

# **Fungoplastics**

## **Part 2**

### **MSE 493**

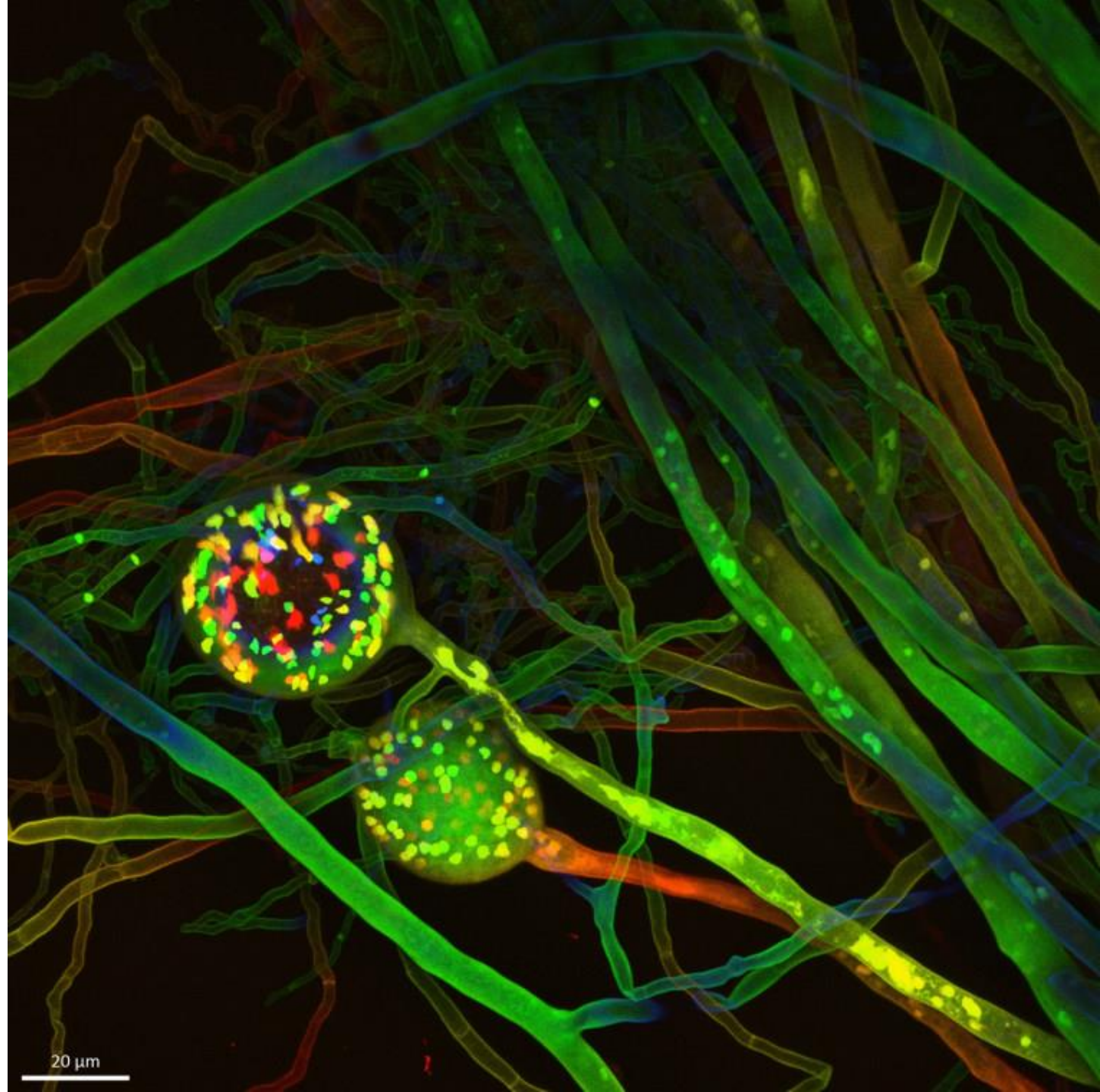
**Prof. Tiffany Abitbol**

**2025**

# Today: mycelium-bound composites

- One example with liquid fermentation
- One example with solid fermentation (classic approach)

['Amazon forests of the underground': Why scientists want to map the world's fungi](#)



20 μm

# My introduction to mycelium

FULL PAPER

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SYSTEMS

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## Biofabrication of Nanocellulose–Mycelium Hybrid Materials

Noam Attias, Michael Reid, Sylwia Carolina Mijowska, Illia Dobryden, Marcus Isaksson, Boaz Pokroy, Yasha J. Grobman, and Tiffany Abitbol\*

Healthy material alternatives based on renewable resources and sustainable technologies have the potential to disrupt the environmentally damaging production and consumption practices established throughout the modern industrial era. In this study, a mycelium–nanocellulose biocomposite with hybrid properties is produced by the agitated liquid culture of a white-rot fungus (*Trametes ochracea*) with nanocellulose (NC) comprised as part of the culture media. Mycelial development proceeds via the formation of pellets, where NC is enriched in the pellets and depleted from the surrounding liquid media. Micrometer-scale NC elements become engulfed in mycelium, whereas it is hypothesized that the nanometer-scale fraction becomes integrated within the hyphal cell wall, such that all NC in the system is essentially surface-modified by mycelium. The NC confers mechanical strength to films processed from the biocomposite, whereas the mycelium screens typical cellulose–water interactions, giving fibrous slurries that dewater faster and films that exhibit significantly improved wet resistance in comparison to pure NC films. The mycelium–nanocellulose biocomposites are processable in the ways familiar to papermaking and are suggested for diverse applications, including packaging, filtration, and hygiene products.

(NC), are exceptionally promising as they can be processed into a versatile range of sustainable alternatives that include packaging,<sup>[1,2]</sup> flame-retardants,<sup>[3,4]</sup> and substitutes for meat and leather.<sup>[5]</sup> The term nanocellulose encompasses the three main families of cellulosic nanomaterials, including cellulose nanocrystals (CNCs), cellulose nanofibrils (CNFs), and bacterial nanocellulose (BNC).<sup>[6]</sup> Here, the focus is on wood-based CNCs and CNFs, although these materials can be derived from other natural cellulose sources, including waste streams.<sup>[7]</sup> CNCs and CNFs are highly crystalline structural building blocks of the plant cell wall, with CNFs liberated by mechanical delamination and CNCs by chemical degradation.<sup>[8]</sup> CNCs are comparatively short and monodisperse ( $\approx 100$  nm length and 5–10 nm width),<sup>[9]</sup> whereas CNF sizes can vary significantly depending on pulp pretreatment and extent of fibrillation, with the finest grades

Impact factor: 6.1

**Year: 2021**

# Fungi for materials



Attias et al., Journal of cleaner production 246 (2019).

## Solid Fermentation: Materials grown to shape



“MyForest Foods” by Ecovative  
Bacon in just 9 days



MycoWorks × Hermès



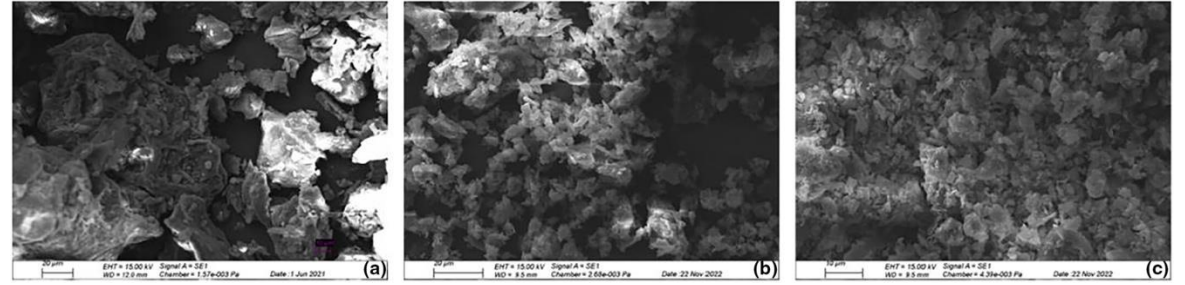
Bolt Threads × Adidas

**Food waste is converted to new food:**



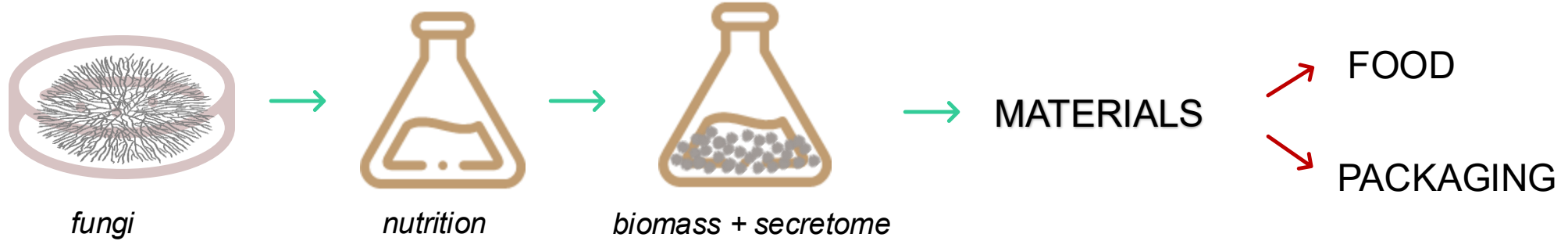
From EU "Smart Protein" project (2020).

**Upcycling cocoa pod husks into a fiber & protein-rich ingredient:**

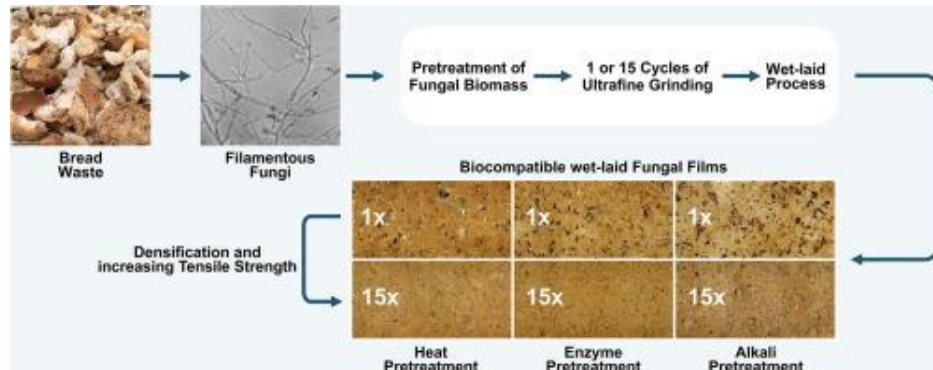


Bickel Haase et al., Food Science & Nutrition 12 (2024).

**Liquid Fermentation:**

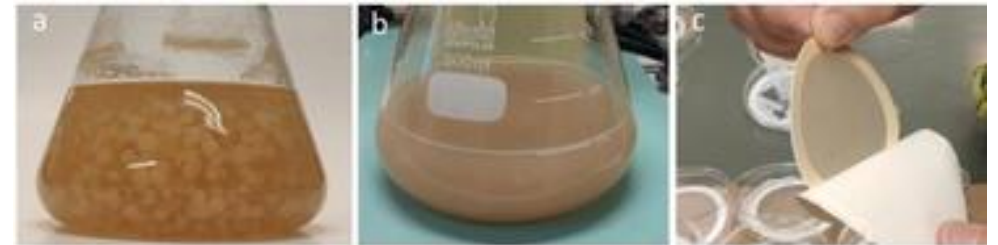


**Wet-laid sheets from bread waste:**



Köhnlein et al., Materials & Design 216 (2022).

**Packaging-relevant films from nanocellulose:**

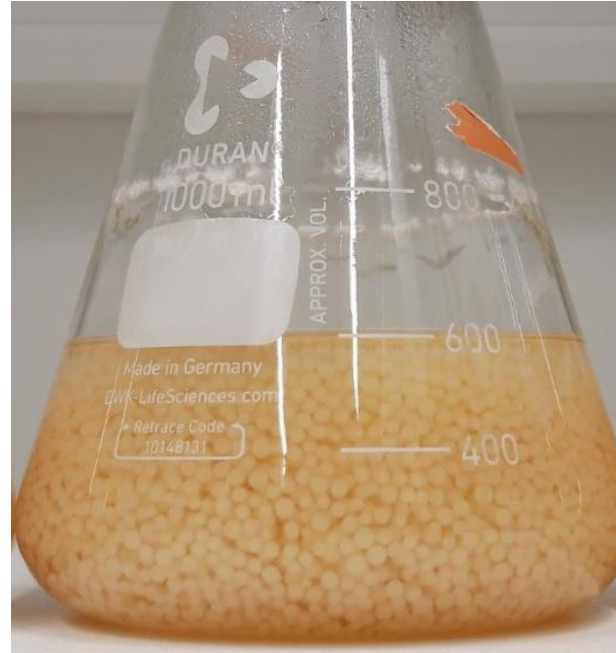


Attias & Abitbol, et al., Advanced Sustainable Systems 5 (2021).

# Liquid fermentation



1) Inoculated media

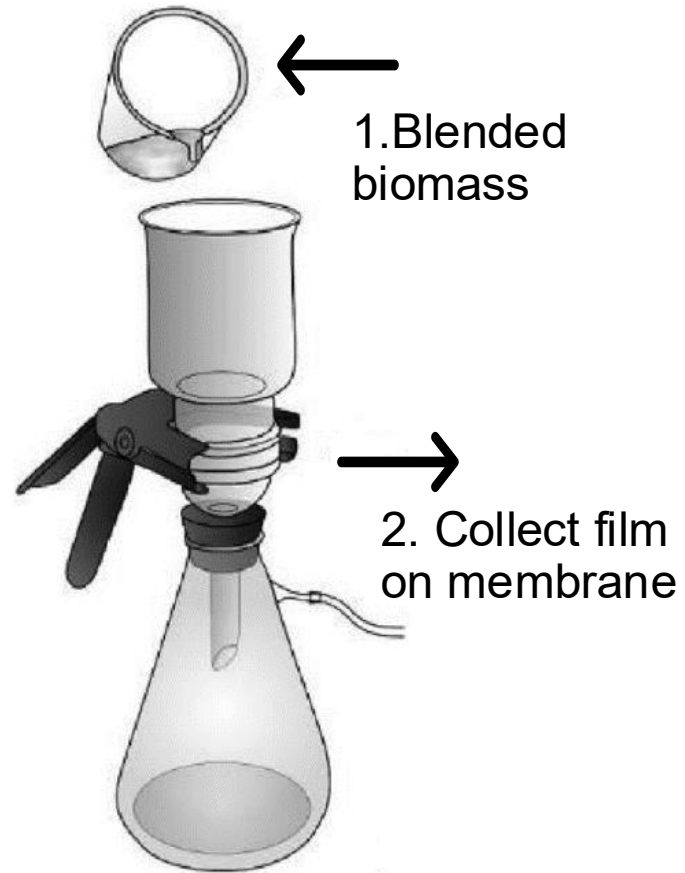


2) Biomass after 2-  
weeks of growth



3) Blended biomass

# Make films

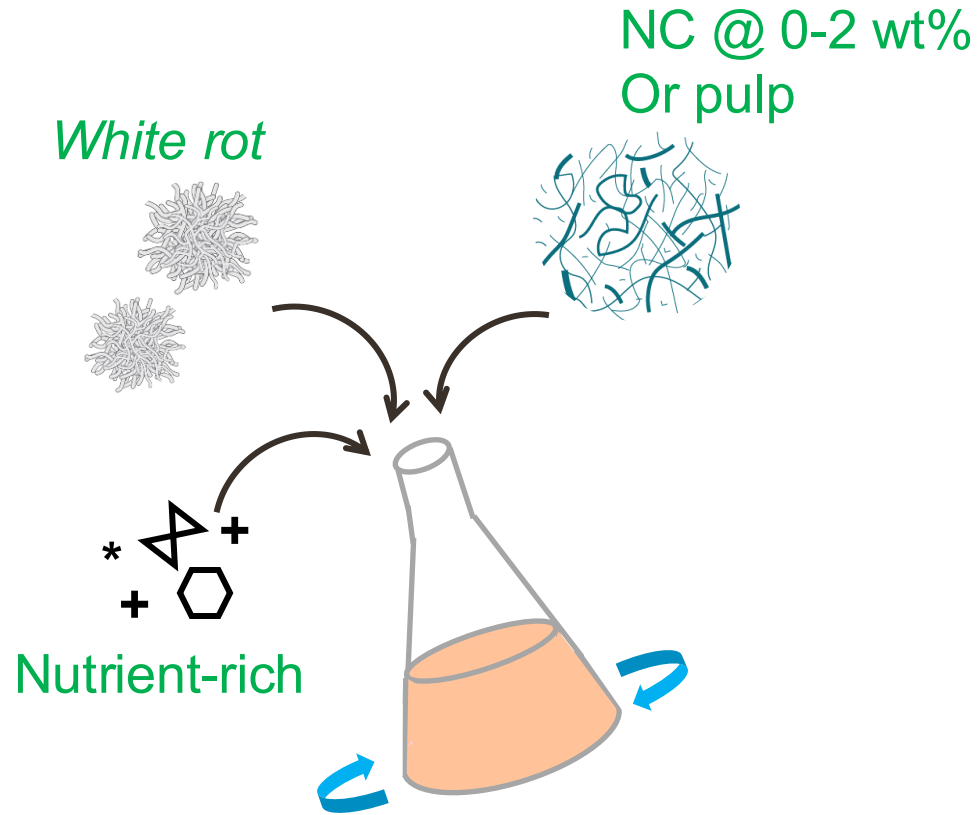


3. Dry in press



4. Resultant film  
7 cm diameter

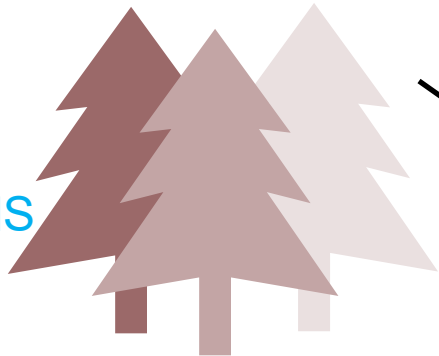
# Mycelium-(nano)cellulose hybrids



- *T. ochracea* inoculum (white rot)
- Cellulose is hard to digest
- Easy to digest nutrient content approx. 20 g/L
- Approx. 2 weeks growth, dark, 23 °C
- Terminate and purify

# Types of NC

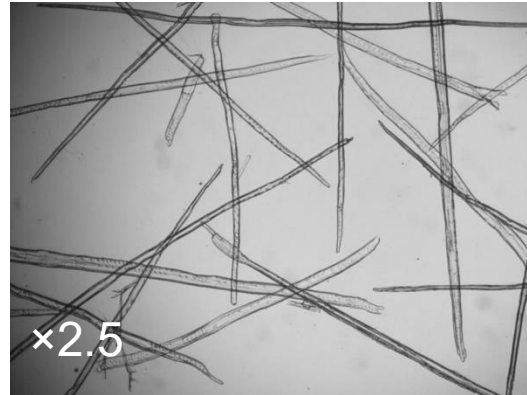
PLANTS  
WASTE STREAMS



PULPING

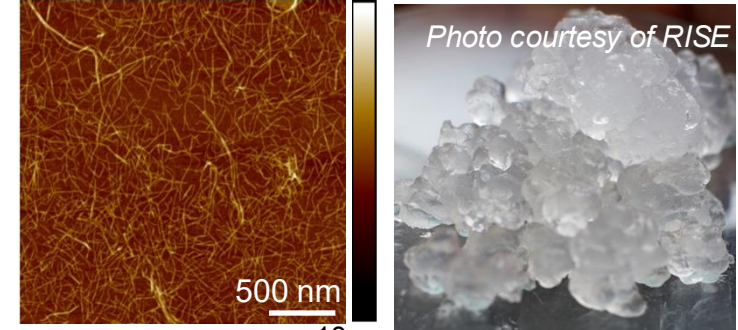
CHEMICAL &  
MECHANICAL

PULP



CARBOXYMETHYLATED  
CELLULOSE NANOFIBRILS  
(CNF)

10 nm



-10 nm

*Photo courtesy of RISE*

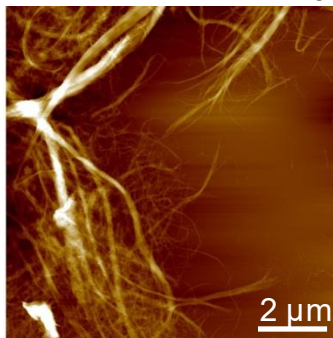
*Intermediate nano-fraction (ca. 25%)*

ENZYMATICALLY PRE-TREATED CNF

150 nm



*Lowest nano-fraction (ca. 15%)*



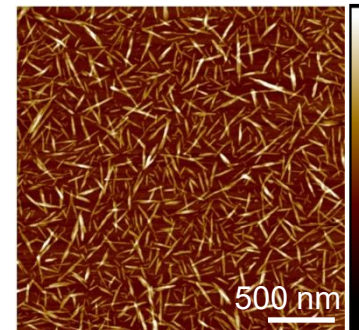
-150 nm

ENZYMES &  
MECHANICAL

CELLULOSE NANOCRYSTALS (CNC)

10 nm

CHEMICAL &  
MECHANICAL



-10 nm



*100% nano*

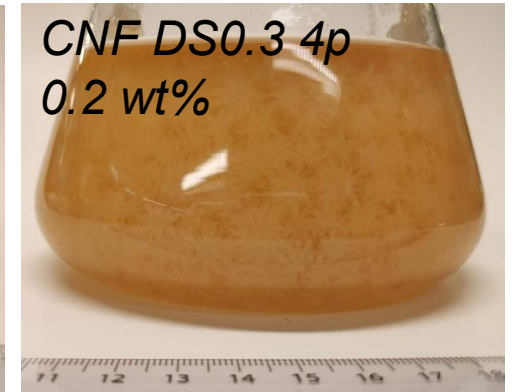
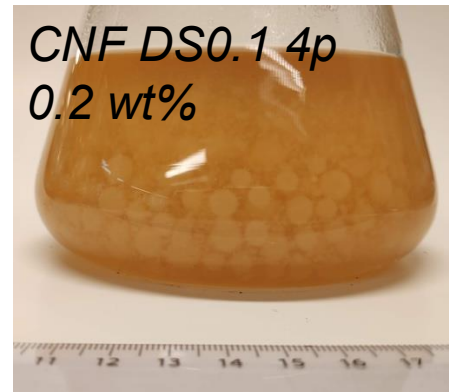
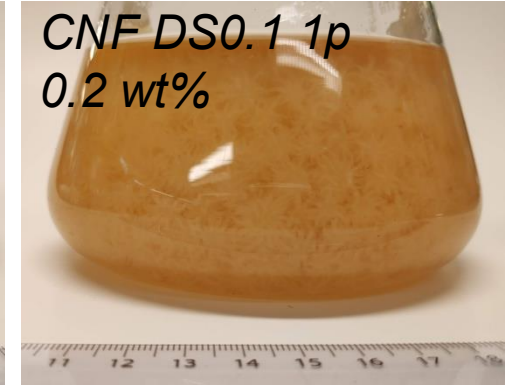
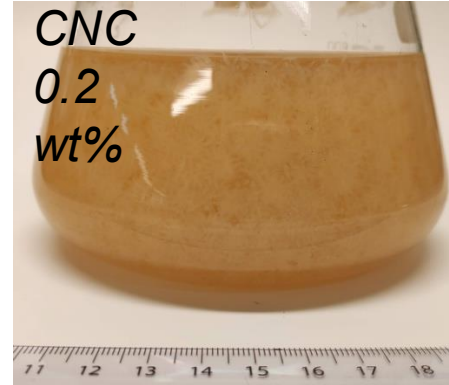
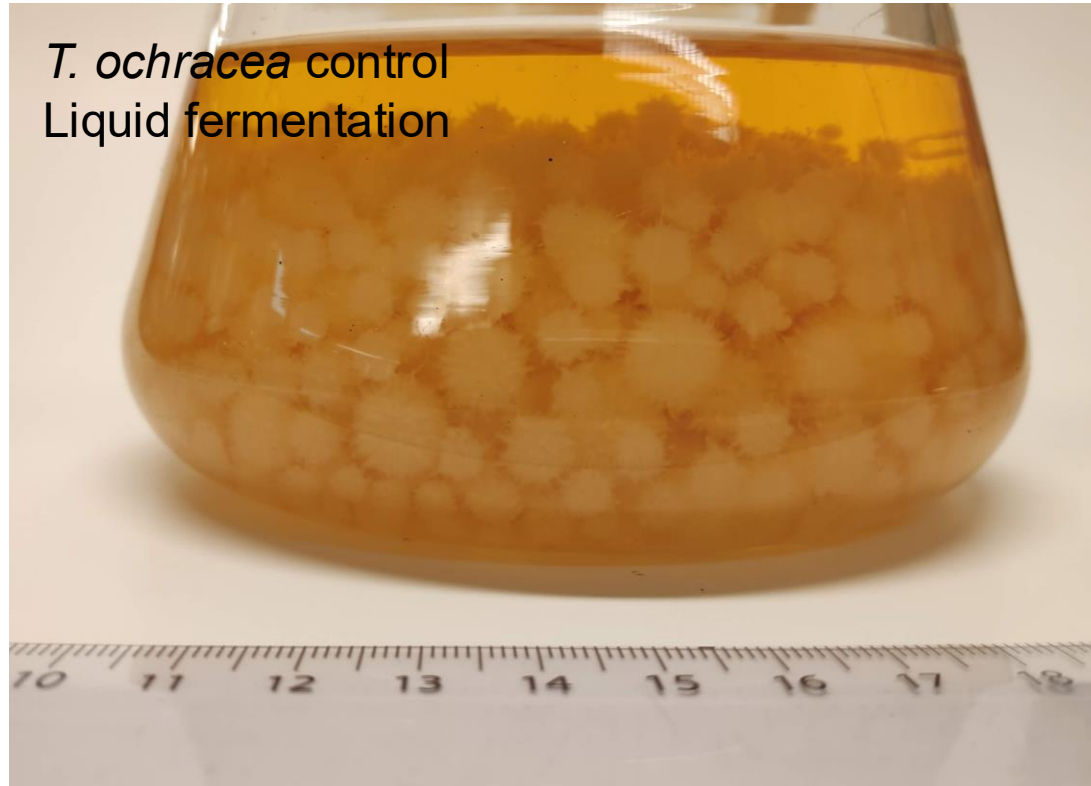
# *Trametes ochracea*



- **Ochre bracket**
- White rot
- Can also digest cellulose but we'd rather it didn't

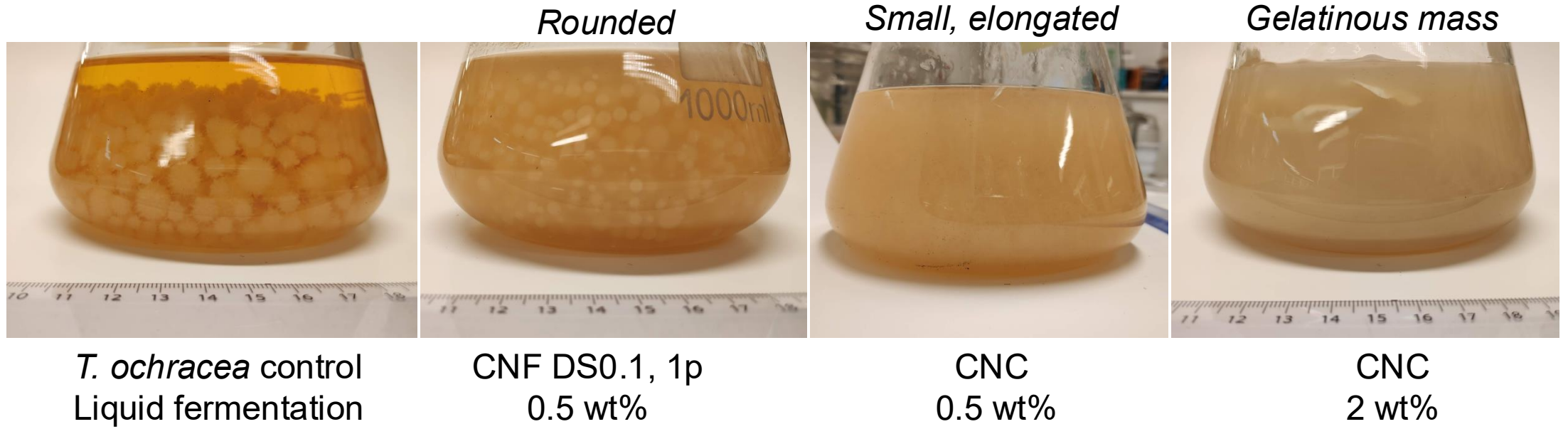
Irene Trummer, Wikipedia, [Creative Commons Attribution-Share Alike 4.0 International](#) license.

# Liquid fermentation with NC – lower C



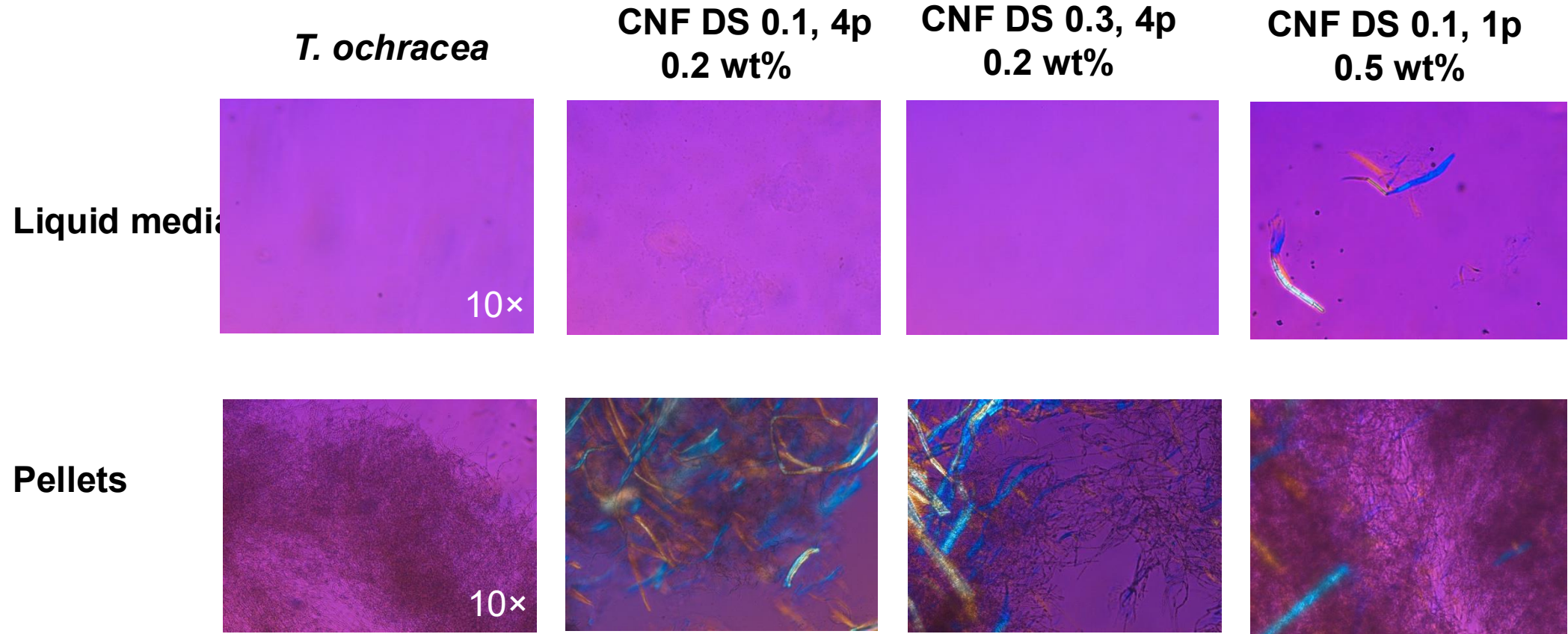
- *Similar morphologies (fuzzy pellets)*
- *Initial broth viscosity similar*
- *@ end, NC broth more viscous and turbid*

# Liquid fermentation with NC – higher C



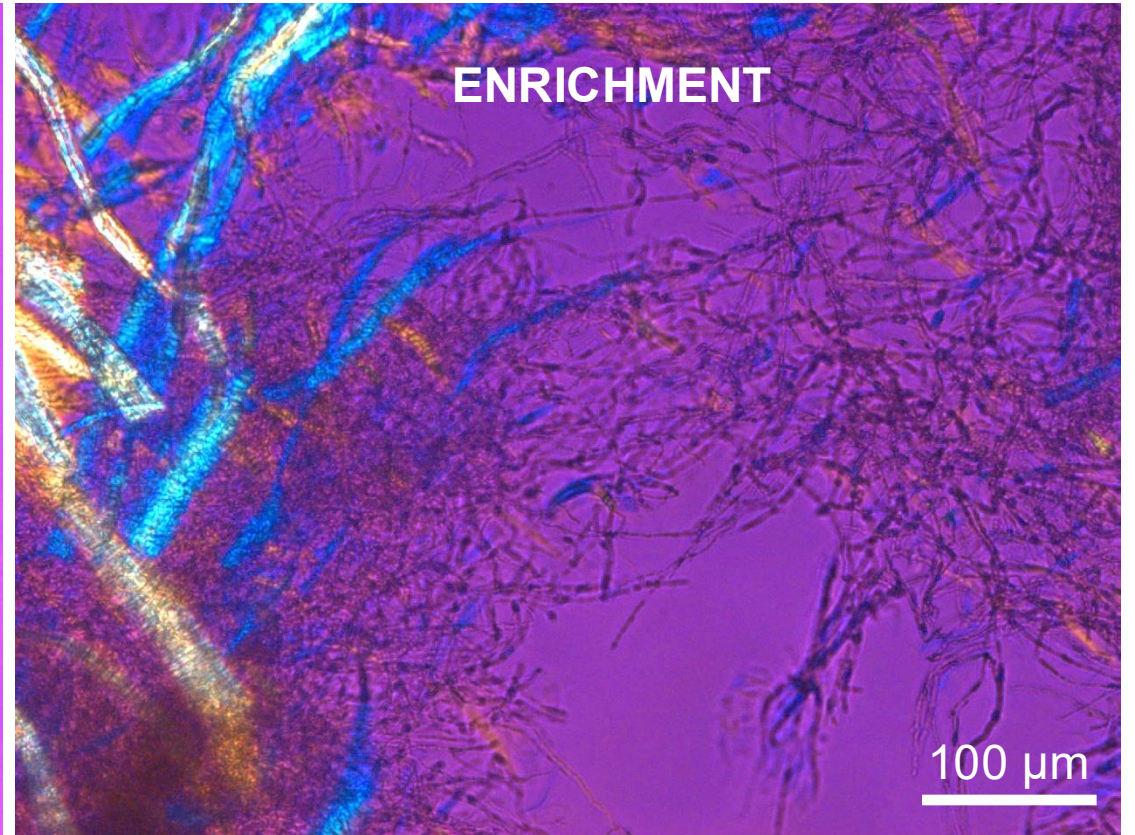
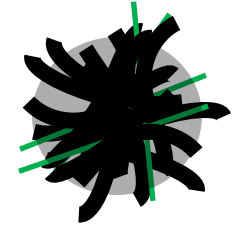
- *Higher NC content (0.5-2 wt%)*
- *From rounded pellets to rice-like pellets to solid mass*
- *Increasing broth viscosity*

# At the micron scale



This is a mycelium-bound composite

# NC depletion and enrichment

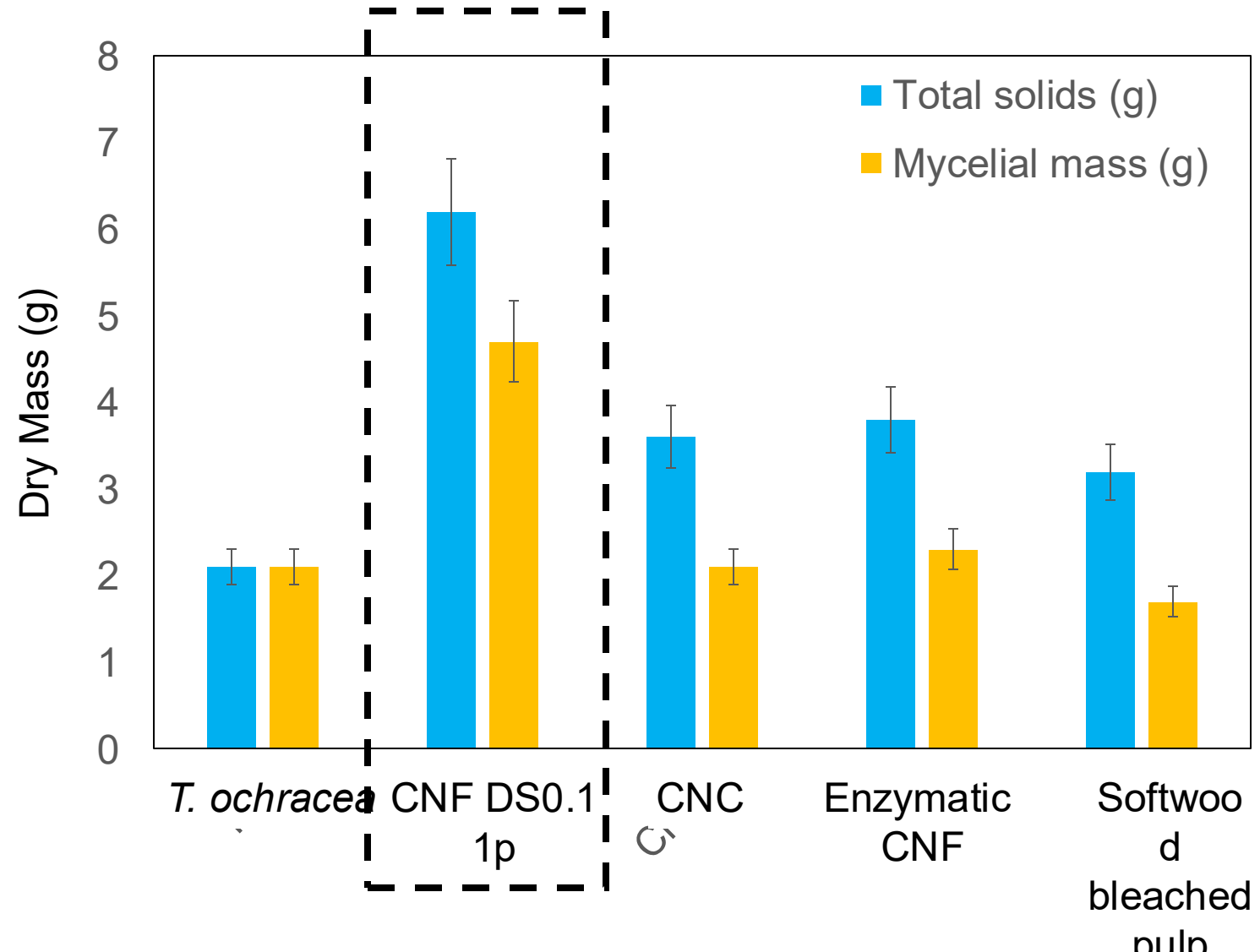


# Biomass yield for different NC at 0.25 wt%

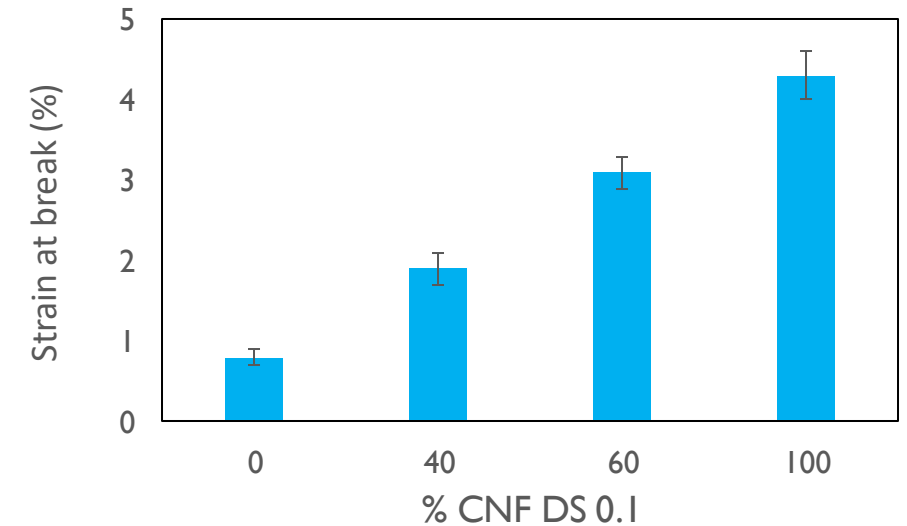
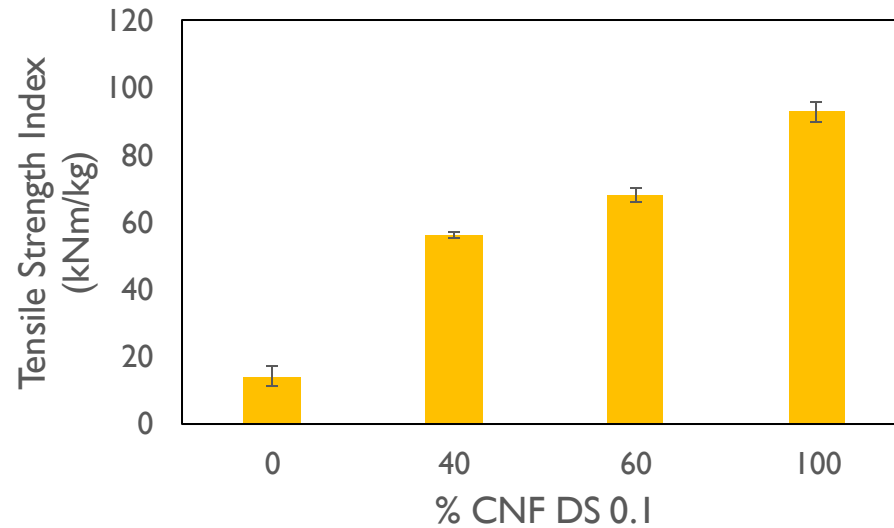
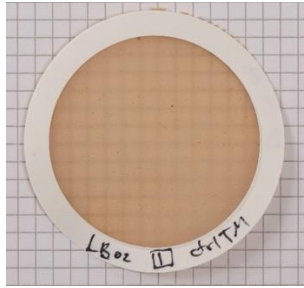


↓  
Homogenize

↓  
Biomass =  
Total solids - NC mass

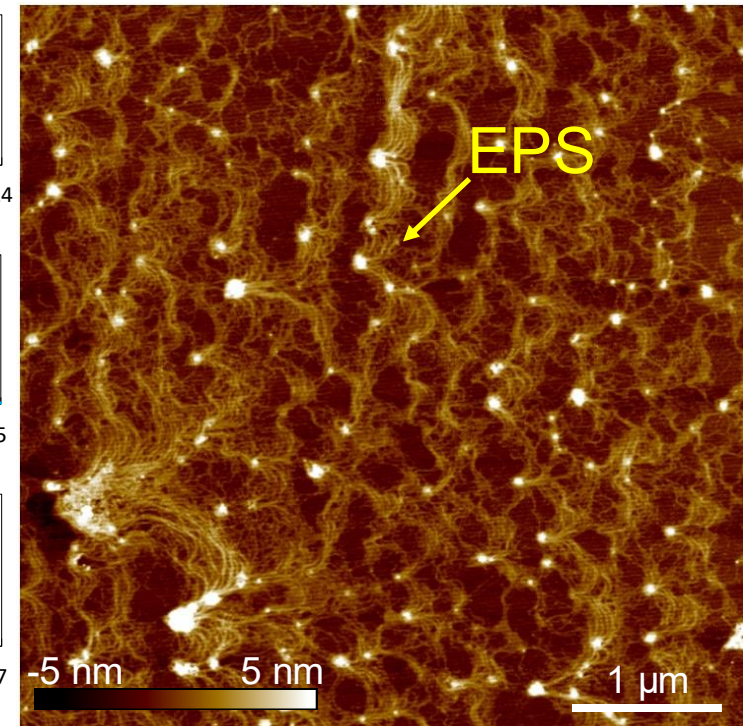
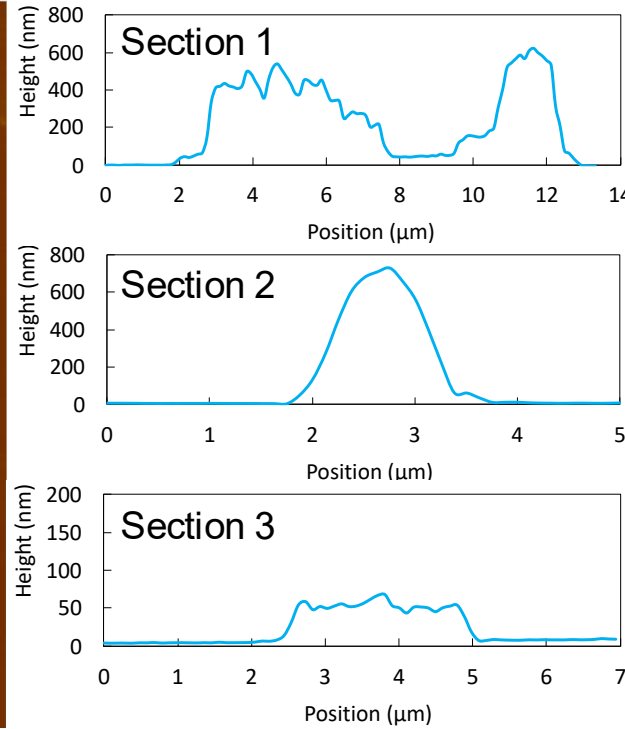
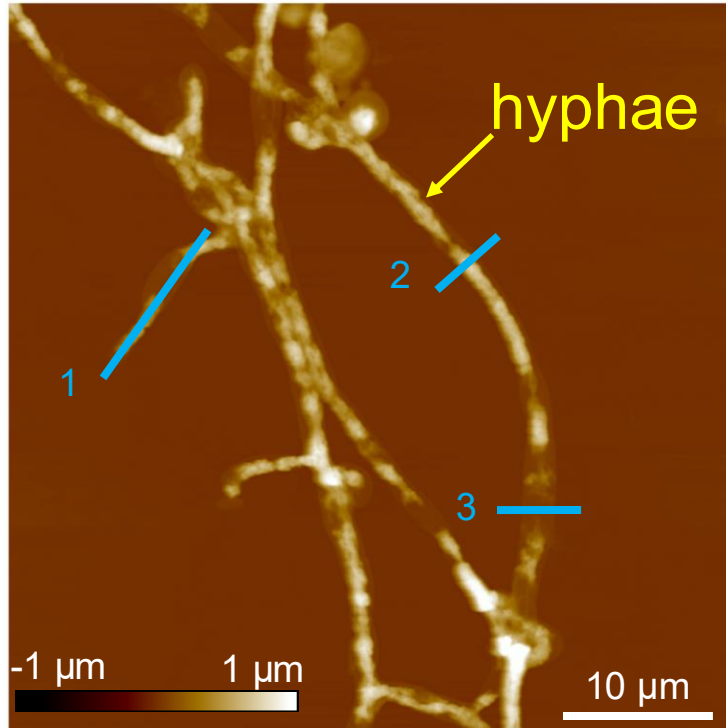


# NC digestion? (Data from 2020)



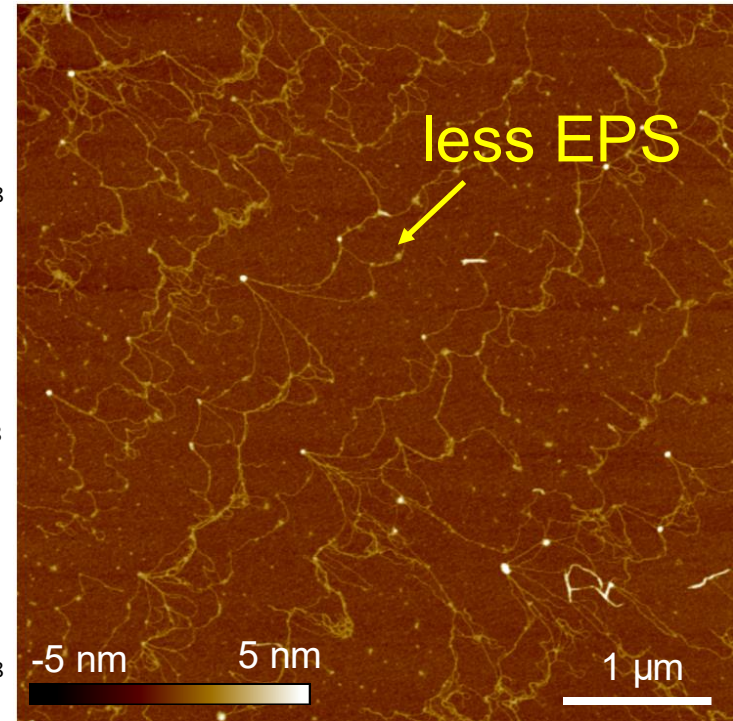
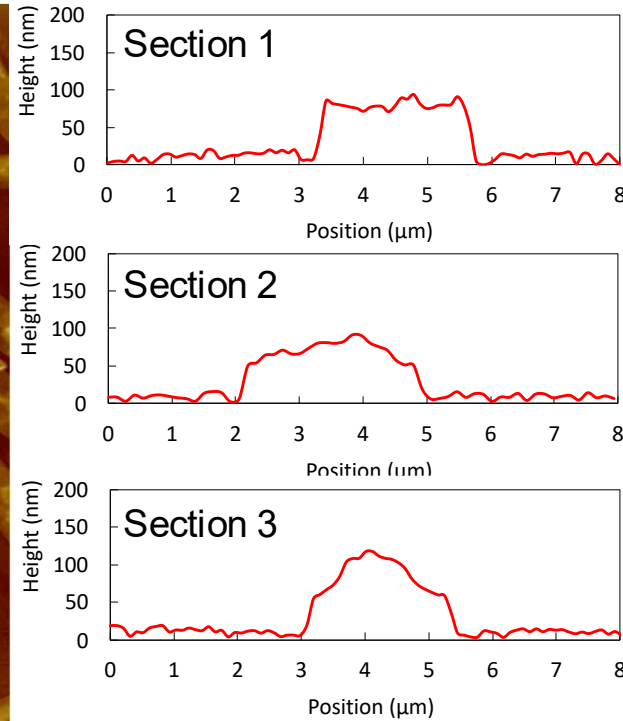
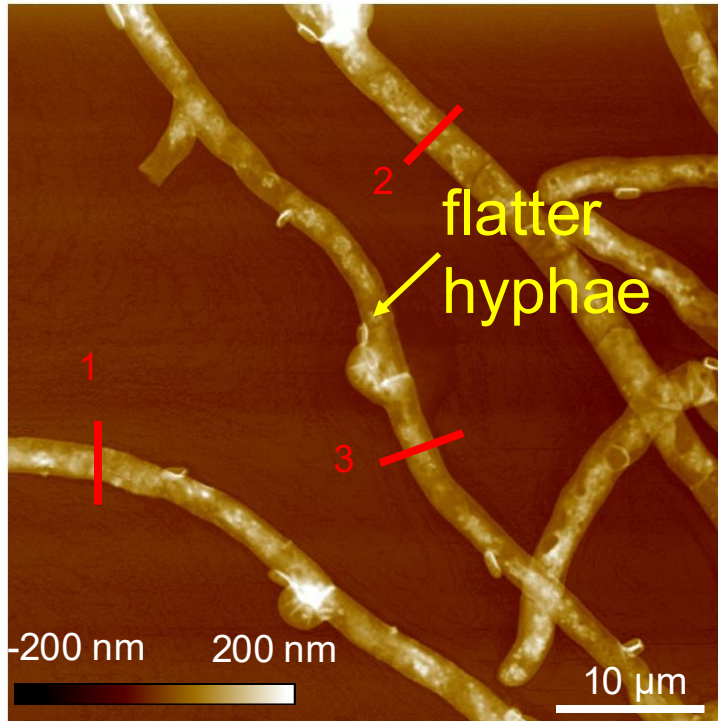
- A lot stronger than a PMM
- Mechanical properties increase nearly linearly with NC
- Fast food buffet

*T. ochracea* :

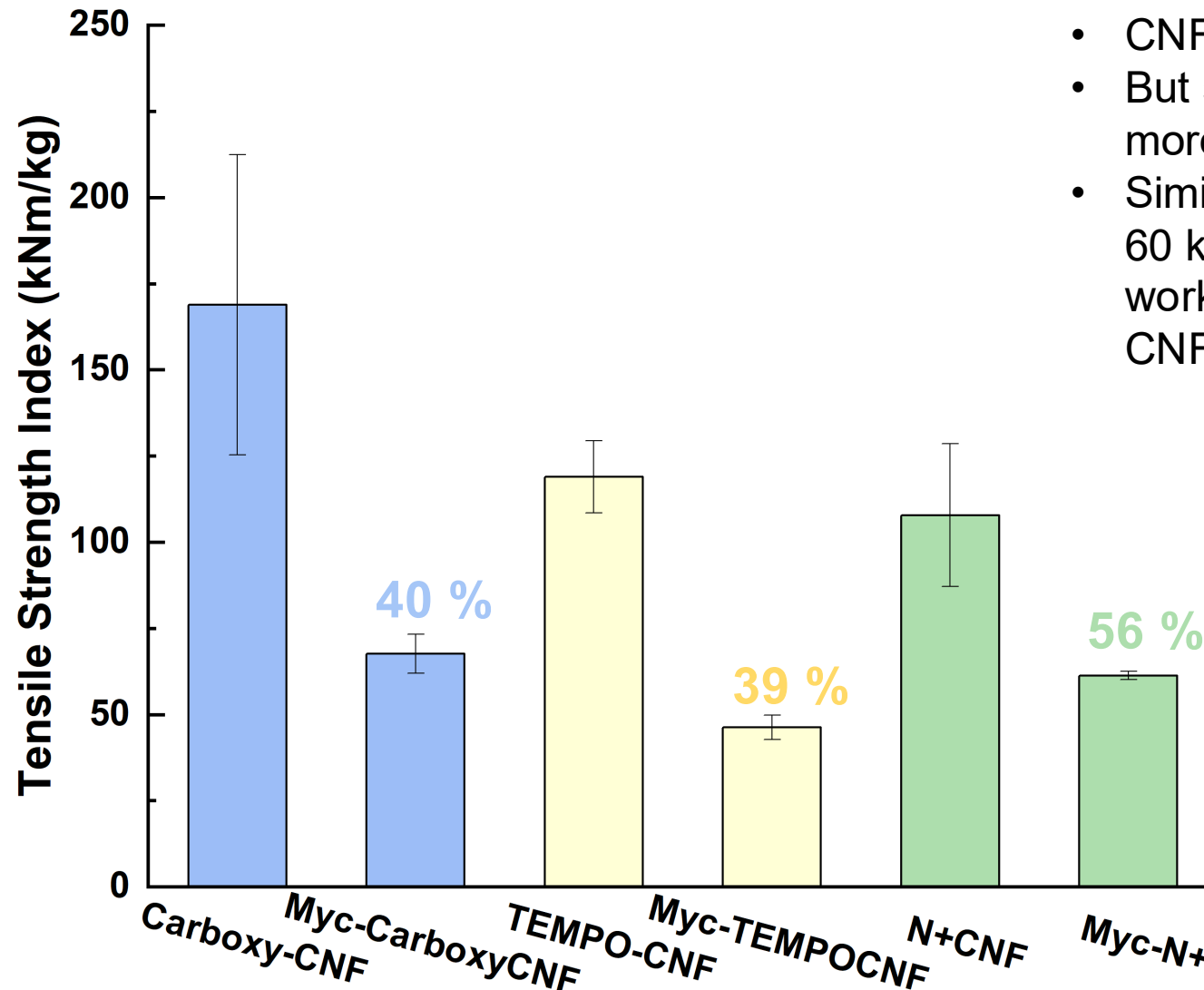


# Nanoscale investigation

DS 0.1 CNF-mycelium hybrid:

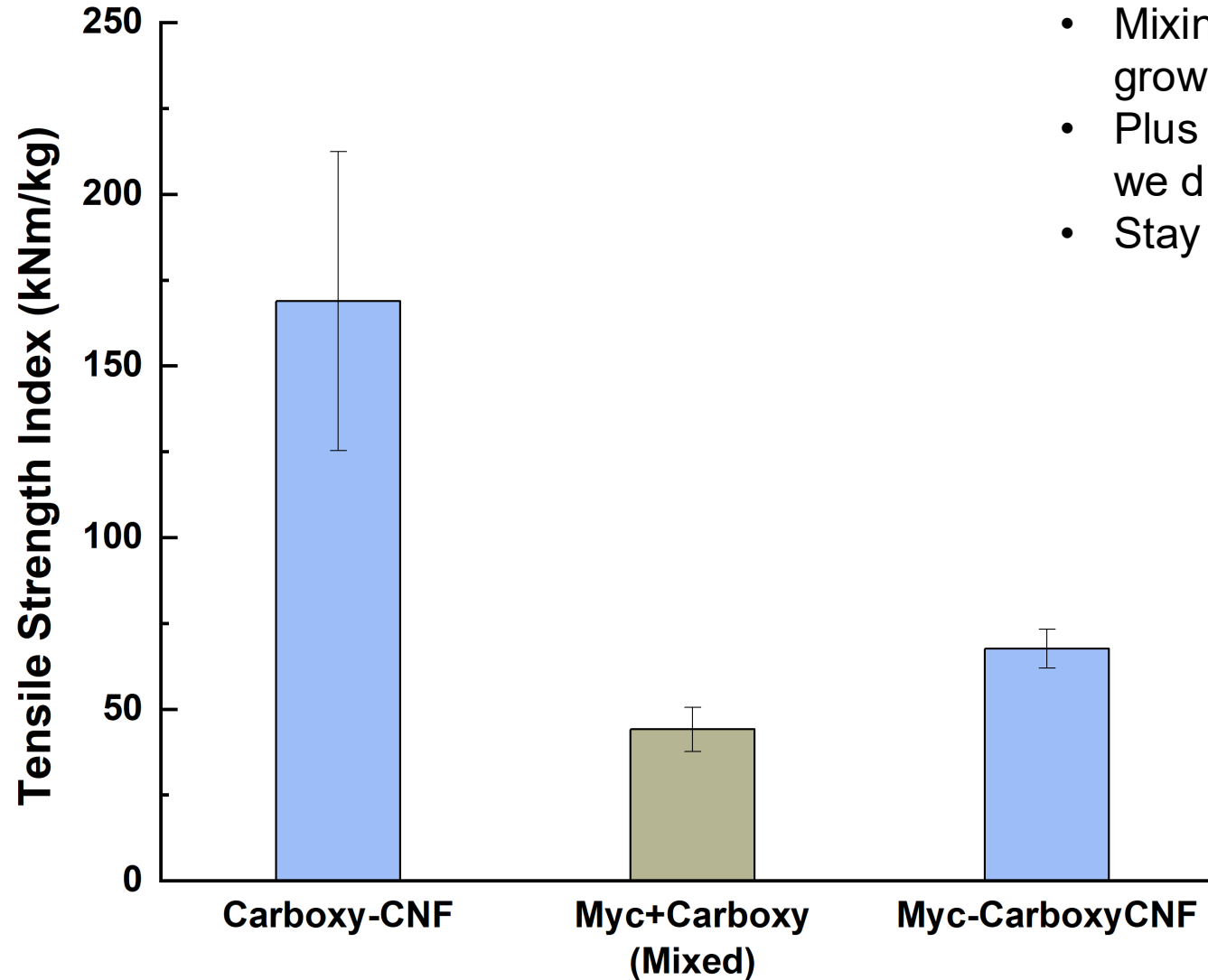


# MBC with CNF (new data)



- CNF content is 25%
- But strength of hybrid is more than linear!
- Similar value of around 60 kNm/kg that previous work achieved for a 40% CNF content...

# MBC with CNF: co-incubated vs mixed (new data)



- Mixing is not as good as growing together
- Plus other benefits that we did not discuss
- Stay tuned...

# Upcycling lignocellulose waste – solid fermentation

Year: 2025

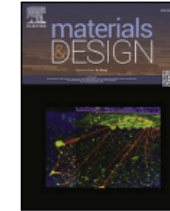
Materials & Design 250 (2025) 113591





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Materials & Design

journal homepage: [www.elsevier.com/locate/matdes](http://www.elsevier.com/locate/matdes)



## Mycelium-Bound composites from agro-industrial waste for broadband acoustic absorption

Wenjing Sun <sup>\*</sup> , Sophie H. Strässle Zúñiga, Valentin Philippe, Louisa Rinaldi, Tiffany Abitbol <sup>\*</sup> 

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### ARTICLE INFO

*Keywords:*

Mycelium  
Living materials  
Composites  
Acoustic absorption  
Additive manufacturing  
Upcycling

### ABSTRACT

This research explores the development of mycelium-bound composites for acoustic applications where natural fungal mycelia is used to bind organic waste into sound absorbing panels. The composites were grown in 3D printed molds to impart precise perforated patterns according to the principles of Helmholtz resonance. This approach led to improvements in sound absorption across a broad frequency range, particularly at low to mid-frequencies. By using agro-industrial waste as the raw material, our approach demonstrates the potential for upcycling while maintaining an entirely biodegradable composition. The study highlights the flexibility in material composition and design, offering a pathway for further refinements to optimize acoustic performance.

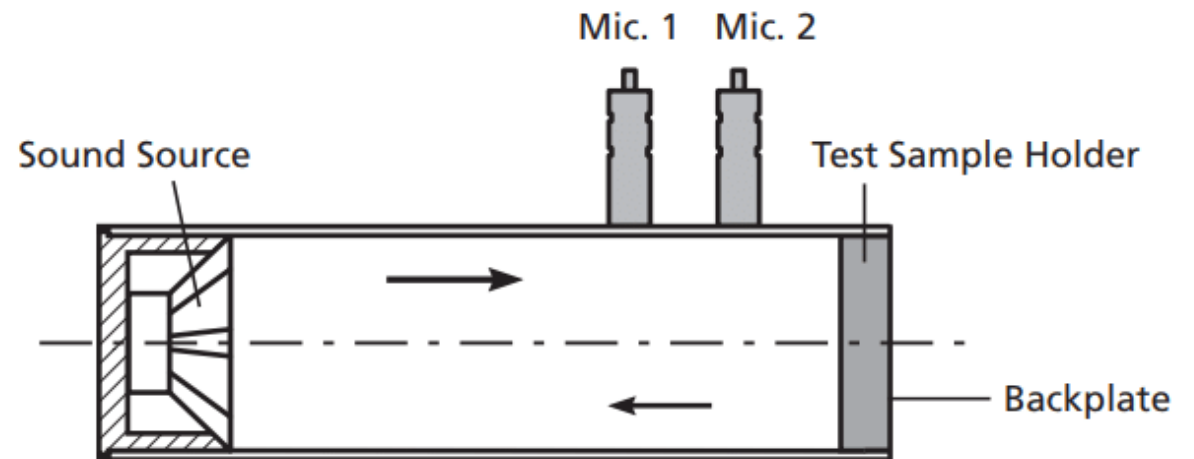


Dr. Wenjing Sun  
Cranfield University

# Measuring sound: Sound absorption coefficient

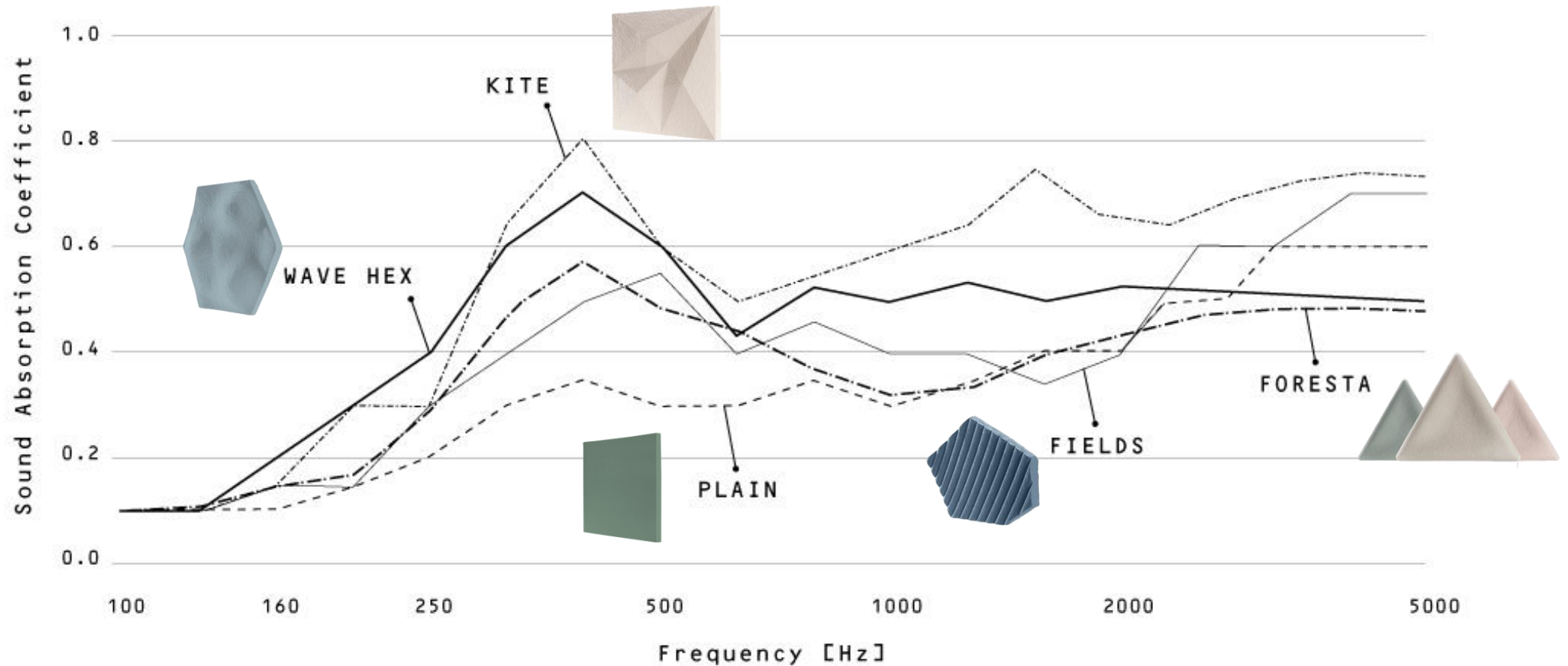
- Ranges from 0 to 1
- Measures how much sound a material absorbs versus reflects
- 0 = total reflection
- 1 = total absorption

- 2 microphone impedance tube set-up
- Sound source at one end and material at other end
- Two mics to measure incident and reflected waves



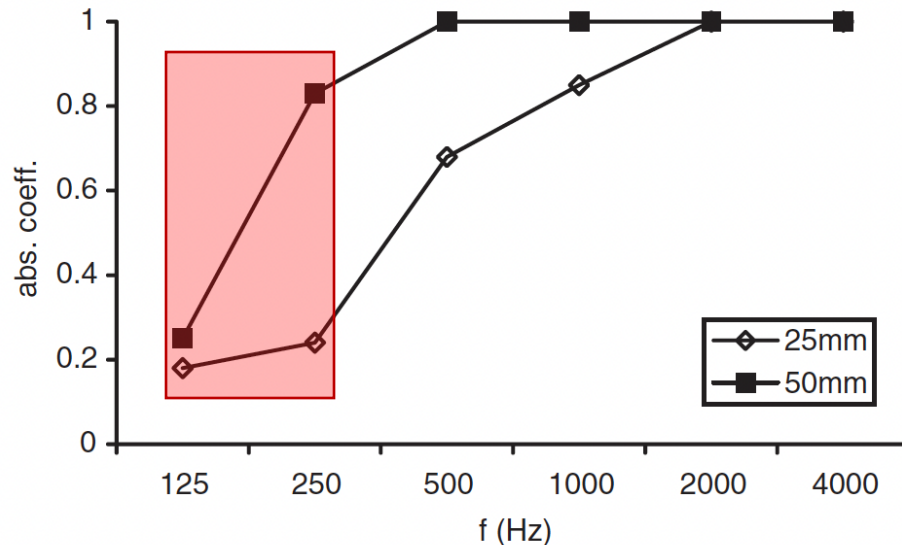
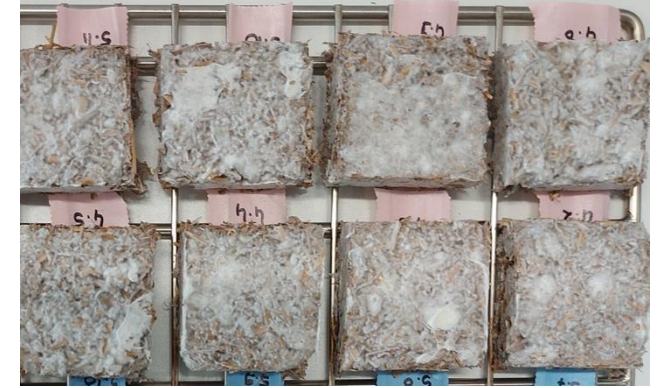
# Porous sound absorbers from mycelium

## Acoustic performance



# Porous sound absorbers - MBCs

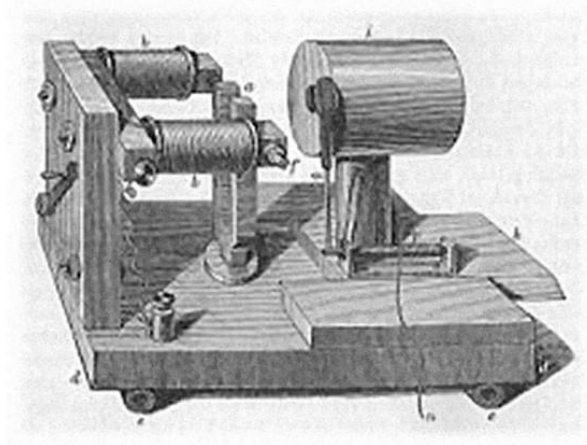
- Mycelium-bound composites are porous
- Sound waves move through pores, dissipating sound energy by friction
- Larger pores – better low frequency absorption
- Still low frequency sounds can be a blind spot for porous absorbers (pores too small)



Some examples of low frequency noise:

- Rumbly sounds
- Refrigerators
- Deep voices
- Growls
- Lawn mowers
- Thunder

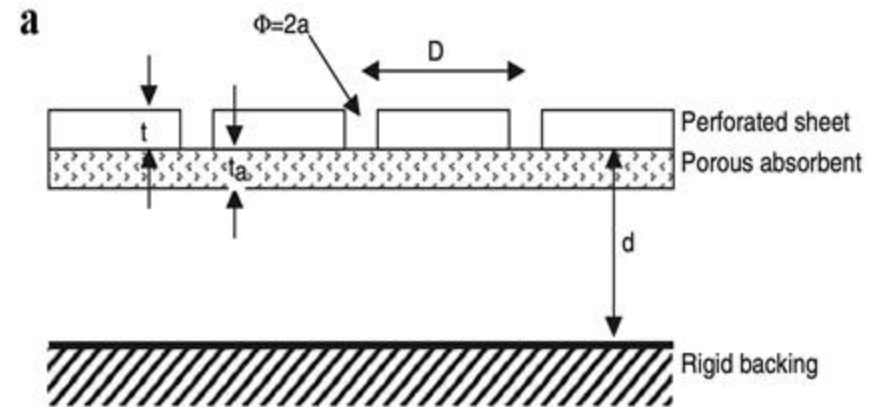
# Helmholtz resonance to low-frequency sound absorption



$$f = \frac{c}{2\pi} \sqrt{\frac{S}{lV_0}}$$

Where  $c$  = the speed of sound,  $S$  = the area of the hole,  $l$  = the length of the hole (thickness of wall that the hole penetrates), and  $V_0$  = the volume of the cylinder

Perforated sheets to add Helmholtz resonance to porous absorbers:



- Area, volume, and length of cavity

# Lignocellulose waste converted to sound absorbers



Rye straw



Spent coffee  
ground



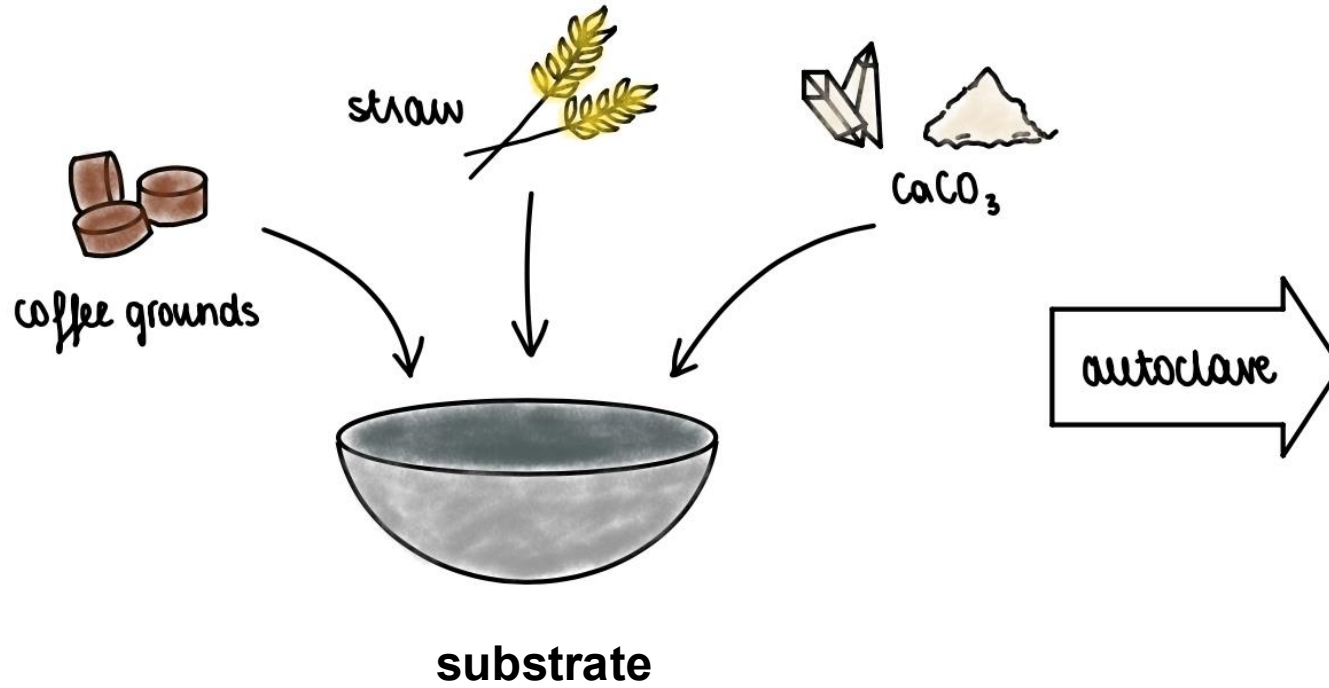
Calcium  
carbonate

+



Commercial  
mycelium  
spawn  
*Ganoderma  
Lucidum*

# Inoculation

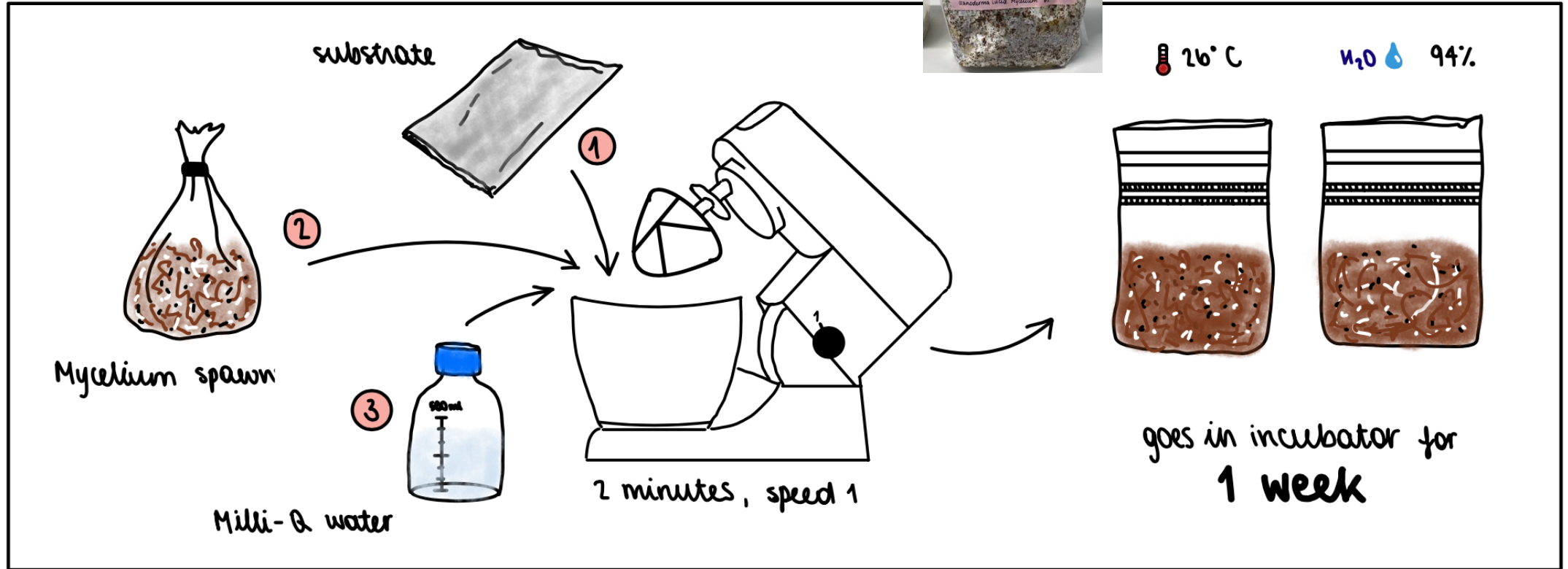


IN BIOSAFETY CABINET



# Growth in bag

IN BIOSAFETY CABINET



26°C

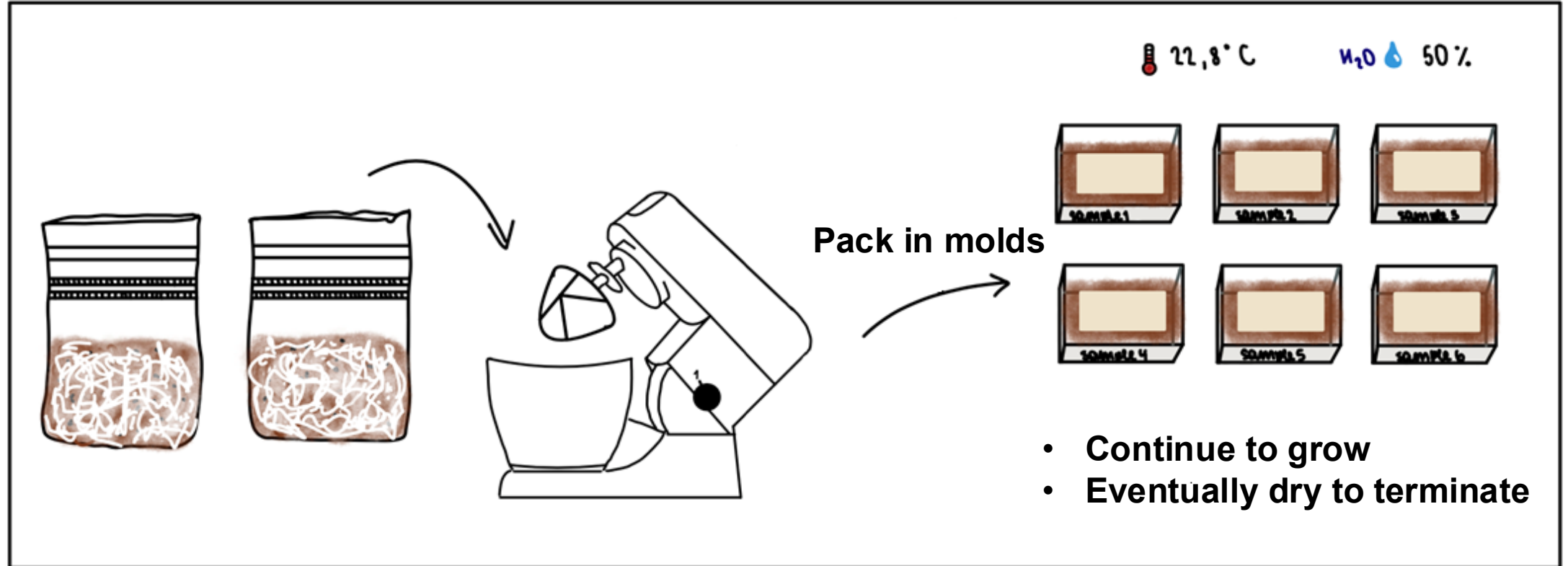
H<sub>2</sub>O 94%



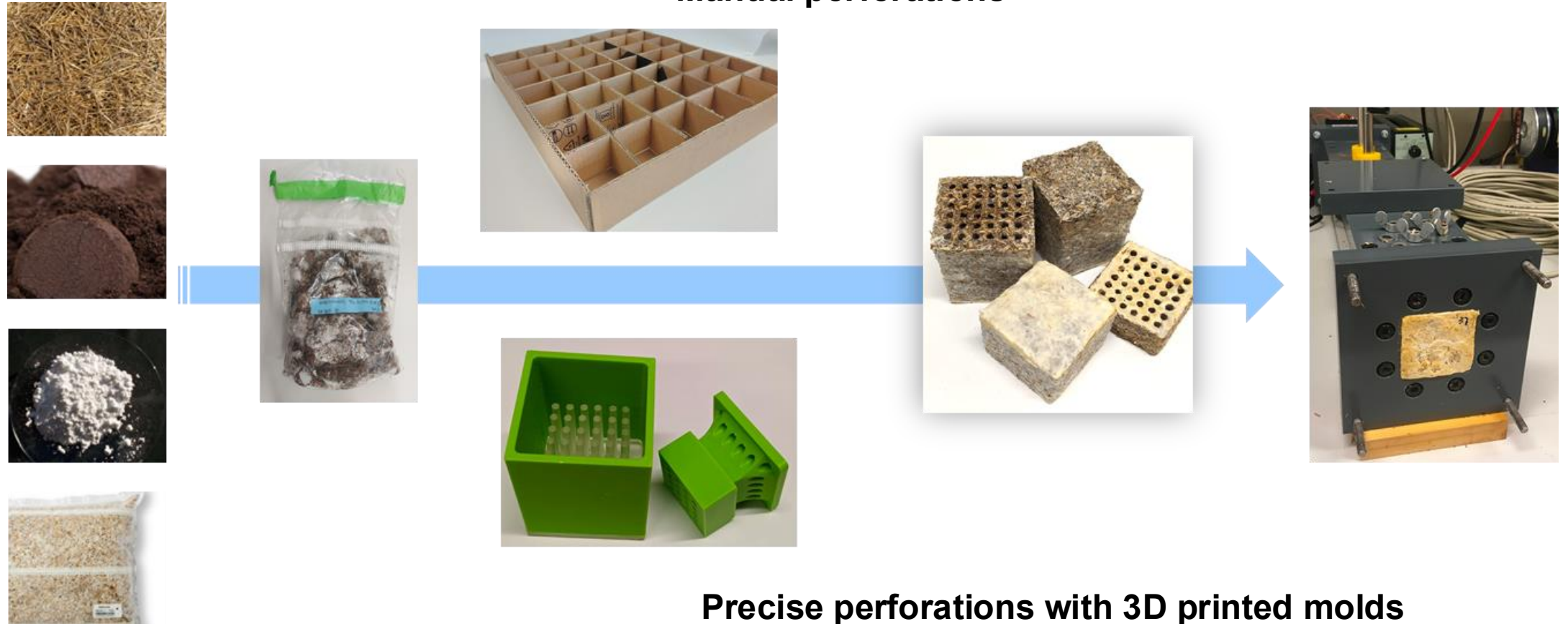
goes in incubator for  
**1 week**

# Pack in molds

IN BIOSAFETY CABINET



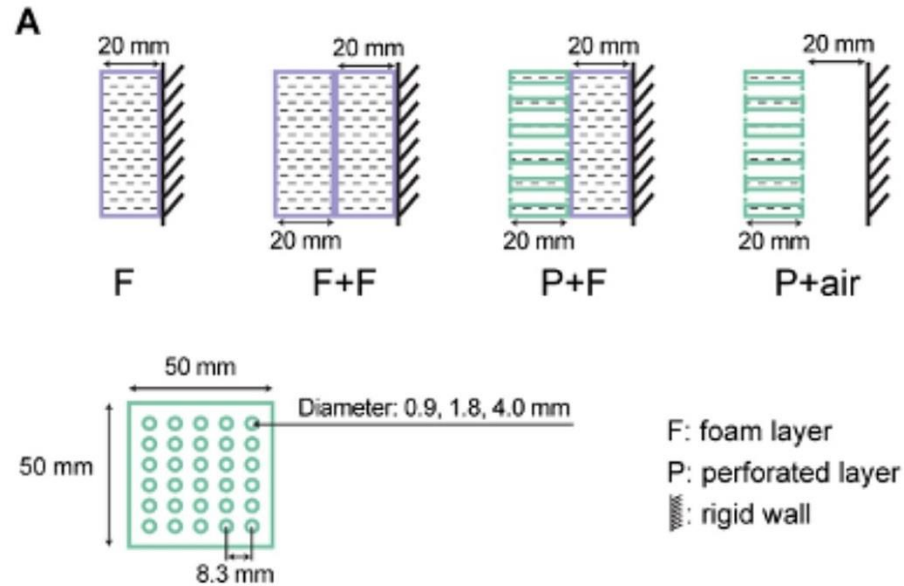
# Overall process flow



## Precise perforations with 3D printed molds

- 1 step to grow an integrated porous absorber with perforated layer

# 1<sup>st</sup> set of experiments: cardboard molds



F = “foam” = porous mycelium-bound composite

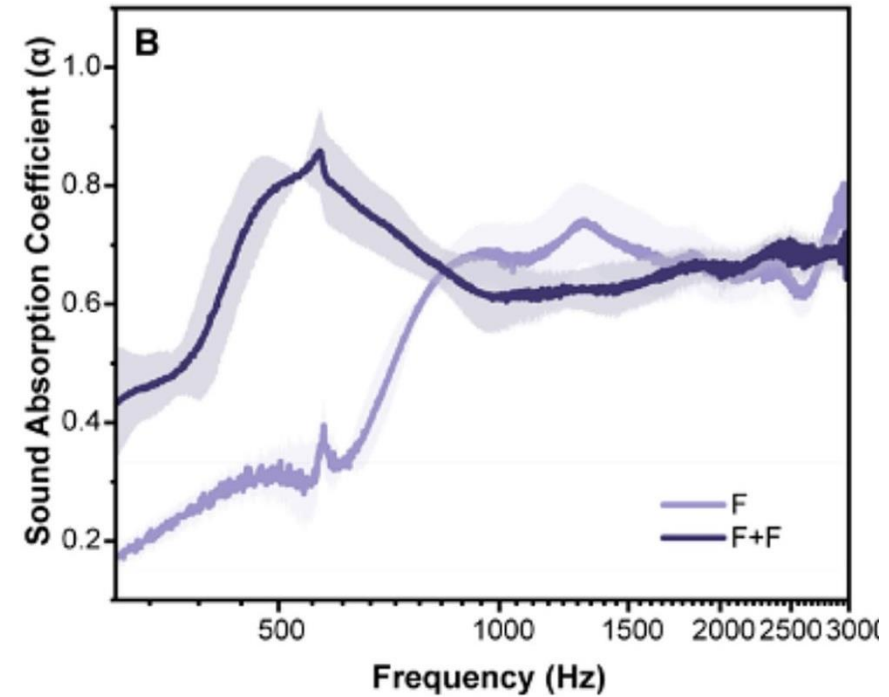
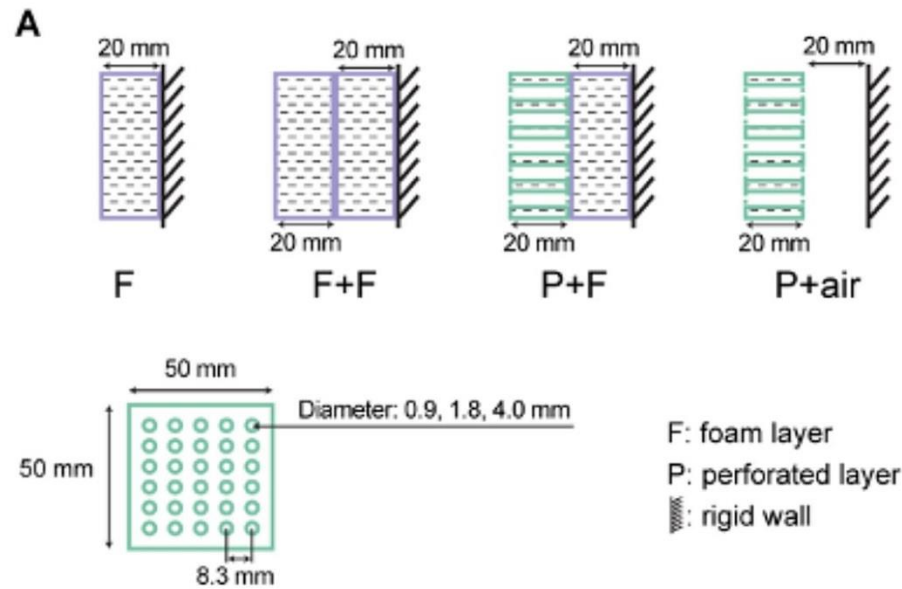
P = perforated layer = layer with holes



Density range: 145 to 180 kg/m<sup>3</sup>

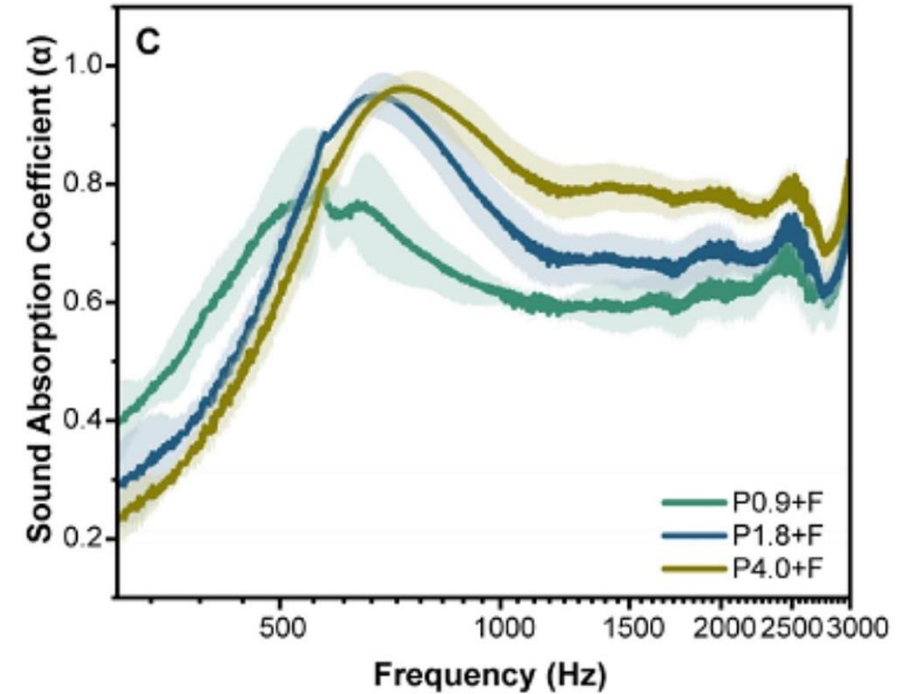
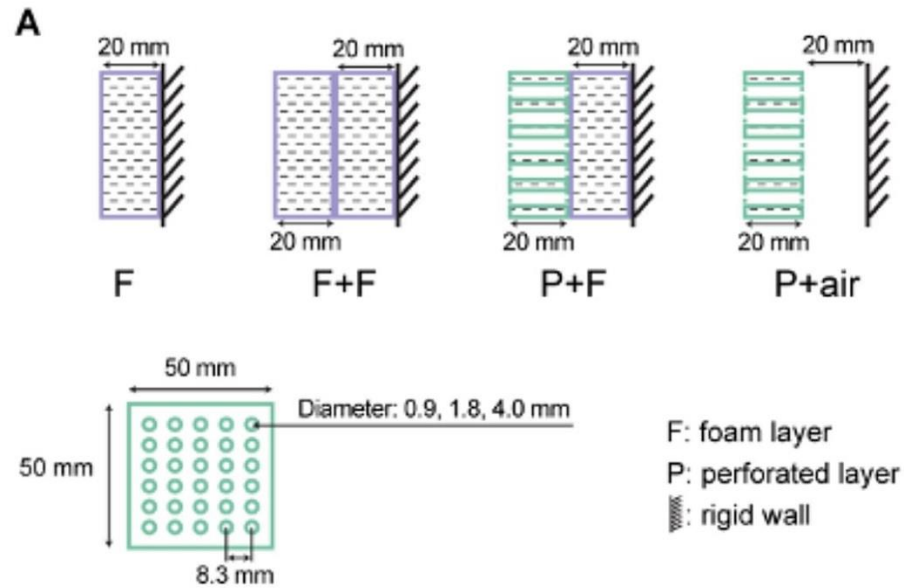
- Cavity depth is the same, diameter/volume varied

# 1<sup>st</sup> set of experiments: cardboard molds



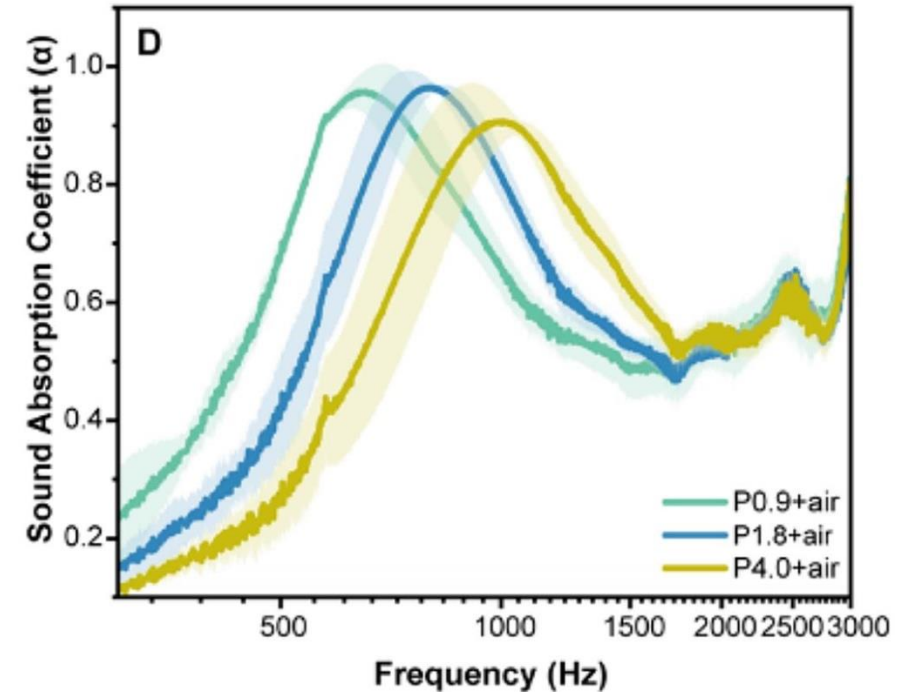
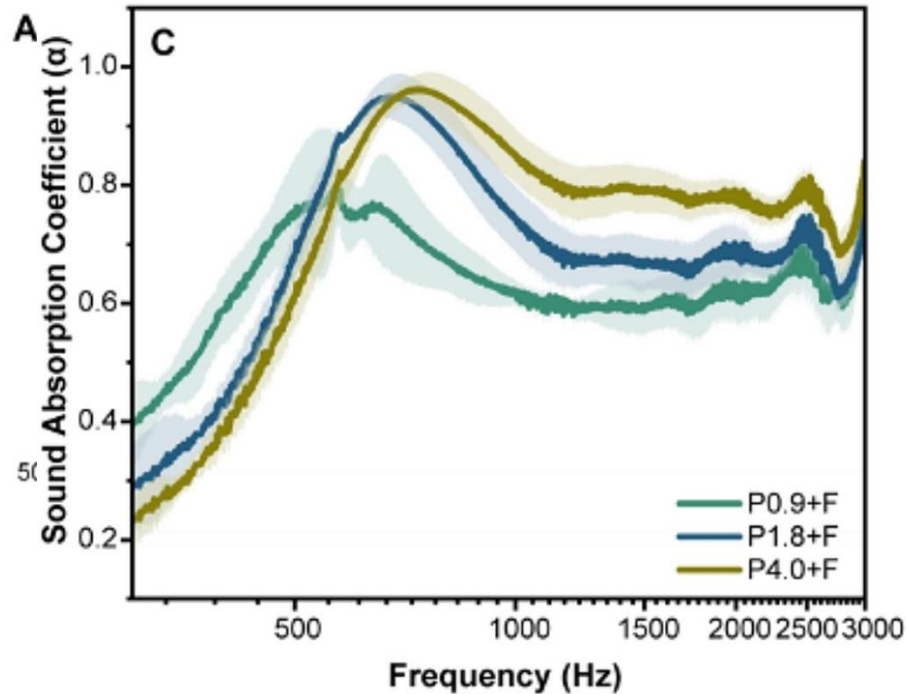
- Consistent with the literature on other mycelium absorbers – “F” increases steadily from low to high frequency and then stabilizes
- Also consistent, thicker layers are better: “F+F” also shows a broad peak at 600 Hz, related to air gaps between layers?

# 1<sup>st</sup> set of experiments: cardboard molds



- Larger perforation diameters: shift resonance to higher frequency
- Smaller perforation increase SAA at lower frequencies

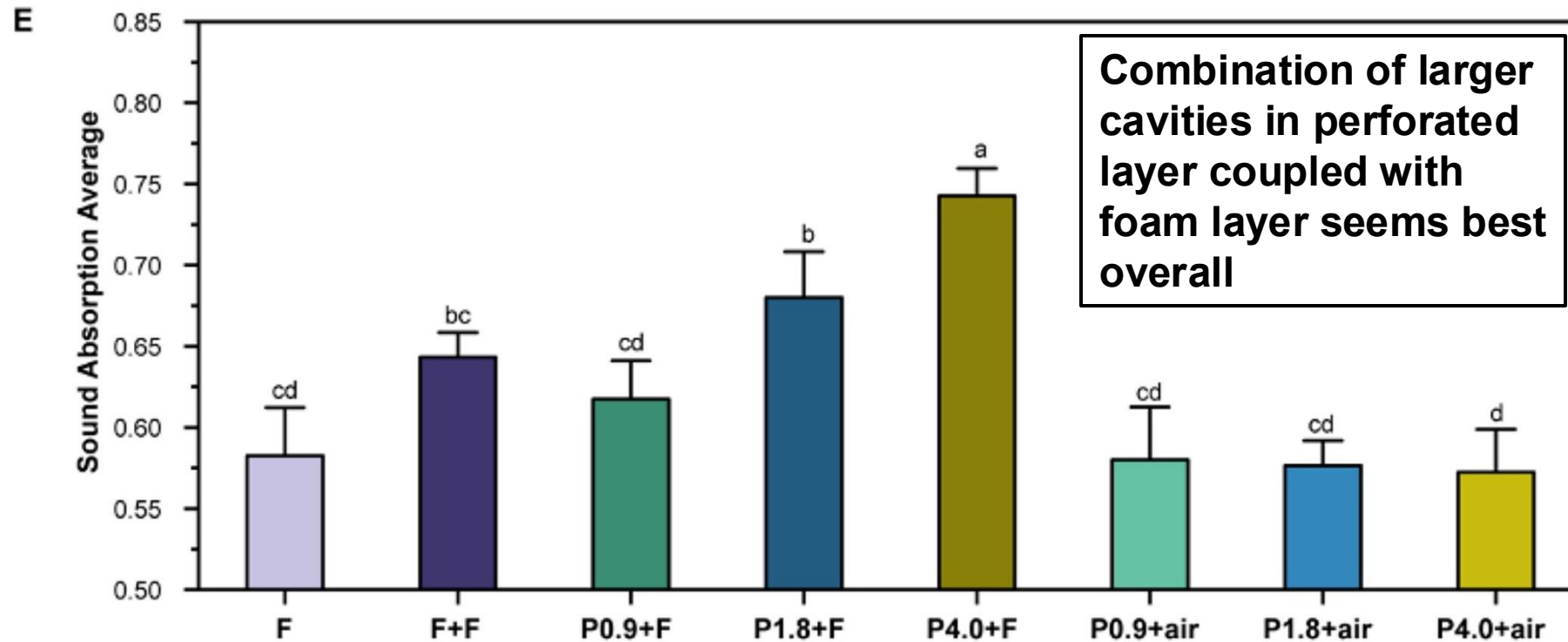
# 1<sup>st</sup> set of experiments: cardboard molds



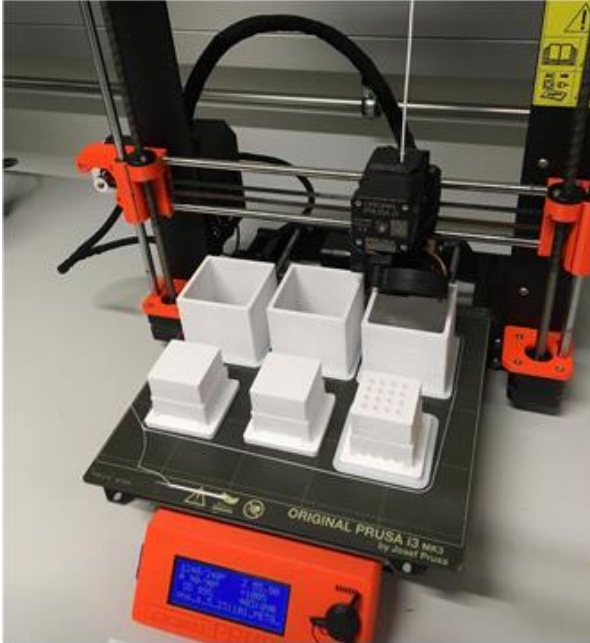
- What's the impact of "F"? Replace with air cavity
- "F" increases absorbance above 1200 Hz, shift resonance to lower frequencies
- With air cavity in place of "F" – resonance frequencies are shifted to higher frequencies (effect of diameter better resolved?)
- "F" layer is critical – added thickness and overall absorption – **even at low frequency!**

# 1<sup>st</sup> set of experiments: cardboard molds

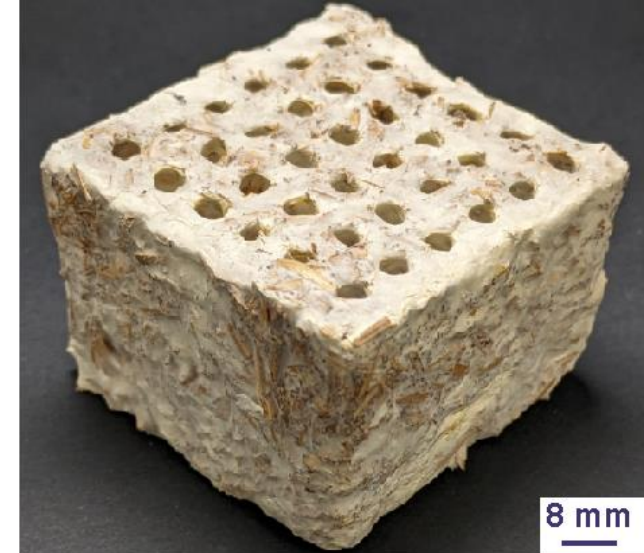
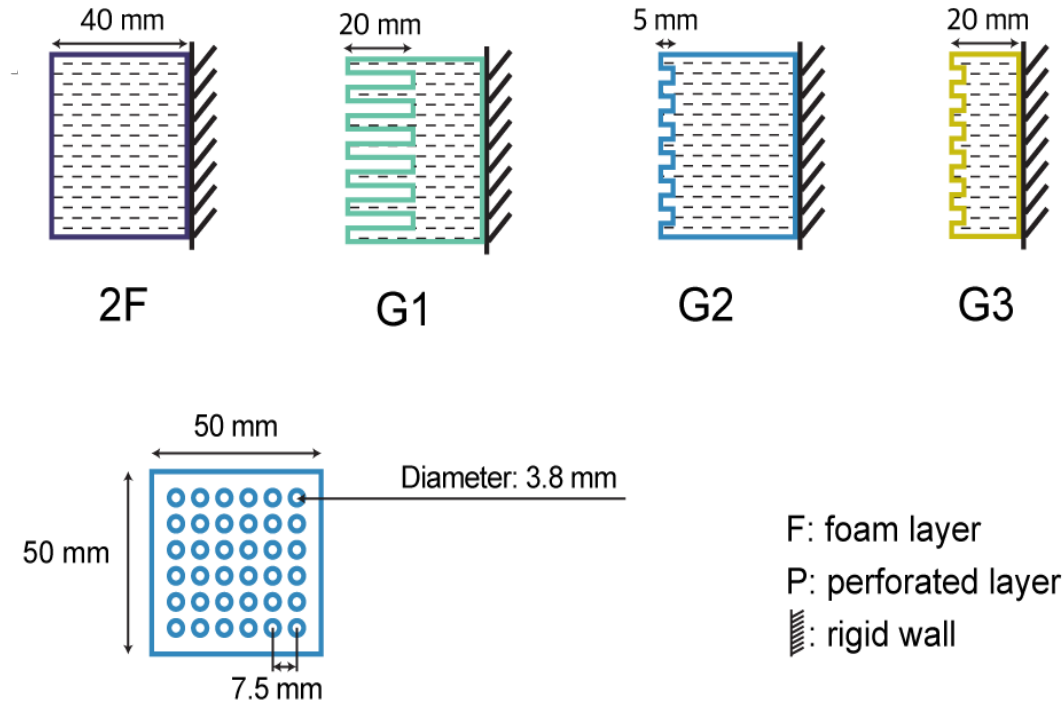
- SAA is the mean value of sound absorption coefficients over the frequency range from 200 to 2500 Hz.



# 2<sup>nd</sup> set of experiments: 3D printed molds

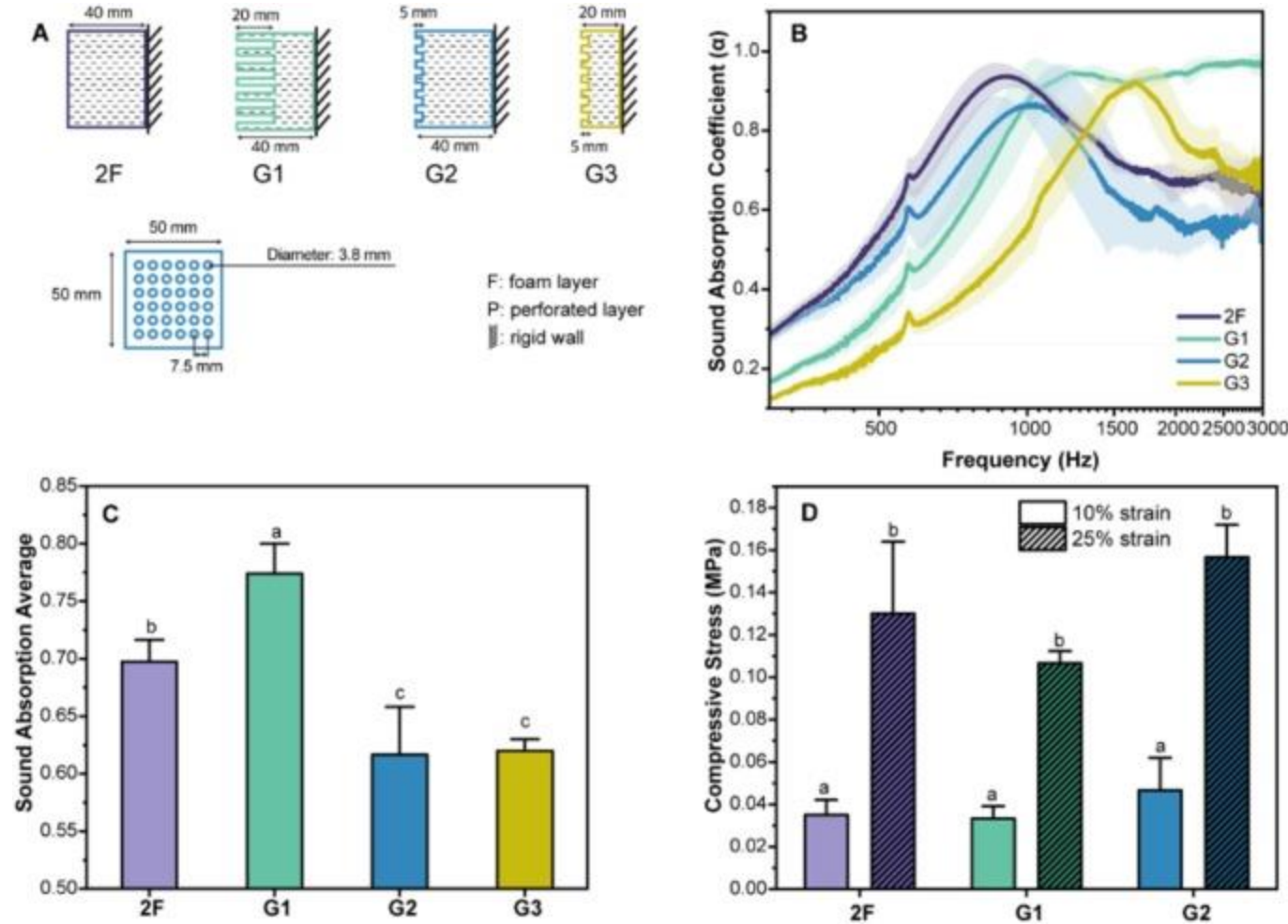


# 2<sup>nd</sup> set of experiments: 3D printed molds



- 2F, G1, G2: all 40 mm, with different cavity depths
- G3: same perforation depth as G2, but half the total thickness at 20 mm

# Our approach to mycelium materials



- **Same total thickness:** 2F, G1, and G2 – resonance seems to shift to higher frequency, with deeper cavities (G1) showing better overall absorption at high frequencies
- **Same cavity depth:** G2 and G3 – resonance shifted to higher frequency with thinner sample (G3), less absorbance at lower frequency

# Takeaways

- Mycelium is really good at binding solids at all sizes
- We can make MBCs **with solid and liquid fermentation** (liquid is not very common, we might have been the 1st)
- In the mycelium world, tunability is all the rage –
- Can we tune properties by additives (yes!), geometry (yes!), post treatments (yes!) species (maybe?), time (maybe? TBD) ...
- You know everything about mycelium now.

