

# **Fungoplastics ???**

## **MSE 493**

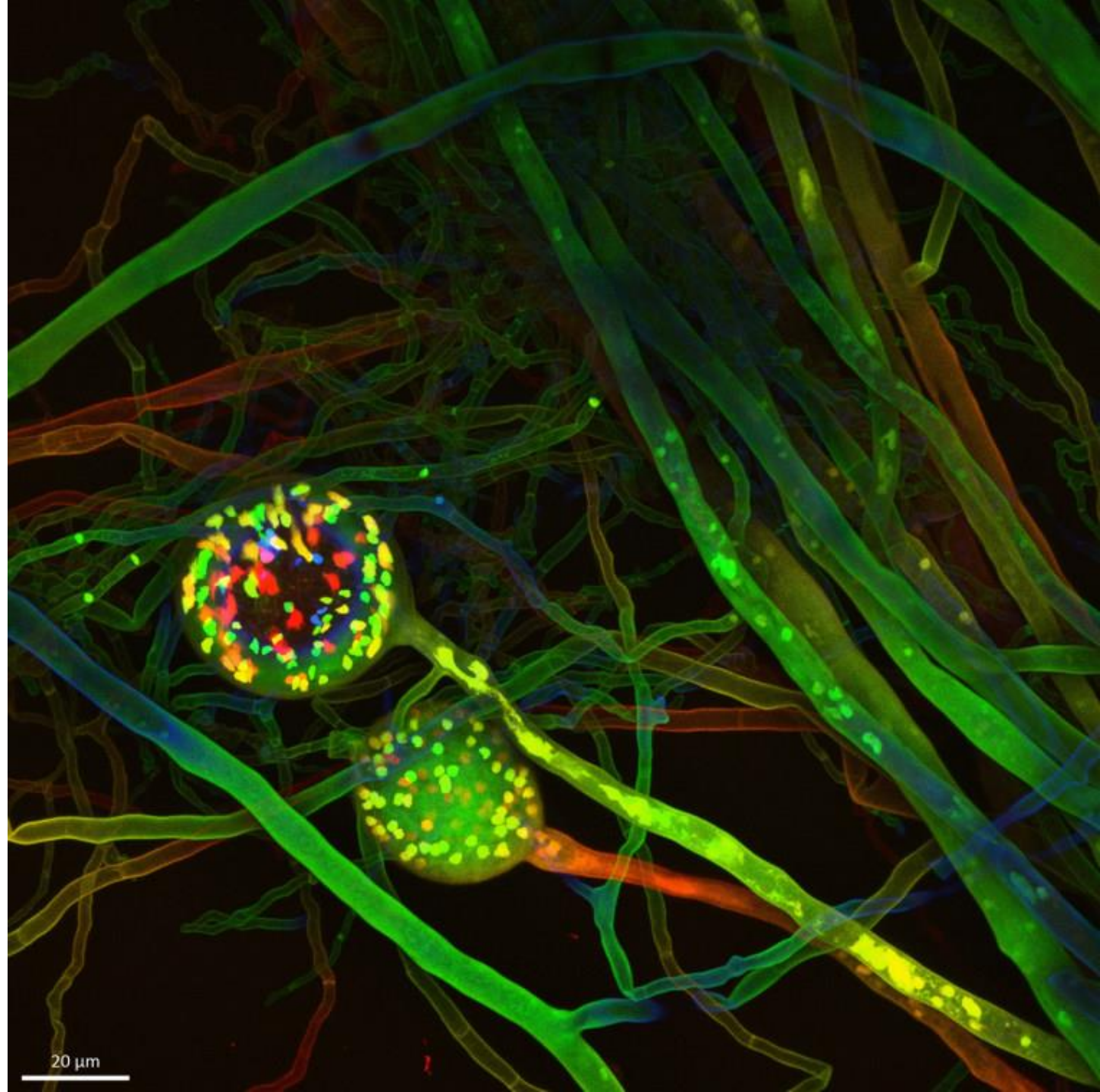
**Prof. Tiffany Abitbol**

**2025**

# Today: mycelium materials

- Pure mycelium materials – PMMs (1<sup>st</sup> half)
- Mycelium bound composites – MBCs (2<sup>nd</sup> half)
  
- Ask yourself – Trendy or real deal?

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



20 μm



# Fungi are...

■ ...

# Mushroom paper?

“We can discover fascinating creatures such as fungi in nature, which may point the way to new paths in the future. They can provide fertile soil, have healing powers, serve as food and restore what has been destroyed.”

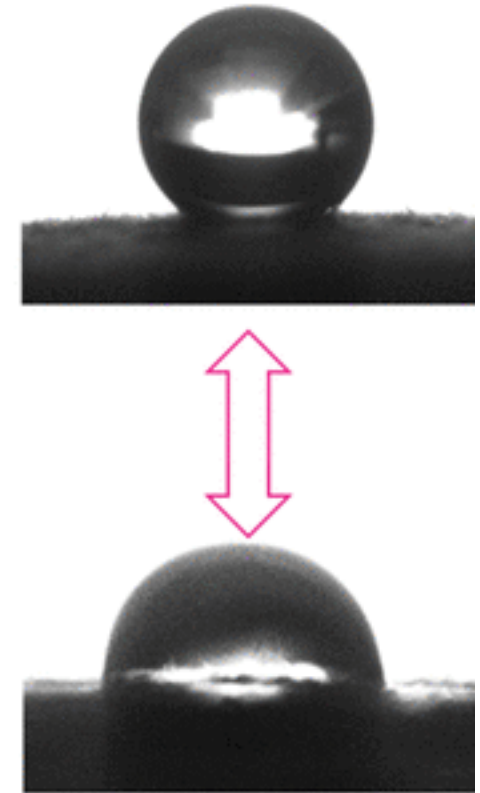
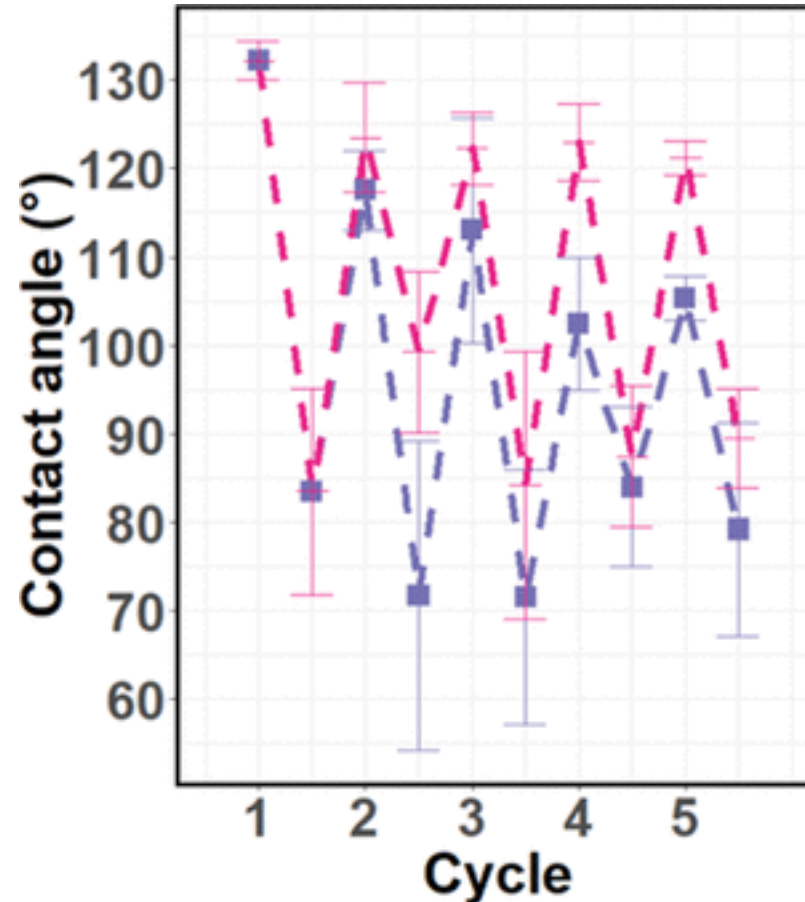
- Tanja Major (2025)



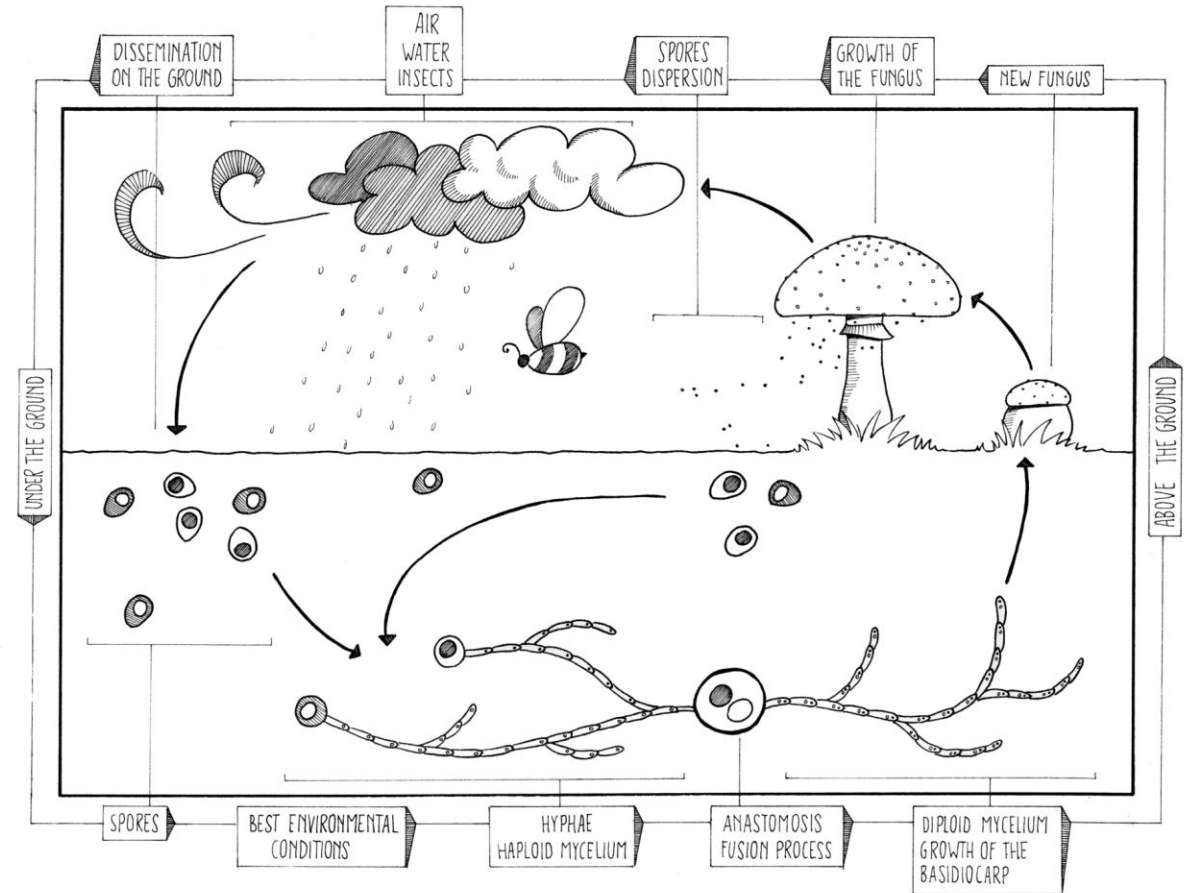
# Materials scientists are also interested in mycelium sheets... why?

- Packaging materials and textiles
- At a fundamental level, there is a desire to map the performance of pure mycelium materials
- Can these materials really behave like plastics? Like leathers?

All-Natural Smart Mycelium Surface with Tunable Wettability, by Sun et al. 2020

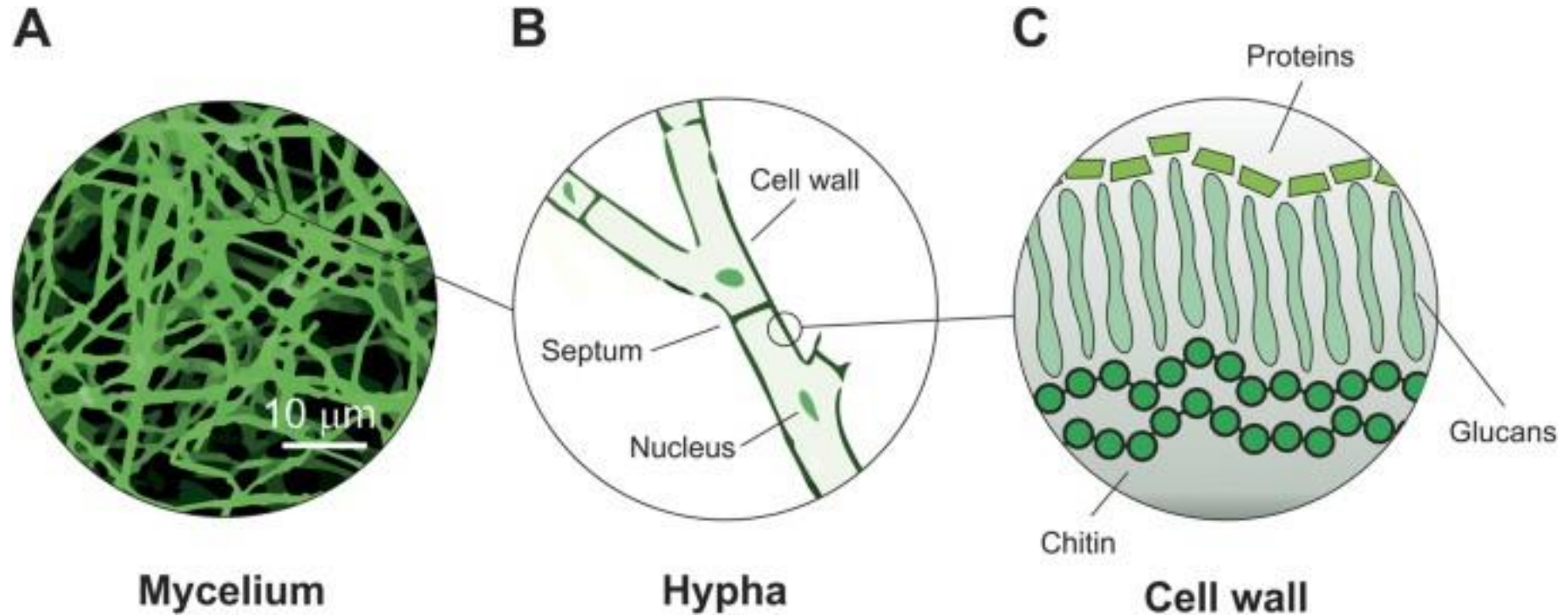


- Most mycelium materials are from Basidiomycota, which are filamentous fungi composed of cells called hyphae
- Why?
  - (1) They can digest lignocellulose
  - (2) They can fuse and bind different substrates
  - (3) They produce dense mats of mycelium



Credits goes to Anita Righetto - Own work, CC BY-SA 4.0,  
<https://commons.wikimedia.org/w/index.php?curid=37081811>

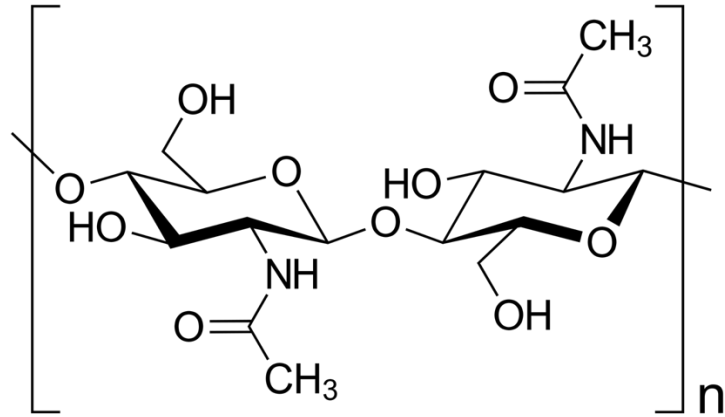
# A closer look at mycelium...



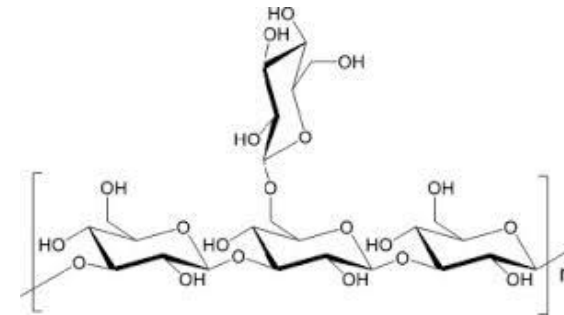
Haneef, M., Ceseracciu, L., Canale, C. *et al.* Advanced Materials From Fungal Mycelium: Fabrication and Tuning of Physical Properties. *Sci Rep* 7, 41292 (2017). <https://doi.org/10.1038/srep41292>

A factory of useful biomaterials!

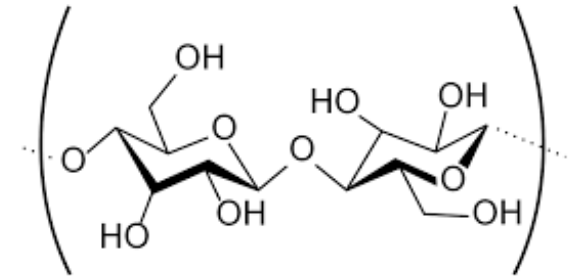
# Chitin and glucans



A **glucan** is a polysaccharide derived from D-glucose,<sup>[1]</sup> linked by glycosidic bonds. Glucans are noted in two forms: alpha glucans and beta glucans. Many beta-glucans are medically important.



SPG



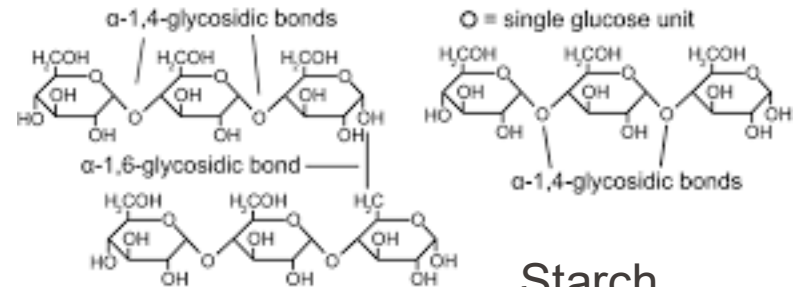
Cellulose



amylopectin



amylose



Starch

# An important paper in the PMM literature

Article | [Open access](#) | Published: 24 January 2017

## Advanced Materials From Fungal Mycelium: Fabrication and Tuning of Physical Properties

[Muhammad Haneef](#), [Luca Ceseracciu](#), [Claudio Canale](#), [Ilker S. Bayer](#), [José A. Heredia-Guerrero](#) ✉ & [Athanasia Athanassiou](#) ✉

[Scientific Reports](#) 7, Article number: 41292 (2017) | [Cite this article](#)

153k Accesses | 521 Citations | 60 Altmetric | [Metrics](#)

Impact factor: 3.9

Open access

Highly influential paper: > 500 citations

Two corresponding authors

This paper is their most cited

**Year: 2017**



José Alejandro Heredia-Guerrero  
(ORCID: 0000-0002-8251-7577)



IHSM La Mayora CSIC-UMA  
Verified email at csic.es - [Homepage](#)

[bioplastics](#) [food packaging](#) [circular economy](#) [sustainability](#)

TITLE	CITED BY	YEAR
-------	----------	------

[Cellulose and xylan nanofiber mats via electrospinning: Lignin-enhanced properties in wood-inspired biocomposites](#)

M García-Rollán, R Ruiz-Rosas, JM Rosas, J Rodríguez-Mirasol, ...  
Carbohydrate Polymer Technologies and Applications, 100968

2025

[Elucidating the modes of incorporation of the ferulic acid amides feruloyltyramine and feruloyloctopamine into the lignin-suberin fraction of potato periderms](#)

2025



Athanasia Athanassiou

Other names >



[Istituto Italiano di Tecnologia](#), Smart Materials Group  
Verified email at iit.it - [Homepage](#)

[biocomposites](#) [biopolymers](#) [natural polymers](#)  
[sustainable materials](#) [stimuli responsive materials](#)

TITLE	CITED BY	YEAR
-------	----------	------

[Method for the detection of nanoproducts](#)

A Athanassiou, F BOCCUNI, S IAVICOLI, P PAPAPOPOULOU  
US Patent 12,405,218

2025

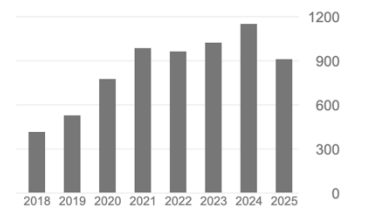
[Plant-Based Electrodes for Bioimpedance Readings of Fruit](#)

S Hamed, P Ibba, A Altana, C Rinaldi, P Lugli, L Petti, A Athanassiou, ...  
Advanced Electronic Materials 11 (14), e00109

2025

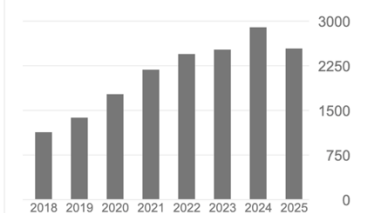
Cited by [VIEW ALL](#)

	All	Since 2020
Citations	7792	5819
h-index	47	42
i10-index	109	92



Cited by [VIEW ALL](#)

	All	Since 2020
Citations	20666	14386
h-index	75	65
i10-index	348	268



# Why is this paper important?

**Abstract.** In this work is presented a new category of self-growing, fibrous, natural composite materials with controlled physical properties that can be produced in large quantities and over wide areas, based on mycelium, the main body of fungi. Mycelia from two types of edible, medicinal fungi, *Ganoderma lucidum* and *Pleurotus ostreatus*, have been carefully cultivated, being fed by two bio-substrates: cellulose and cellulose/potato-dextrose, the second being easier to digest by mycelium due to presence of simple sugars in its composition. After specific growing times the mycelia have been processed in order to cease their growth. Depending on their feeding substrate, the final fibrous structures showed different relative concentrations in polysaccharides, lipids, proteins and chitin. Such differences are reflected as alterations in morphology and mechanical properties. The materials grown on cellulose contained more chitin and showed higher Young's modulus and lower elongation than those grown on dextrose-containing substrates, indicating that the mycelium materials get stiffer when their feeding substrate is harder to digest. All the developed fibrous materials were hydrophobic with water contact angles higher than  $120^\circ$ . The possibility of tailoring mycelium materials' properties by properly choosing their nutrient substrates paves the way for their use in various scale applications.

# Why is this paper important?

**Abstract.** In this work is presented a new category of self-growing, fibrous, natural composite materials with controlled physical properties that can be produced in large quantities and over wide areas, based on mycelium, the main body of fungi. Mycelia from two types of edible, medicinal fungi, *Ganoderma lucidum* and *Pleurotus ostreatus*, have been carefully cultivated, being fed by two bio-substrates: cellulose and cellulose/potato-dextrose, the second being easier to digest by mycelium due to presence of simple sugars in its composition. After specific growing times the mycelia have been processed in order to cease their growth. Depending on their feeding substrate, the final fibrous structures showed different relative concentrations in polysaccharides, lipids, proteins and chitin. Such differences are reflected as alterations in morphology and mechanical properties. The materials grown on cellulose contained more chitin and showed higher Young's modulus and lower elongation than those grown on dextrose-containing substrates, indicating that the mycelium materials get stiffer when their feeding substrate is harder to digest. All the developed fibrous materials were hydrophobic with water contact angles higher than 120°. The possibility of tailoring mycelium materials' properties by properly choosing their nutrient substrates paves the way for their use in various scale applications.

- Yes, this is an **oversimplification** but still might have some use



## PERSPECTIVE

Global  
Challenges

www.global-challenges.com

## “You Are What You Eat”: How Fungal Adaptation Can Be Leveraged toward Myco-Material Properties

*Alicia Vivas Hernando, Wenjing Sun, and Tiffany Abitbol\**

Fungi adapt to their surroundings, modifying their behaviors and composition under different conditions like nutrient availability and environmental stress. This perspective examines how a basic understanding of fungal genetics and the different ways that fungi can be influenced by their surroundings can be leveraged toward the production of functional mycelium materials. Simply put, within the constraints of a given genetic script, both the quality and quantity of fungal mycelium are shaped by what they eat and where they grow. These two levers, encompassing their global growth environment, can be turned toward different materials outcomes. The final properties of myco-materials are thus intimately shaped by the conditions of their growth, enabling the design of new biobased and biodegradable material constructions for applications that have traditionally relied on petroleum-based chemicals. This perspective highlights aspects of fungal genetics and environmental adaptation that have potential materials science implications, along the way touching on key studies, both to situate the state of the art within the field and to punctuate the viewpoints of the authors. Finally, this work ends with future perspectives, reinforcing key topics deemed important to consider in emerging myco-materials research.

Materials are at the forefront of the sustainability revolution (for example, UN SDG 12 on responsible consumption and production), playing a crucial role in providing environmentally-sound solutions that can help tackle today's climate and energy crises.<sup>[5-8]</sup> Until recently, the perception of inexhaustible resources has prevailed, fueling unchecked exploitation to meet growing demands.<sup>[9]</sup> Reflective of humanity's misuse of resources, since the 1970s we have been living in an ecological overshoot, meaning that the demands placed on the planet's ecosystem and resources surpass its regenerative capacity.<sup>[4]</sup> Thus, abandoning the “take-make-discard” status-quo relationship with materials is essential for a sustainable future.<sup>[8]</sup>

In this context, fungal biotechnology plays a role in the transition to a circular economy, with its potential breadth aligning with many of the 17 UN SDGs.<sup>[10]</sup>



*Ganoderma lucidum*

Reishi



*Pleurotus ostreatus*

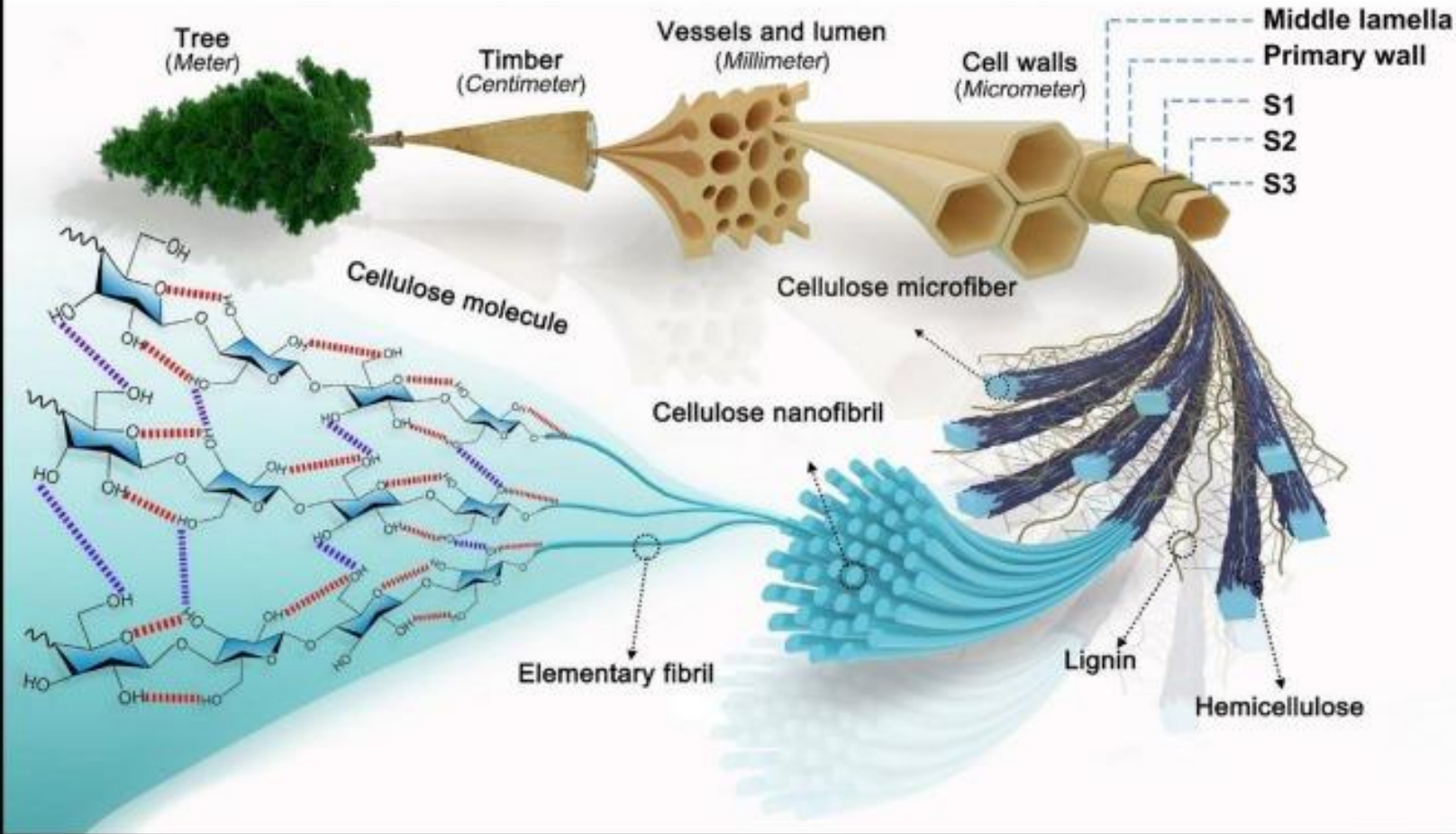
Oyster mushroom



Both: Saprotrophic, white-rot fungi

Saprotrophic: digest dead or decaying matter  
White-rot: have enzymes to digest lignin

(a) The hierarchical and porous structure of wood



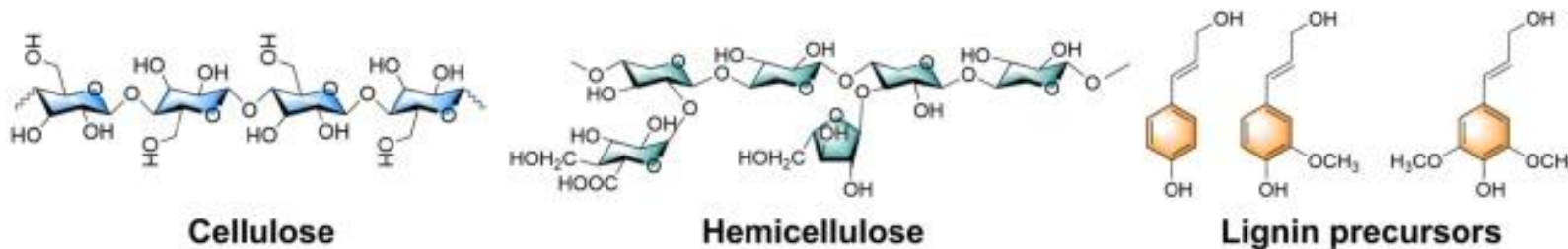
Cellulose = white  
Lignin = brown

White-rot: Digests lignin first  
Brown rot: Digests cellulose first

Lignin and cellulose are not easy to digest!  
Thanks fungi!

(b) The main composition of wood

(~39-53% cellulose content; ~17-34% hemicellulose content; ~18-36% lignin content)



# How did they grow their mycelium?



Simple experiment:

- Grow two species: *P. ostreatus* and *G. Lucidum*
- Test two different substrates: microcrystalline cellulose (MCC) and a 1:1 mixture of (MCC) and potato dextrose broth (PDB)
- MCC is harder to digest than PDB



vs.



# Digression: What is MCC?

A pure cellulose that is **highly crystalline** and produced by acid hydrolysis of natural sources of cellulose!

It's used a lot in food and pharma.

It's not that different from *cellulose nanocrystals*...

## MICROCRYSTALLINE CELLULOSE

*The oldest polymer finds new industrial uses*

O. A. BATTISTA

P. A. SMITH

From the day that the term "hydrocellulose" was first coined in 1875 until the present, treatment of cellulose with acids has been considered the wrong direction to go. By going in this direction (and making a fortunate detour) we have been rewarded with a view of an entirely new area of cellulose chemistry.

Uses of cellulose have always depended upon—and been largely limited by—its fibrous nature. In this new area, cellulose is a colloid, with all of the implied possibilities. Industrial uses are promising for:

- Flour. Nonfibrous, free flowing, absorbent, with extremely high surface area
- Compacted pellets. Hard, heat resistant, absorbent, inert
- Structural materials. Hard, insulating materials, resistant even to an oxyacetylene torch
- Gels and creams. Smooth, opaque, stable, fat-like but noncaloric
- Cellulose derivatives. Produced with greater ease and economy, and in new colloidal form

Production of the flour form is the basic step in manufacture of these types of microcrystalline cellulose. Severe acid hydrolysis removes the hinges of amorphous cellulose which link the naturally occurring microcrystals, yielding cellulose of the so-called "level-off degree of polymerization" or "D.P. cellulose." The microcrystals are freed from their fibrous, packed structure by mechanical shearing, performed in a water slurry. This is the novel step which determines the unique character of this cellulose. Drying then produces a flour of colloidal size.

The flour can be redispersed with water to form thick gels or thinner creams. It can be compacted into tablets or to large structural sheets. An entirely different, denser structural sheet results when a thick gel is dried.

**AUTHOR** O. A. Battista is the Manager of the Corporate Applied Research Department of American Viscose Corp., Marcus Hook, P. A. Smith is a Chemist in the Fiber Research Department, American Viscose.

**Acknowledgment.** The authors wish to acknowledge the help of A. M. Belfort, M. M. Craz, Jr., E. G. Fleck, Jr., C. T. Herald, and J. E. Tucker. W. A. Sisson has been especially helpful over a period of many years. F. F. Murehead provided the electron micrographs.

Appreciation is extended to F. H. Reichel, Jr., Director of Corporate Research, under whose direction microcrystalline cellulose was advanced to commercial production.



# How did the materials look?

- *P.o* larger than *G.l*
- *G.l* hyphae look the same on both substrates
- *P.o* looks collapsed with the mixed substrate

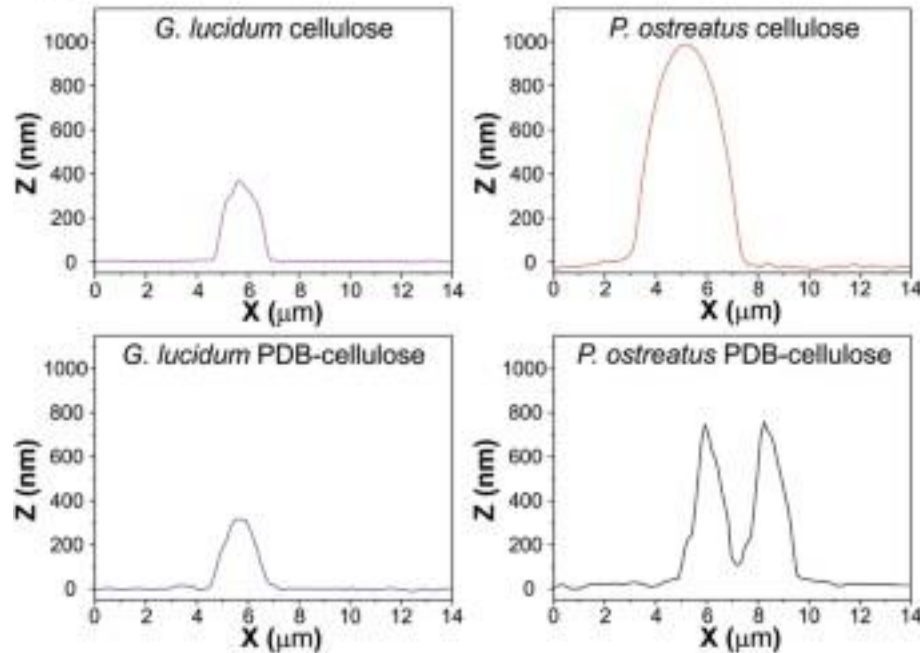
A

20 days old



• 2 days old

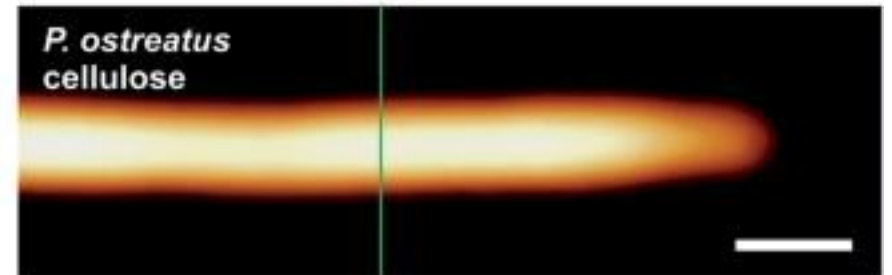
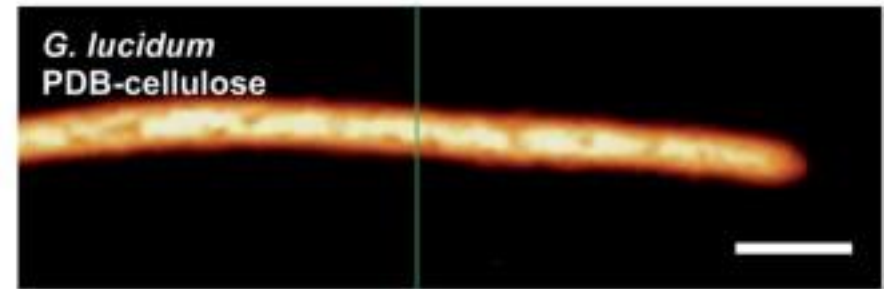
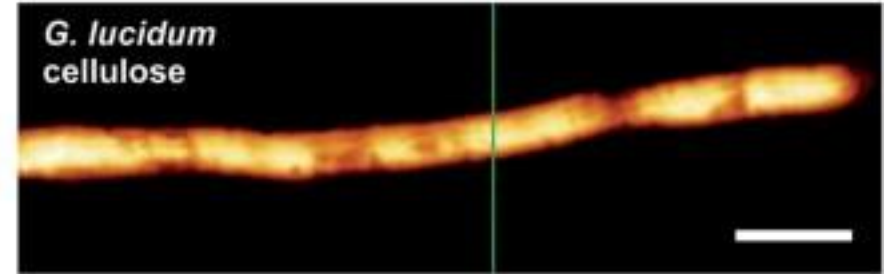
C



B

• 2 days old

18

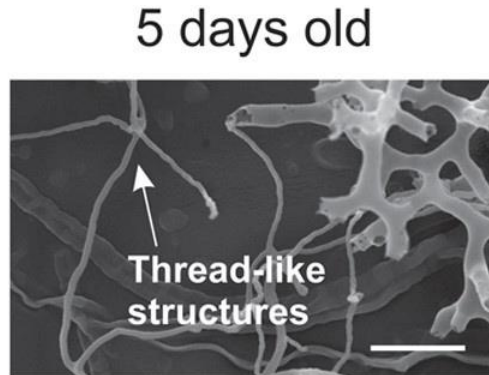




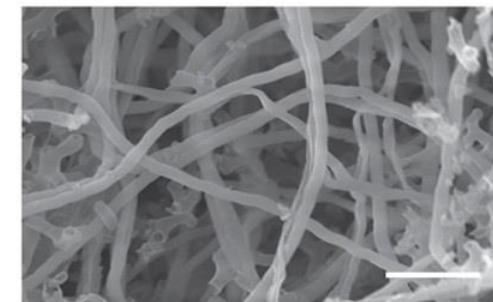
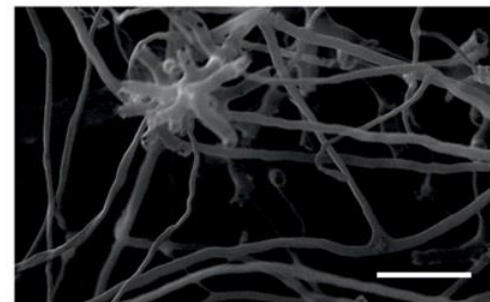
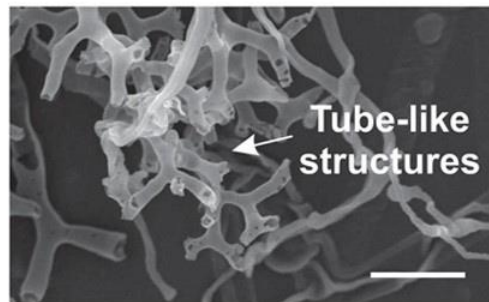
# Hyphal development

A

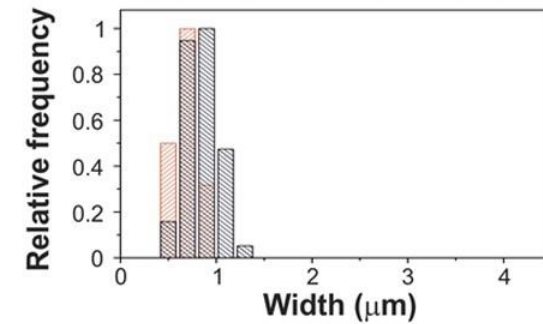
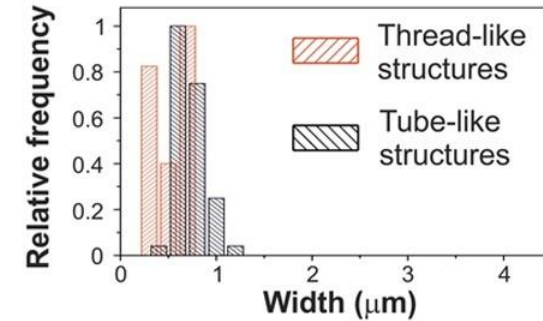
*G. lucidum*  
cellulose



*G. lucidum*  
PDB-cellulose



B

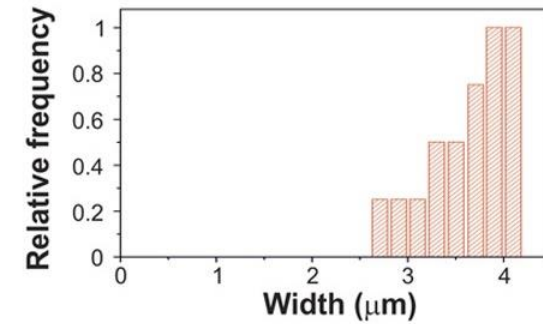
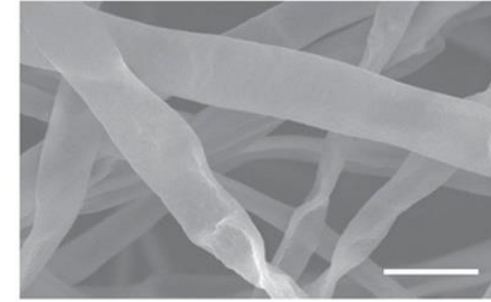
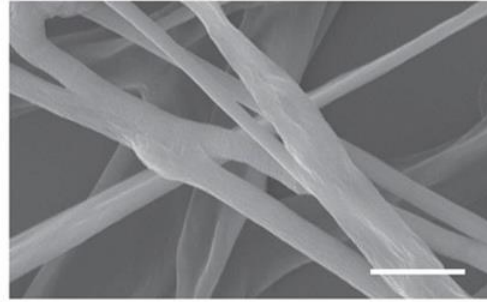
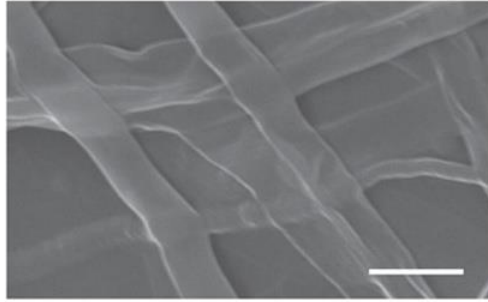


- Density increases with time
- Tubes and threads, threads increases with time
- Diameter is around  $0.8 \mu\text{m}$  on both substrates (a little bigger than AFM)
- (Btw – it's rare that materials studies look at time!)

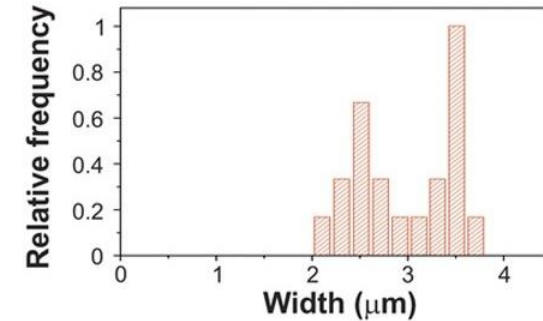
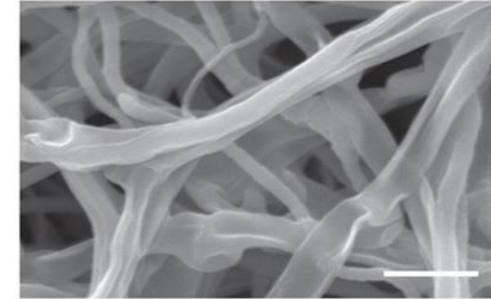
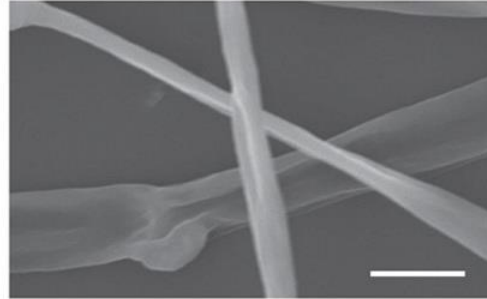
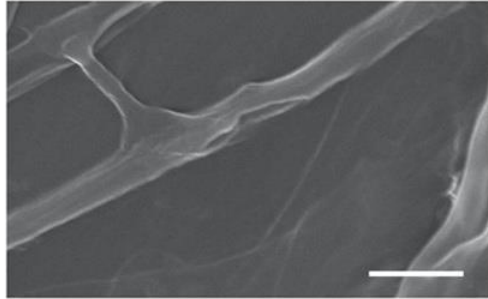


# Hyphal development

*P. ostreatus*  
cellulose



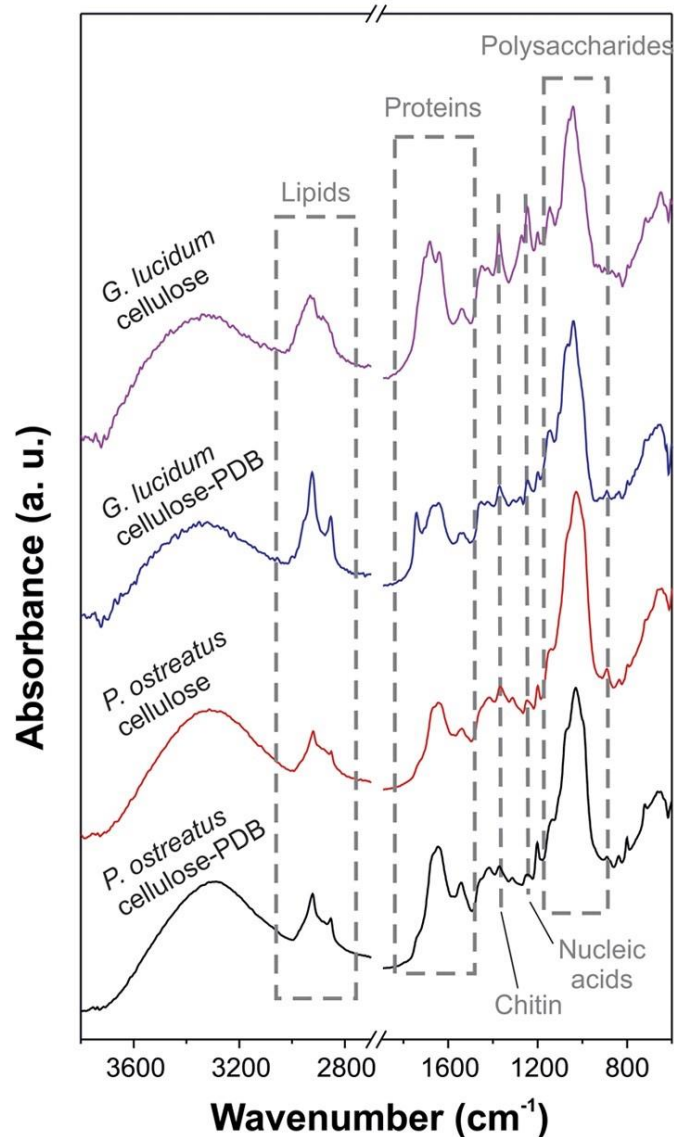
*P. ostreatus*  
PDB-cellulose



- Only one type of “compressed” filament
- Here, width seems to depend on substrate, higher when grown on cellulose
- Hyphae are collapsed when grown on mixed substrate: why?
- Hypothesis: Cell wall protects against osmotic lysis by a counterbalancing internal “turgor” pressure, so when the internal pressure is removed by drying, the cell wall may collapse and flatten
- They say this doesn’t happen with the other species because its smaller
- So why does one collapse and the other not? (Stay tuned!)

# Chemistry is the answer?

A



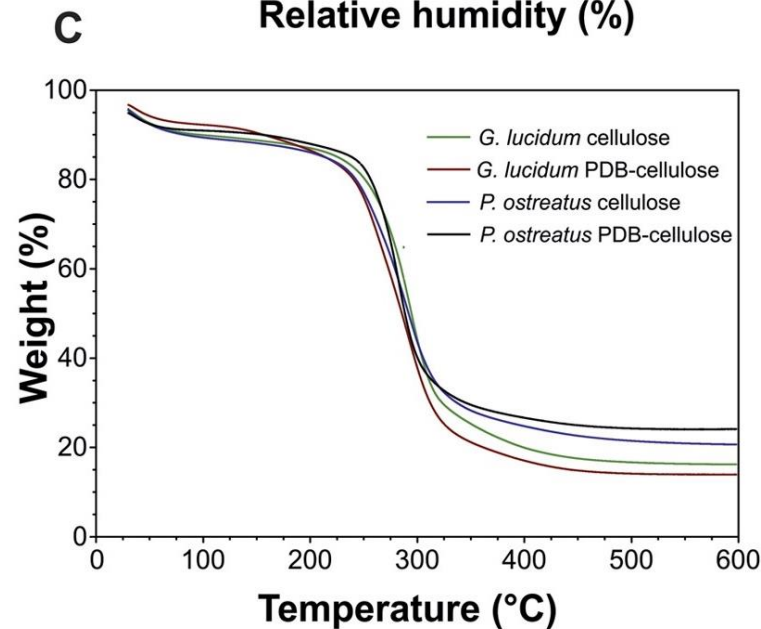
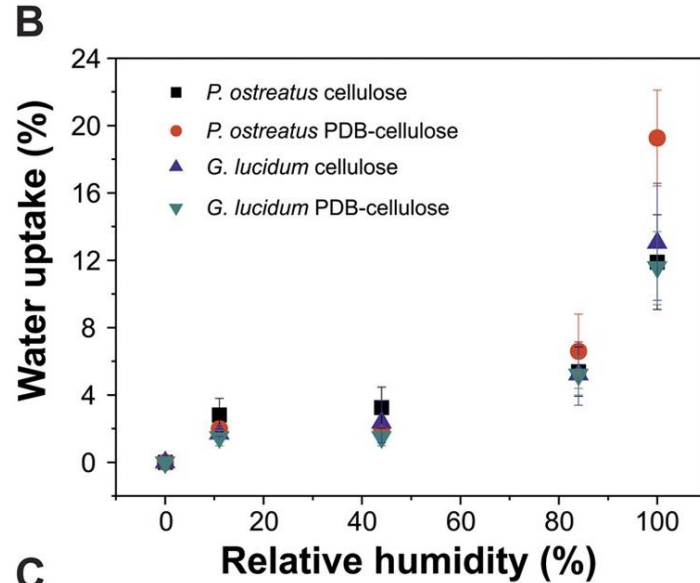
- *Ganoderma* has more lipids
- *Pleurotus* has more polysaccharides
- More lipids when grown on mixed substrate
- More chitin when grown on cellulose

Specifically looked at the ratio IR bands of chitin/polysaccharides:

*Ganoderma*: 0.3 (cellulose) vs. 0.1 (mixed)  
*Pleurotus*: 0.08 (cellulose) vs. 0.06 (mixed)

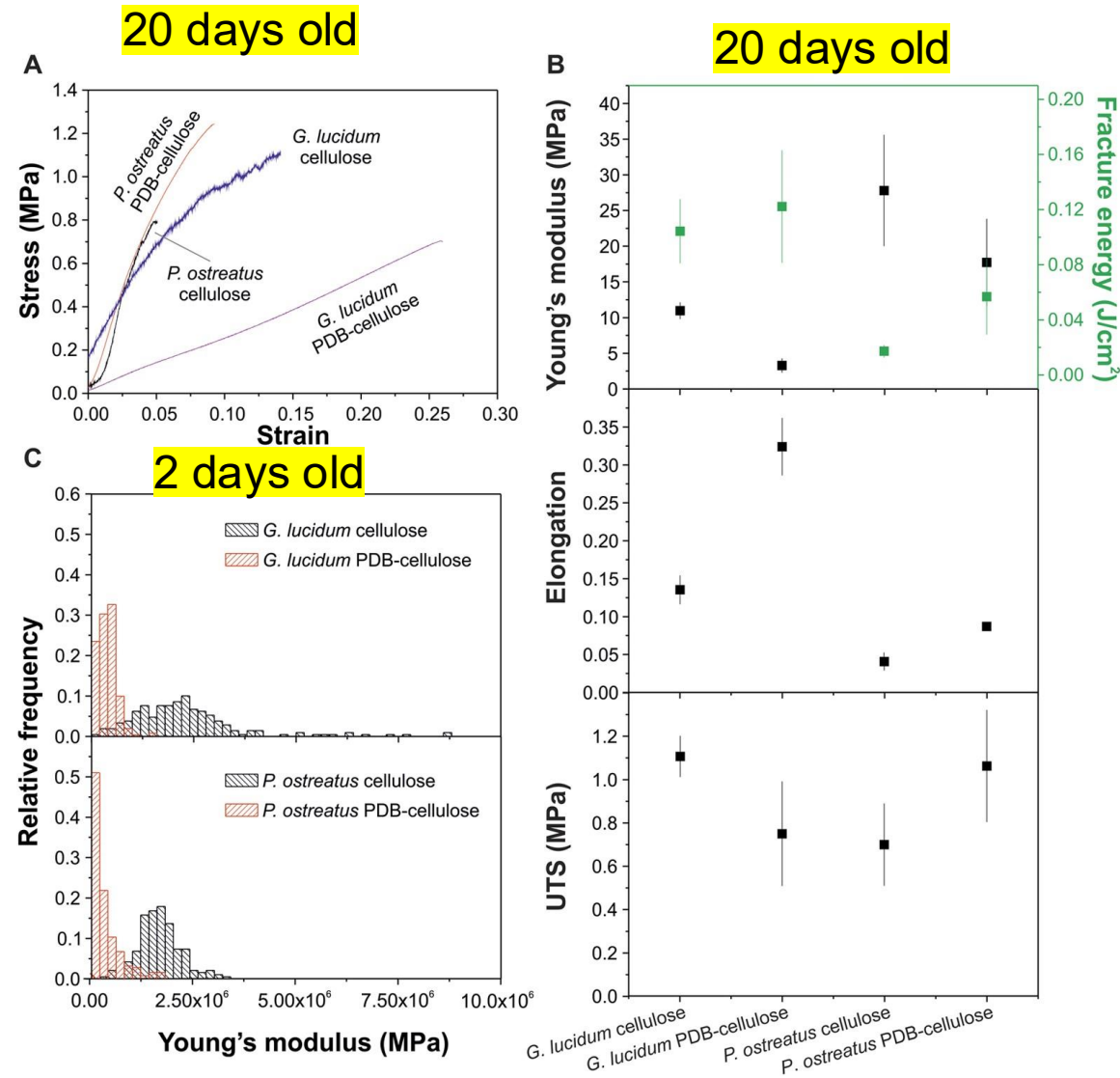
They say that the decrease in chitin content in *Pleurotus* is probably why the cell wall collapses...  
 “mutants that are unable to synthesize chitin are morphologically altered and osmotically sensitive”

# Material properties



- All films are resilient to humidity
- *But P. ostreatus* grown on mixed substrate took up the most water at 100% - they link this to reduction in relative chitin content
- All films are hydrophobic > 120°; related to mannoproteins
- All material degrade around 225 °C; with a char of 15-25%
- (Char is a good thing for flame retardant materials, as the C-rich layer acts as a barrier)

# Mechanical properties



## Tensile tests on 20-day old films:

- Species: *Pleurotus* is stiffer and less extensible than *Ganoderma*, UTS is unaffected; fracture energy is higher for *Ganoderma*
- Substrate: cellulose gives stiffer materials, whereas PDB stimulates plasticizers (protein & lipids) relative to chitin, giving a more ductile material**

## Nanoindentation on 2-day old samples:

- Confirms that cellulose substrate yields stiffer materials

# Context and comparison!

**Table 2 Summary of main properties of fungal fibers, bacterial cellulose and poly(3-hydroxybutyrate).**

From: [Advanced Materials From Fungal Mycelium: Fabrication and Tuning of Physical Properties](#)

Parameter	<i>Ganoderma lucidum</i> on cellulose	<i>Ganoderma lucidum</i> on cellulose-PDB	<i>Pleurotus ostreatus</i> on cellulose	<i>Pleurotus ostreatus</i> on cellulose-PDB	Bacterial cellulose	Poly (3-hydroxybutyrate)
<b>Morphological description</b>	White fibrillar films. $\sim 0.9 \mu\text{m}$ and $\sim 0.6 \mu\text{m}$ hyphae diameters.		White fibrillar films. $\sim 4 \mu\text{m}$ hyphae diameter.		Semi-transparent fibrillar films. 40–60 nm fiber diameter <sup>50,53,54,55</sup>	Granules. 0.2–0.5 $\mu\text{m}$ diameter <sup>56</sup>
<b>E (MPa)</b>	12	4	28	17	$\sim 9700$ <sup>57</sup>	$\sim 3500$ <sup>58</sup>
<b>Stress at break (MPa)</b>	1.1	0.8	0.7	1.1	$\sim 240$ <sup>57</sup>	$\sim 40$ <sup>58</sup>
<b>Elongation at break (%)</b>	14	33	4	9	$\sim 2.6$ <sup>57</sup>	$\sim 6$ <sup>58</sup>
<b>Water contact angle (°)</b>	$\sim 122$	$\sim 122$	$\sim 121$	$\sim 121$	$\sim 26$ <sup>59</sup>	$\sim 89$ <sup>60</sup>
<b>T thermal decomposition (°C)</b>	294	293	295	295	365 <sup>61</sup>	$\sim 300$ <sup>62</sup>

Let's remember:

4-28 MPa  
Young's modulus

4-33%  
elongation at break

$\sim 1$  UTS

# Do you like this paper? Why or why not?



**YES**



**NO**

# Some important follow ups with *S. commune*



*Schizophyllum commune*

Splitgill

Found worldwide on rotting wood

Article | [Open access](#) | Published: 16 March 2018

# Hydrophobin gene deletion and environmental growth conditions impact mechanical properties of mycelium by affecting the density of the material

[Freek V. W. Appels](#), [Jan Dijksterhuis](#), [Catherine E. Lukasiewicz](#), [Kaspar M. B. Jansen](#), [Han A. B. Wösten](#)  & [Pauline Krijgsheld](#)

[Scientific Reports](#) **8**, Article number: 4703 (2018) | [Cite this article](#)

12k Accesses | 146 Citations | 6 Altmetric | [Metrics](#)



Utrecht  
University

Search employee



Nederlands Edit

Employees Organogram



Prof. dr. H.A.B. (Han) Wösten

Professor

Molecular Microbiology



+31 30 253 3448



[h.a.b.wosten@uu.nl](mailto:h.a.b.wosten@uu.nl)



Hugo R. Kruytgebouw

Profile

CV

**Year: 2018**

Activities

Research

Teaching

“With fungi we can recycle waste streams into high quality materials.”

Research focus: Microbiology, Bio-art, Environmental biology, Mycelium design

- Not on Google Scholar
- Same journal
- Very active authors in field

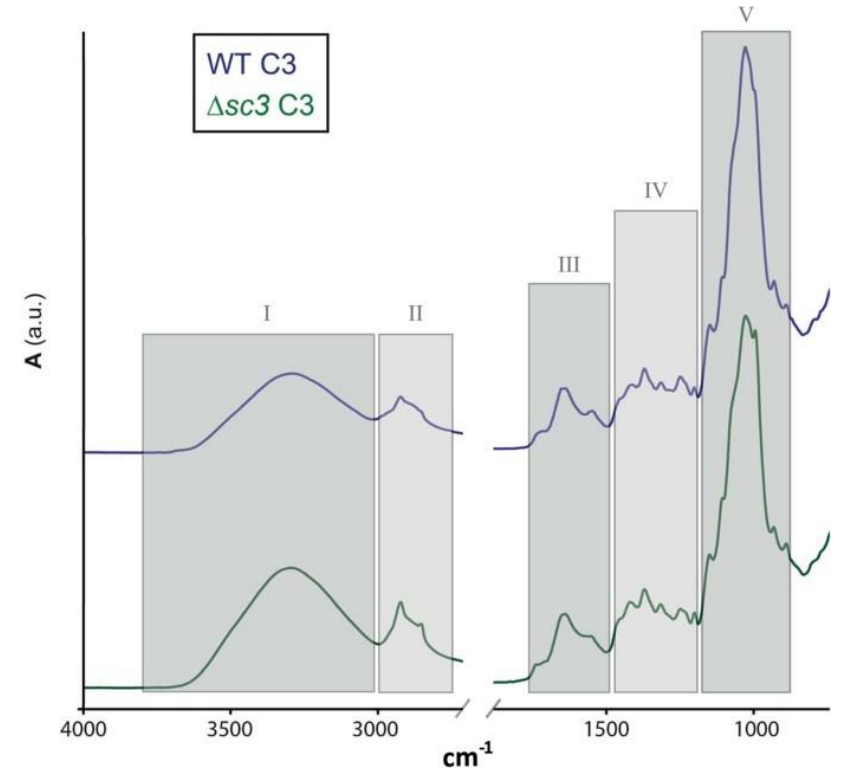
# Why is this paper important?

Filamentous fungi colonize substrates by forming a mycelium. This network of hyphae can be used as a bio-based material. Here, **we assessed the impact of environmental growth conditions and deletion of the hydrophobin gene *sc3* on material properties of the mycelium of the mushroom forming fungus *Schizophyllum commune*.** Thermogravimetric analysis showed that  $\Delta sc3$  mycelium retained more water with increasing temperature when compared to the wild type. **The Young's modulus ( $E$ ) of the mycelium ranged between 438 and 913 MPa when the wild type strain was grown in the dark or in the light at low or high  $CO_2$  levels. This was accompanied by a maximum tensile strength ( $\sigma$ ) of 5.1–9.6 MPa. In contrast,  $E$  and  $\sigma$  of the  $\Delta sc3$  strain were 3–4- fold higher with values of 1237–2727 MPa and 15.6–40.4 MPa, respectively. These values correlated with mycelium density, while no differences in chemical composition of the mycelia were observed as shown by ATR-FTIR. Together, genetic modification and environmental growth conditions impact mechanical properties of the mycelium by affecting the density of the mycelium. As a result, mechanical properties of wild type mycelium were similar to those of natural materials, while those of  $\Delta sc3$  were more similar to thermoplastics.**

# Why is this paper important?

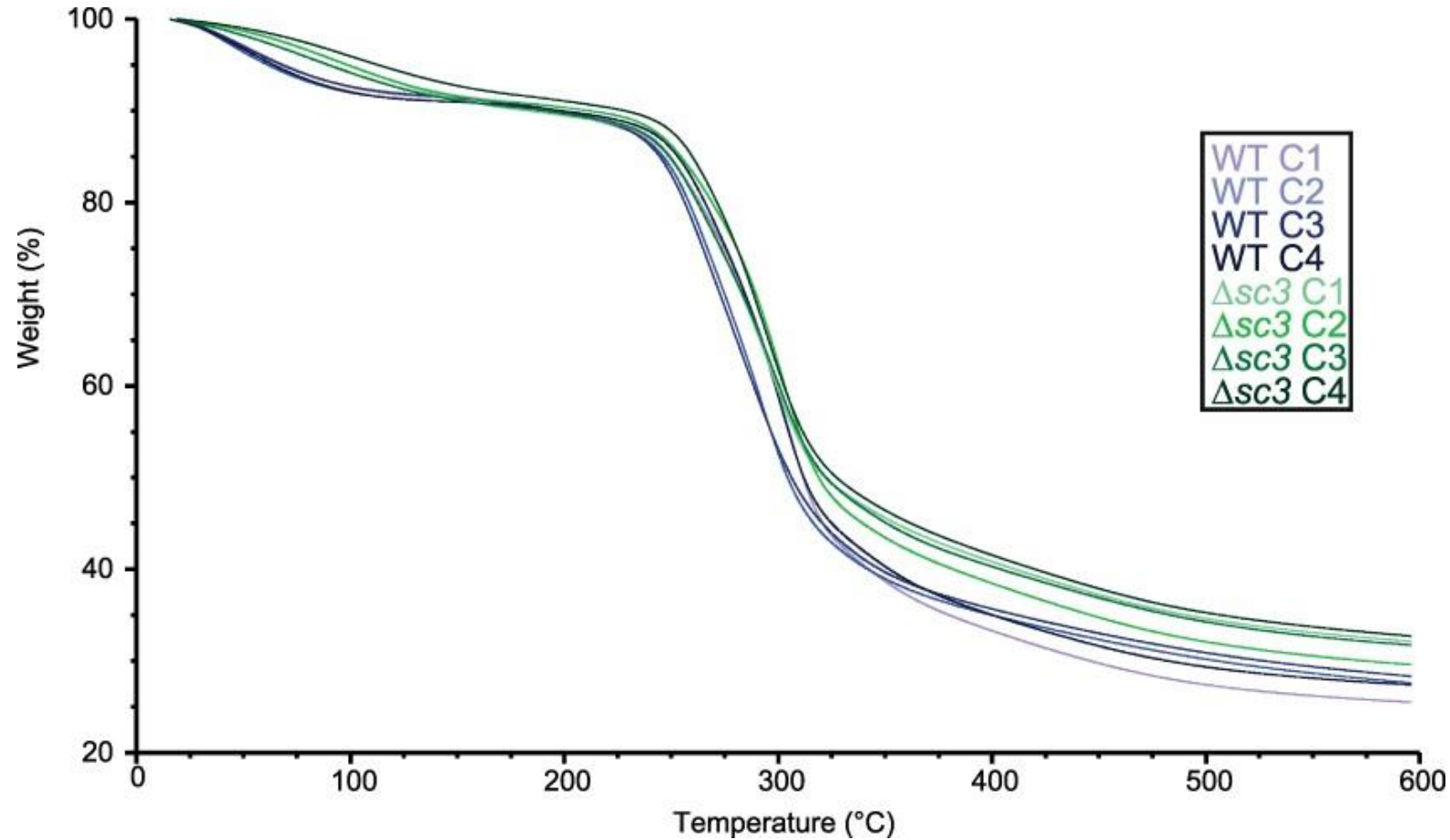
Comparing the two papers:

1. Genetics matter (suppressing aerial hyphae is maybe beneficial) – *same as previous*
2. Growth conditions kind of matter (they suppress aerial hyphae or not) – *same as previous*
3. Chemistry doesn't matter – ***different!***
4. Density matters but how it is impacted by different conditions is unclear – **not addressed**
5. Tunable mechanical properties – *same as previous*



In this case: no difference in chemistry between wild-type and mutant even though they had very different mechanical properties

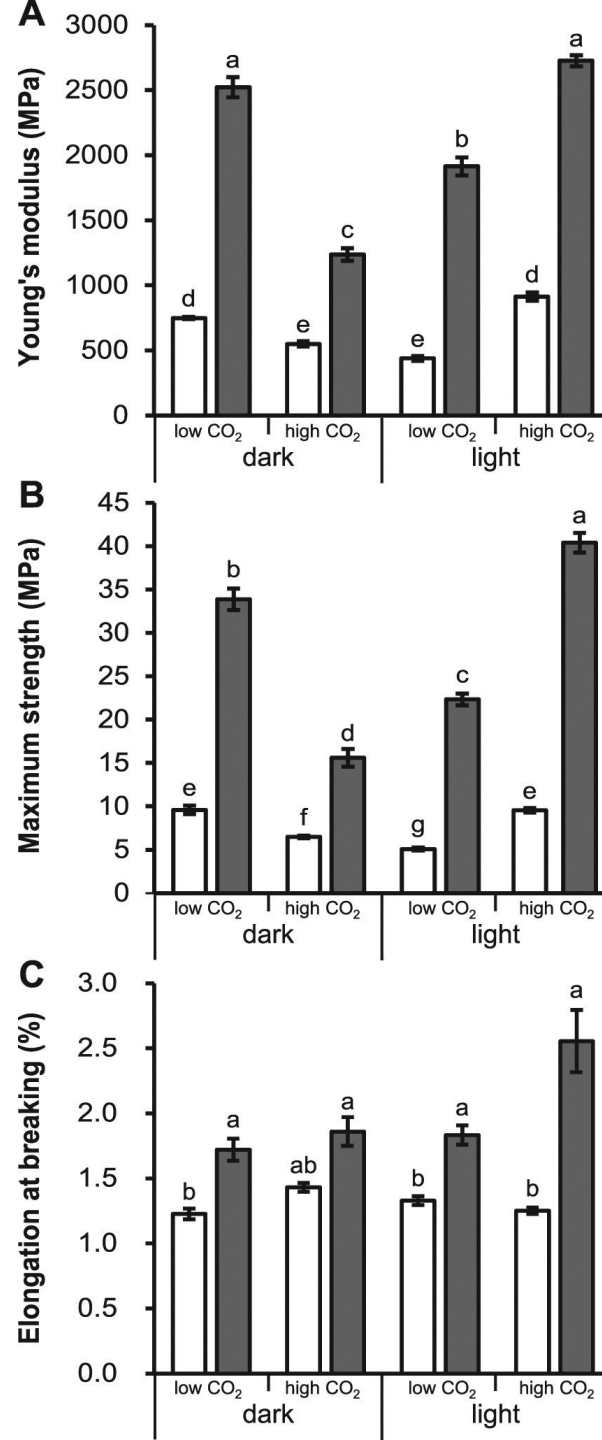
# Thermal properties



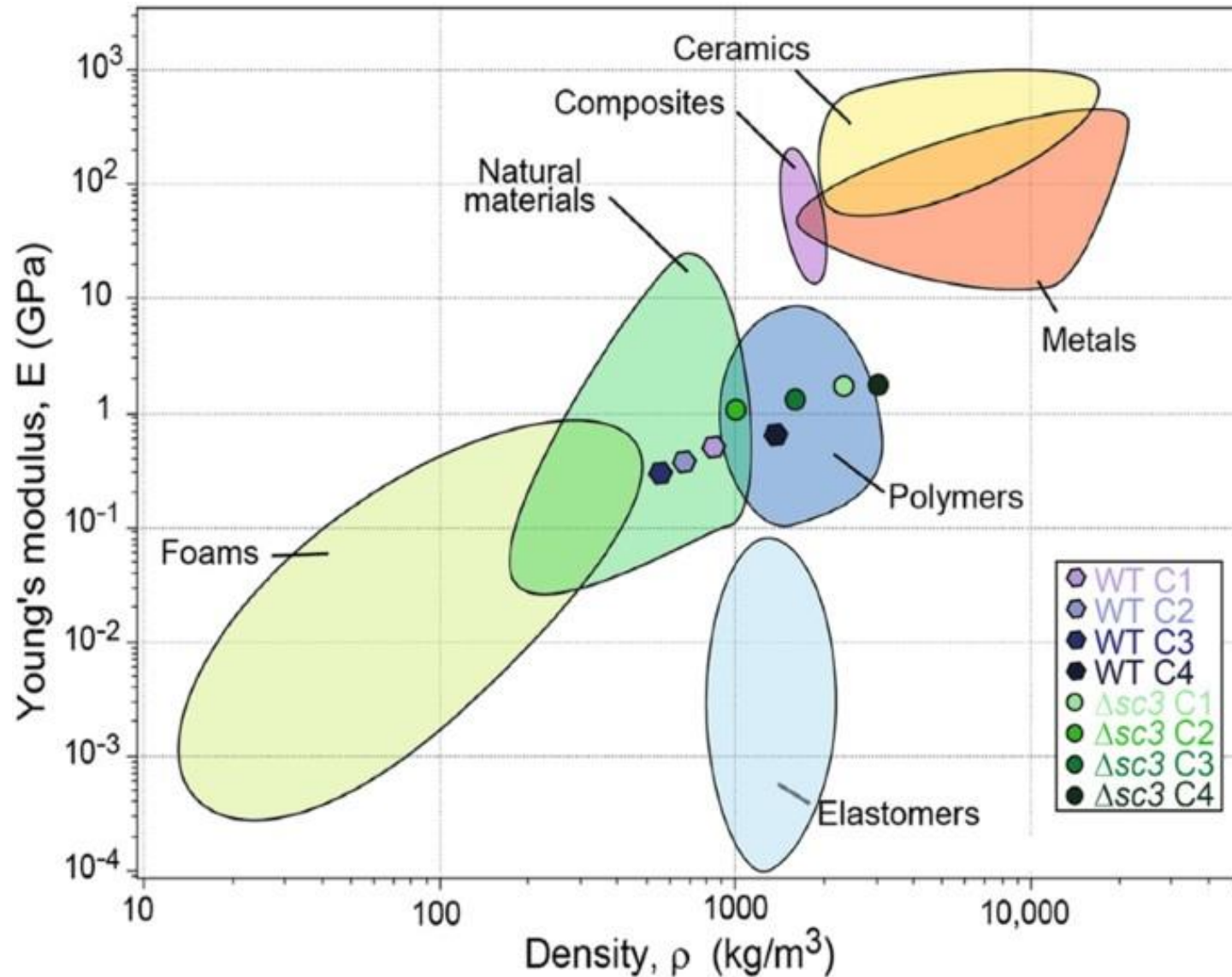
- High char content, > 20%
- Consistent with other species
- Promising as a flame retardant

# Summary of mechanics

- Young's modulus between 0.5-2.5 GPa
- UTS between 5-35 MPa
- Elongation between 1-3%
- **Very different than previous work with other species... so species matters? Let's see...**



# Context and comparison!



- Tunable between natural materials and polymers in this aspect alone.
- Can you think of polymer properties that are absent in these materials?

# The authors could!

# How do we make materials stretchy in this class?



► [Commun Biol. 2020 Jun 26;3:334. doi: 10.1038/s42003-020-1064-4](#)

## Fungal mycelium classified in different material families based on glycerol treatment

[Freek V W Appels](#)<sup>1</sup>, [Jeroen G van den Brandhof](#)<sup>1</sup>, [Jan Dijksterhuis](#)<sup>2</sup>, [Gijs W de Kort](#)<sup>3</sup>, [Han A B Wösten](#)<sup>1,✉</sup>

► [Author information](#) ► [Article notes](#) ► [Copyright and License information](#)

PMCID: PMC7320155 PMID: [32591629](#)

IF = 5.2

Open access

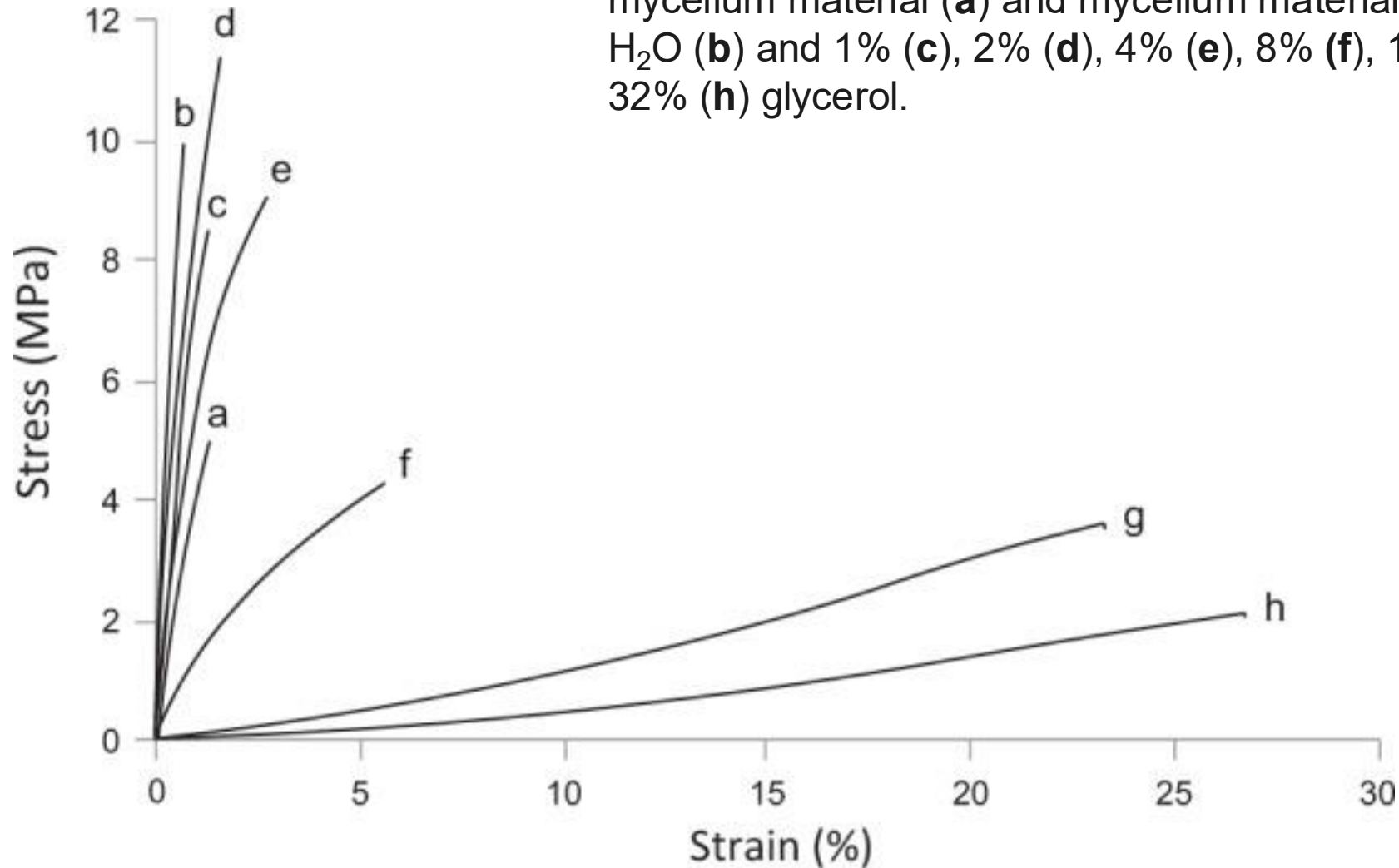
Same-ish team: Utrecht University

**Year: 2020**

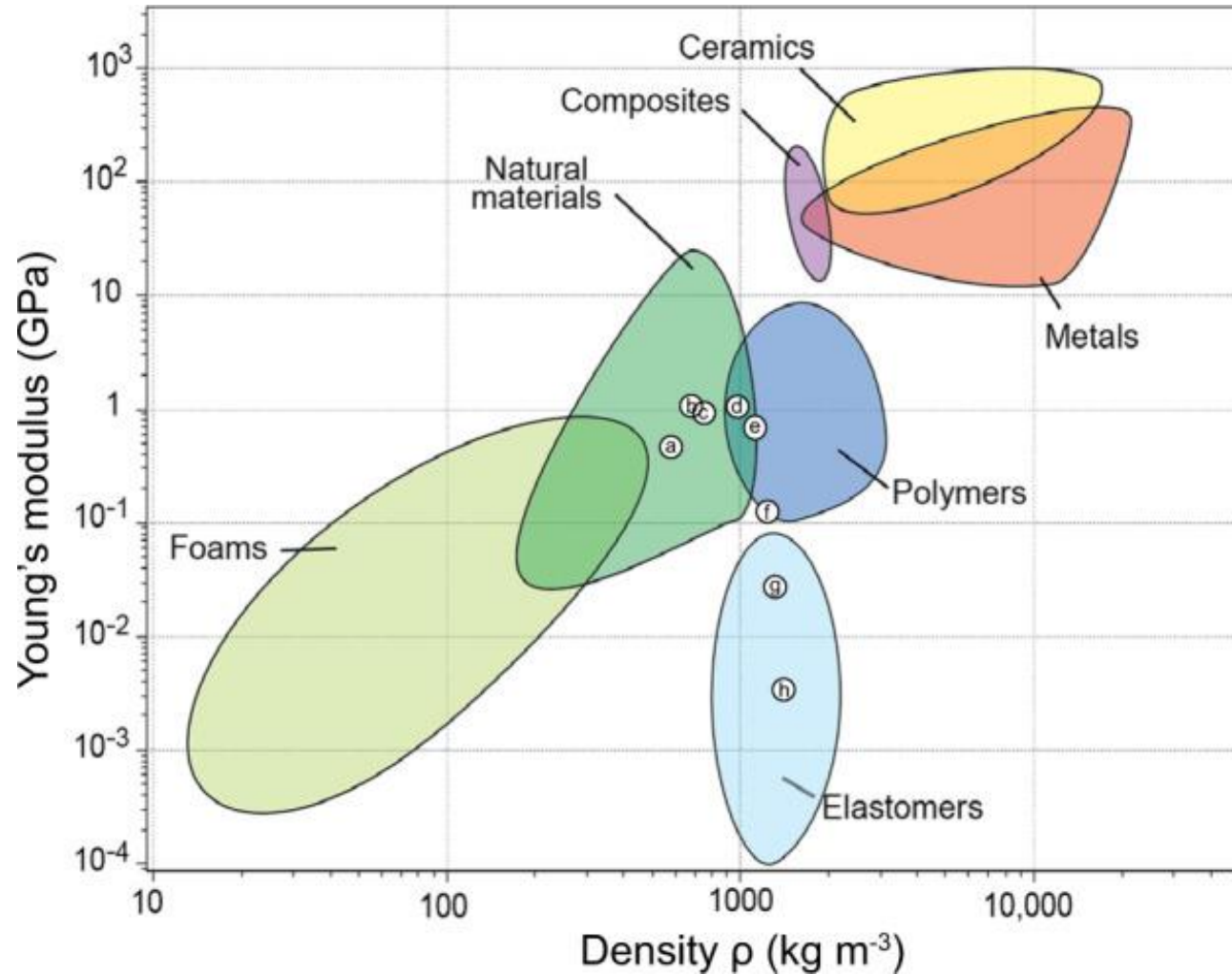
# Why is this paper important?

- **Abstract.** Fungal mycelium is an emerging bio-based material. Here, mycelium films are produced from liquid shaken cultures that have a Young's modulus of 0.47 GPa, an ultimate tensile strength of 5.0 MPa and a strain at failure of 1.5%. Treating the mycelial films with 0–32% glycerol impacts the material properties. The largest effect is observed after treatment with 32% glycerol decreasing the Young's modulus and the ultimate tensile strength to 0.003 GPa and 1.8 MPa, respectively, whereas strain at failure increases to 29.6%. Moreover, glycerol treatment makes the surface of mycelium films hydrophilic and the hyphal matrix absorbing less water. Results show that mycelium films treated with 8% and 16–32% glycerol classify as polymer- and elastomer-like materials, respectively, while non-treated films and films treated with 1–4% glycerol classify as natural material. Thus, mycelium materials can cover a diversity of material families.
- *S. commune* wild type

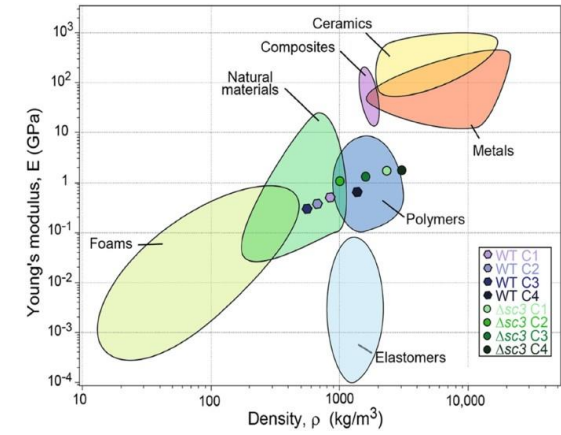
Representative stress/strain curves of non-treated mycelium material (**a**) and mycelium material treated with H<sub>2</sub>O (**b**) and 1% (**c**), 2% (**d**), 4% (**e**), 8% (**f**), 16% (**g**) and 32% (**h**) glycerol.



# Context and comparison!



## Old paper

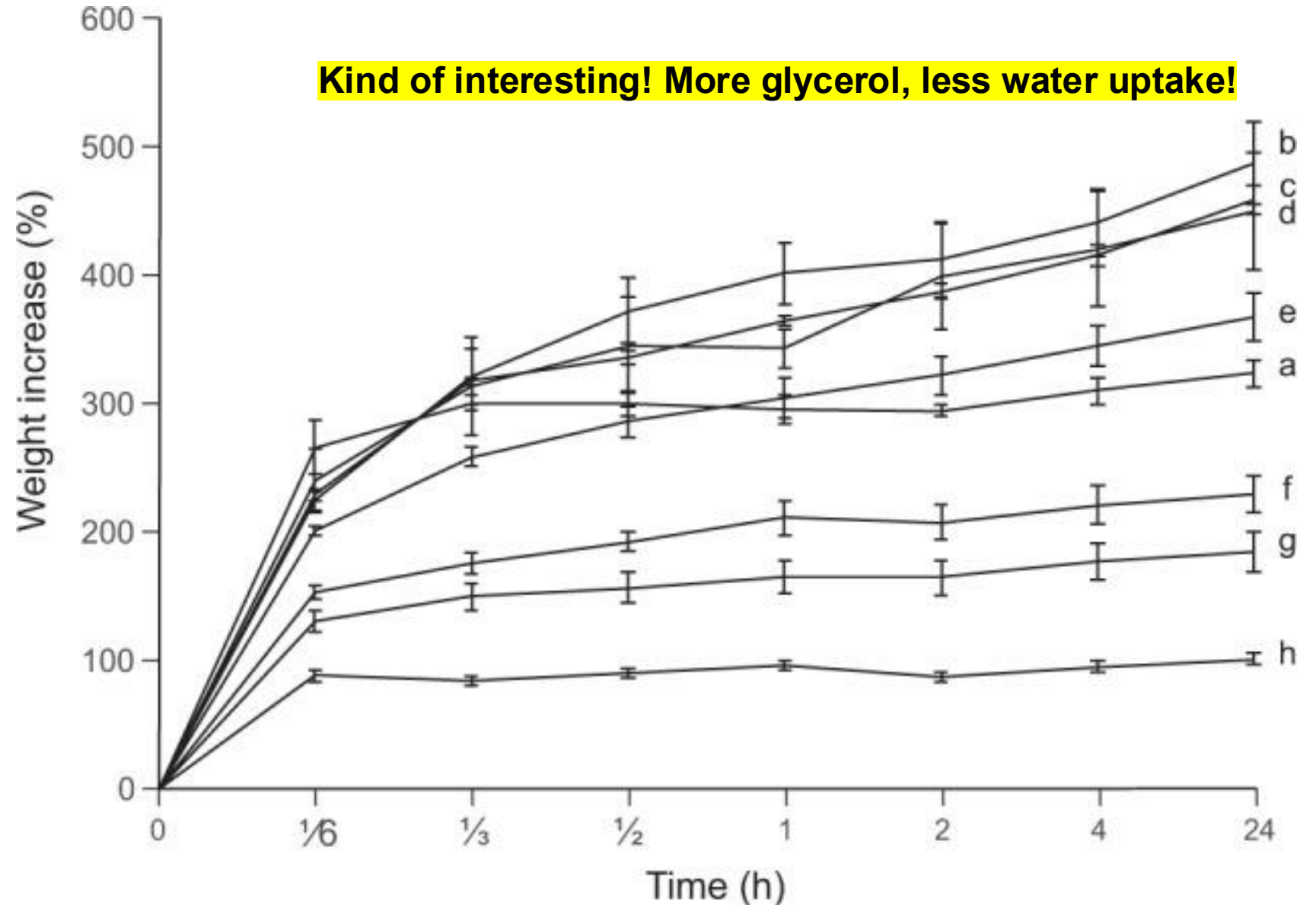


- They are now in the elastomer space with very high glycerol loadings
- Same results as before for wild type, so pretty consistent

# Water contact angle and water uptake

	WCA (°)
Control (a)	$129 \pm 2^{b-h}$
H <sub>2</sub> O (b)	$99 \pm 8^{a,g,h}$
1% glyc (c)	$102 \pm 2^{a,g,h}$
2% glyc (d)	$101 \pm 2^{a,g,h}$
4% glyc (e)	$93 \pm 7^{a,h}$
8% glyc (f)	$86 \pm 5^{a,h}$
16% glyc (g)	$71 \pm 6^{a-d}$
32% glyc (h)	$49 \pm 3^{a-f}$

Kind of interesting! More glycerol, less water uptake!



# Why is this paper important?

**Abstract.** Pure mycelium materials (PMMs) are a sustainable alternative for a range of non-sustainable products such as textile, leather and meat. So far, properties of PMMs of different fungi have not been systematically assessed. Here, 11 mushroom-forming fungi, of which 10 isolated from nature, were grown in liquid shaken cultures. *Schizophyllum commune*, *Ganoderma resinaceum*, and *Trametes betulina* produced the highest biomass (8.62, 7.58, and 6.94 g L<sup>-1</sup>, respectively) when grown as mono-cultures in malt extract broth. Therefore, PMM properties were determined of mono-cultures, mixed-cultures, and co-cultures of these three fungi. The maximum tensile strength of the PMMs of the mono-cultures, mixed-cultures, and co-cultures of *S. commune*, *G. resinaceum*, and *T. betulina* did not show significant differences and ranged between 4.5 to 6.3 MPa. The elongation at break of the different PMMs was generally low and ranged between 0.8 and 1.6%. The Young's modulus of the PMMs also showed relatively small differences ranging between 408 and 710 MPa. The *G. resinaceum* PMMs showed the lowest water uptake, while the *S. commune* mono-, mixed- and co-culture PMMs showed the highest water contact angle. Together, it is concluded that the properties of the mono-, mixed-, and co-cultures of *S. commune*, *G. resinaceum*, and *T. betulina* are not very different. These data suggest that the species of mushroom forming fungi does not have a major impact on PMM properties of biomass from liquid shaken cultures.

# Why is this paper important?

The maximum tensile strength of the PMMs of the mono-cultures, mixed-cultures, and co-cultures of *S. commune*, *G. resinaceum*, and *T. betulina* did not show significant differences and ranged between 4.5 to 6.3 MPa. The elongation at break of the different PMMs was generally low and ranged between 0.8 and 1.6%. The Young's modulus of the PMMs also showed relatively small differences ranging between 408 and 710 MPa.

- Hmm wait? Are they now saying that all mushrooms have the same mechanical properties, more or less? ***Is this controversial?***
- Keep in mind: all wild-type, all grown in same, non-optimized environment

# Summary of mechanical properties

Species	Mass (g)	Shrinkage (%)	Thickness (mm)	Density (kg m <sup>-3</sup> )	$\sigma$ (MPa)	$\epsilon$ (%)	$E$ (MPa)	$n$
Mono-cultures								
GR	0.23 ± 0.01 <sup>ab</sup>	34.4 ± 2.7 <sup>a</sup>	0.49 ± 0.02 <sup>a</sup>	730 ± 14 <sup>a</sup>	5.2 ± 0.7 <sup>a</sup>	0.9 ± 0.1 <sup>a</sup>	562 ± 98 <sup>ab</sup>	44
SC	0.22 ± 0.01 <sup>ac</sup>	27.4 ± 2.5 <sup>bc</sup>	0.61 ± 0.03 <sup>bc</sup>	550 ± 30 <sup>cd</sup>	6.3 ± 0.7 <sup>a</sup>	1.3 ± 0.1 <sup>c</sup>	546 ± 96 <sup>ab</sup>	36
TB	0.24 ± 0.01 <sup>bd</sup>	33.9 ± 4.3 <sup>abc</sup>	0.68 ± 0.03 <sup>d</sup>	545 ± 23 <sup>c</sup>	5.9 ± 0.9 <sup>a</sup>	0.9 ± 0.1 <sup>a</sup>	677 ± 191 <sup>ab</sup>	29

*So, not tunable afterall?*

- They go on to say a lot of things about how to maximize tensile strength, like:
- Blending the biomass is important
- Post treatments like wet-dry cycling is important (a 2024 paper we did not look at)
- Still some open questions...

# Takeaways

- PMM history (it's pretty recent – we only started in 2017)
- Tunable properties?
- Is tunability more about post-processing than anything else?
- How different can we expect similar mushrooms to be? (I don't know, maybe not that different?)
  
- **Will we make materials out of mushrooms? (Hint: We already are!)**
- Next class: mycelium-bound composites and an example from our research

