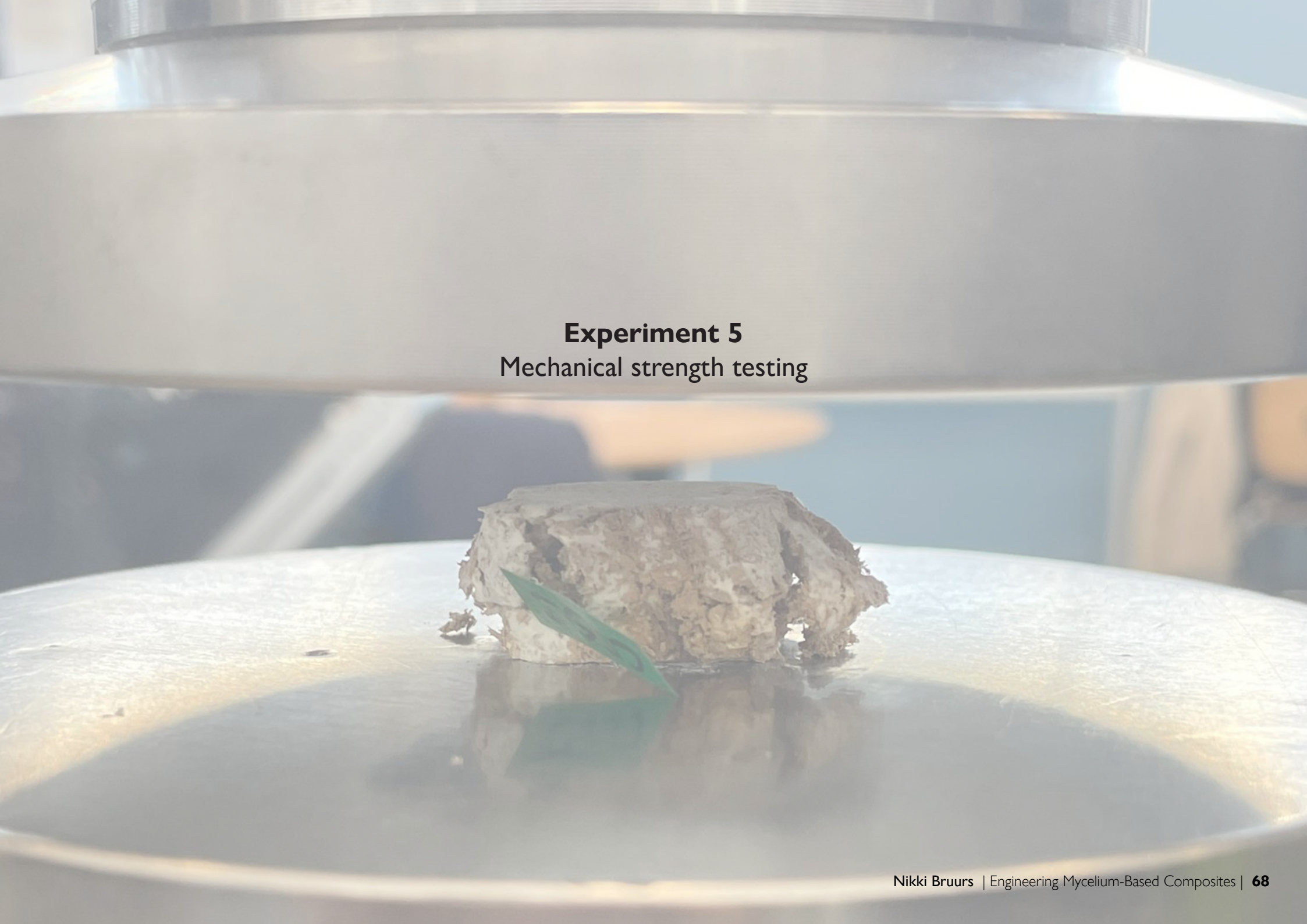
Oak sawdust (soaked)

Cotton

Jute

Pleurotus ostreatus

Ganoderma lucidum



Experiment 5
Mechanical strength testing

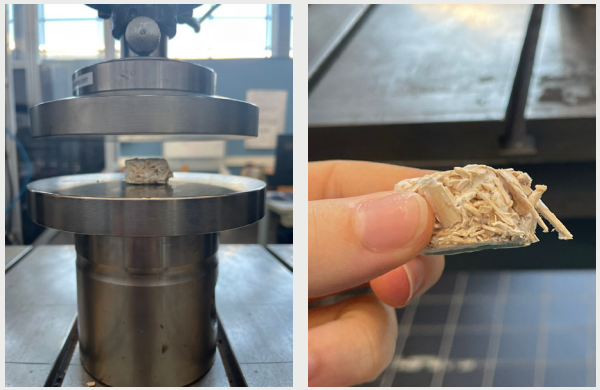
Experiment 5 | Mechanical strength testing

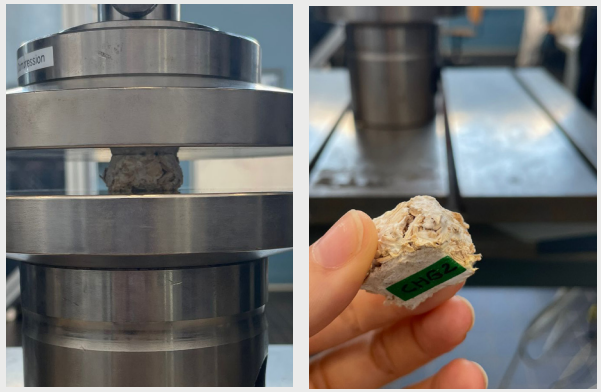
Compression

Pleurotus ostreatus

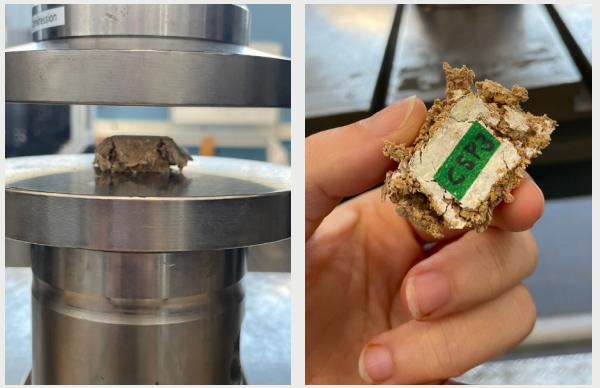
Ganoderma lucidum

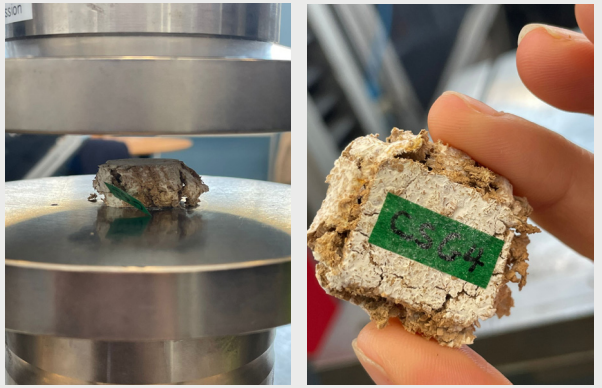
Hemp





Sawdust





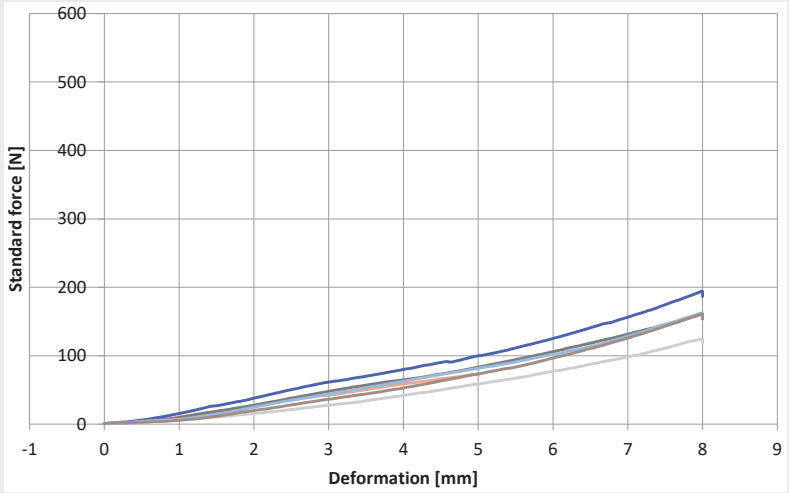
Experiment 5 | Mechanical strength testing

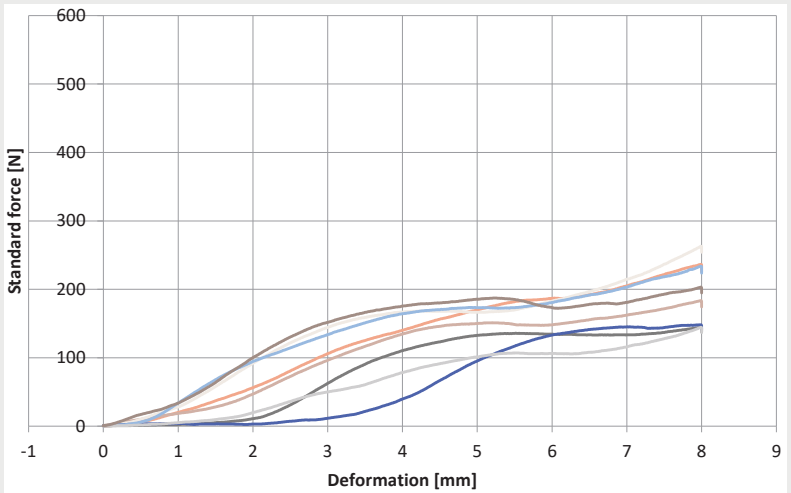
Compression

Hemp

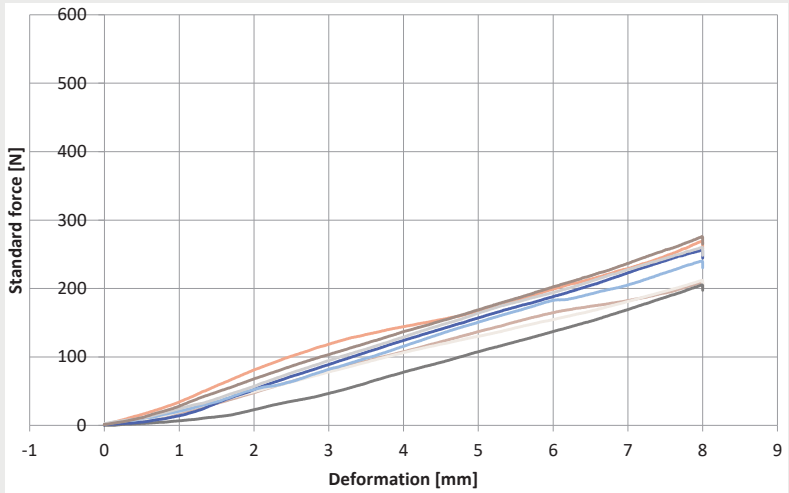
Sawdust

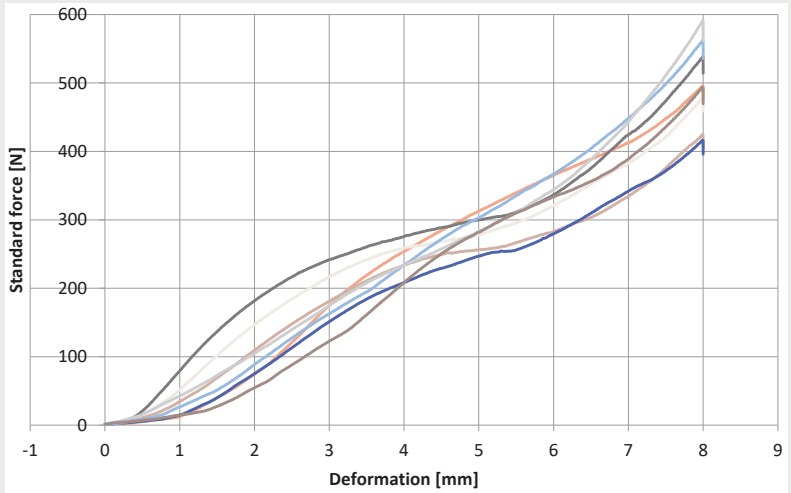
Pleurotus ostreatus





Ganoderma lucidum





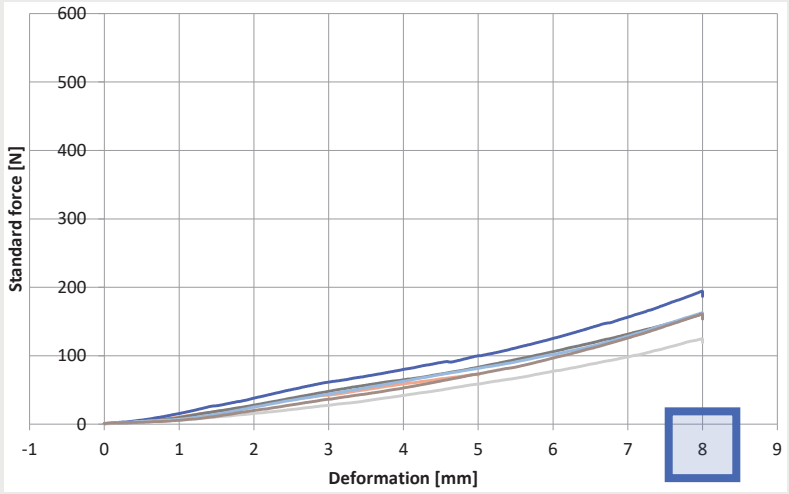
Experiment 5 | Mechanical strength testing

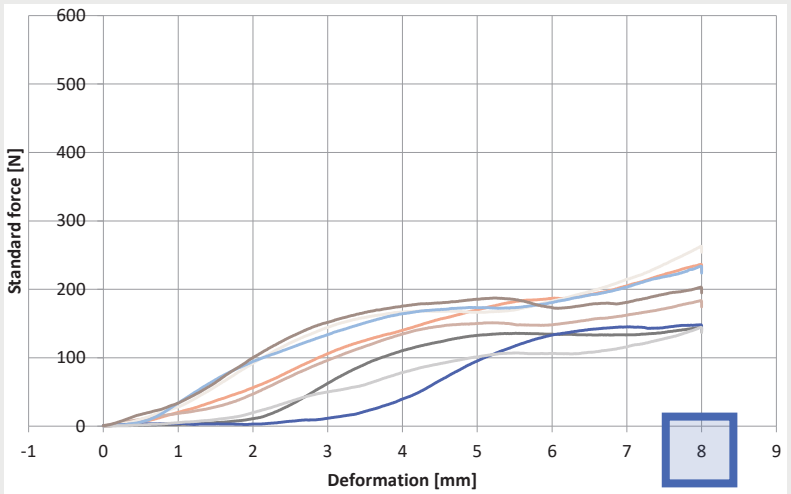
Compression

Hemp

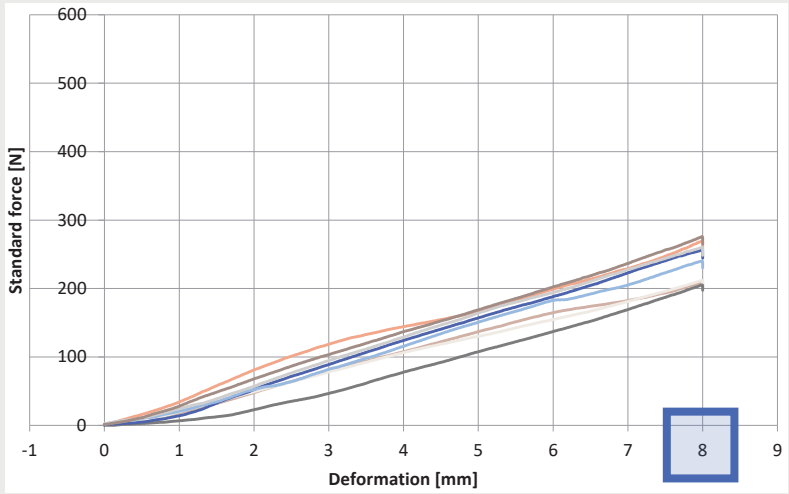
Sawdust

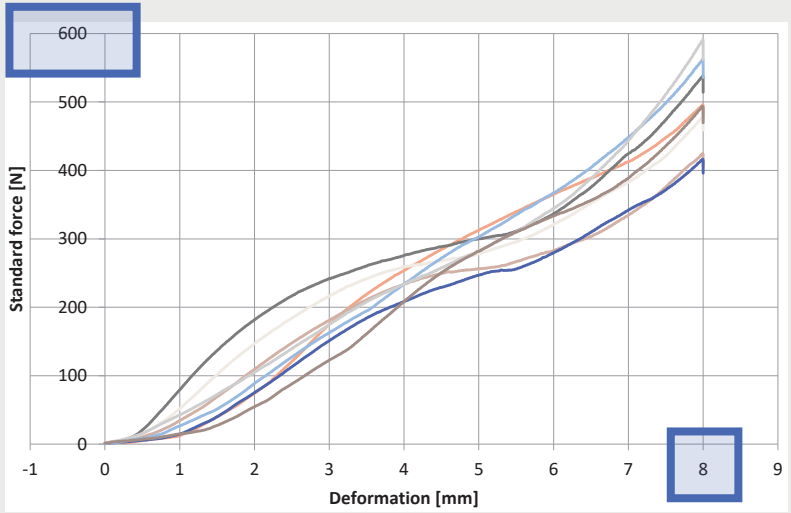
Pleurotus ostreatus





Ganoderma lucidum



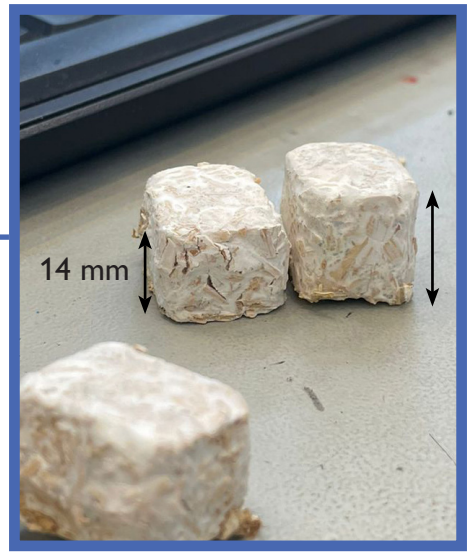


Experiment 5 | Mechanical strength testing

Compression

1 Mycelium growth
2 Mycelium growth with *Pl. ostreatus*
3 Substrates with *Pl. ostreatus*
4 Fungal species comparison
5 Mechanical strength testing
6 Prototype making
7 Prototype testing

	Sample number	σ [MPa]	E [MPa]	Mean E [MPa]
Hemp *Pl. ostr.*	CHP1	0,64	6,4	
	CHP4	0,83	8,3	
	CHP5	0,97	9,67	
	CHP6	0,83	8,31	
	CHP7	0,64	6,41	
	CHP8	0,82	8,23	7,89
Hemp *Gan. luc.*	CHG1	1,33	13,28	
	CHG2	1,14	11,35	
	CHG3	1,11	11,09	
	CHG4	1,12	11,24	
	CHG5	1,4	14,03	
	CHG6	1,29	12,91	
	CHG7	1,4	13,96	
	CHG8	1,43	14,31	12,77
Sawdust *Pl. ostr.*	CSP1	1,29	12,88	
	CSP2	1	9,98	
	CSP3	1,22	12,16	
	CSP4	0,94	9,48	
	CSP5	1,01	10,08	
	CSP6	1,13	11,33	
	CSP7	0,79	7,99	
	CSP8	0,97	9,7	10,45
Sawdust Gan. luc.	CSG1	2,76	27,58	
	CSG2	2,05	20,52	
	CSG3	2,23	22,23	
	CSG4	2,32	23,26	
	CSG5	2,19	21,9	
	CSG6	2,93	29,31	
	CSG7	2,78	27,78	
	CSG8	2,69	26,92	24,94



Low Young's Modulus: more flexible rubber-like material

Higher Young's Modulus: stiffer material

Experiment 5 | Mechanical strength testing

3-point Bending

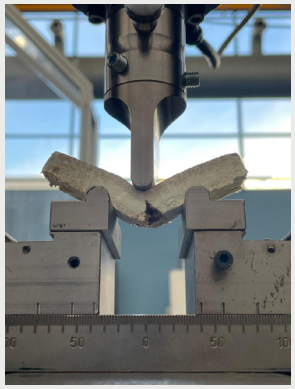
Pleurotus ostreatus

Ganoderma lucidum

Hemp


Sawdust





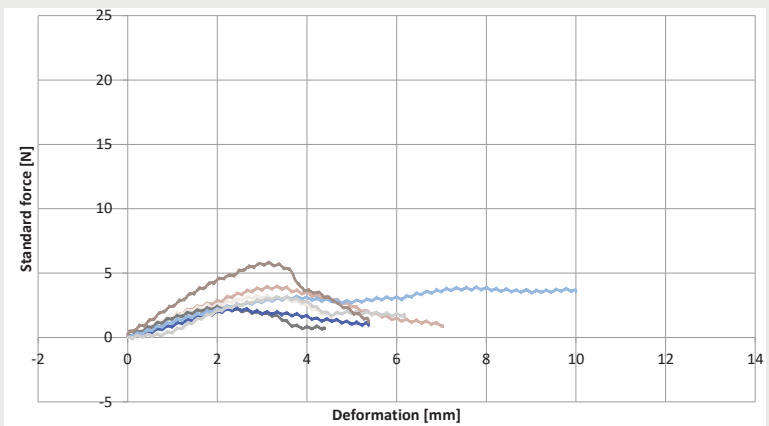

Experiment 5 | Mechanical strength testing

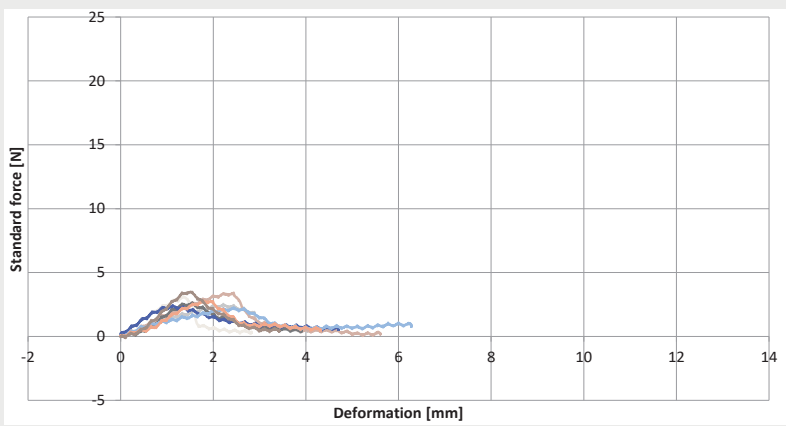
3-point Bending

Hemp

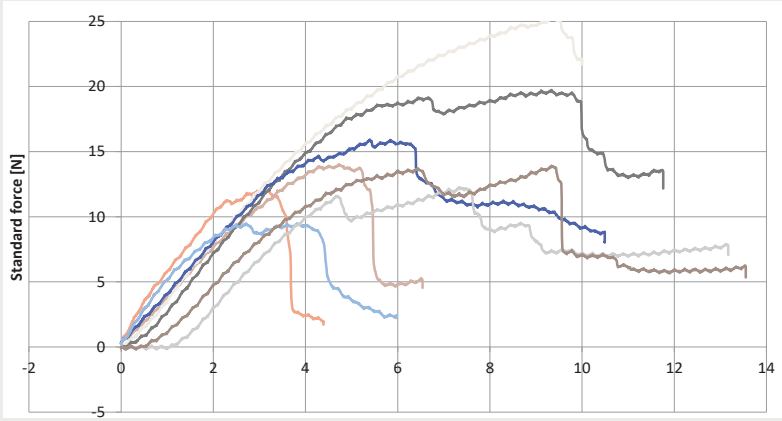
Sawdust

Pleurotus ostreatus





Ganoderma lucidum



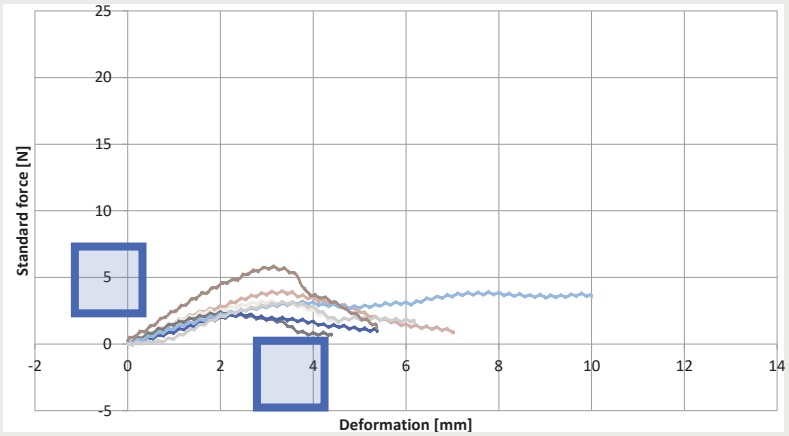
Experiment 5 | Mechanical strength testing

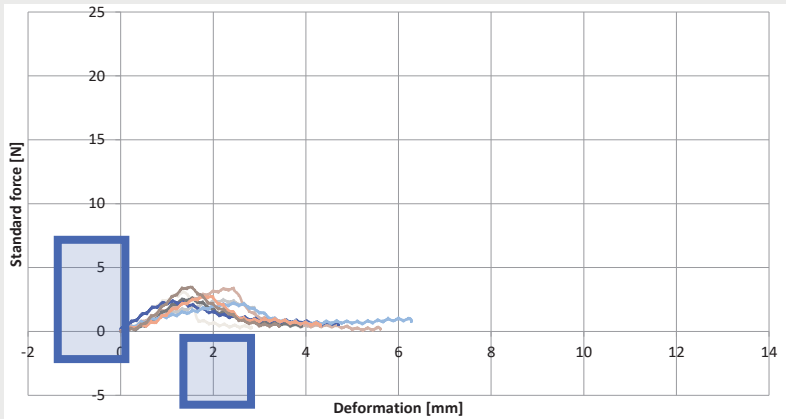
3-point Bending

Hemp

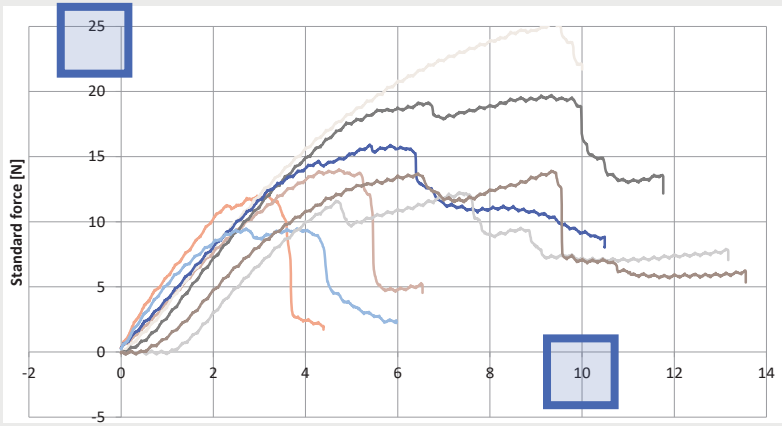
Sawdust

Pleurotus ostreatus





Ganoderma lucidum

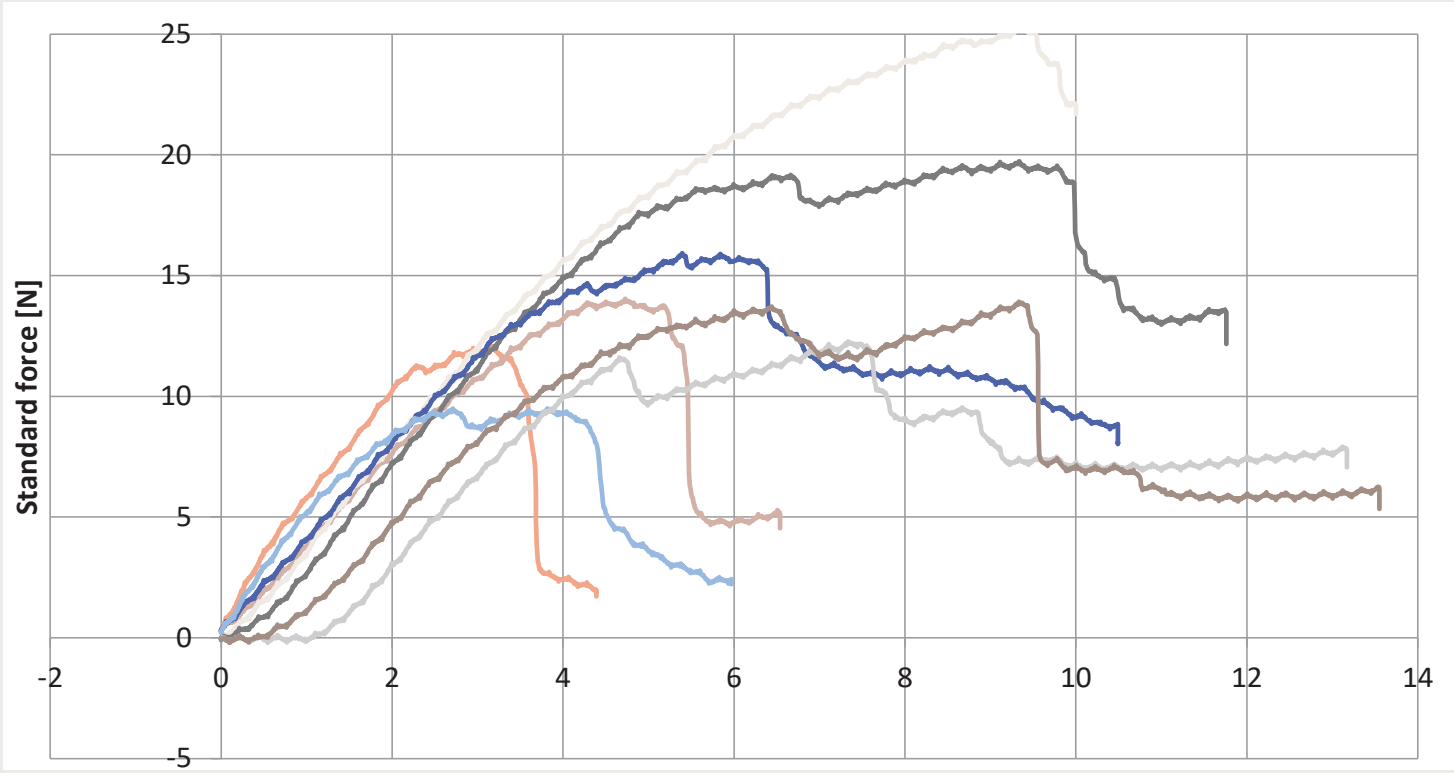


Experiment 5 | Mechanical strength testing

3-point Bending

Divergent results,
Low consistency:
Other distribution per sample.

Sawdust + *Ganoderma lucidum*

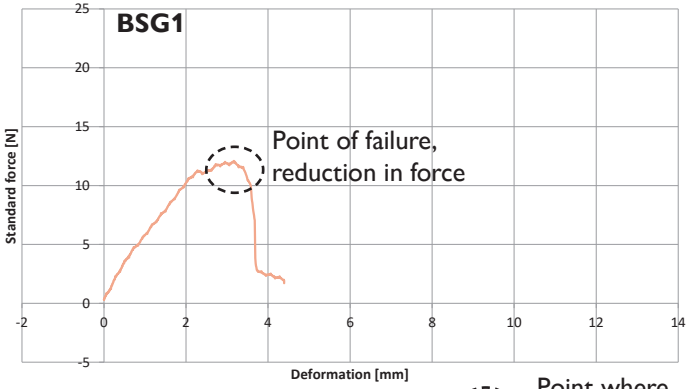


Experiment 5 | Mechanical strength testing

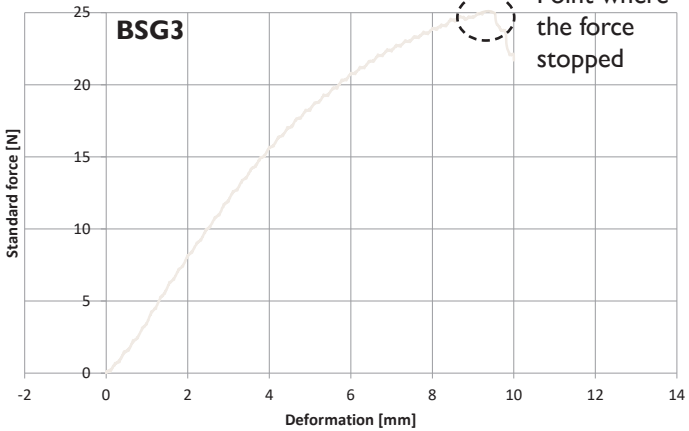
3-point Bending: Sawdust Ganoderma lucidum

Sawdust + *Ganoderma lucidum*

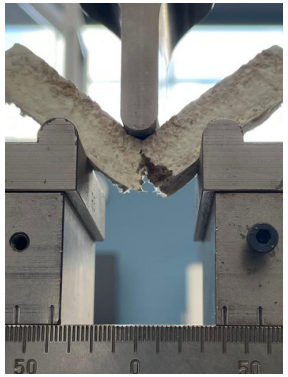
Sample 1: BSG1

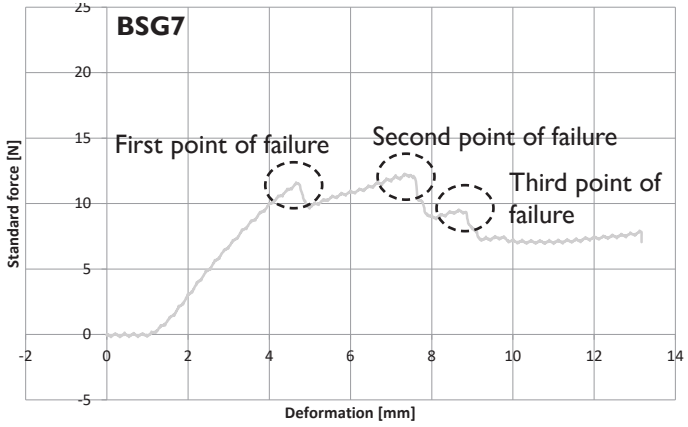


Sample 3: BSG3



Sample 7: BSG7



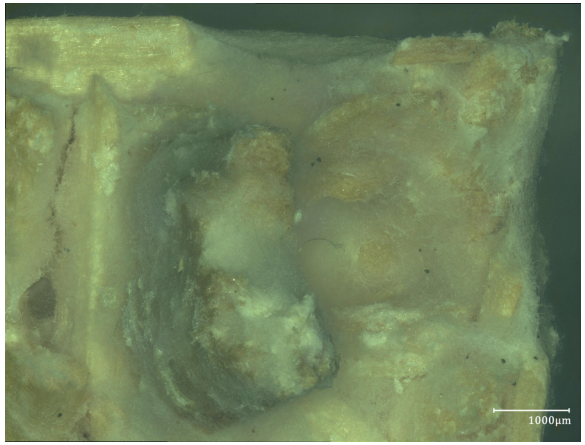


Divergent results,
Low consistency:
Other distribution per sample.

Microscopic research

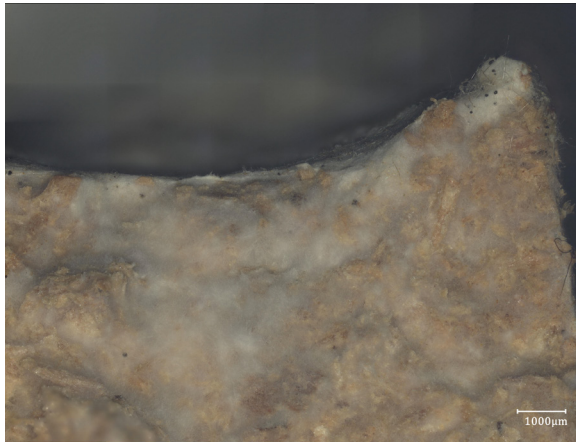
Sample behaviour

Hemp + *Pleurotus ostreatus*



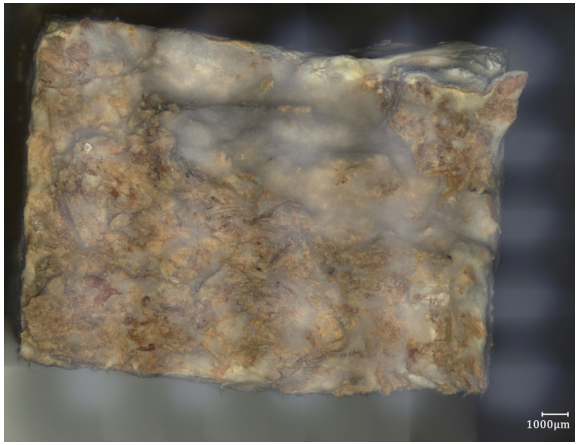
Cross section breaking point | 100x magnification

Sawdust + *Pleurotus ostreatus*



Cross section breaking point | 100x magnification

Sawdust + *Ganoderma lucidum*

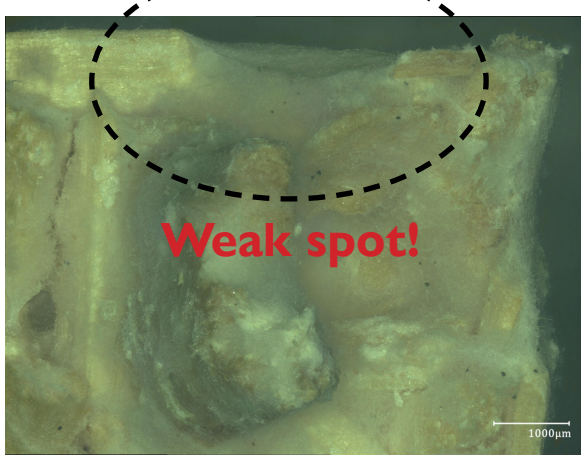


Cross section breaking point | 50x magnification

Microscopic research

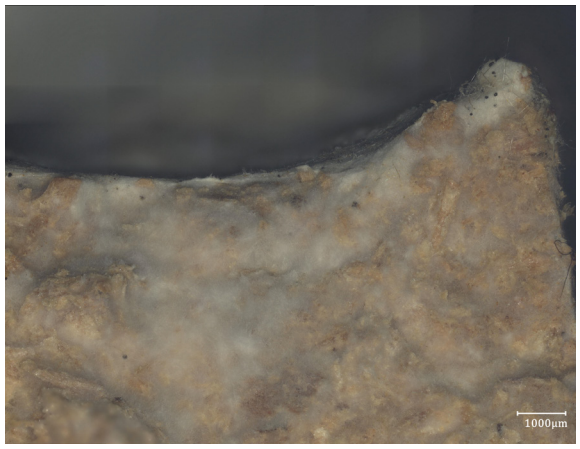
Sample behaviour

Hemp + *Pleurotus ostreatus*



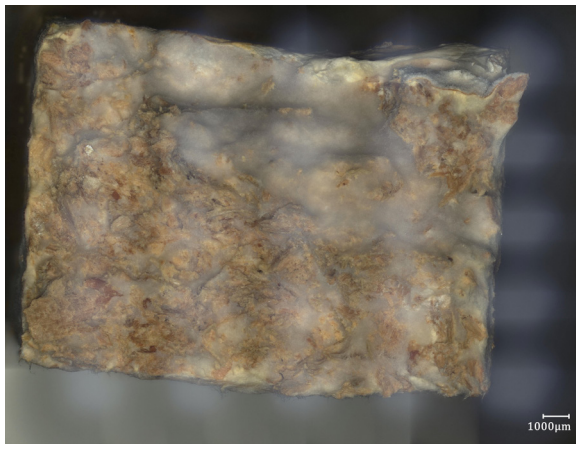
Cross section breaking point | 100x magnification

Sawdust + *Pleurotus ostreatus*



Cross section breaking point | 100x magnification

Sawdust + *Ganoderma lucidum*



Cross section breaking point | 50x magnification

Experiment 5 | Mechanical strength testing

Sawdust + Ganoderma lucidum


Sawdust + *Ganoderma lucidum*

Strongest combination, but not comparable to construction materials

Diverse results in testing, unsure about the distribution and properties

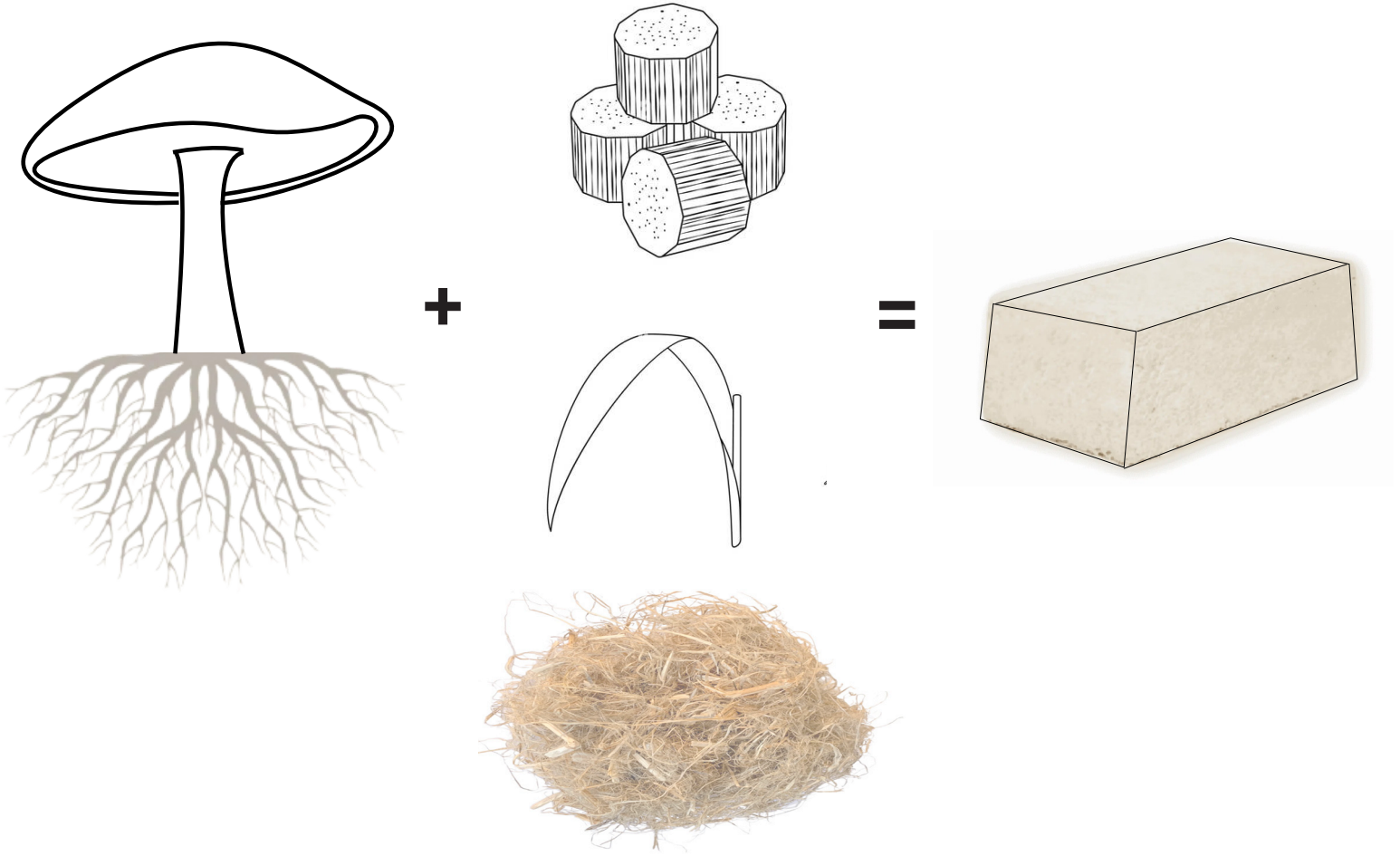
Building materials

	Mechanical properties			Physical properties		
Material	**Compressive strength**	**Tensile Strength**	**Young's modulus**	**Density**	**Thermal conductivity**	**Source**
	[MPa]	[MPa]	[GPa]	[kg/m^3]	[W/mK]	
Concrete (insulating lightweight)	0,5 - 2,8	0,1 - 0,3	0,6 - 1,53	900 - 1,4e3	0,1 - 0,7	Granta EduPack 2023
High density concrete	30,6 - 36,6	3,1 - 3,7	40,2 - 41,6	4,9e3 - 5,5e3	1,6 - 2,5	Granta EduPack 2023
Low alloy steel, SAE 8630, cast, quenched & tempered	827 - 914	915 - 1,01e3	196 - 204	7,81e3 - 7,84e3	42 - 48	Granta EduPack 2023
Stainless steel, austentic, AMST CH-10, cast, water quenched	333 - 363	547 - 667	189 - 197	7,67e3 - 7,77e3	14 - 16	Granta EduPack 2023
Timber: oak (l, quercus spp.)	68,2 - 83,3	133 - 162	20,6 - 25,2	850 - 1,03e3	0,16 - 0,2	Granta EduPack 2023
Timber: oak (t, quercus spp.)	12,8 - 15,6	7,1 - 8,7	5 - 5.58	850 - 1,03e3	0,16 - 0,2	Granta EduPack 2023
Mycelium-based composites	0,17 - 1,1	0,03 - 0,18	0,05e-3 - 0,29e-3*	59 - 552	0,05	(Jones et al., 2020)
MBC (sawdust + *Gan. luc.*)	Not tested	Not tested	0,025	299,48 - 587,5	Not tested	Own experiments

Experiment 6
Prototype configuration

Experiment 6 | Prototype configuration

Added tensile strength



Experiment 6 | Prototype configuration

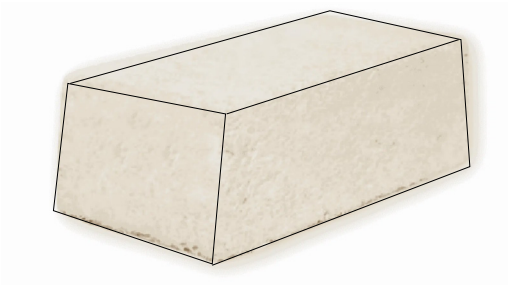
Added tensile strength

Ganoderma lucidum

+

Substrate

=

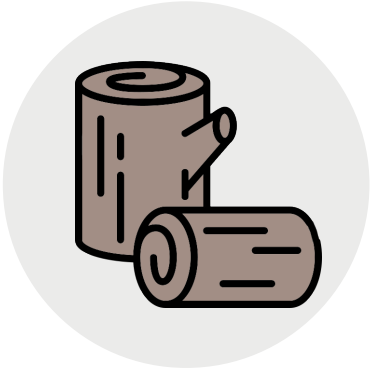


Mycelium-based composite (MBC)

Experiment 6 | Prototype configuration

Added tensile strength

+



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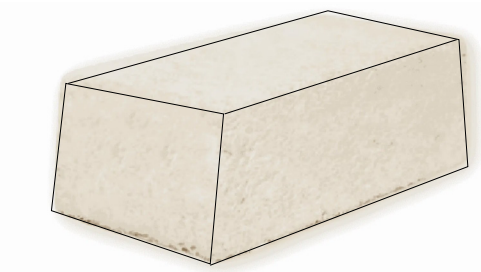
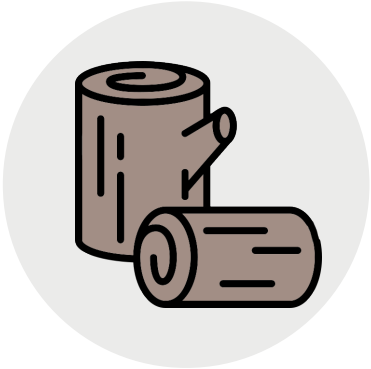


Ganoderma lucidum **Sawdust** **Mycelium-based composite (MBC)**

Experiment 6 | Prototype configuration

Added tensile strength

+



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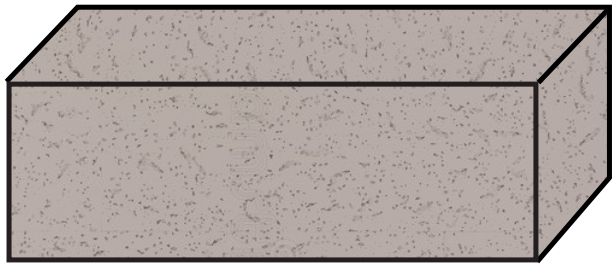
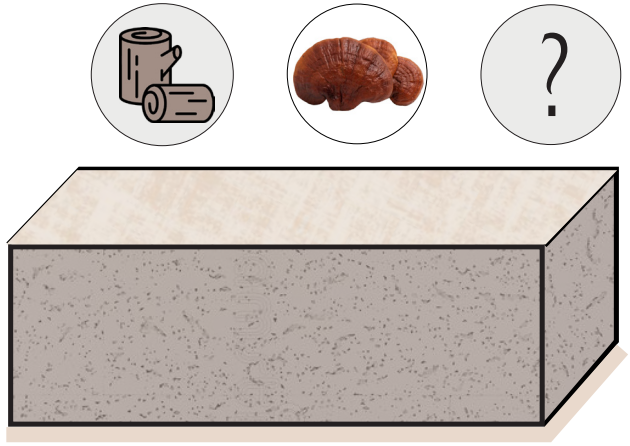


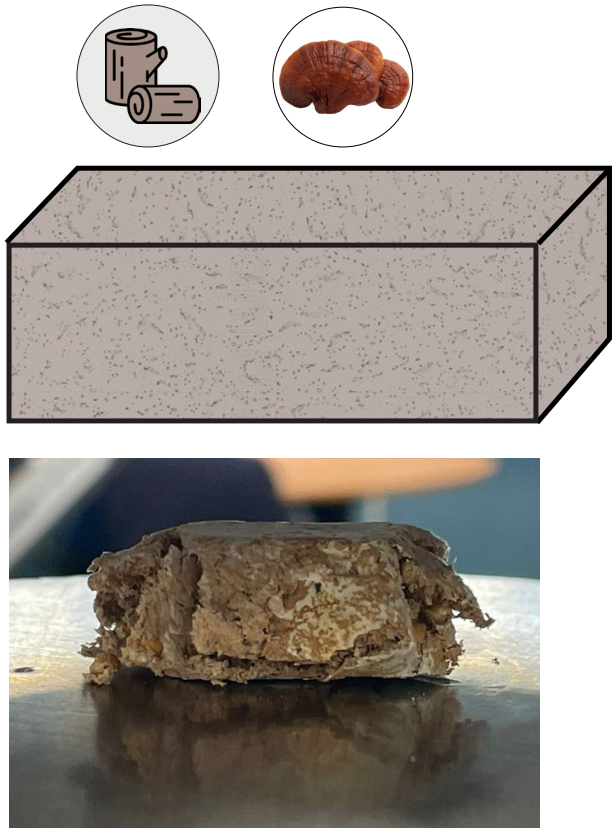
Ganoderma lucidum **Sawdust** **Mycelium-based composite (MBC)**

Experiment 6 | Prototype configuration

Added tensile strength



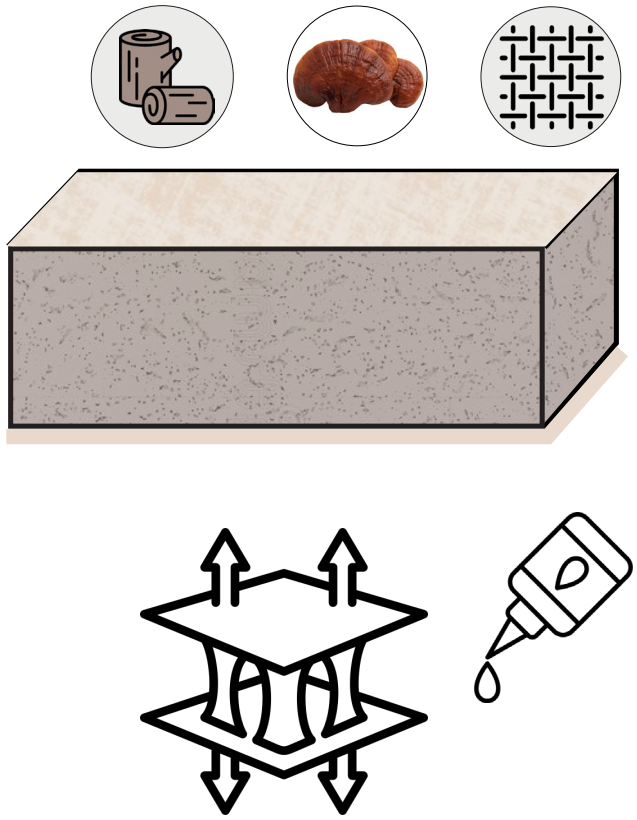
Mycelium-based composite (MBC)
+ reinforcement layers



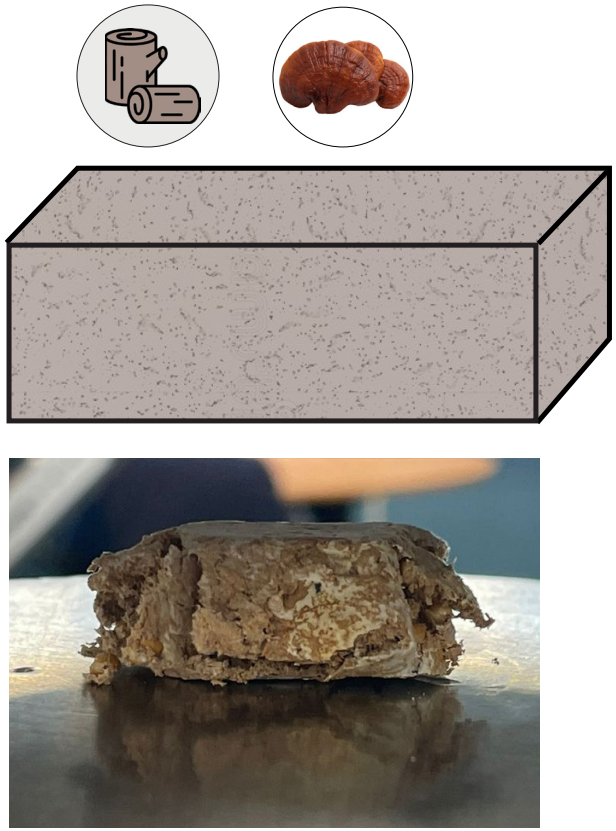
Mycelium-based composite (MBC)

Experiment 6 | Prototype configuration

Added tensile strength



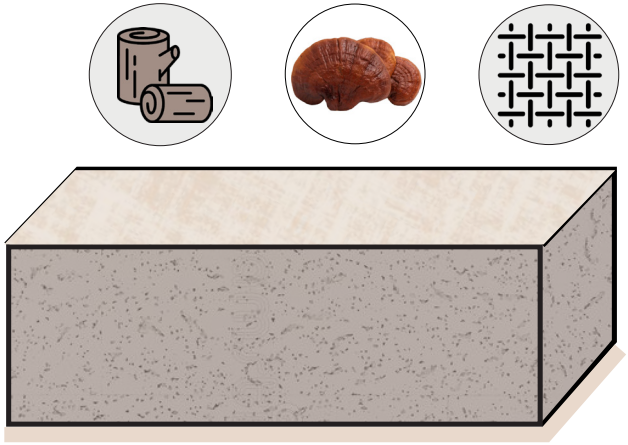
Mycelium-based composite (MBC)
+ reinforcement layers



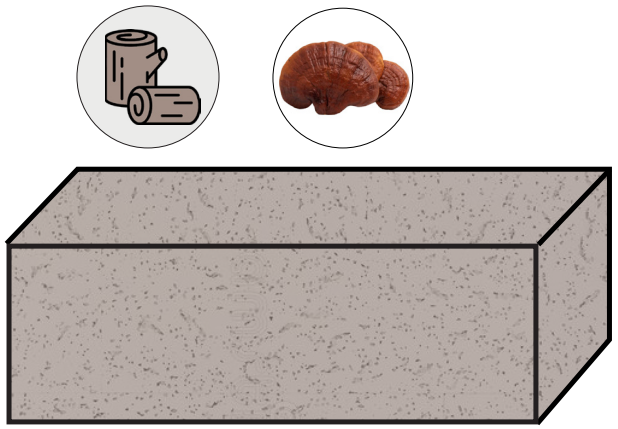
Mycelium-based composite (MBC)

Experiment 6 | Prototype configuration

Added tensile strength



Mycelium-based composite (MBC)
+ reinforcement layers



Mycelium-based composite (MBC)

Experiment 6 | Prototype configuration

Added tensile strength

Variant 1: Mycelium as top layer

Variant 2: Mycelium + sawdust as top layer

1 Mycelium growth

2 Mycelium growth with *Pl. ostreatus*

3 Substrates with *Pl. ostreatus*

4 Fungal species comparison

5 Mechanical strength testing

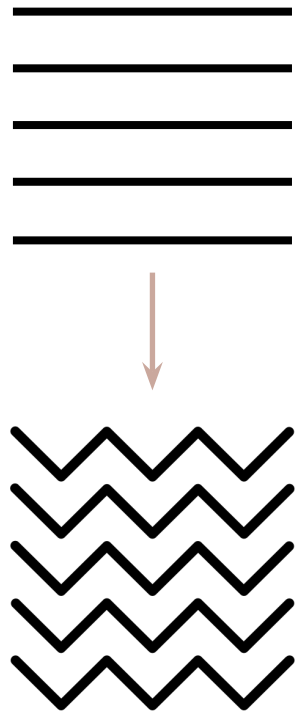
6 Prototype making

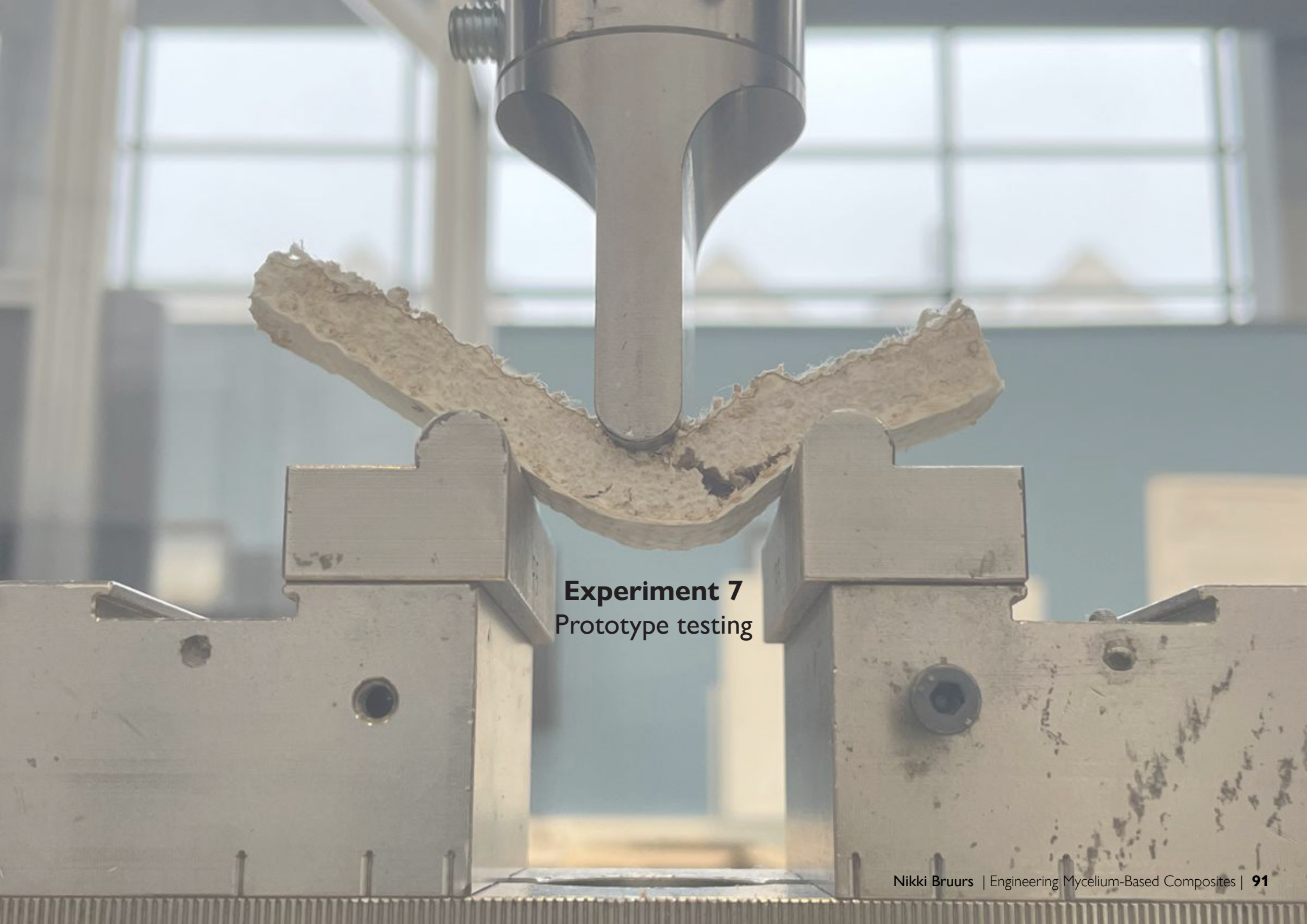
7 Prototype testing

Experiment 6 | Prototype configuration

Added tensile strength

	Variant 1	*Variant 2*	*Variant 3*	
Layer 1				Jute (tensile strength)
Layer 2				Mycelium layer (binder)
Layer 3				1. Extra mycelium 2. Sawdust + mycelium 3. Sawdust + mycelium
Layer 4				Formwork components (mechanical strength)
Layer 5				1. Extra mycelium (filler) 2. Sawdust + mycelium (filler) 3. Sawdust + mycelium (filler)
Layer 6				Mycelium layer (binder)
Layer 7				Jute (tensile strength)
Layer 8				1. Extra mycelium (stiffness) 2. Extra mycelium (stiffness) 3. Sawdust + mycelium (stiffness)



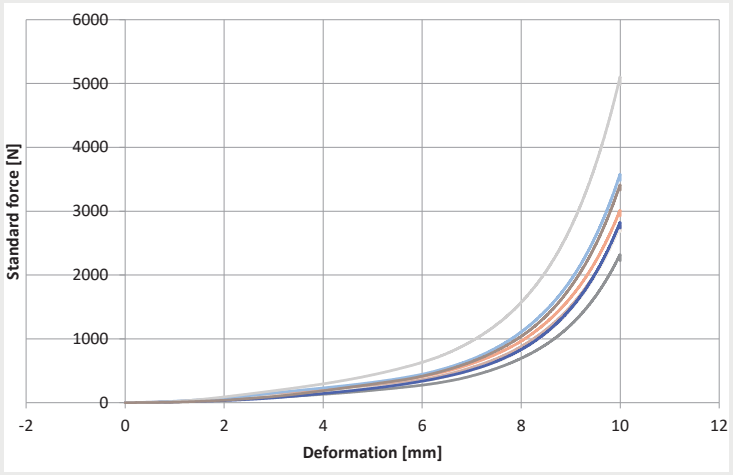


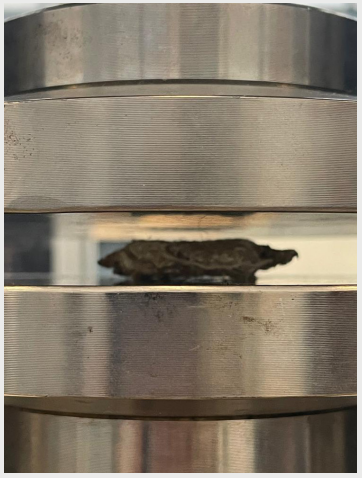
Experiment 7
Prototype testing

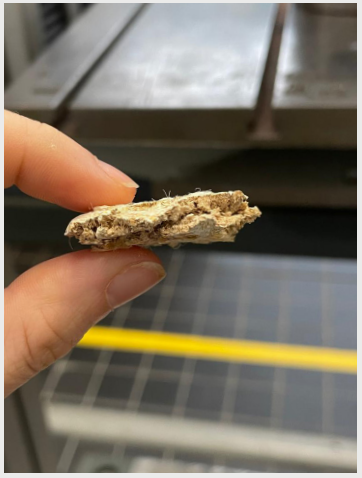
Experiment 7 | Prototype testing

Compression

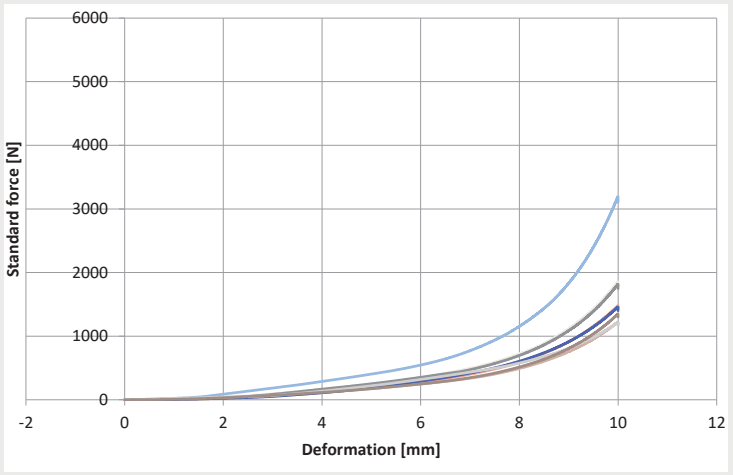
Variant 1: Mycelium top layer

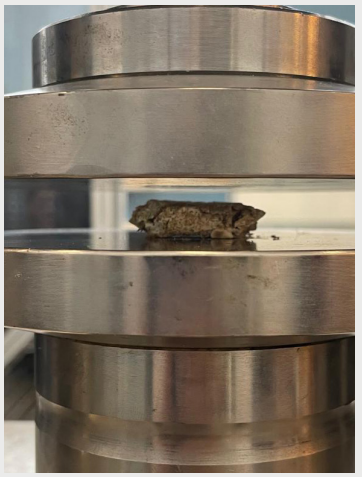


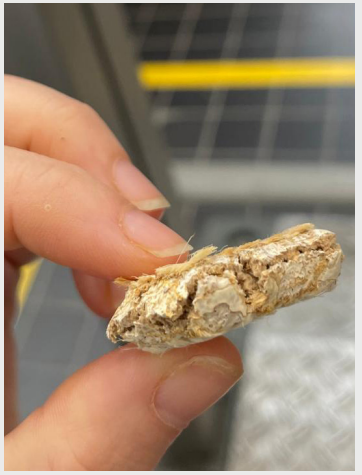




Variant 2: Mycelium + sawdust top layer



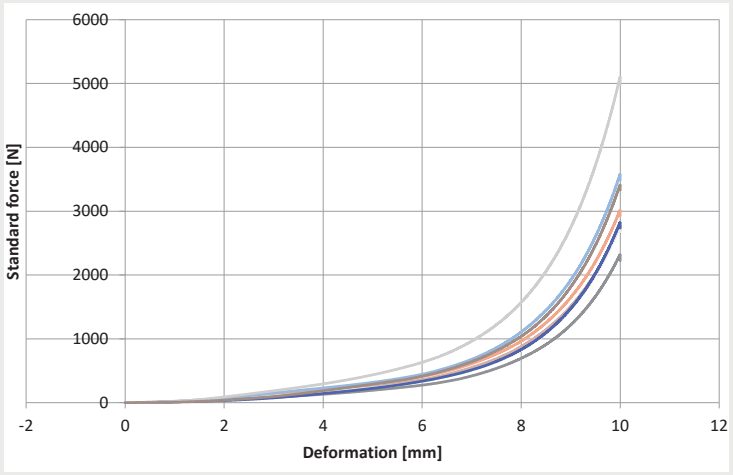




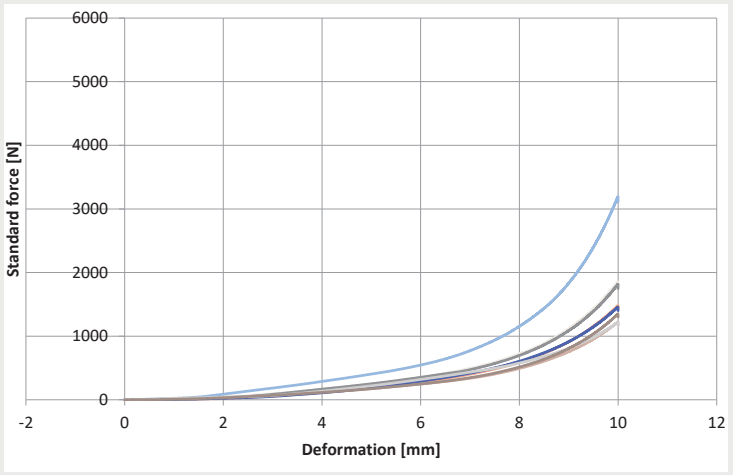
Experiment 7 | Prototype testing

Compression

Variant 1: Mycelium top layer

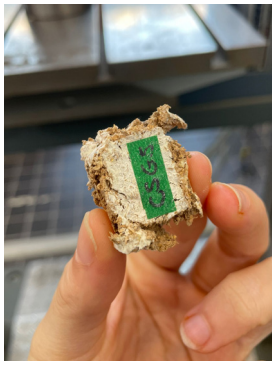


Variant 2: Mycelium + sawdust top layer



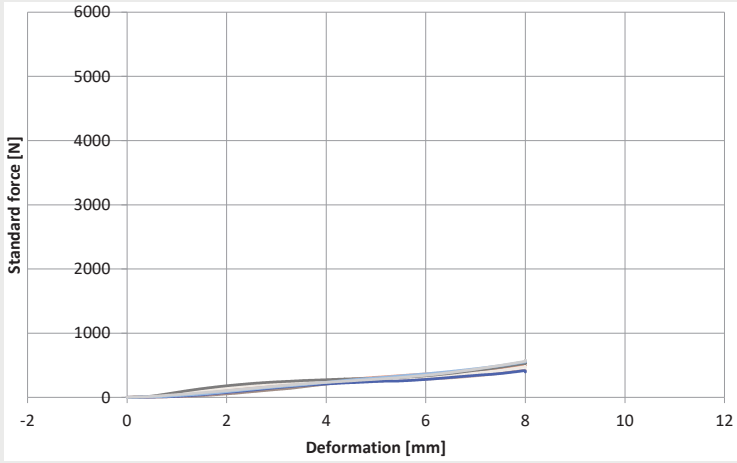
with jute

vs



without jute

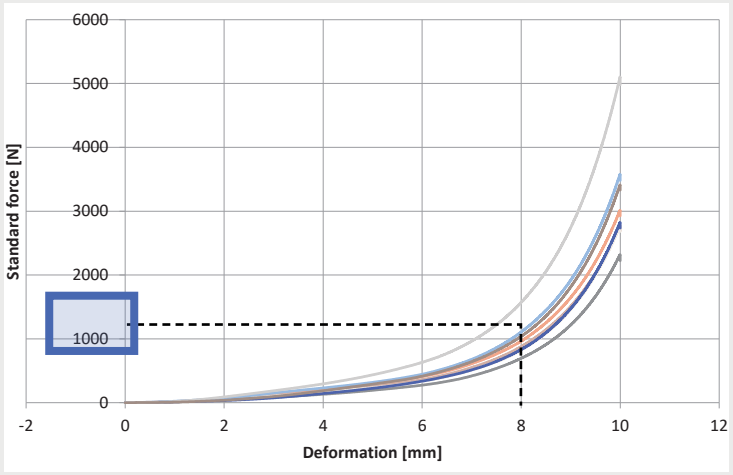
Exp. 5: Sawdust *Ganoderma lucidum* (excl. jute)



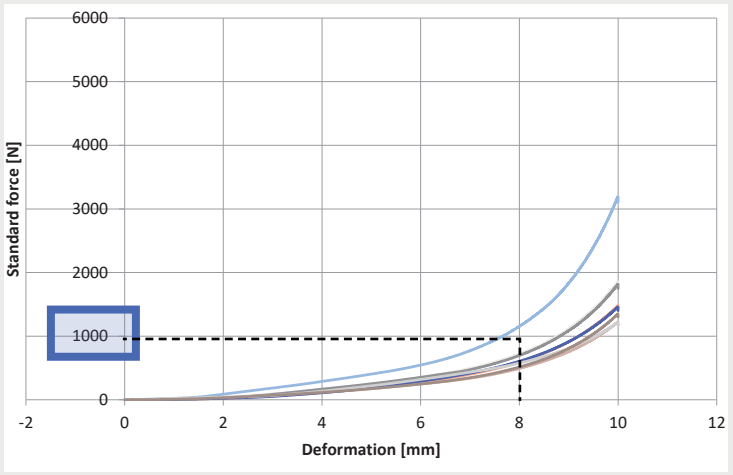
Experiment 7 | Prototype testing

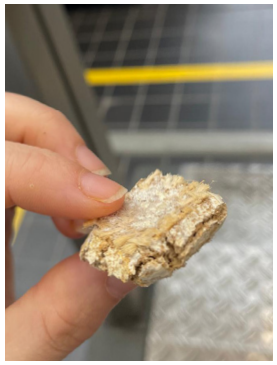
Compression

Variant 1: Mycelium top layer



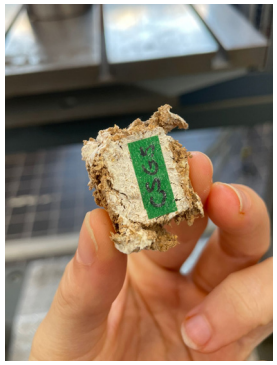
Variant 2: Mycelium + sawdust top layer





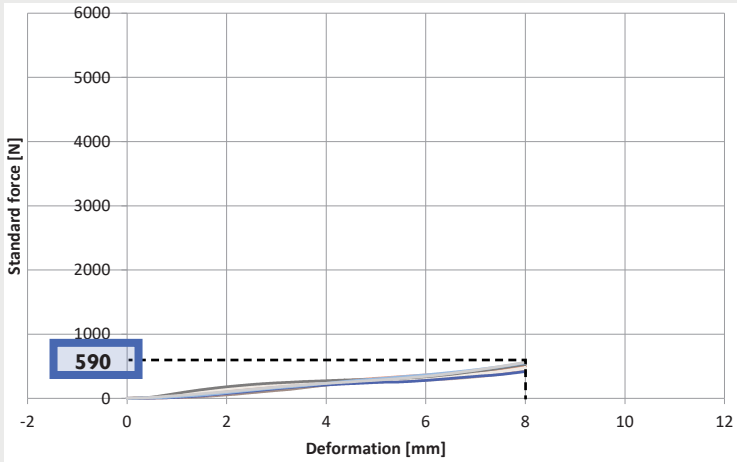
with jute

vs



without jute

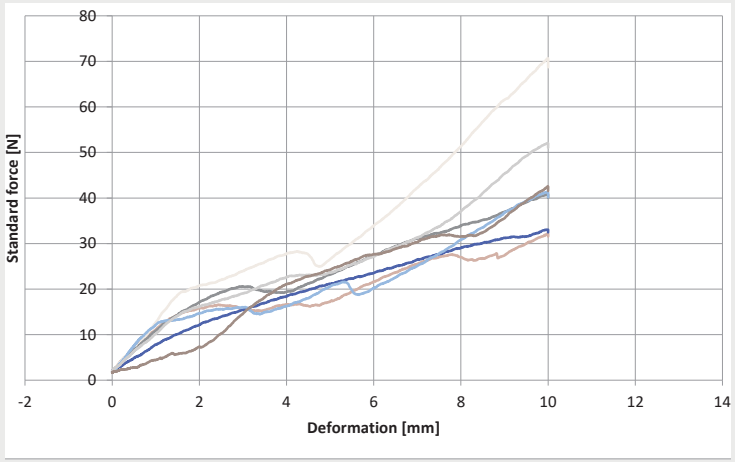
Exp. 5: Sawdust *Ganoderma lucidum* (excl. jute)

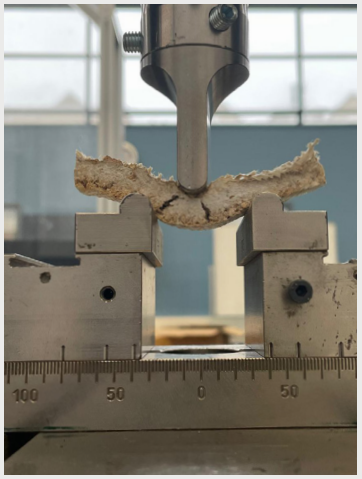


Experiment 7 | Prototype testing

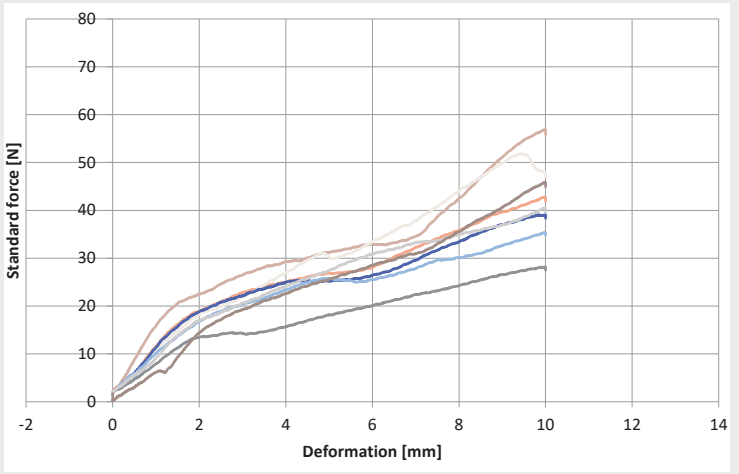
3-point Bending

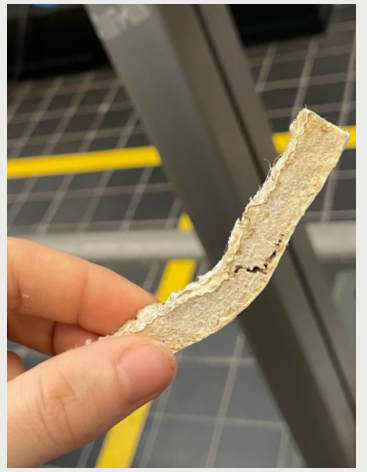
Variant 1: Mycelium top layer





Variant 2: Mycelium + sawdust top layer

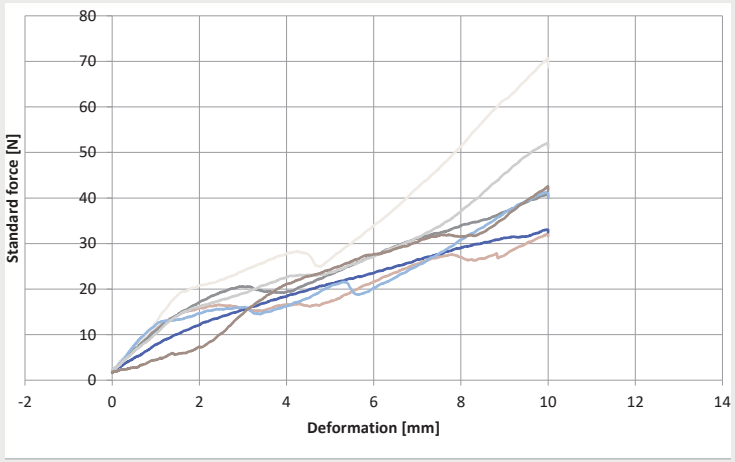




Experiment 7 | Prototype testing

3-point Bending

Variant 1: Mycelium top layer



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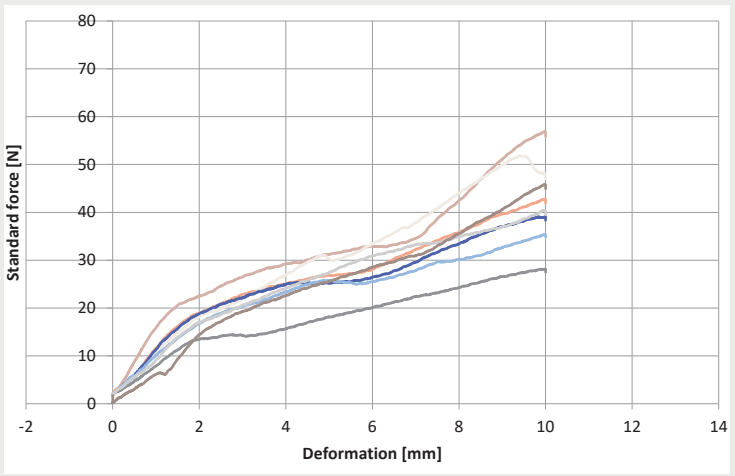
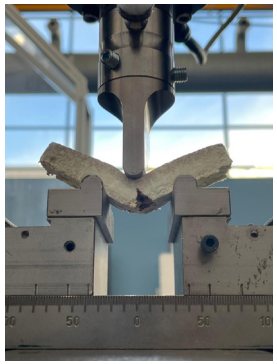


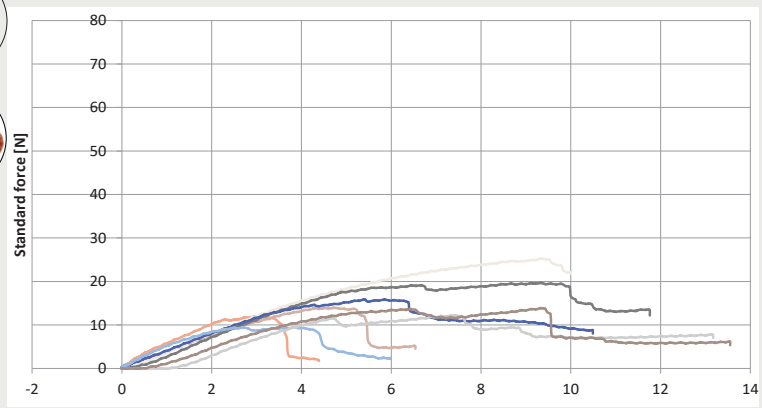
with jute

vs



without jute

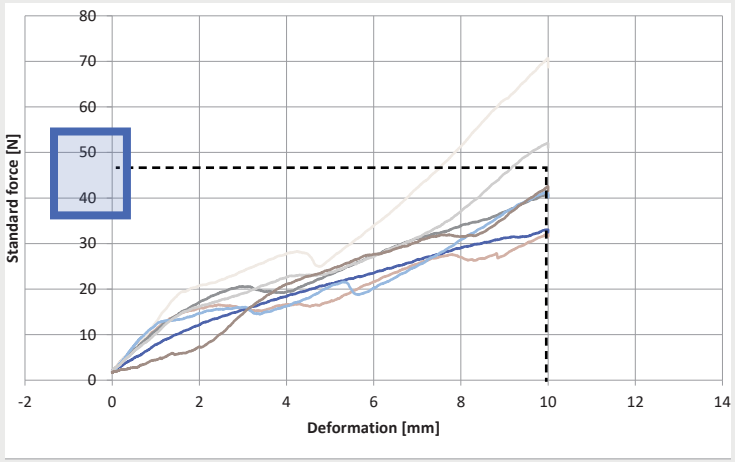
Exp. 5: Sawdust *Ganoderma lucidum* (excl. jute)



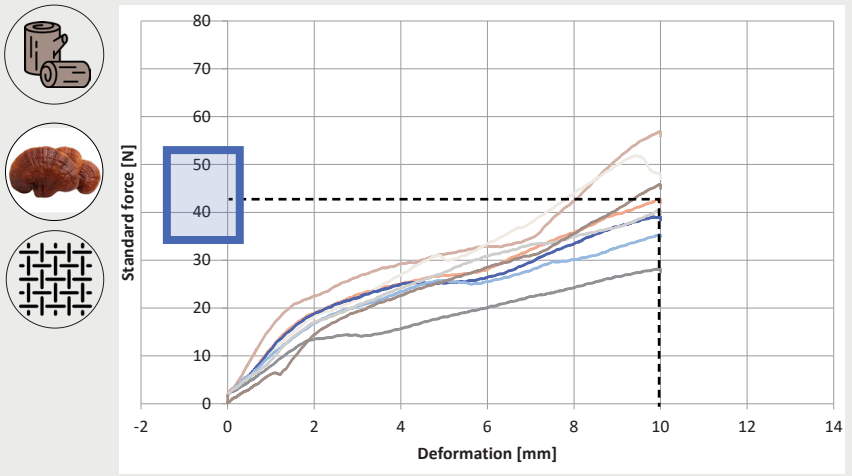
Experiment 7 | Prototype testing

3-point Bending

Variant 1: Mycelium top layer

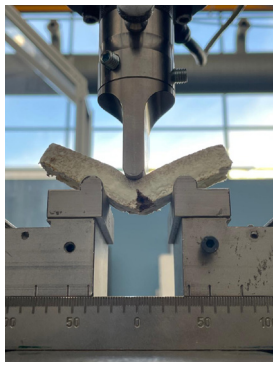


Variant 2: Mycelium + sawdust top layer



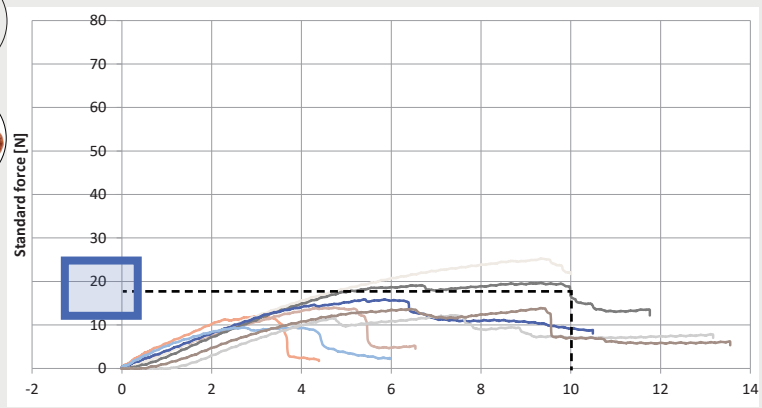
with jute

vs



without jute

Exp. 5: Sawdust *Ganoderma lucidum* (excl. jute)



Experiment 7 | Prototype testing

3-point Bending

1 Mycelium growth

2 Mycelium

7 Prototype testing

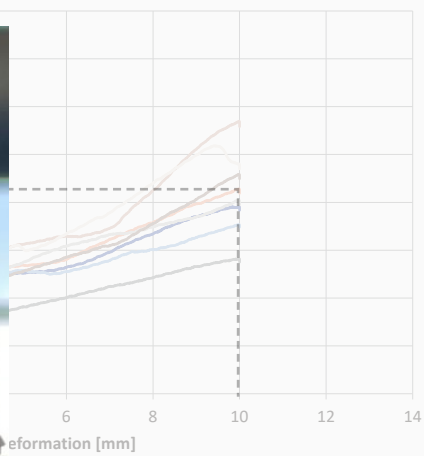
Variant 1: Mycelium top layer

with jute

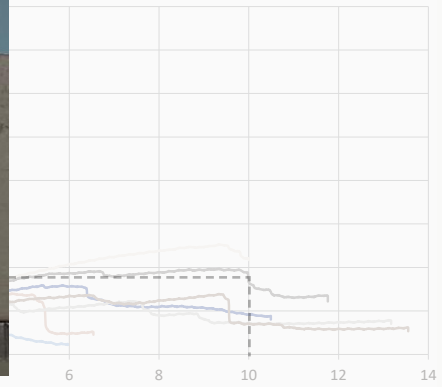
vs

Variant 2: Mycelium + sawdust top layer

without jute



***derma lucidum* (excl. jute)**



Conclusion of the experiments

Sawdust + *Ganoderma lucidum* + jute

Strongest combination, but still not comparable to construction materials

Less diverse results in testing, more ensurance about the properties

Building materials

	Mechanical properties			Physical properties		
Material	**Compressive strength**	**Tensile Strength**	**Young's modulus**	**Density**	**Thermal conductivity**	**Source**
	[MPa]	[MPa]	[GPa]	[kg/m^3]	[W/mK]	
Concrete (insulating lightweight)	0,5 - 2,8	0,1 - 0,3	0,6 - 1,53	900 - 1,4e3	0,1 - 0,7	Granta EduPack 2023
High density concrete	30,6 - 36,6	3,1 - 3,7	40,2 - 41,6	4,9e3 - 5,5e3	1,6 - 2,5	Granta EduPack 2023
Low alloy steel, SAE 8630, cast, quenched & tempered	827 - 914	915 - 1,01e3	196 - 204	7,81e3 - 7,84e3	42 - 48	Granta EduPack 2023
Stainless steel, austentic, AMST CH-10, cast, water quenched	333 - 363	547 - 667	189 - 197	7,67e3 - 7,77e3	14 - 16	Granta EduPack 2023
Timber: oak (l, quercus spp.)	68,2 - 83,3	133 - 162	20,6 - 25,2	850 - 1,03e3	0,16 - 0,2	Granta EduPack 2023
Timber: oak (t, quercus spp.)	12,8 - 15,6	7,1 - 8,7	5 - 5.58	850 - 1,03e3	0,16 - 0,2	Granta EduPack 2023
Mycelium-based composites	0,17 - 1,1	0,03 - 0,18	0,05e-3 - 0,29e-3*	59 - 552	0,05	(Jones et al., 2020)
MBC (sawdust + *Gan. luc.*)	Not tested	Not tested	0,025	299,48 - 587,5	Not tested	Own experiments
Sandwich panel (MBC + jute)	Not tested	Not tested	0,028	433,33 - 855,41	Not tested	Own experiments

04 Design & manufacture

Material-driven ← **Application-driven approach**

To suit the unique properties of mycelium

Mycelium advantages

- Reduce CO2 emissions by production in large scale
- Easily biodegradable or compostable at the end of life
- Very little waste during production
- Multifunctional and versatile
- 100% Bio-based (Fungi + bio-based substrate)
- No tools or difficult machines needed
- Lightweight
- Thermal and acoustic insulation values

Limitations

- Low mechanical strength
- Shorter lifespan than traditional construction materials

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Final design render

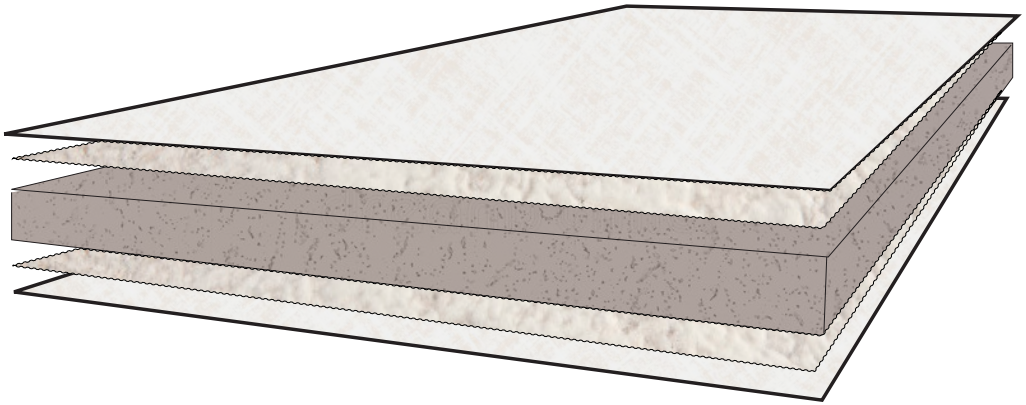
Seperation wall blocks

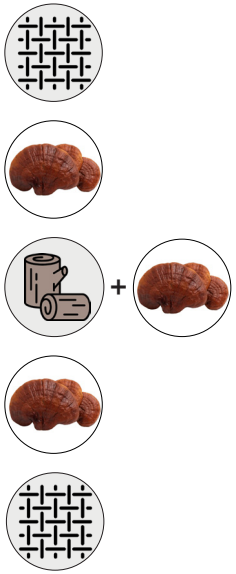
Layering to suit the unique properties of mycelium

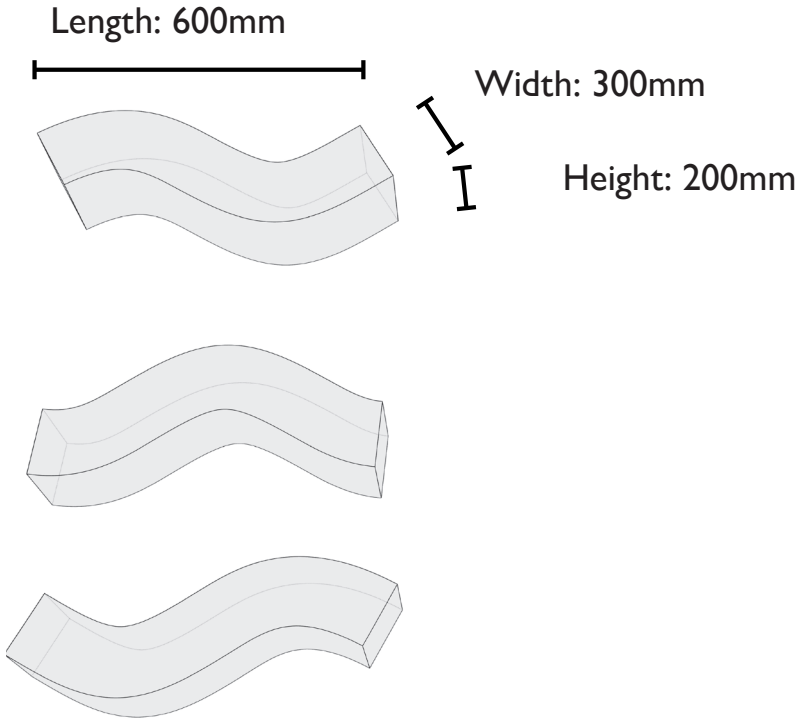
Jute
for tensile strength
(strong directional fibers)

Mycelium-based composite
(sawdust + *Ganoderma luc.*)
for acoustic insulation

Mycelium
as binder







Corrugated blocks:

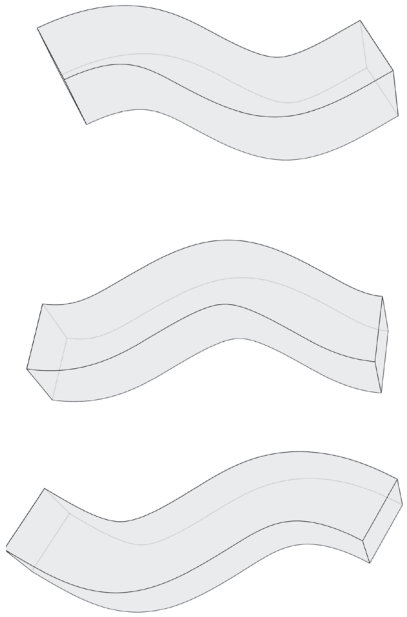
Efficient in **structural strength** and **stiffness**: distributing loads more effectively

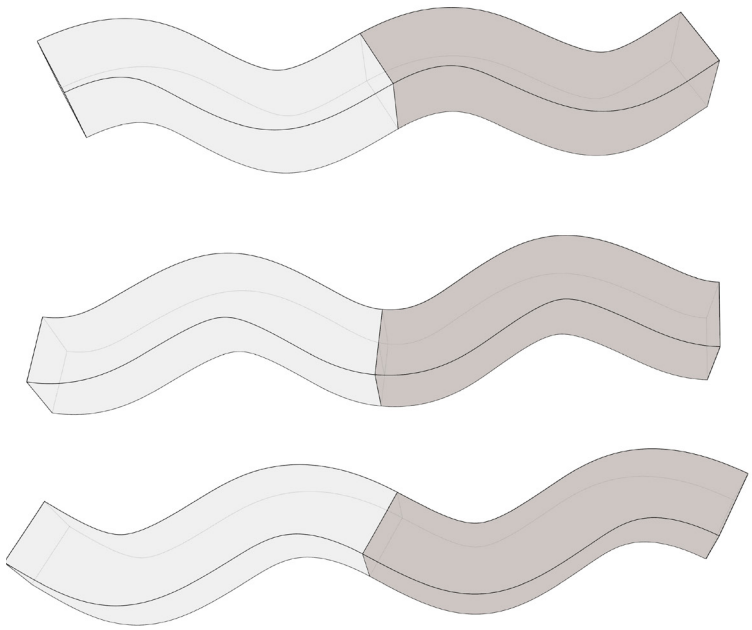
Efficient in **acoustic insulation**: the waves and the rough texture of the jute contribute to reduction of echos and reverberation

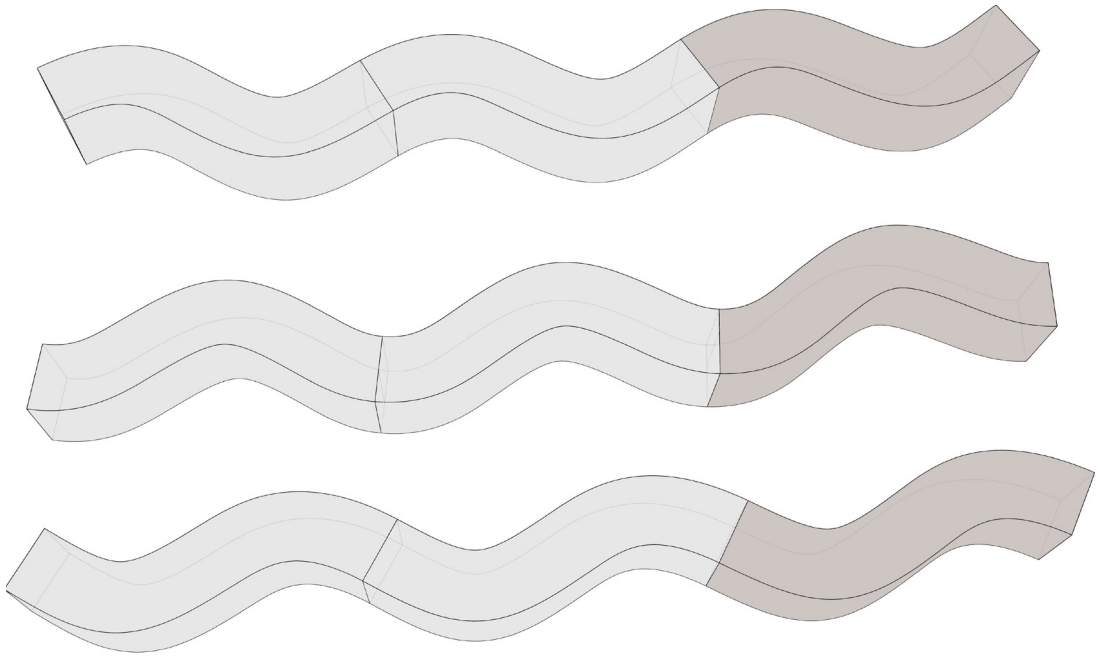
Aesthetic versatility: the corrugated design can serve as an aesthetic element, offering a modern and dynamic appearance

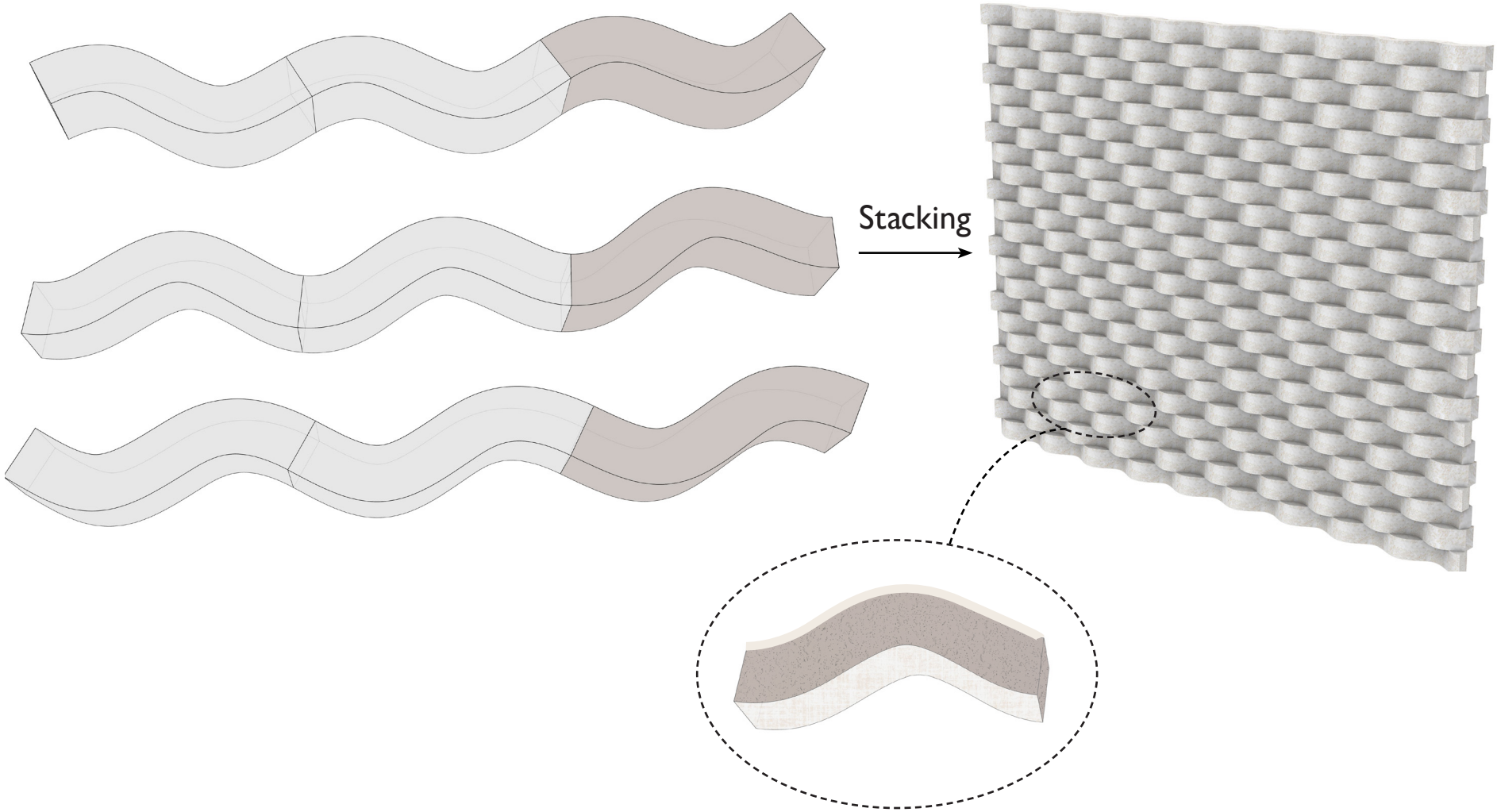
Manufacture

Corrugated blocks

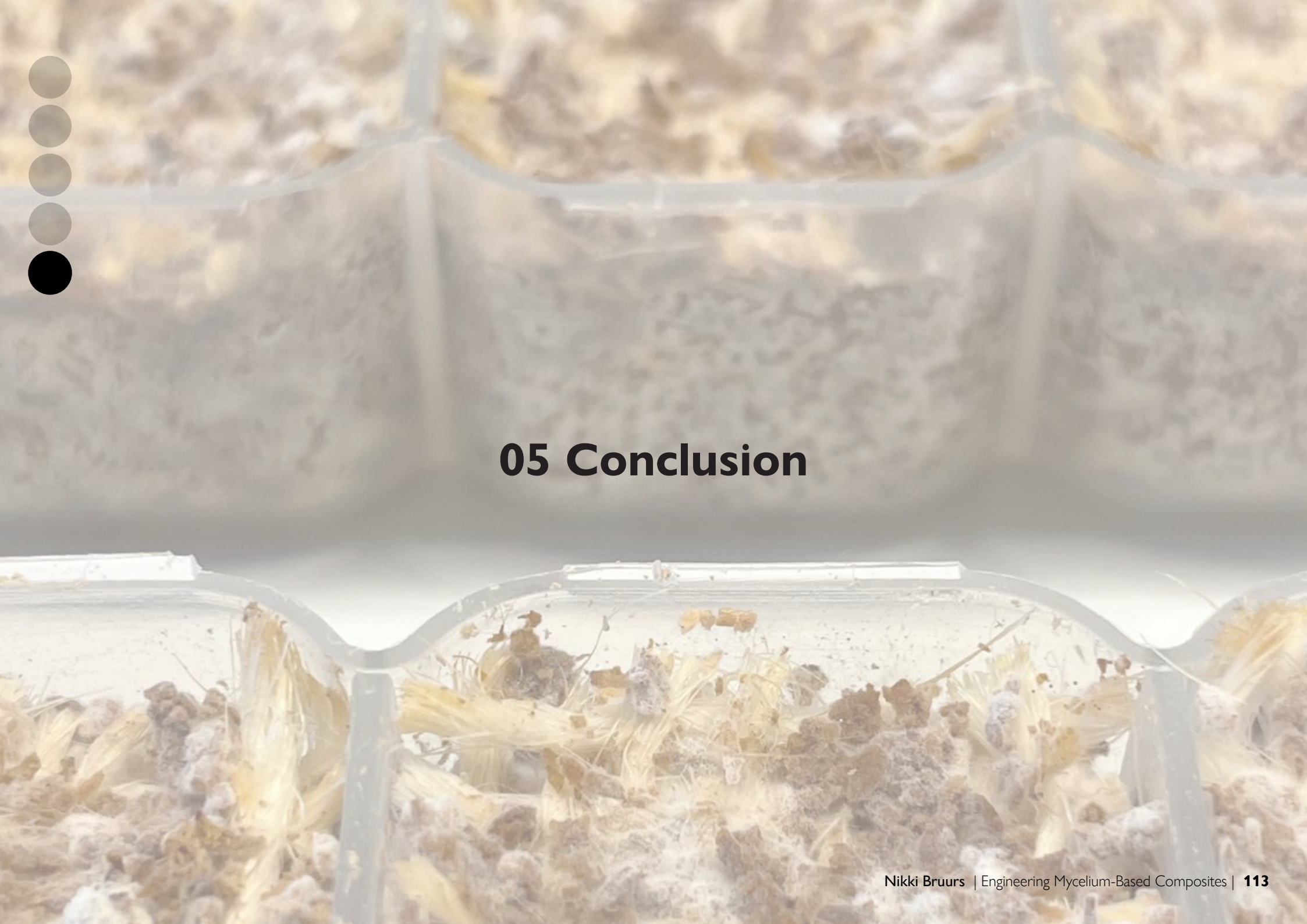







Stacking

05 Conclusion



How can **mycelium-based composites** be engineered and optimized for use as a **building element** in **internal applications**?

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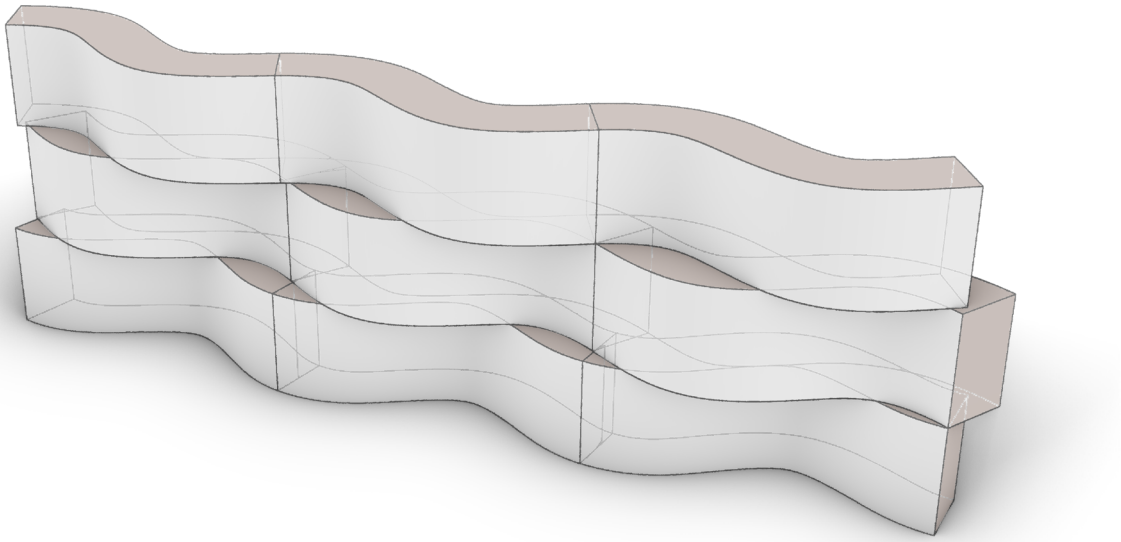
1. Optimisation of the material
Sawdust + *Ganoderma lucidum* + jute



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1. **Optimisation of the material**
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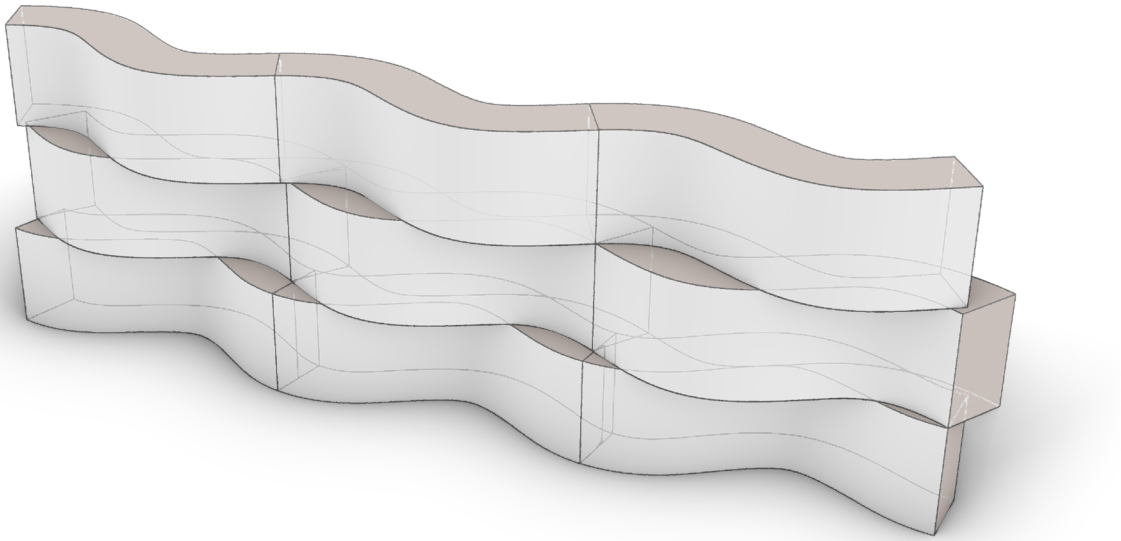
2. **Mycelium as a binder and main material**
   Bio-based glue that binds the composite together
   Simplify the materials composition



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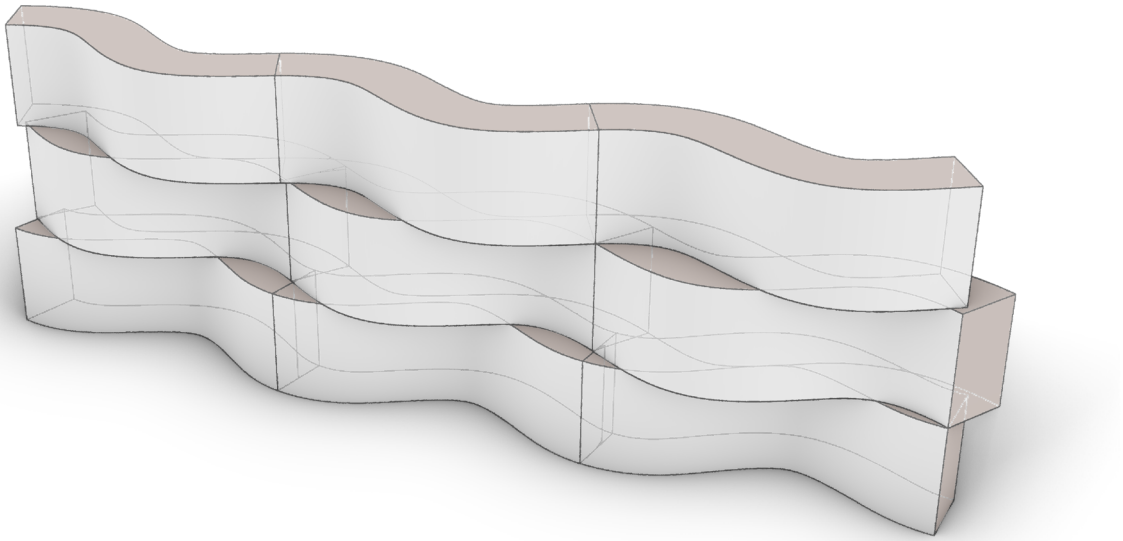
   Efficient in structural strength and stiffness:
   Efficient in acoustic insulation
   Aesthetic versatility



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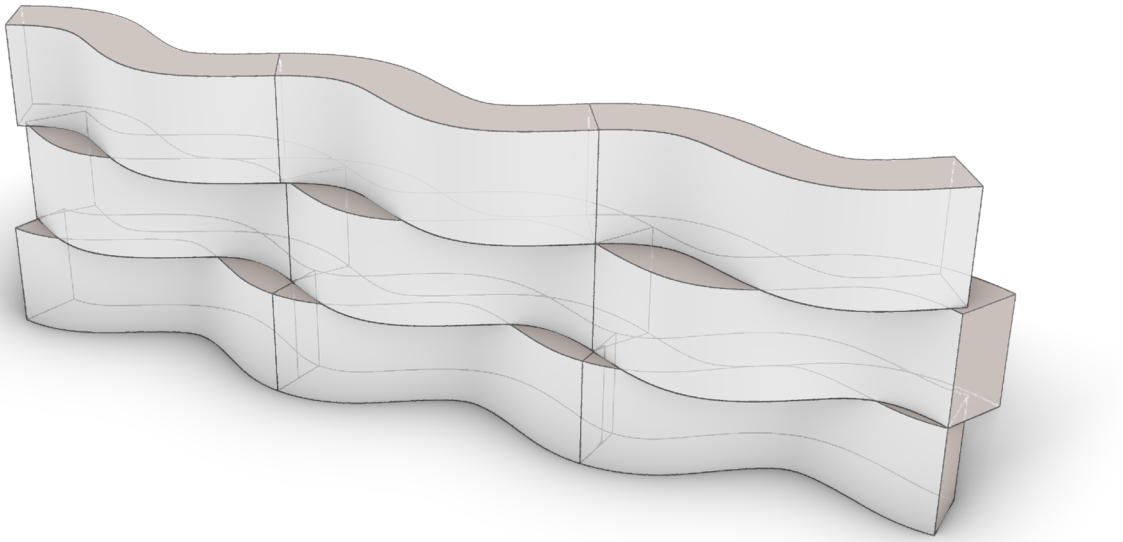
The big picture...

- Understanding and working with mycelium-based composites
- Significant step toward integrating mycelium-based composites into sustainable building practices



Context

Waste management office Voorhout

Render provided by: Witteveen + Bos

Context

Waste management office Voorhout

Render provided by: Witteveen + Bos

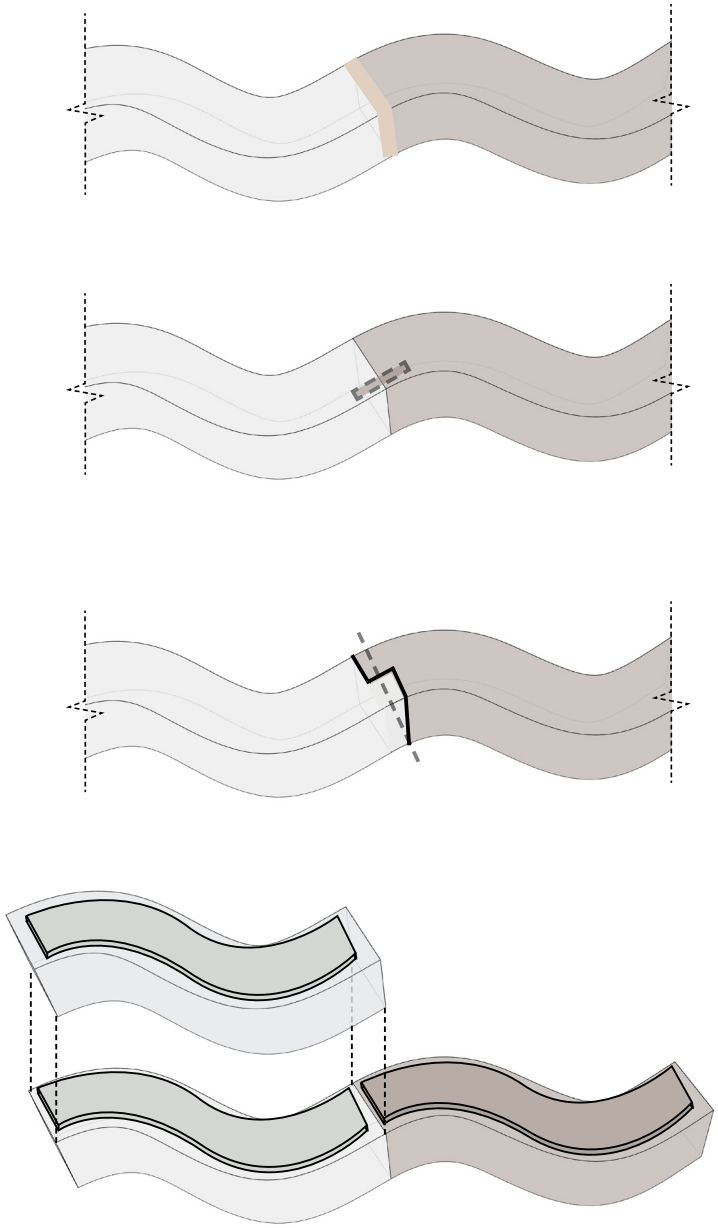
Final design

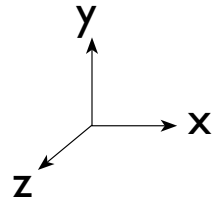
Waste management office Voorhout


Thank you for your attention
Are there any questions?
TU Delft
Witteveen Bos

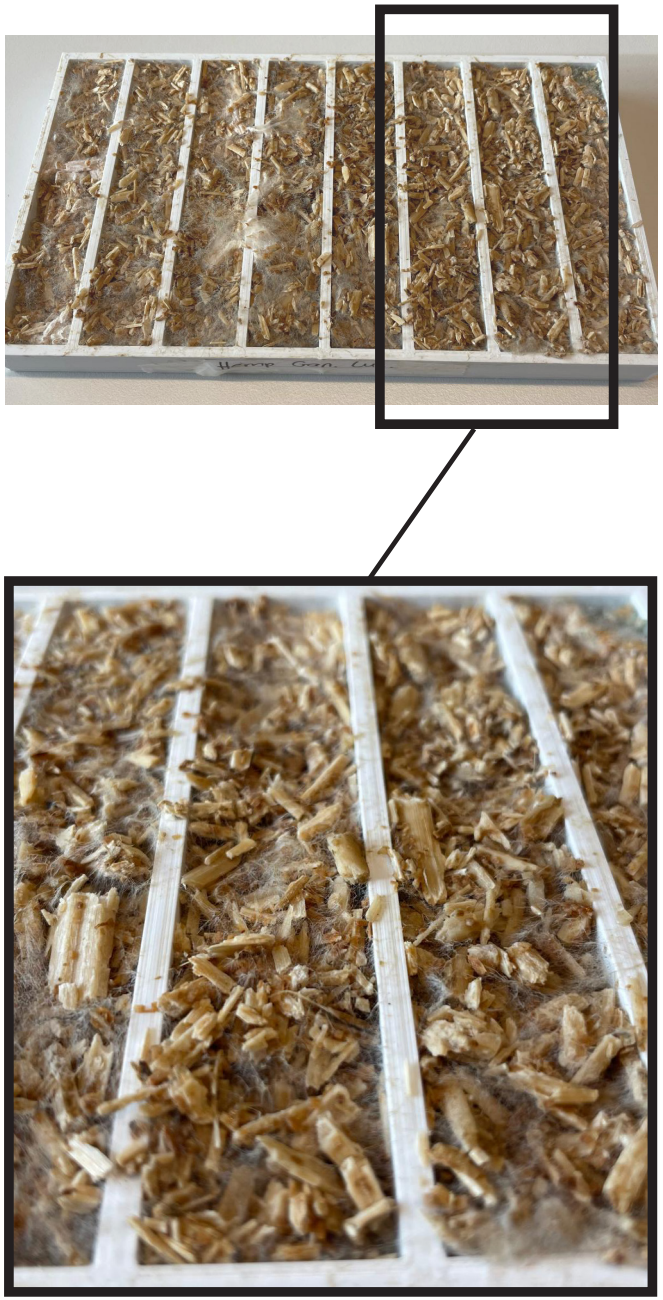
Connection between blocks

Bio-based solutions





Bending Hemp *Ganoderma lucidum*



Calculations compression tests

Calculations stiffness (Young's modulus / Elastic modulus E)

		Formula	Formula applied	Quantity	Unit
A	Area A	A [mm2] = Width [mm] x Length [mm]	24 * 20 mm	48	mm2
ΔL	Total deformation			8	mm
L0	Total length			20	mm
ε	Strain	ε = (ΔL pt.2 / height) [mm] - (ΔL pt. 1 / height) [mm]	(4/20) - (2/20)	0,1	
σ	Stress	σ [N/mm2] or [MPa] = load [N] / area [mm2]			
E	Elastic modulus	E [MPa] = σ [MPa] / ε			

	Sample number	Linear trendline formula	F2 [N]	F2 / A [N/mm2]	F4 [N]	F4 / A [N/mm2]	σ [MPa]	E [MPa]	Mean E [MPa]
Hemp *Pl. ostr.*	CHP1	y = 15,396x - 3,4288	27,34	0,57	58,06	1,21	0,64	6,4	
	CHP4	y = 19,932x - 10,844	29,02	0,6	68,88	1,43	0,83	8,3	
	CHP5	y = 23,227x - 8,8501	37,02	0,78	84,05	1,75	0,97	9,67	
	CHP6	y = 19,934x - 13,209	26,66	0,56	66,53	1,39	0,83	8,31	
	CHP7	y = 15,387x - 13,043	17,73	0,37	48,51	1,01	0,64	6,41	
	CHP8	y = 19,743x - 17,552	21,93	0,46	61,42	1,28	0,82	8,23	7,89
Hemp *Gan. luc.*	CHG1	y = 31,853x + 10,737	74,43	1,55	138,17	2,88	1,33	13,28	
	CHG2	y = 27,236x - 3,9454	50,52	1,05	105,01	2,19	1,14	11,35	
	CHG3	y = 26,607x - 3,4679	49,74	1,04	102,97	2,15	1,11	11,09	
	CHG4	y = 26,988x - 24,218	29,76	0,62	83,73	1,74	1,12	11,24	
	CHG5	y = 33,642x - 12,686	54,58	1,14	121,93	2,54	1,4	14,03	
	CHG6	y = 30,968x - 8,1679	53,76	1,12	115,72	2,41	1,29	12,91	
	CHG7	y = 33,463x - 6,3097	60,59	1,26	127,59	2,66	1,4	13,96	
	CHG8	y = 34,32x - 2,256	66,38	1,38	135,05	2,81	1,43	14,31	12,77
Sawdust *Pl. ostr.*	CSP1	y = 30,869x + 1,4605	63,18	1,31	124,98	2,6	1,29	12,88	
	CSP2	y = 23,95x + 10,111	58,04	1,21	105,96	2,21	1	9,98	
	CSP3	y = 29,222x + 23,226	81,84	1,7	140,18	2,92	1,22	12,16	
	CSP4	y = 22,717x - 8,7262	36,61	0,76	82,1	1,7	0,94	9,48	
	CSP5	y = 24,062x - 32,985	14,71	0,31	63,09	1,31	1,01	10,08	
	CSP6	y = 27,278x + 27,447	82,39	1,72	136,77	2,85	1,13	11,33	
	CSP7	y = 19,113x - 8,3211	29,74	0,62	68,08	1,41	0,79	7,99	
	CSP8	y = 23,52x + 43,689	91,6	1,91	138,17	2,88	0,97	9,7	10,45
Sawdust Gan. luc.	CSG1	y = 65,855x - 32,258	98,6	2,05	230,98	4,81	2,76	27,58	
	CSG2	y = 49,358x + 7,5135	106,43	2,22	204,94	4,27	2,05	20,52	
	CSG3	y = 53,677x + 21,189	129,23	2,69	235,95	4,92	2,23	22,23	
	CSG4	y = 56,813x + 35,02	150,18	3,13	261,81	5,45	2,32	23,26	
	CSG5	y = 52,35x - 19,482	84,53	1,76	189,63	3,95	2,19	21,9	
	CSG6	y = 70,439 x - 43,093	96,58	2,01	237,25	4,94	2,93	29,31	
	CSG7	y = 68,505x - 32,53	104,72	2,18	238,04	4,96	2,78	27,78	
	CSG8	y = 64,209x - 50,73	75,69	1,58	204,88	4,27	2,69	26,92	24,94

Young's modulus

	Ganod. luc. + sawdust without jute	Variant 1 Mycelium top layer + jute	Variant 2 MBC top layer + jute
Mean E	24,94 MPa	28,17 MPa	23,48 MPa

Calculations bending tests

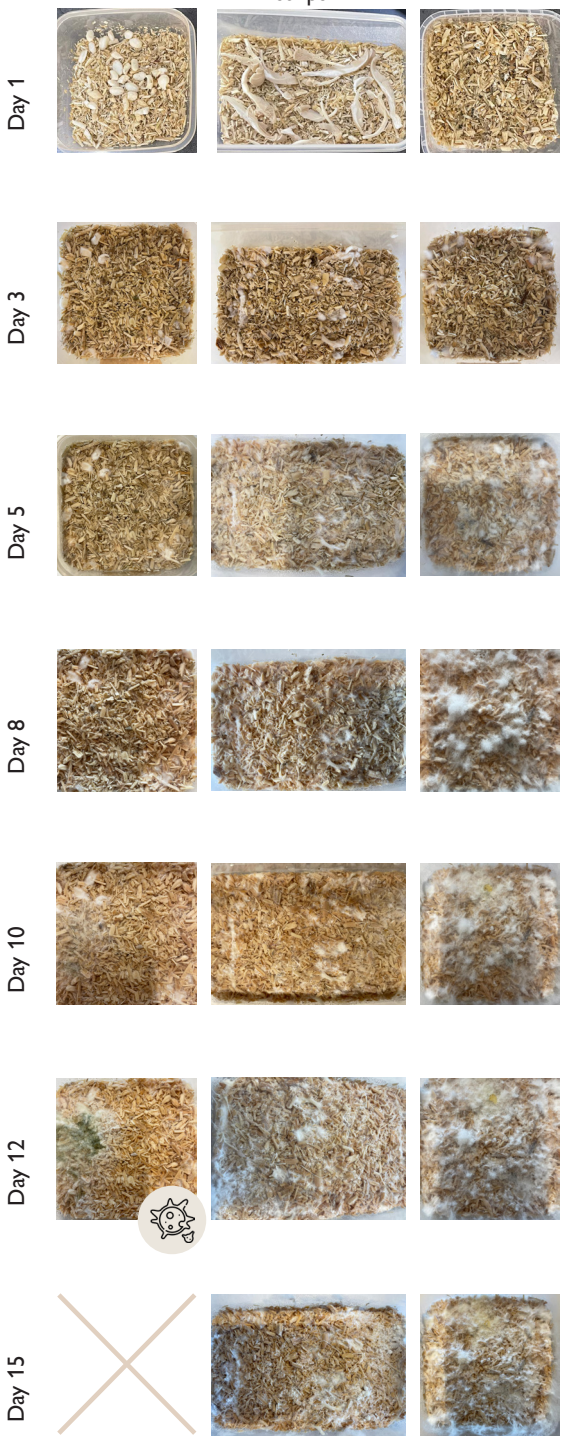
		Formula	Formula applied	Quantity	Unit
l	Span			40	mm
p	Load				N
M	Bending moment	(pl/4)	(p*40) / 4		Nmm
σ	Stress	σ [N/mm2] or [MPa] = load [N] / area [mm2]			[MPa]
		σ max = 6M / bd^2	6M / 4500		
		bd^2 = 20 mm * 15 mm^2 = 4500 mm^3			
E	Elastic modulus	E [MPa] = σ [MPa] / ε			

	Hemp *Pleurotus ostreatus*					Sawdust *Pleurotus ostreatus*					Sawdust *Ganoderma lucidum*				
Sample number	Maximum strength [N]	Standard Deviation [N]	Maximum moment [Nmm]	Maximum stress σ [MPa]	Standard Deviation [MPa]	Maximum strength [N]	Standard Deviation [N]	Maximum moment [Nmm]	Maximum stress σ [MPa]	Standard Deviation [MPa]	Maximum strength [N]	Standard Deviation [N]	Maximum moment [Nmm]	Maximum stress σ [MPa]	Standard Deviation [MPa]
1	-	-	-	-	-	2,54	0,31	25,4	0,03	0,01	12,09	3,16	120,9	0,16	0,05
2	4,03	0,44	40,3	0,05	0	3,42	0,57	34,2	0,05	0,01	14,04	1,21	140,4	0,19	0,02
3	3,32	0,27	33,2	0,04	0,01	3,15	0,3	31,5	0,04	0	25,33	10,08	253,3	0,34	0,13
4	2,48	1,11	24,8	0,03	0,02	2,66	0,19	26,6	0,04	0	19,74	4,49	197,4	0,26	0,05
5	2,27	1,32	22,7	0,03	0,02	2,45	0,4	24,5	0,03	0,01	15,93	0,68	159,3	0,21	0
6	3,92	0,33	39,2	0,05	0	2,28	0,57	22,8	0,03	0,01	9,5	5,75	95	0,13	0,08
7	3,23	0,36	32,3	0,04	0,01	2,81	0,04	28,1	0,04	0	12,28	2,97	122,8	0,16	0,05
8	5,89	2,3	58,9	0,08	0,03	3,5	0,65	35	0,05	0,01	13,92	1,33	139,2	0,19	0,02
Mean	3,59	0,88	35,91	0,05	0,01	2,85	0,38	28,51	0,04	0,01	15,25	3,71	153,54	0,21	0,05

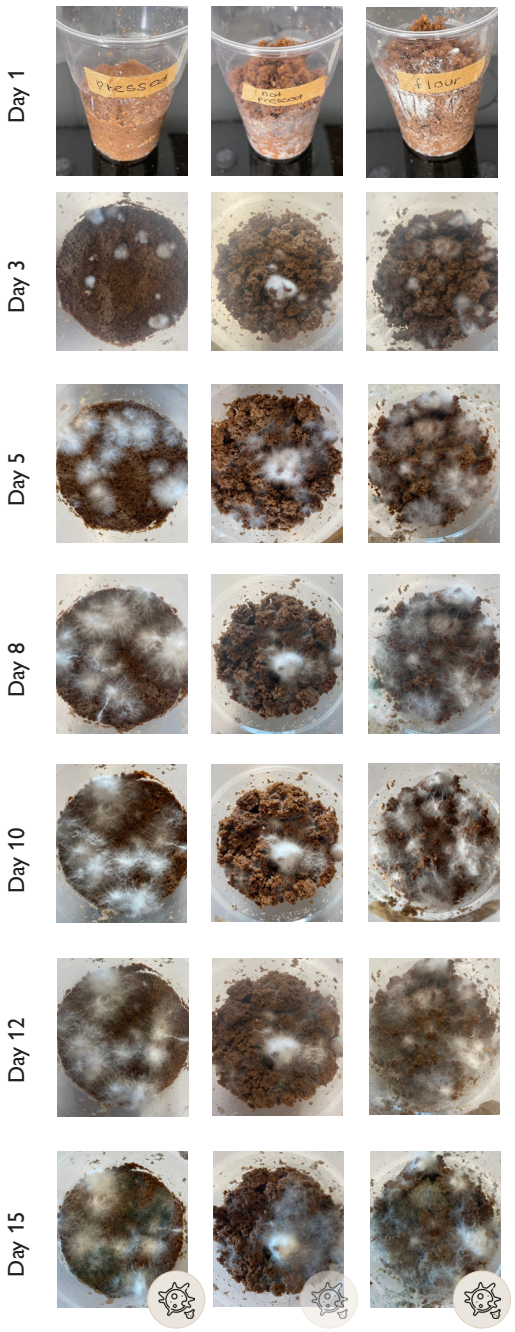
$$s = \sqrt{\frac{\sum(x - \bar{x})^2}{n - 1}}$$

Growing process chosen substrates

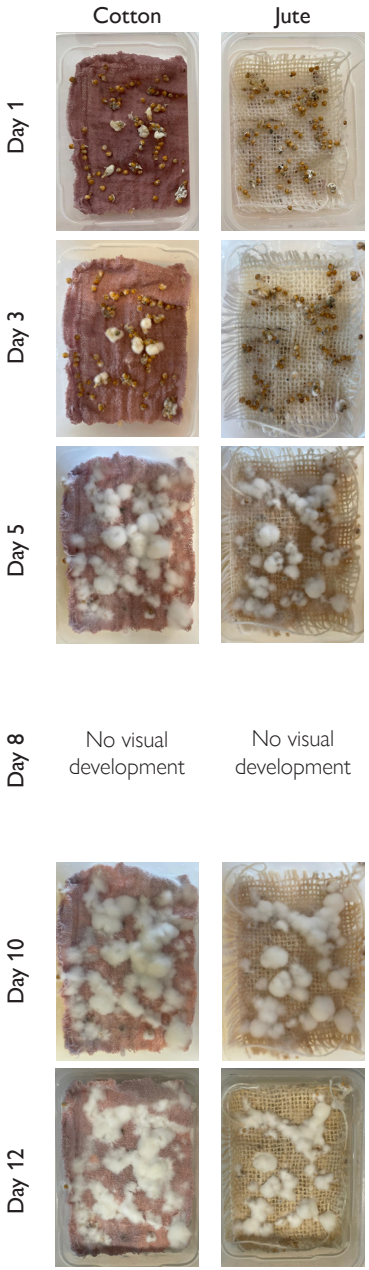
Growing process on hemp fiber particles
(granular material)



Growing process on sawdust
Soaked in boiling water | Grain spawn
(loose material)



Growing process grain spawn on woven materials
Cotton & Jute
(woven material)



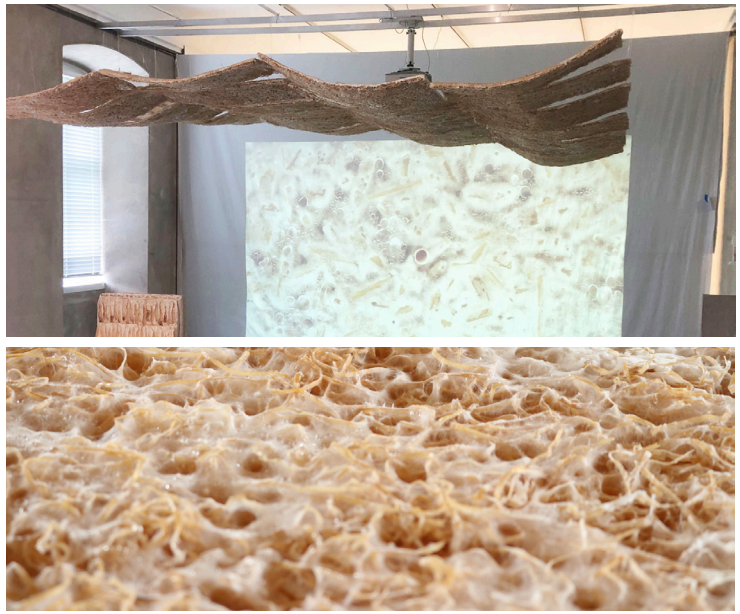
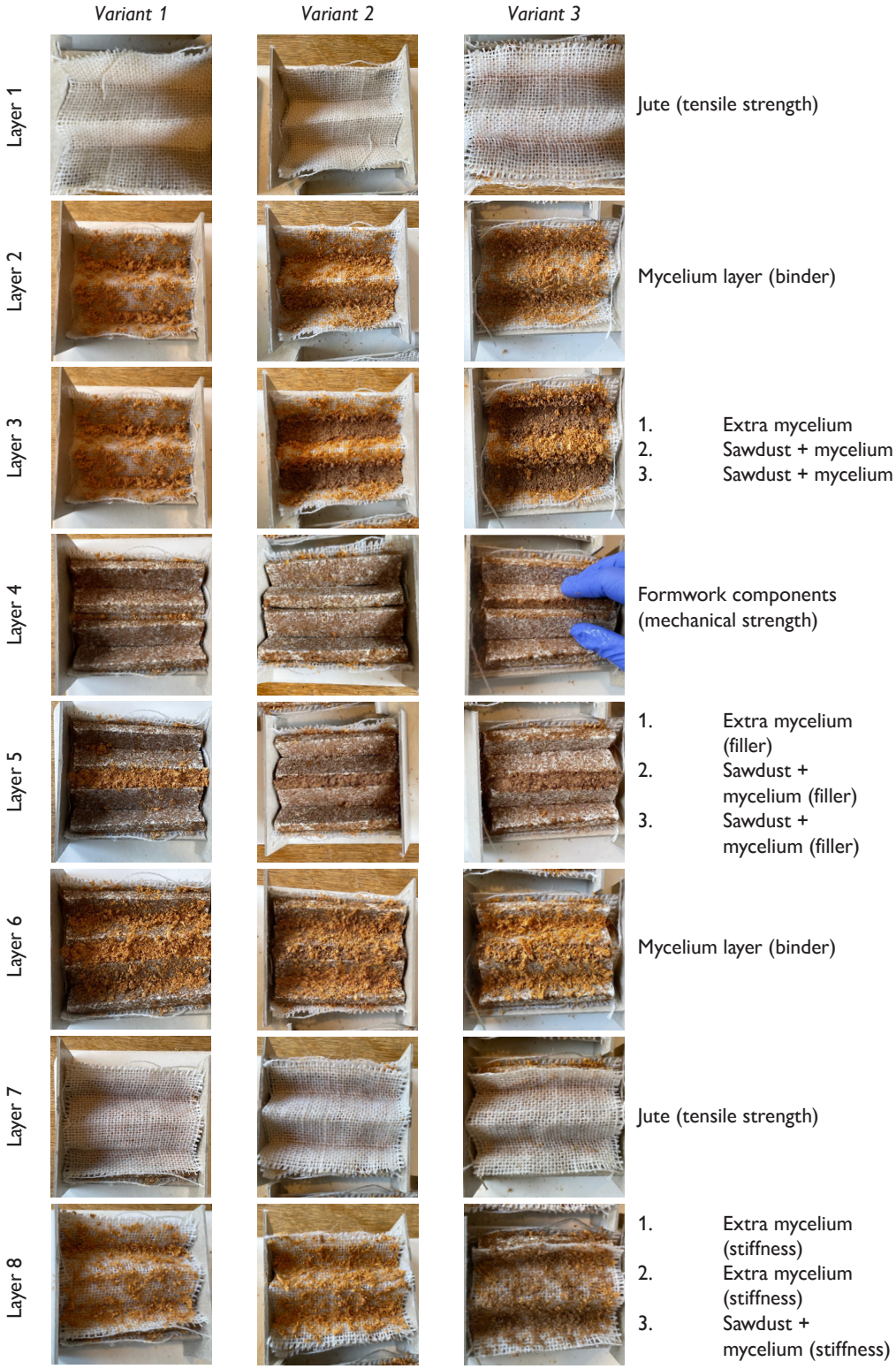
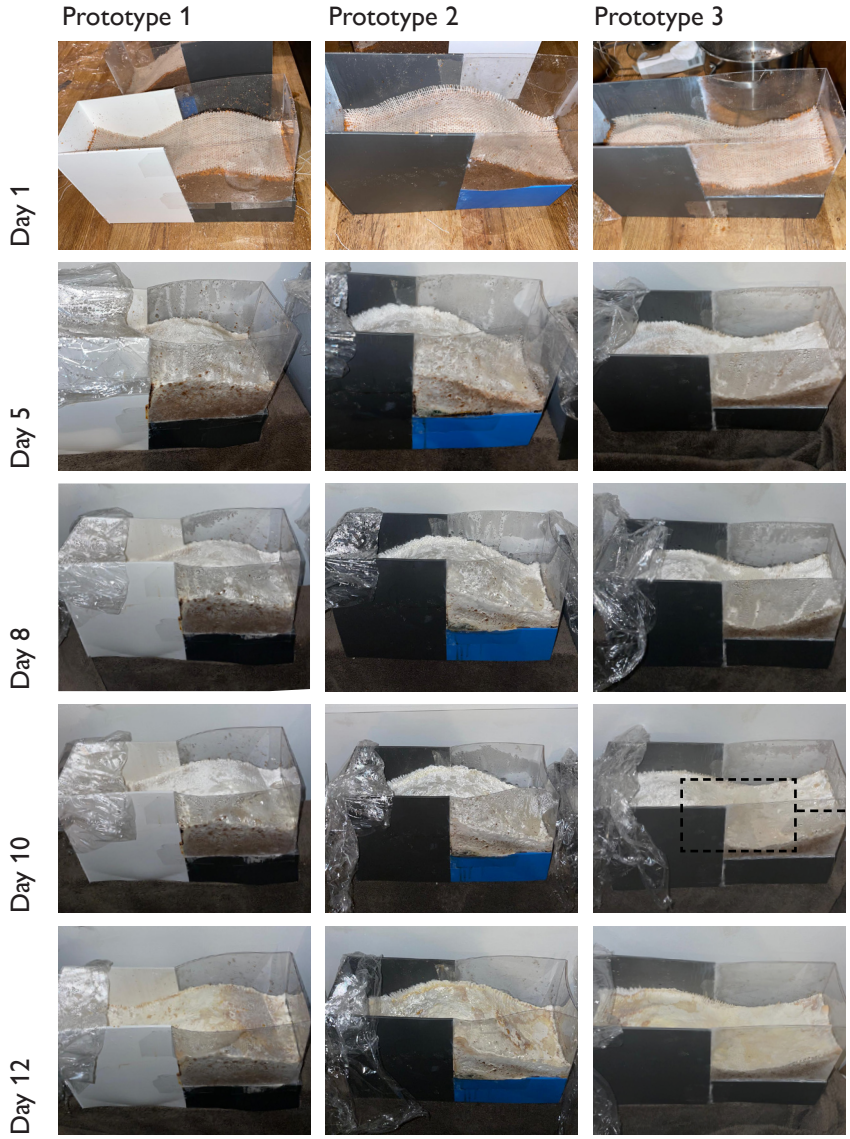


Figure 19. Setup, close-up and layers built-up diagram of the Myx Sail (Dwan et al., 2024)

Figure 17. Shell Mycelium Pavilion-2016 (Almpani-Lekka et al., 2021)


Variant 1
Variant 2
Variant 3
Layer 1
Layer 2
Layer 3
Layer 4
Layer 5
Layer 6
Layer 7
Layer 8
Jute (tensile strength)
Mycelium layer (binder)
1. Extra mycelium
2. Sawdust + mycelium
3. Sawdust + mycelium
Formwork components (mechanical strength)
1. Extra mycelium (filler)
2. Sawdust + mycelium (filler)
3. Sawdust + mycelium (filler)
Mycelium layer (binder)
Jute (tensile strength)
1. Extra mycelium (stiffness)
2. Extra mycelium (stiffness)
3. Sawdust + mycelium (stiffness)

Growing process



Gel development

At day 10, all three variants exhibited signs of gel formation in the lowest points of the blocks. This phenomenon is likely to have occurred due to excessive moisture accumulation in these areas. To ascertain the potential for further mycelial development, the gel is extracted from the samples.

	Size [b x l x h]	Temperature [° C]	Humidity level [%]	Light influence	Duration	Pressed?	Weight day 1	Weight per piece last day	Density ρ [kg/m3]
V1	100 x 300 x 150 mm	18 - 28	Unknown	Natural light	12 days	Hand-pressed before growing process	5203 g	1879 g	417,55
V2	100 x 300 x 150 mm	18 - 28	Unknown	Natural light	12 days	Hand-pressed before growing process	5449 g	2013 g	447,33
V3	100 x 300 x 150 mm	18 - 28	Unknown	Natural light	12 days	Hand-pressed before growing process	4983 g	1724 g	383,11