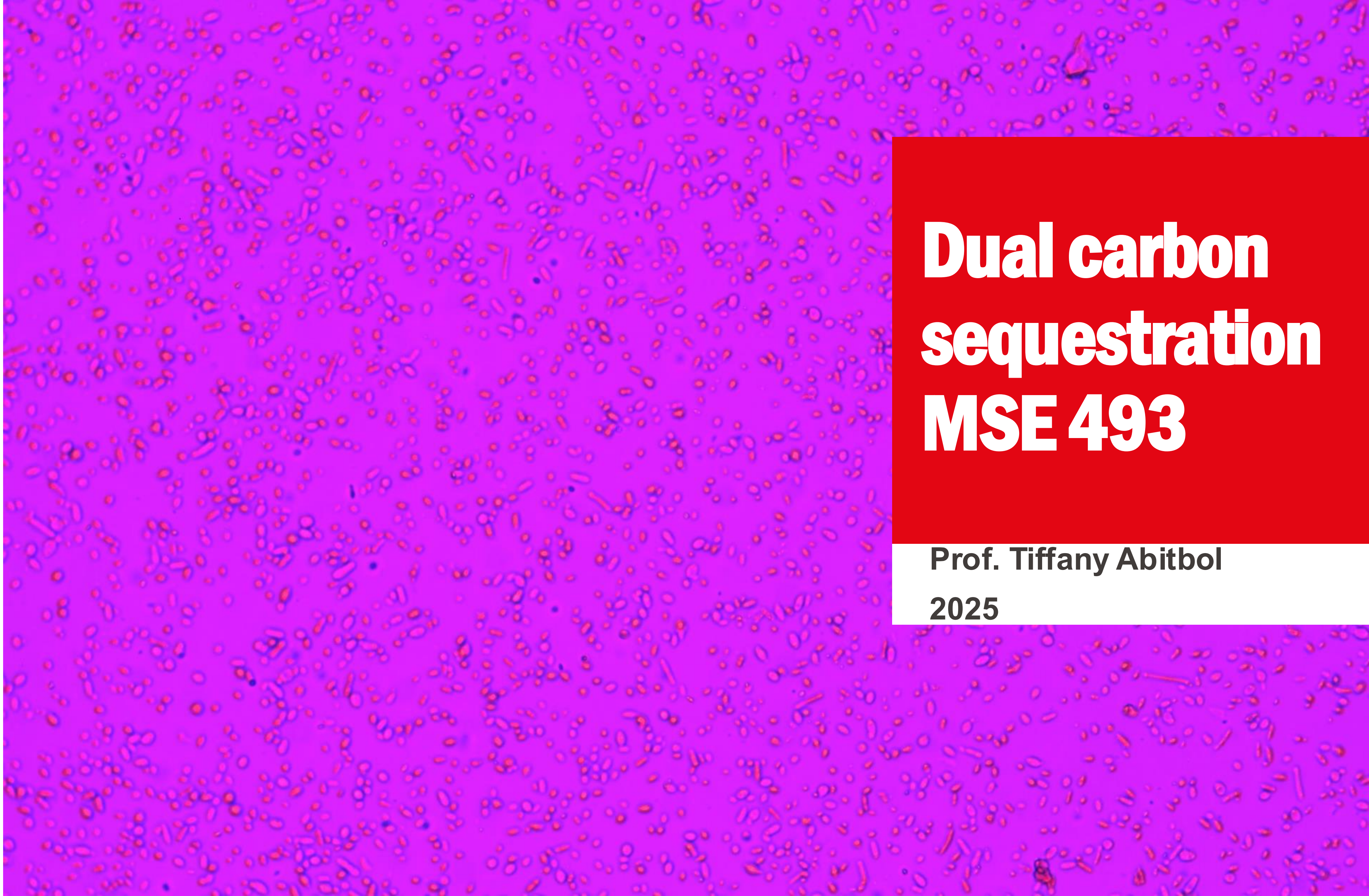

Dual carbon sequestration MSE 493

Prof. Tiffany Abitbol

2025

The paper

Impact factor: 15.7 (2024)

- A measure of the average number of article citations over a two-year period

nature communications

Article

https://doi.org/10.1038/s41467-025-58761-y

Dual carbon sequestration with photosynthetic living materials

Teamwork makes the dream work!

Received: 6 May 2024

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Check for updates

Dalia Dranseike[1,7], Yifan Cui[1,7], Andrea S. Ling[2], Felix Donat[3], Stéphane Bernhard[1], Margherita Bernero[4], Akhil Areeckal[1], Marco Lazic[1], Xiao-Hua Qin[4], John S. Oakey[5], Benjamin Dillenburger[2], André R. Studart[6] & Mark W. Tibbitt[1]

Natural ecosystems efficiently sequester CO_2 but containing and controlling living systems remains challenging. Here, we engineer a photosynthetic living material for dual CO_2 sequestration that leverages biomass production and insoluble carbonate formation via microbially induced carbonate precipitation (MICP). To achieve this, we immobilize photosynthetic microorganisms within a printable polymeric network. Digital design and fabrication of the living structures ensure sufficient light access and nutrient supply to encapsulated cyanobacteria, enabling long-term culture for over a year. We showcase that photosynthetic living materials are able to sequester 2.2 ± 0.9 mg of CO_2 per gram of hydrogel material over 30 days and 26 ± 7 mg of CO_2 over 400 days. These findings highlight the potential of photosynthetic living materials for scalable, low-maintenance carbon sequestration with applications in carbon-neutral infrastructure and CO_2 mitigation.

The research group

ETH Zürich

Prof. Dr. Mark Tibbitt | ETH Zurich

Mark Tibbitt is an Associate Professor in the Macromolecular Engineering Laboratory within the Department of Mechanical and…

H-index

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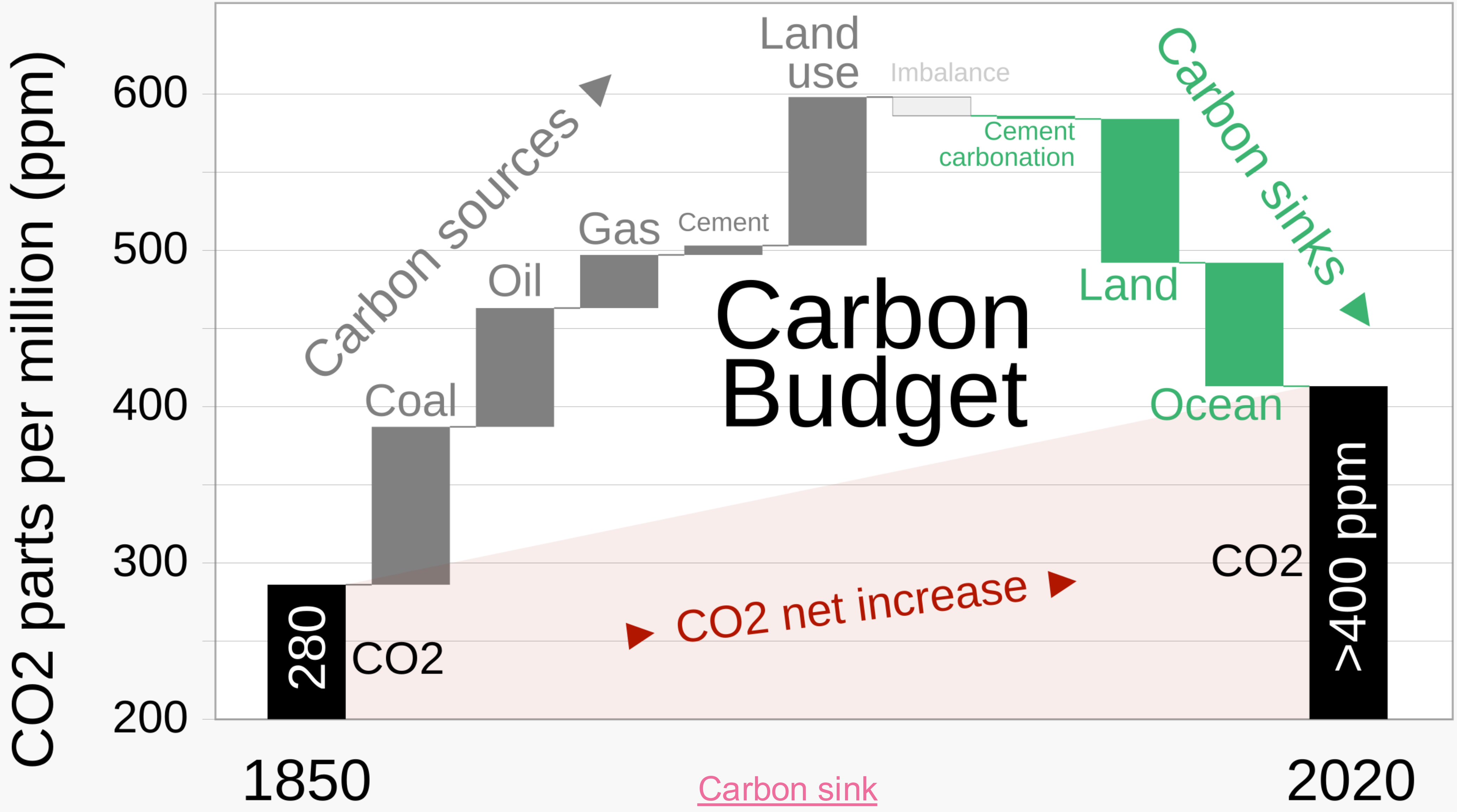
Affiliation

ETH Zürich

Context of carbon sequestration



[Carbon sink]

Title (break down)

Dual carbon sequestration with photosynthetic living materials

What is a "good" title?

The title will be read by many people. Only a few will read the entire paper, therefore all words in the title should be chosen with care. Too short a title is not helpful to the potential reader. However too long a title can sometimes be even less meaningful. Remember a title is not an abstract. Also a title is not a sentence.

Goals:

- Fewest possible words that describe the contents of the paper.
- Avoid waste words like "Studies on", or "Investigations on"
- Use specific terms rather than general
- Watch your word order and syntax
- Avoid abbreviations and jargon

UCI Writing a Scientific Paper

What's supposed to be in a paper abstract?

125 words

What is an abstract?

There are as many kinds as abstracts as there are types of research papers. The classic abstract is usually a "Informative" abstract. This kind of abstract communicates compressed information and include the purpose, methods, and scope of the article. They are usually short (250 words or less) and allow the reader to decide whether they want to read the article.

The goal is to communicate:

- What was done?
- Why was it done?
- How was it done?
- What was found?
- What is the significance of the findings?

Journal guidelines:

The abstract — which should be no more than 200 words long and contain no references — should serve both as a general introduction to the topic and as a brief, non-technical summary of the main results and their implications.

UCI Writing a Scientific Paper

Abstract

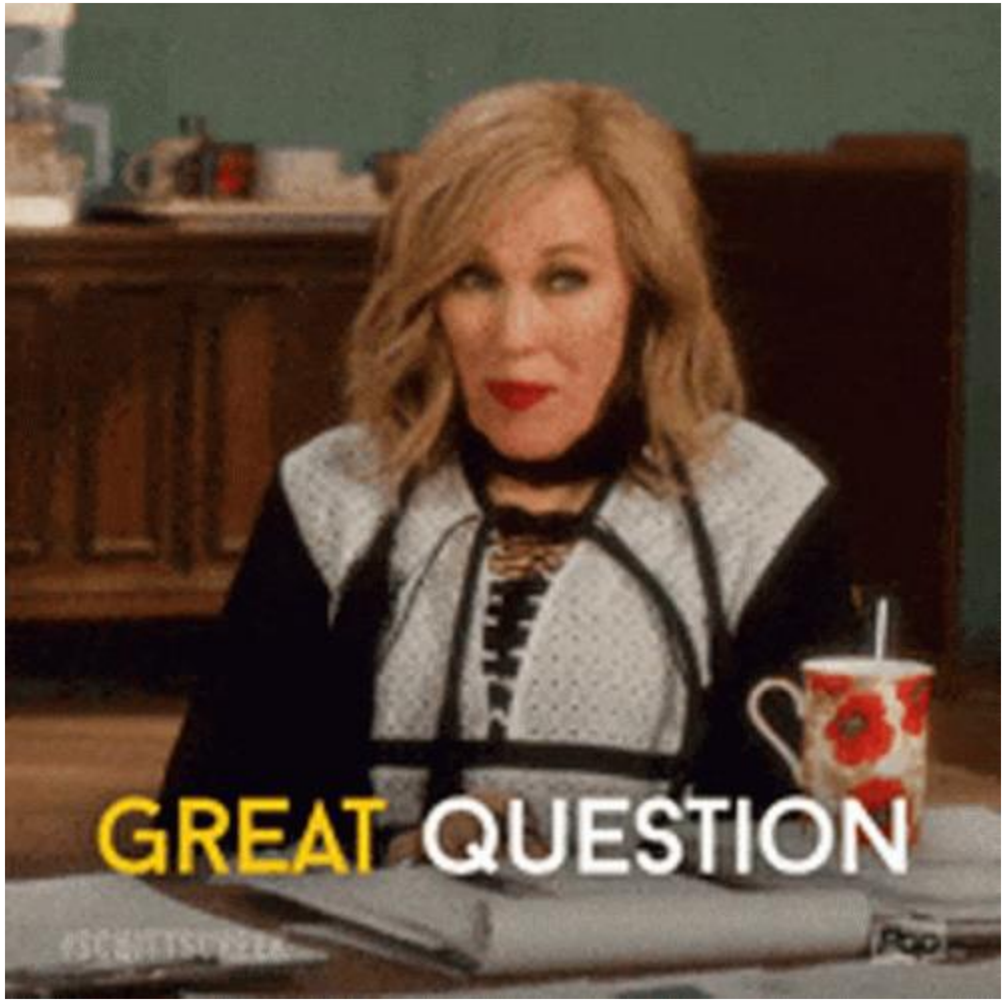
Natural ecosystems efficiently sequester CO_2 but containing and controlling living systems remains challenging. Here, we engineer a photosynthetic living material for dual CO_2 sequestration that leverages biomass production and insoluble carbonate formation via microbially induced carbonate precipitation (MICP). To achieve this, we immobilize photosynthetic microorganisms within a printable polymeric network. Digital design and fabrication of the living structures ensure sufficient light access and nutrient supply to encapsulated cyanobacteria, enabling long-term culture for over a year. We showcase that photosynthetic living materials are able to sequester 2.2 ± 0.9 mg of CO_2 per gram of hydrogel material over 30 days and 26 ± 7 mg of CO_2 over 400 days. These findings highlight the potential of photosynthetic living materials for scalable, low-maintenance carbon sequestration with applications in carbon-neutral infrastructure and CO_2 mitigation.

Abstract (break down) – 5 min

- What was done?
- Why was it done?
- How was it done?
- What was found?
- What is the significance of the findings?

Why "Dual carbon sequestration?"

?



Why "Dual carbon sequestration?"

- Biomass growth (reversible)
- Carbonate formation (irreversible)

Duh

Introduction

Biological ecosystems, such as forests, aquatic systems, and wetlands, offer efficien pathways for carbon sequestration (storing carbon in a carbon pool) and conversion int carbon-based materials[1]. Natural systems operate under ambient conditions with sunlight an commonly available small molecules as their sole inputs. Further, living systems can sense self-repair, and respond to their surroundings, making them resilient to environmenta changes[1,2]. Biological carbon sequestration, for example via afforestation or the growth o marine phytoplankton and algae, is also cost-efficient and environmentally-friendly[3]. In thi context, natural carbon sequestration can serve as a passive, low-impact complement t industrial carbon sequestration, which normally requires specific, extreme, and energy intensive conditions[1,4] and proximity to large emission sources[5]. However, natural carbo sequestration is typically slower than industrial carbon sequestration, and the control of livin systems outside of their native environments is often challenging[5,6].

Strategies to engineer living systems for active CO_2 sequestration would provide an additiona approach to mitigate the accumulation of human-generated CO_2 in the atmosphere. The CO concentrating mechanism of many photosynthetic microorganisms accumulates CO_2 withi the cell body up to 1000-fold above ambient levels[6,7]. Subsequently, concentrated carbon ca be fixed in the form of biomass generated during growth[8,9]. In addition to biomass production microbially-induced calcium carbonate precipitation (MICP) in certain species can sequeste CO_2 irreversibly in the form of inorganic carbonate precipitates. MICP proceeds via multipl metabolic pathways, including ureolysis, sulfate reduction, and denitrification[10,11]. In some organisms, MICP can occur as a direct by-product of photosynthesis, whereby the inorgani precipitates effectively act as an additional carbon sink[12], enabling dual carbon sequestration In this context, immobilizing photosynthetic microorganisms, such as algae and cyanobacteri within a support matrix may provide an approach to drive biological CO_2 sequestration in th form of engineered photosynthetic living materials via dual carbon sequestration.

To date, engineered living materials have primarily been used for applications in biomedicine sustainable materials production, and as living building materials[13–17]. For example, MICP ha been exploited, primarily via ureolysis, to mechanically reinforce living materials based on th in situ formation of a stiff mineral phase[18]. Robust composites were produced vi biomineralization using ureolytic MICP within a cellulose matrix[19,20]. Similarly, precipitate deposited in porous materials filled cracks and improved mechanical properties of composit building structures as well as consolidated soils[21]. Ureolytic MICP is attractive due to its sho incubation period (typically 1-4 days), resistance to contamination, and rapid biomineralizatio however, it poses substantial environmental concerns due to the associated production o large amounts (1-2 equimolar) of ammonia[22]. Further, ureolytic MICP requires a consta supply of urea and only proceeds in a narrow range of environmental conditions[23–25]. These challenges restrict the use of ureolytic MICP for long-term CO_2 sequestration[26]. Many of these limitations can be addressed with photosynthetic MICP, which requires no additiona feedstocks and produces no toxic by-products[18,25]. Recently, photosynthetic MICP was use to design living building materials that mineralized over time[17]. While photosynthetic livin

Introduction

(Let’s keep breaking things down)

Elements of an introduction?

Mostly – I sort of missed the nature and scope? Where are they suggesting implementing the technology?

What is a "good" introduction?

This is where you describe briefly and clearly why you are writing the paper. The introduction supplies sufficient background information for the reader to understand and evaluate the experiment you did. It also supplies a rationale for the study.

Goals:

- Present the problem and the proposed solution
- Presents nature and scope of the problem investigated
- Reviews the pertinent literature to orient the reader
- States the method of the experiment
- State the principle results of the experiment

Problem

- Need to "mitigate the accumulation of human-generated CO_2 in the atmosphere"

- "… photosynthetic living materials … have not been explored for CO_2 sequestration via biomass accumulation *and* irreversible MICP using atmospheric CO_2 as the main carbon source and light as the sole source of energy."

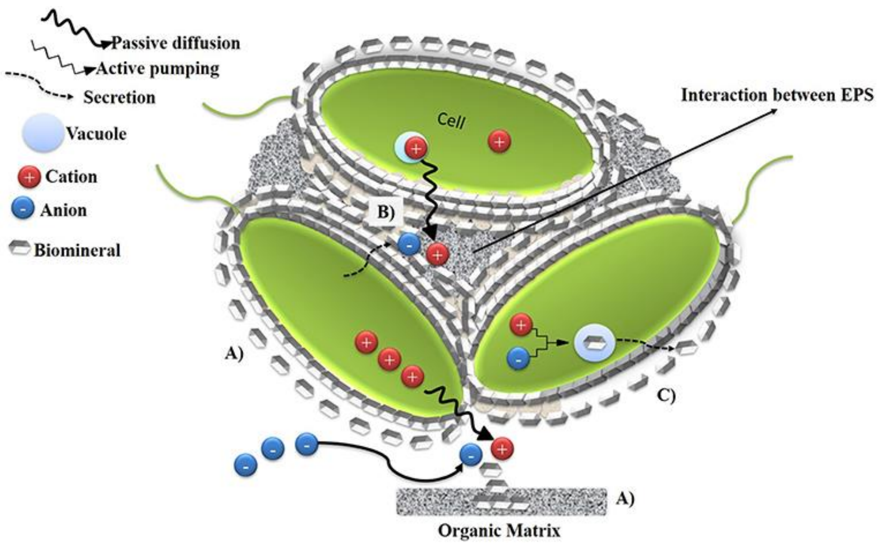
Solution

- Engineered living systems for active CO_2 sequestration as complement to other technologies

- “In this context, immobilizing photosynthetic microorganisms, such as algae and cyanobacteria, within a support matrix may provide an approach to drive biological CO_2 sequestration in the form of engineered photosynthetic living materials via dual carbon sequestration.”

Nature and scope of the problem (sorta)

- ELMs mostly used in biomedicine, sustainable materials production, and as living building materials (*is this fully true?*)
- Ureolytic MICP: reinforce living materials via mineral phase formation or fill cracks in composites and soils, *disadvantage is build-up of ammonia, need to constantly supply urea, narrow range of environmental conditions*
- Photosynthetic MICP to the rescue! No additional feedstocks, no toxic byproducts
- ELM can be used to irreversibly fix CO_2 into carbonates (CCS)



MICP

In ureolytic MICP: urease breaks down urea into ammonia and carbonate ions, which then react with calcium ions

EPFL

Literature review

https://doi.org/10.1002/adma.202305505

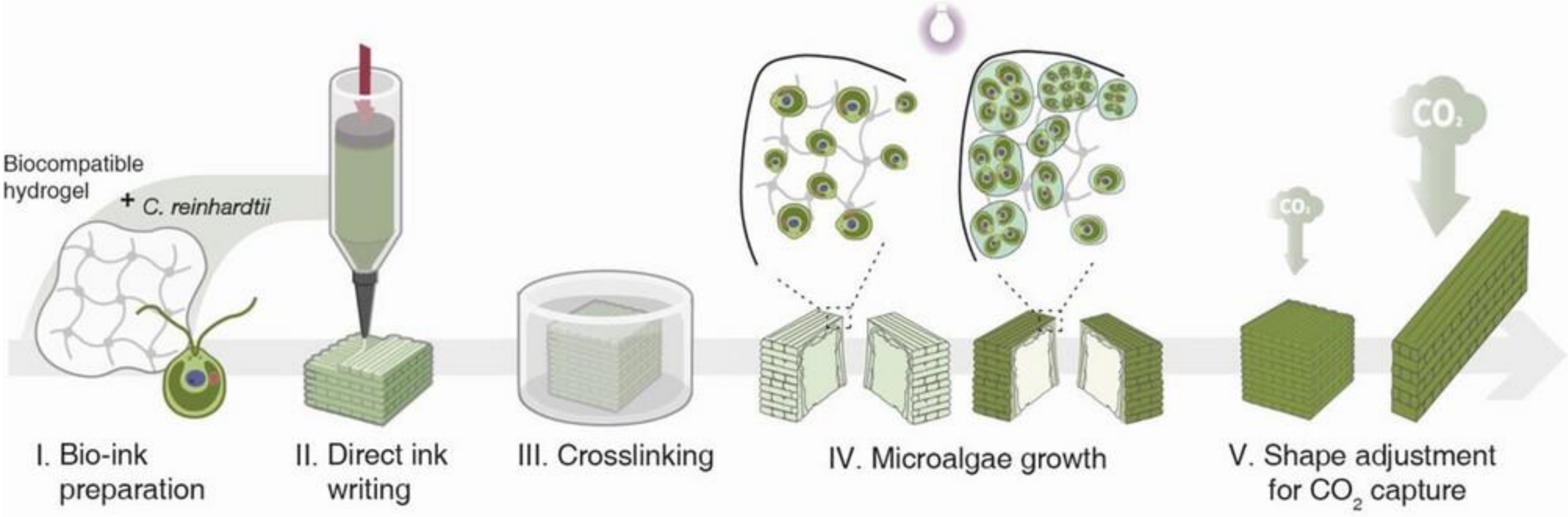
- C sequestration via photosynthesis
- Microalgae
- No MICP
- “reversible” upon biomass degradation

RESEARCH ARTICLE

ADVANCED MATERIALS
www.advmat.de

Growth, Distribution, and Photosynthesis of *Chlamydomonas Reinhardtii* in 3D Hydrogels

Jeong-Joo Oh, Satya Ammu, Vivian Dorine Vriend, Roland Kieffer, Friedrich Hans Kleiner, Srikkanth Balasubramanian, Elvin Karana, Kunal Masania, and Marie-Eve Aubin-Tam**



Literature review

https://doi.org/10.1016/j.matt.2019.11.016

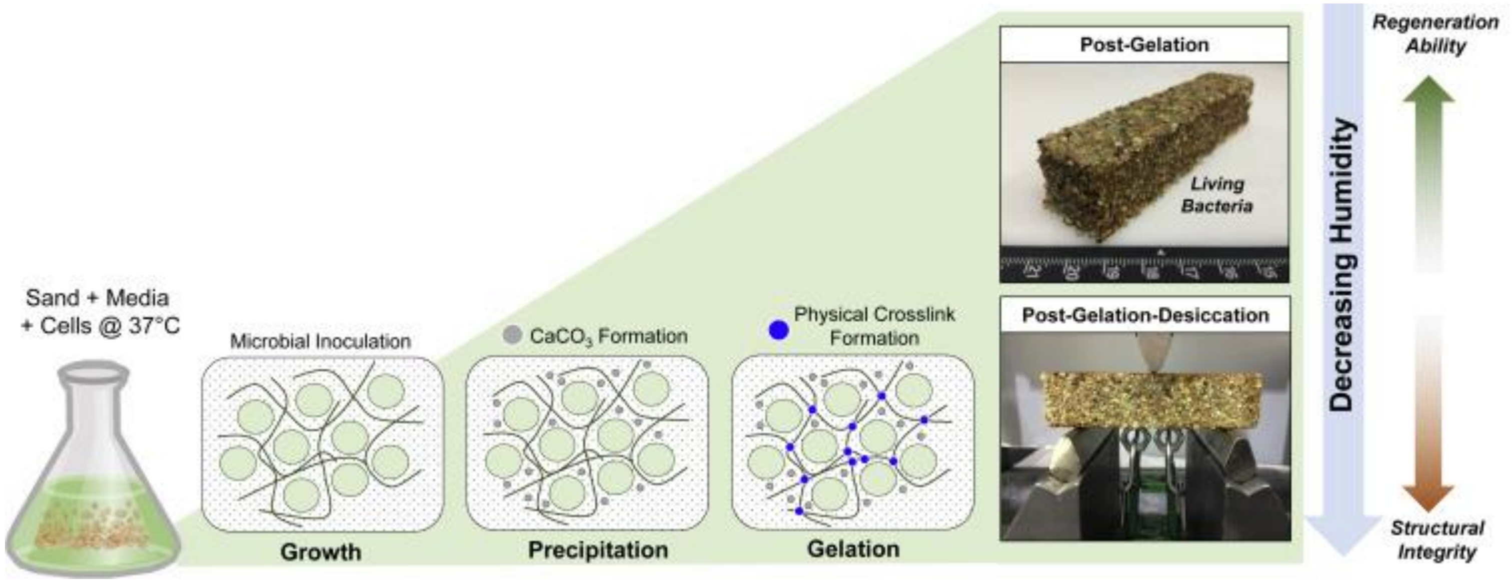
- Carbon sequestration via photosynthesis
- MICP
- Cyanobacteria
- But here the CO_2 is not sequestered from the atmosphere it is from the enzymatic break down of calcium lactate

Matter

Article

Biomineralization and Successive Regeneration of Engineered Living Building Materials

Chelsea M. Heveran,[1,2] Sarah L. Williams,[6] Jishen Qiu,[1] Juliana Artier,[3] Mija H. Hubler,[1] Sherri M. Cook,[1] Jeffrey C. Cameron,[3,4,5] and Wil V. Srubar III[1,6,7,*]



Methodology

Biology part:

Cyanobacterium *Synechococcus* sp. strain PCC 7002. **Why?**

- Can synthesize complex carbohydrates using light, inorganic nutrients found in seawater, and **atmospheric CO_2 as the main carbon source**
- Capable of photosynthetic MICP, exhibits a fast-doubling time (~2.6 h under optimal conditions)
- Tolerates variations in light intensity and osmotic pressure

Materials part:

Pluronic F-127 (F127)-based hydrogel. **Why?**

- Bio-inert
- Transparent
- 3D printable – enables design to enhance access to light and nutrient exchange (open lattices, branched forms, and discrete pillars)

Main outcomes

- “Dual carbon sequestration via biomass generation and insoluble carbonate formation proceeded over the lifecycle (beyond one year) of the bio-printed structures.”

- “The mineral phase mechanically reinforced the living materials and stored sequestered carbon in a more stable form.”

Now onto the results

A lot of supporting results in an SI section. No need to have everything in the main manuscript, only most important parts. A lot of journals limit the number of figures.

Writing a "good" results section

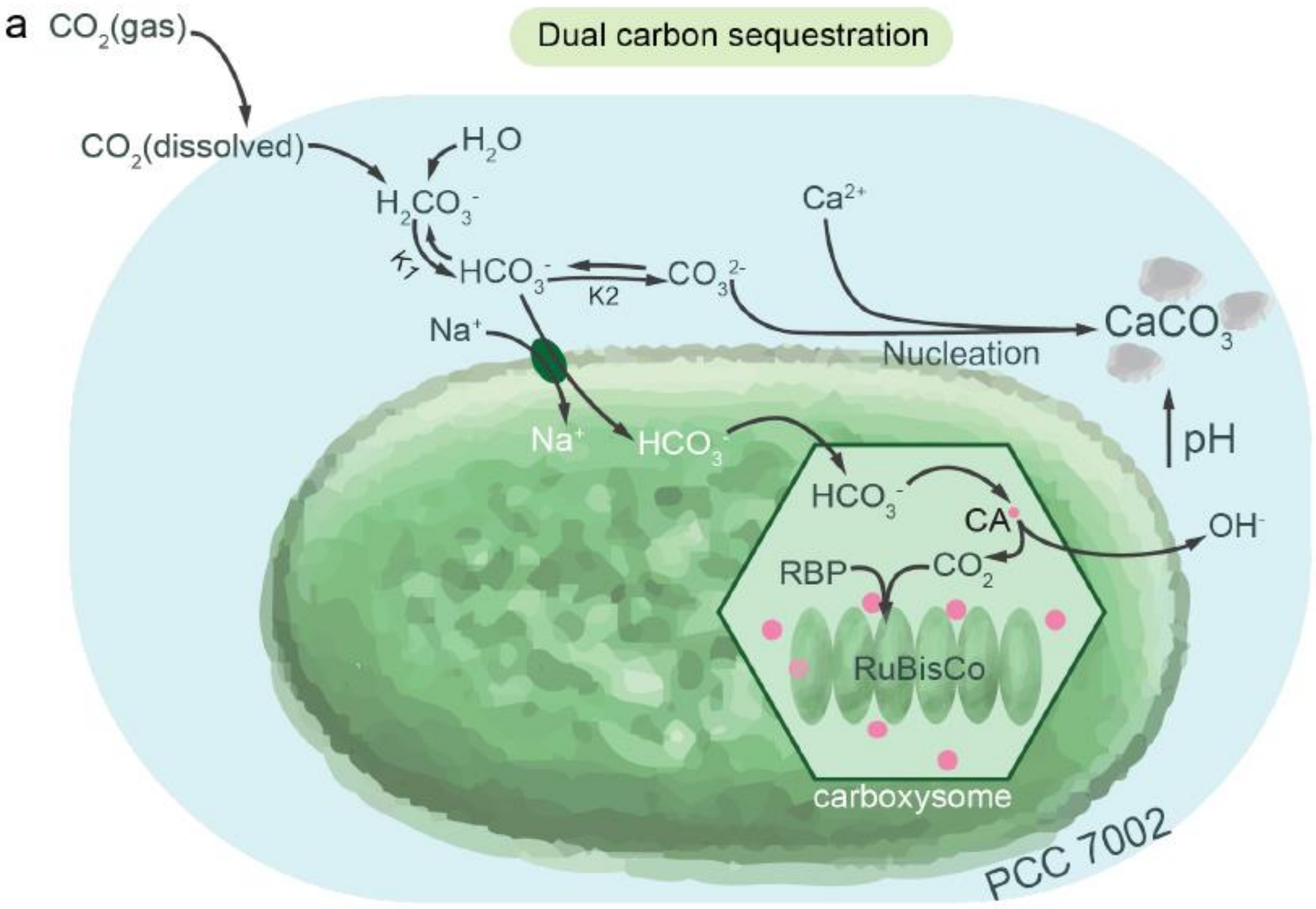
This is the core of the paper. Don't start the results sections with methods you left out of the Materials and Methods section. You need to give an overall description of the experiments and present the data you found.

Goals:

- Factual statements supported by evidence. Short and sweet without excess words
- Present representative data rather than endlessly repetitive data
- Discuss variables only if they had an effect (positive or negative)
- Use meaningful statistics
- Avoid redundancy. If it is in the tables or captions you may not need to repeat it

Now onto the results (not really a result, more like how cyanobacteria work)

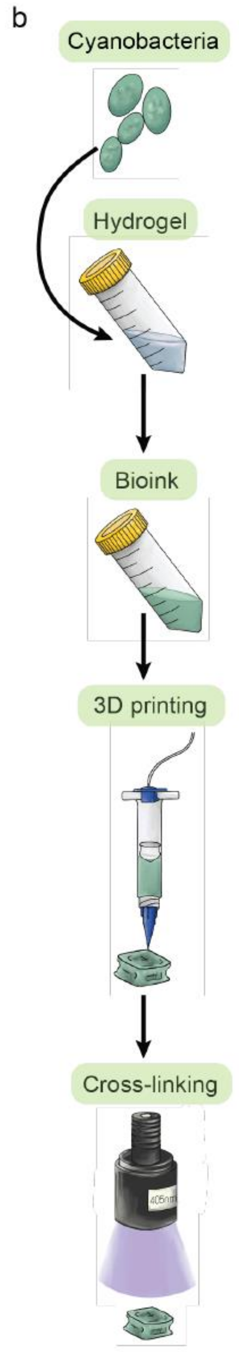
Like what we saw last week… except for CO_2 source



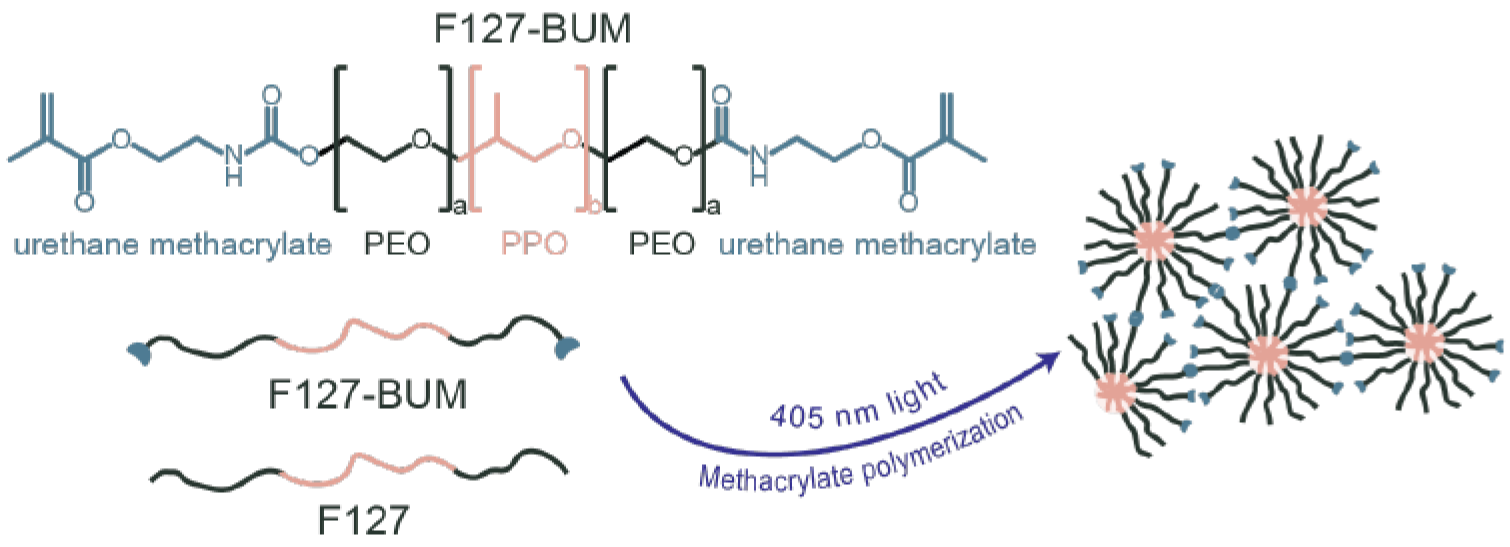
- CO_2 dissolves to give HCO_3^-
- HCO_3^- transported to "carboxysome"
- HCO_3^- converted to OH^- and CO_2 by carbonic anhydrase (CA)
- OH^- secreted, local pH increases
- RuBisCo fixes CO_2 into 2 molecules of phosphoglycerate, **which is enzymatically converted to sugars for biomass development**
- Local pH and anion EPS on cell membrane create a favorable environment for carbonate nucleation and growth
- In presence of Mg^{2+}or Ca^{2+}, CO_3^{2-} is consumed and fixed as an insoluble carbonate

Now onto the results

- A cute vertical schematic of concept of the work
- P7002 encapsulated into hydrogel to give bioink
- Bioink is 3D printed
- 3D printed object is photo crosslinked

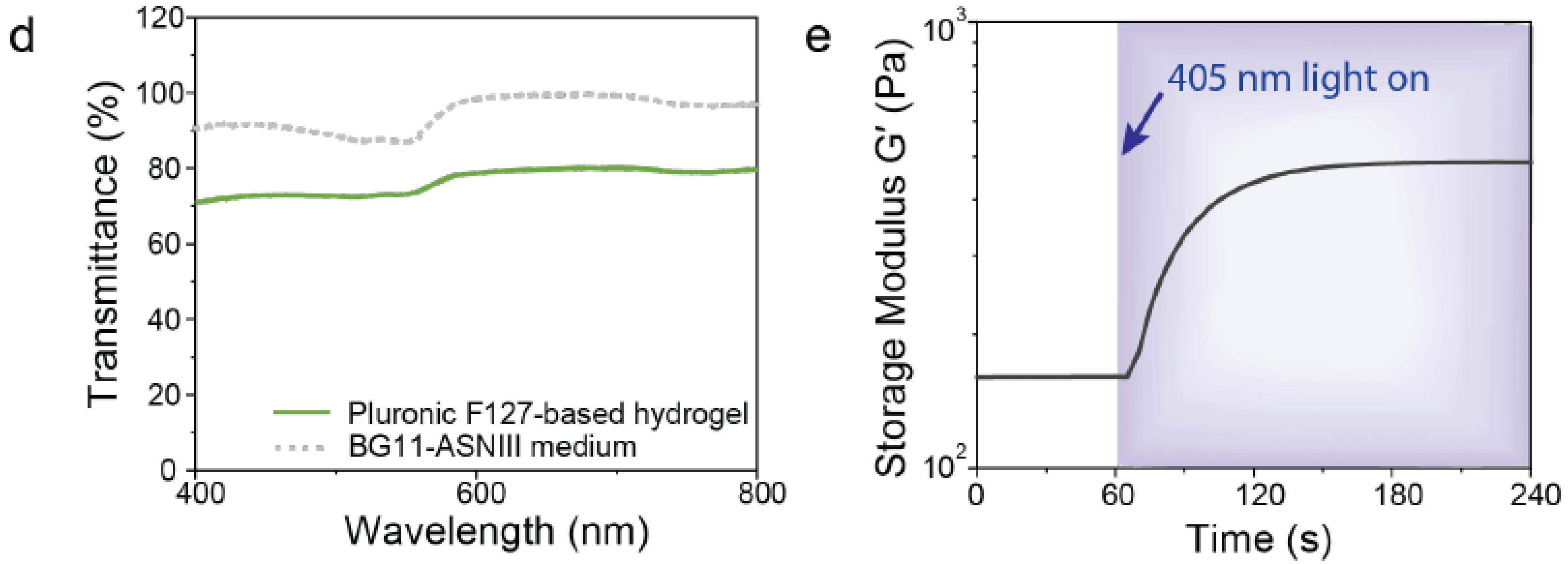


Now onto the results (is this a result?)



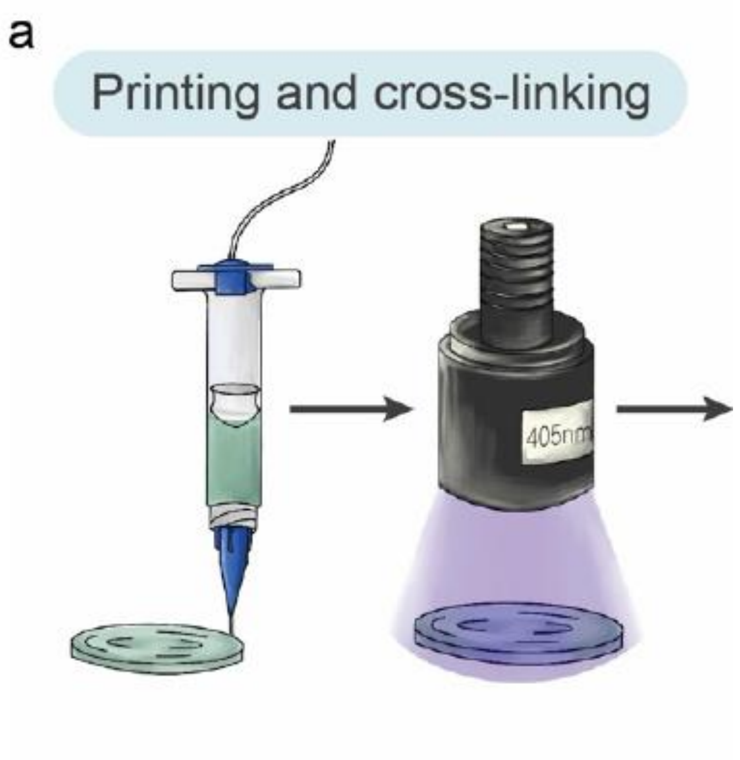
- The bioink consists of 2 polymers
- F127 (13.2%) and F127-BUM (7.3%)
- High viability of 7002
- Good printability (DIW and light-based additive manufacturing)
- Polymer synthesis described in ESI
- Cells suspended into ink by centrifugation

Now onto the results (this looks like results)



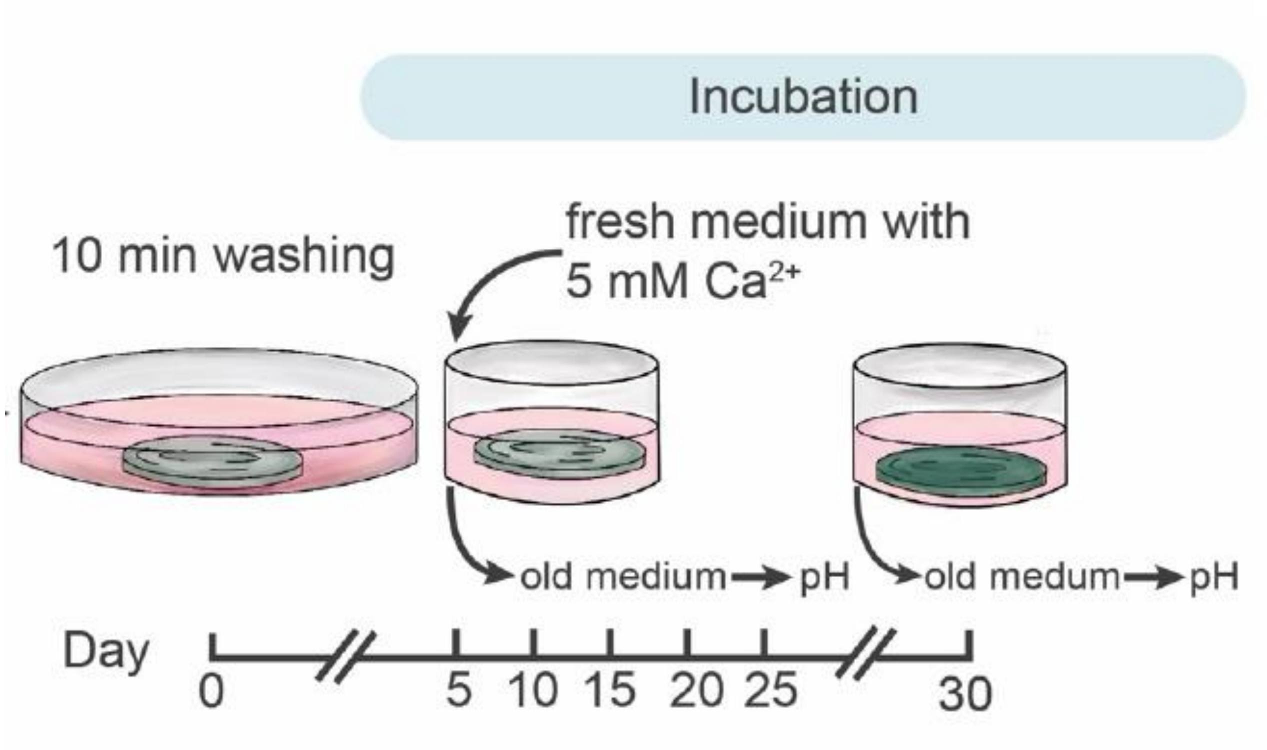
- Transparency is needed for photosynthesis
- Storage modulus increase with illumination at 405 nm due to photo crosslinking
- Any cells in this figure? No, just hydrogel materials properties

Now onto the results (dual sequestration schematic)



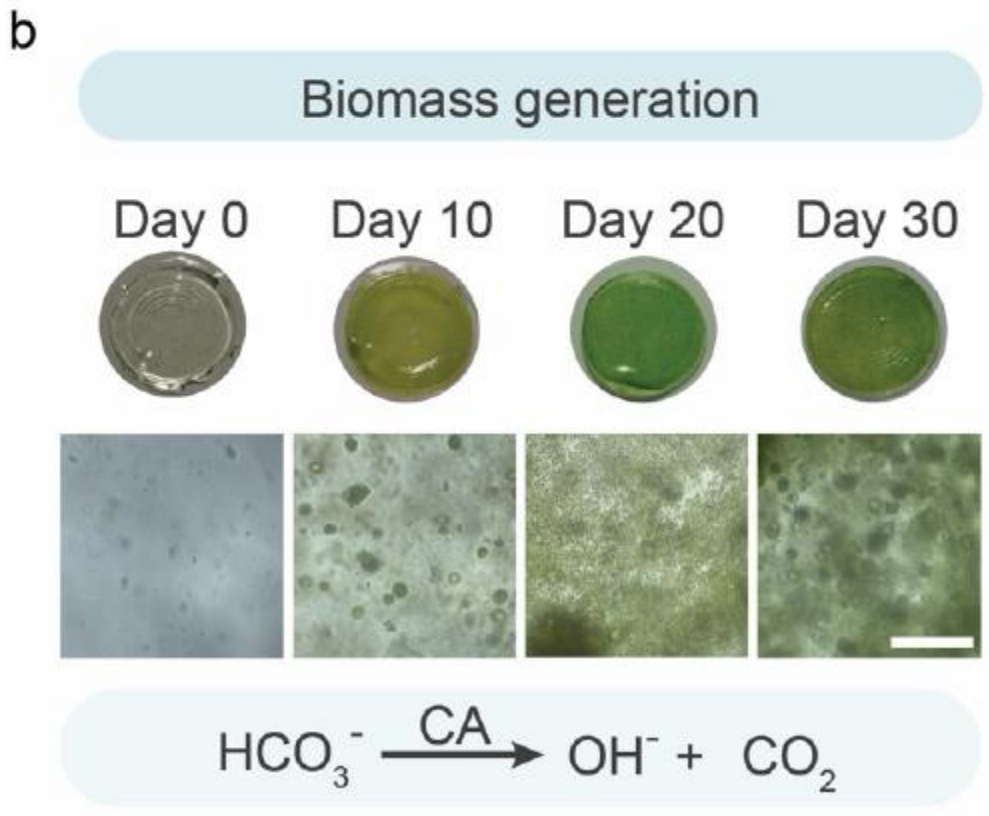
- 10 mm diameter discs; 40 µL volume
- DIW and photocrosslinking

Now onto the results (another schematic)



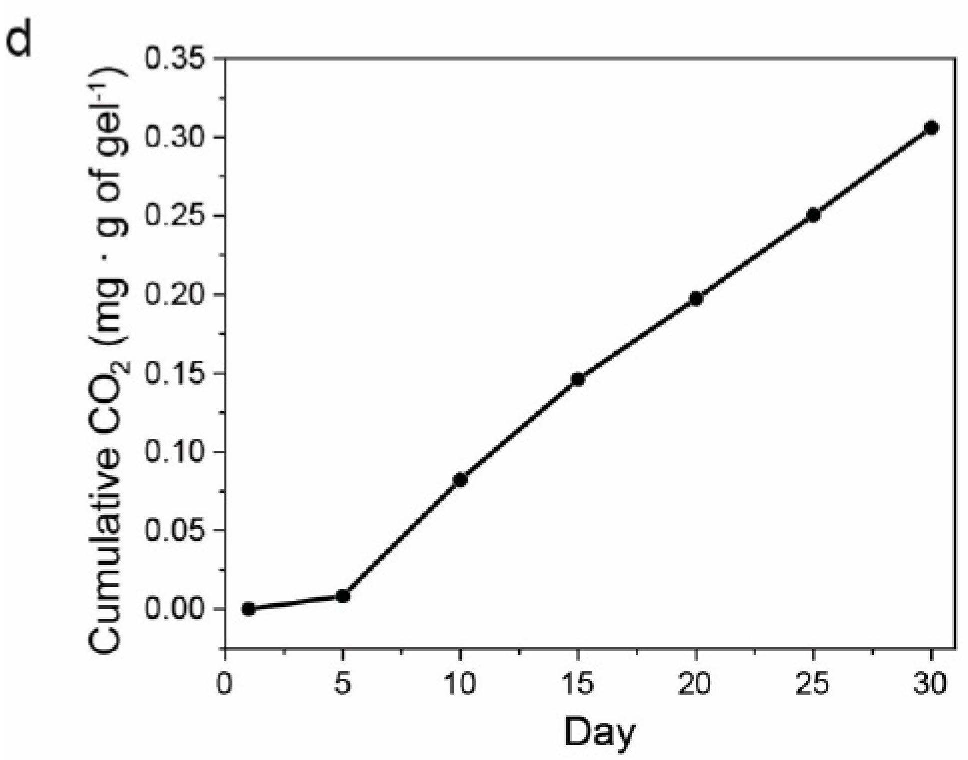
- Disks incubated for 30 days
- Media changed every 5 days
- From day 5, Ca^{2+} in medium was set to 8.65 mM via $CaCl_2$ to mimic seawater
- All HCO_3^- needed was provided by atmospheric CO_2

Now onto the results (yes!)



- Biomass growth confirmed by microscopy and pH
- No pH change in abiotic control
- *How does growth affect transparency/photosynthetic efficiency?*

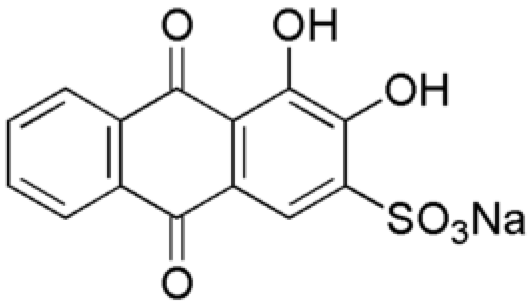
Now onto the results (yes!)

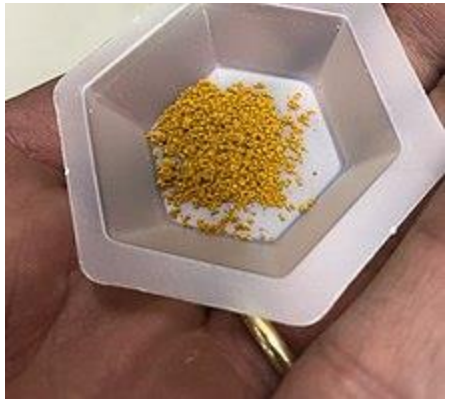


- Cumulative CO_2 sequestered was calculated from the pH change (shown in SI)
- 0.31 mg/g living material of sequestered CO_2 after 30 days
- **This is only due to biomass growth**

Alizarin Red S

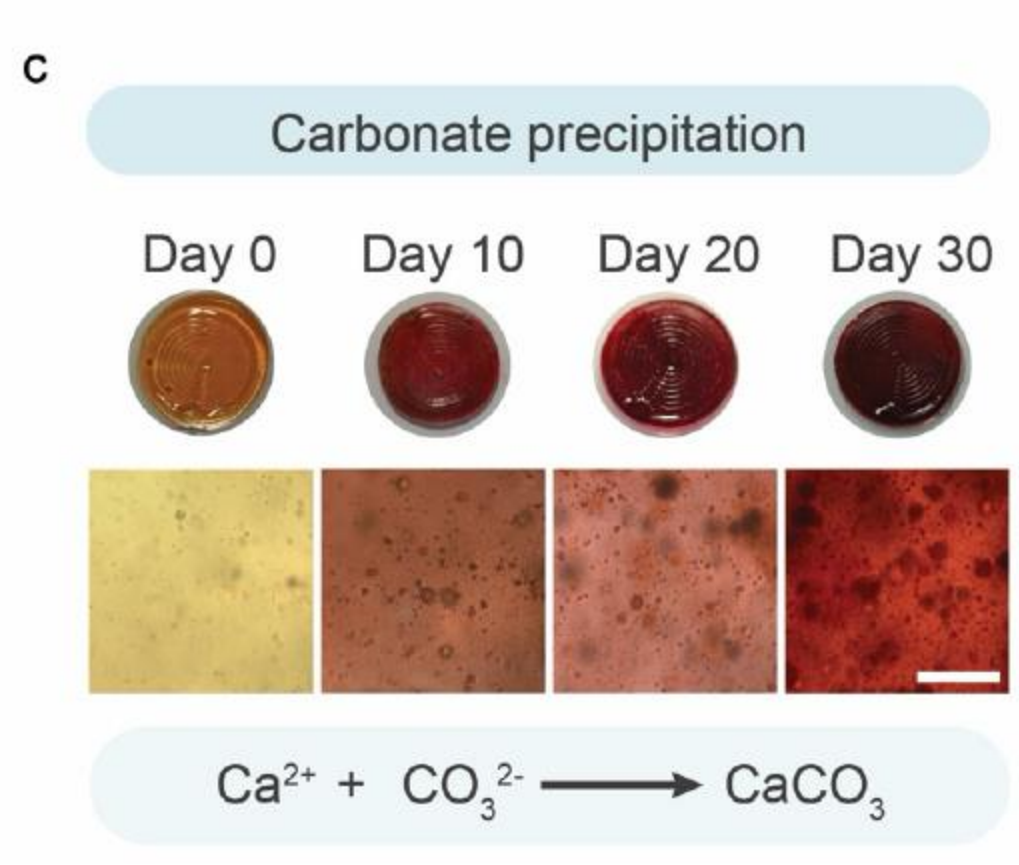
- Water soluble, sodium salt
- Used to stain calcium deposits in tissues and to stain and differentiate carbonate minerals
- Goes from orange to red with binding
- Can stain other divalent ions
- Considered semi-quantitative





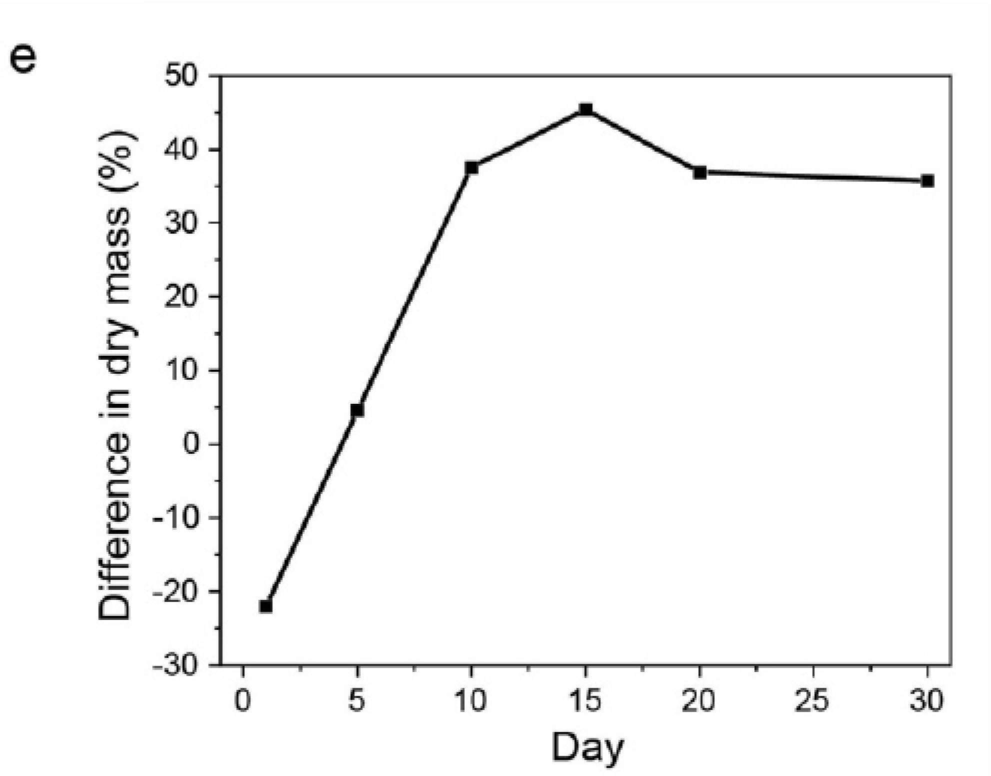
Alizarin Red

Now onto the results (yes!)



- To confirm MICP, calcium staining with Alizarin red
- Abiotic samples (and day 0 samples) remain orange
- Biotic samples turn red at day 10 indicating mineralization

Now onto the results (yes!)

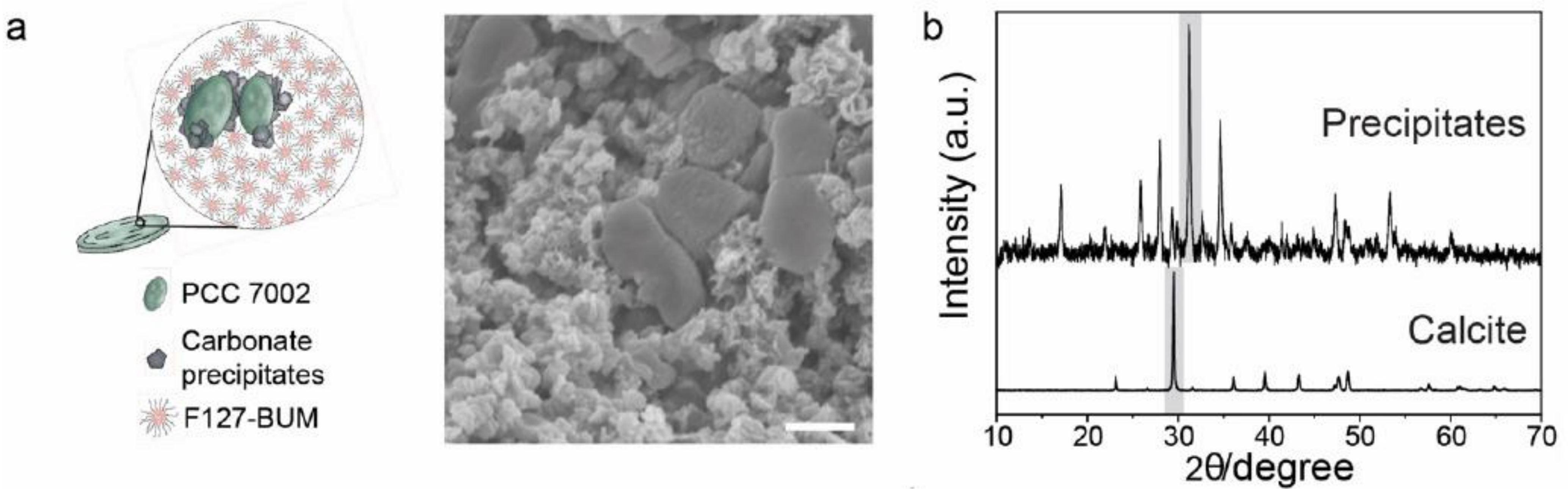


- To assess amount of biomass and precipitate compared biotic and abiotic samples
- Over 30 days, approx. 36% more mass in biotic sample
- Biomass and carbonate precipitates account for 45% of final sample mass

Now onto the results (yes!)

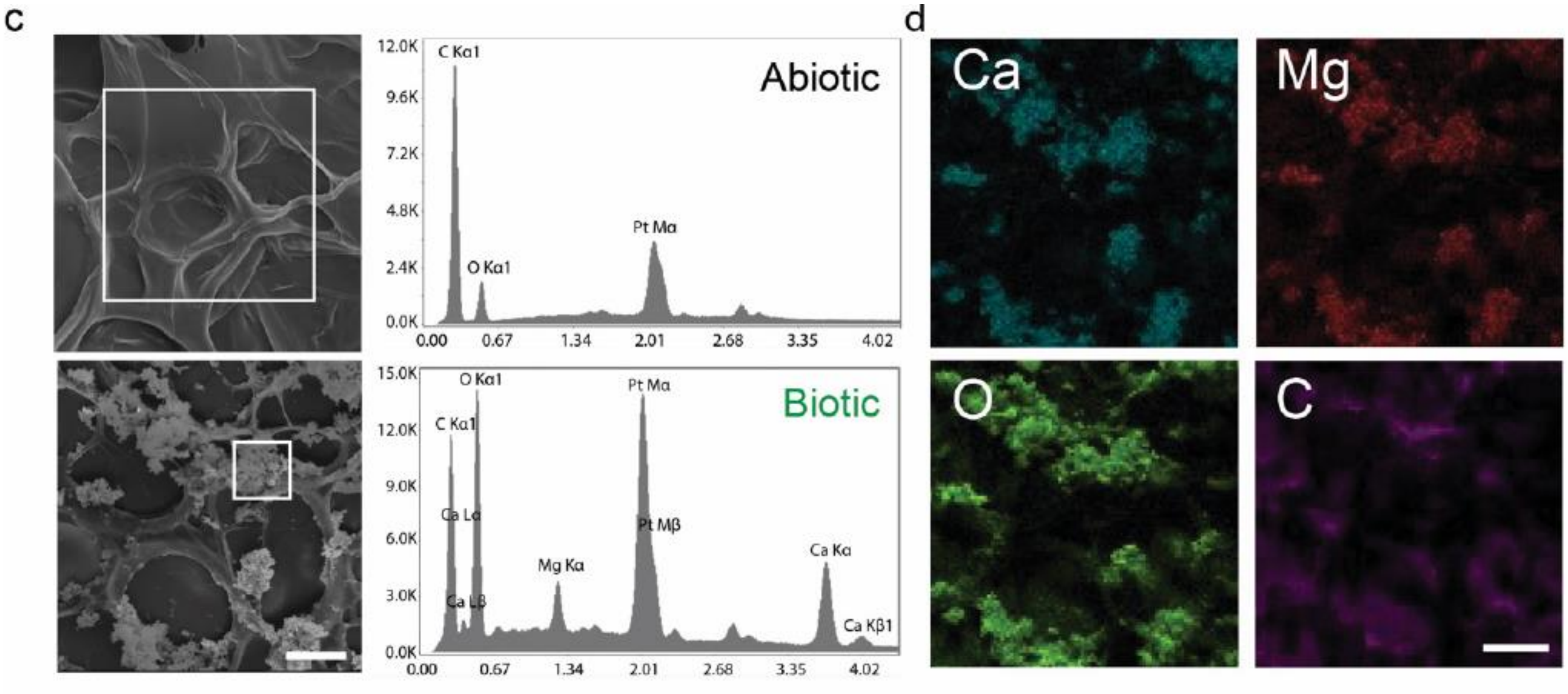
- How much is carbonate precipitates vs. biomass?
- Determined by thermal decomposition
- At 600 °C, whatever is left is the carbonate
- 50 µmol (2.2 ± 0.9 mg) of CO_2 sequestered via MICP per gram of hydrogel – 1 order of magnitude higher than what was achieved by biomass growth!

Now onto the results (yes!)



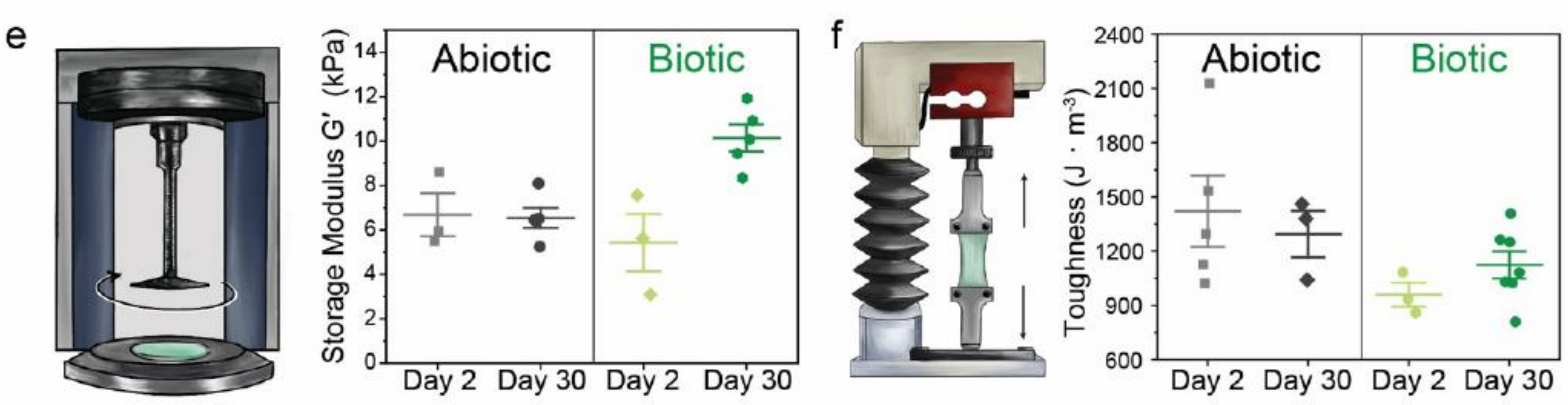
- XRD confirms a crystalline calcite phase (done after thermal degradation)

Now onto the results (yes!)



- 20 µm scale bars
- EDS (energy dispersive spectroscopy) confirms “pericellular” carbonate formation

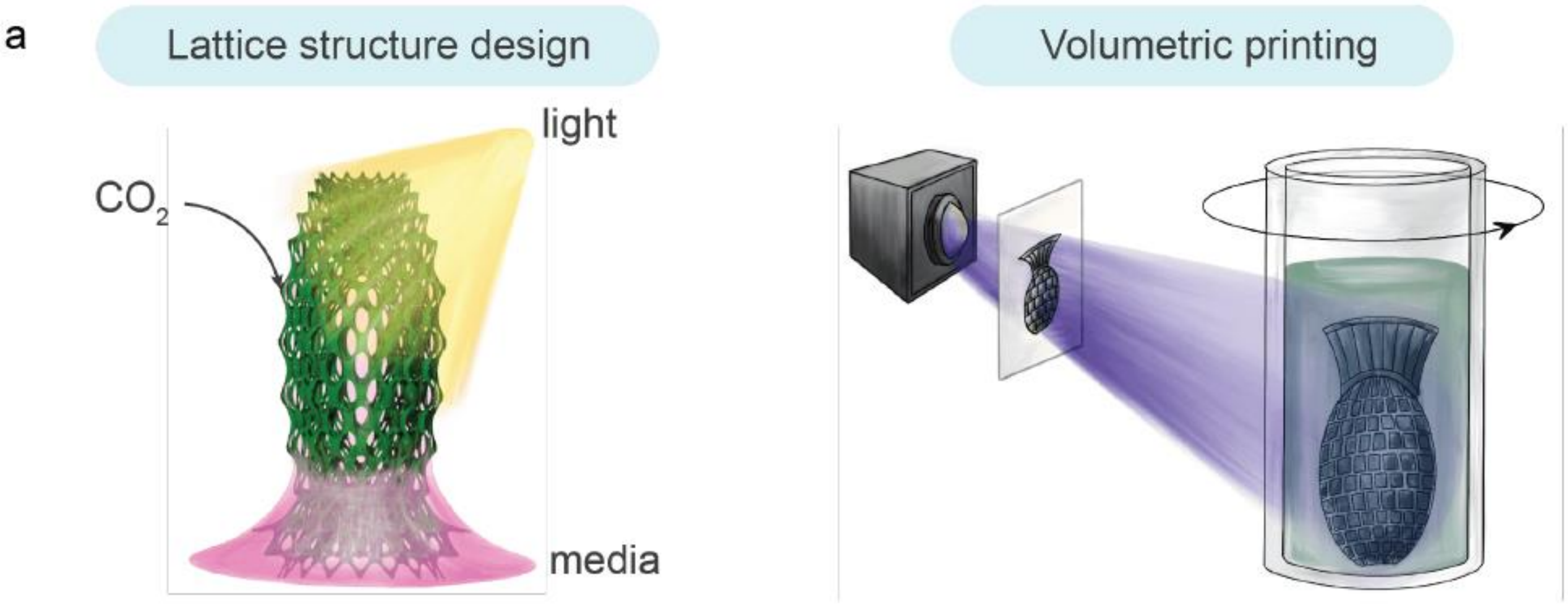
Now onto the results (yes!)



- G' slightly lower on day 2 for biotic
- At day 30, see increase of G' for biotic, no change for abiotic
- Similar for toughness, day 30 biotic is tougher than day 2
- Attributed to reinforcing precipitates

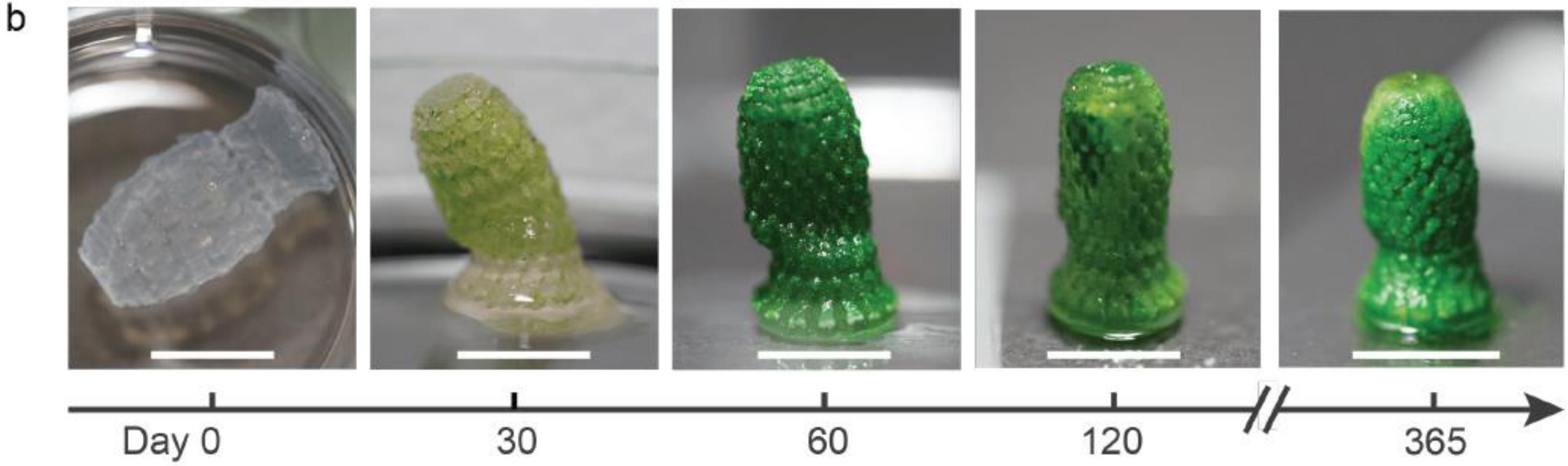
Now onto the results (a schematic?)

https://www.youtube.com/watch?v=31xHZvUP1Ls



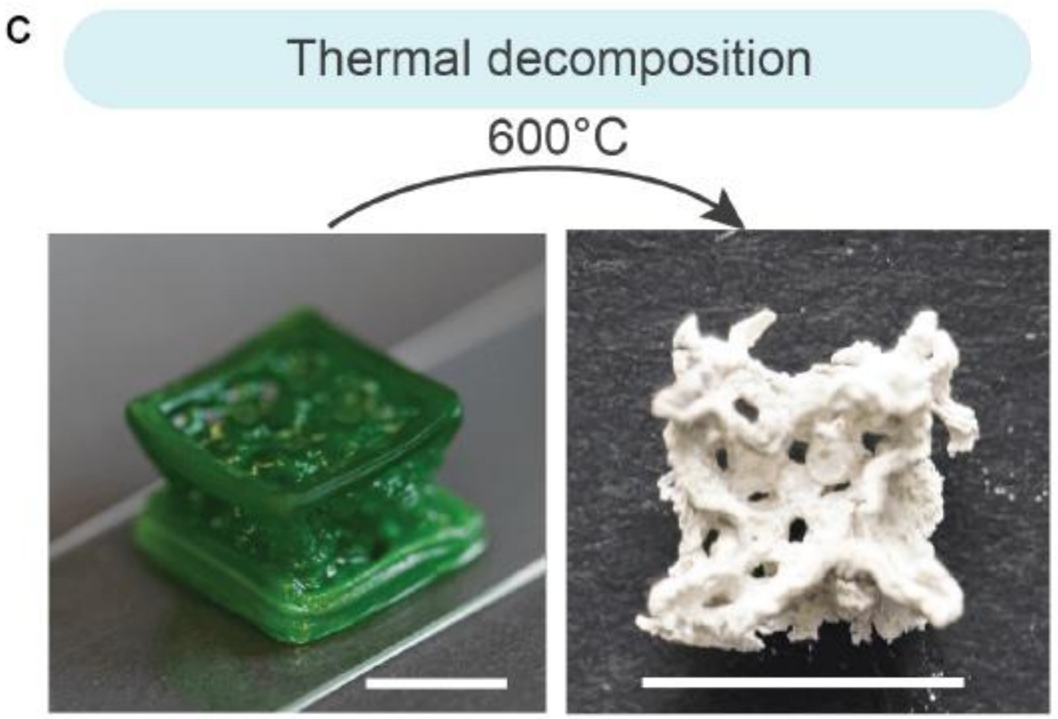
- Design to improve CO_2 sequestration and long-term viability
- Lattice structures with strut sizes between 0.15 mm and 0.70 mm to facilitate gas and nutrient transport
- Inspired by cellular fluidics, growth media passively transported by capillary action, full immersion not needed
- Volumetric printing for 1 step printing of object (not layer by layer)

Now onto the results (yes!)



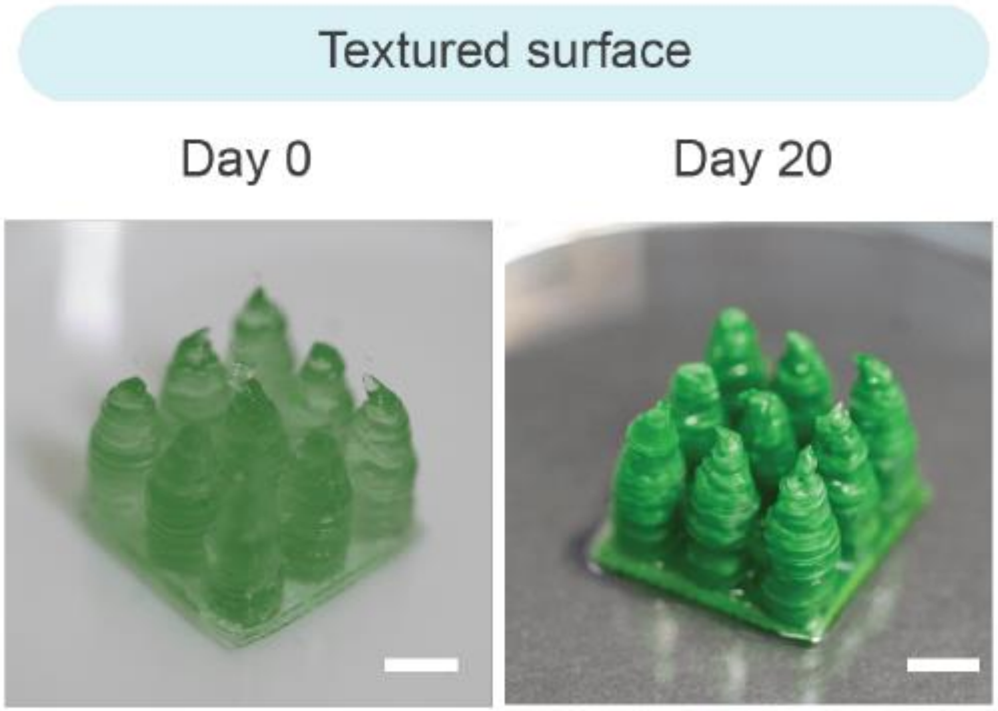
- Scale bar = 1 cm
- Volumetric printing for cm-scaled objects with complex geometries and an optical resolution of 28 x 28 μm within tens of seconds
- Viable for 1 year
- After 30 days, could stand upright and liquid actively drawn up
- Further stiffening with time

Now onto the results (yes!)



- Thermally degraded after 60 days
- Remaining carbonates retained shape of porous structure
- Thus, carbon sequestration deemed homogeneous, despite only partial immersion

Now onto the results (yes!)



- 3 by 3 pillar array on a 2 by 2 cm base to “minimize self shielding)
- With this design, increased volume by 150%, without compromising viability
- Highlight synergy between living materials and design of living structures to increase carbon sequestration efficiency

Discussion

Writing a "good" discussion section

This is is usually the hardest section to write. You are trying to bring out the true meaning of your data without being too long. Do not use words to conceal your facts or reasoning. Also do not repeat your results, this is a discussion.

Goals:

- Present principles, relationships and generalizations shown by the results
- Point out exceptions or lack of correlations. Define why you think this is so.
- Show how your results agree or disagree with previously published works
- Discuss the theoretical implications of your work as well as practical applications
- State your conclusions clearly. Summarize your evidence for each conclusion.
- Discuss the significance of the results

Discussion (it's 1 page)

Positions their work in the larger context of ELMs and their potential e.g., growth, bioremediation

Recaps their work:

- printable photosynthetic ELMs for carbon sequestration via biomass growth and inorganic carbonate precipitation
- design strategies to enhance sequestration
- After 400 days, total CO_2 sequestered was 26 ± 7 mg per gram of photosynthetic living material (12 times more than after day 30 – *seems almost linear?*)

Discussion (it's 1 page)

Frames their work in a larger context:

- Chemical mineralization, e.g., carbonation of recycled concrete aggregates can sequester 6.7 mg recycled aggregate – claim their method with 26 g/g is competitive; *what about time?*
- However, both chemical and biological (this study) sequestration are less efficient than CCS, but CCS requires a concentrated CO_2 source and controlled conditions of T and P – their system works under ambient conditions
- *Back to MSE 341…*

Discussion (it's 1 page)

What could be better?

- Needs improved "usability" and upscaling
- Gives ideas to how this can be done – using larger scale porous or granular scaffolds
- Further optimizing light harvesting
- Make it better by genetic modification or microorganism consortia

Discussion (it's 1 page)

Where do we see this technology one day?

- As surface coatings for green building materials or bioreactors in sequestration plants – bio remediating CO_2 emissions and supporting carbon negative or carbon neutral infrastructure

- Simple requirements and easy maintenance enable installation in various environments for long-term sequestration

Conclusion (UCI has no template for this – now onto nature.com)

Papers that report experimental work are often structured chronologically in five sections: first, *Introduction*; then *Materials and Methods*, *Results*, and *Discussion* (together, these three sections make up the paper's body); and finally, *Conclusion*.

- The *Introduction* section clarifies the motivation for the work presented and prepares readers for the structure of the paper.
- The *Materials and Methods* section provides sufficient detail for other scientists to reproduce the experiments presented in the paper. In some journals, this information is placed in an appendix, because it is not what most readers want to know first.
- The *Results* and *Discussion* sections present and discuss the research results, respectively. They are often usefully combined into one section, however, because readers can seldom make sense of results alone without accompanying interpretation — they need to be told what the results mean.
- The *Conclusion* section presents the outcome of the work by interpreting the findings at a higher level of abstraction than the *Discussion* and by relating these findings to the motivation stated in the *Introduction*.

- Way more concise!
- There are no fixed rules
- But their needs to be a supported logic and story throughout

Conclusions

- New cyanobacteria-laden photosynthetic living material for dual carbon sequestration
- Performed this sequestering over a long lifetime > 400 days with light and atmospheric carbon as its energy and carbon source
- Base formulation enabled DIW and light-based additive manufacturing, enabling structure design for photosynthetic efficiency
- Something about "*spatiotemporal control provided by 3D printing allows scale up for potential applications in disparate fields, such as civil engineering and architecture*"…OK

EPFL

I skipped the methods

Often at the end of papers, not always read, but SO CRITICALLY important. If you are writing a paper, now is the time to include all details and not restrict yourself!

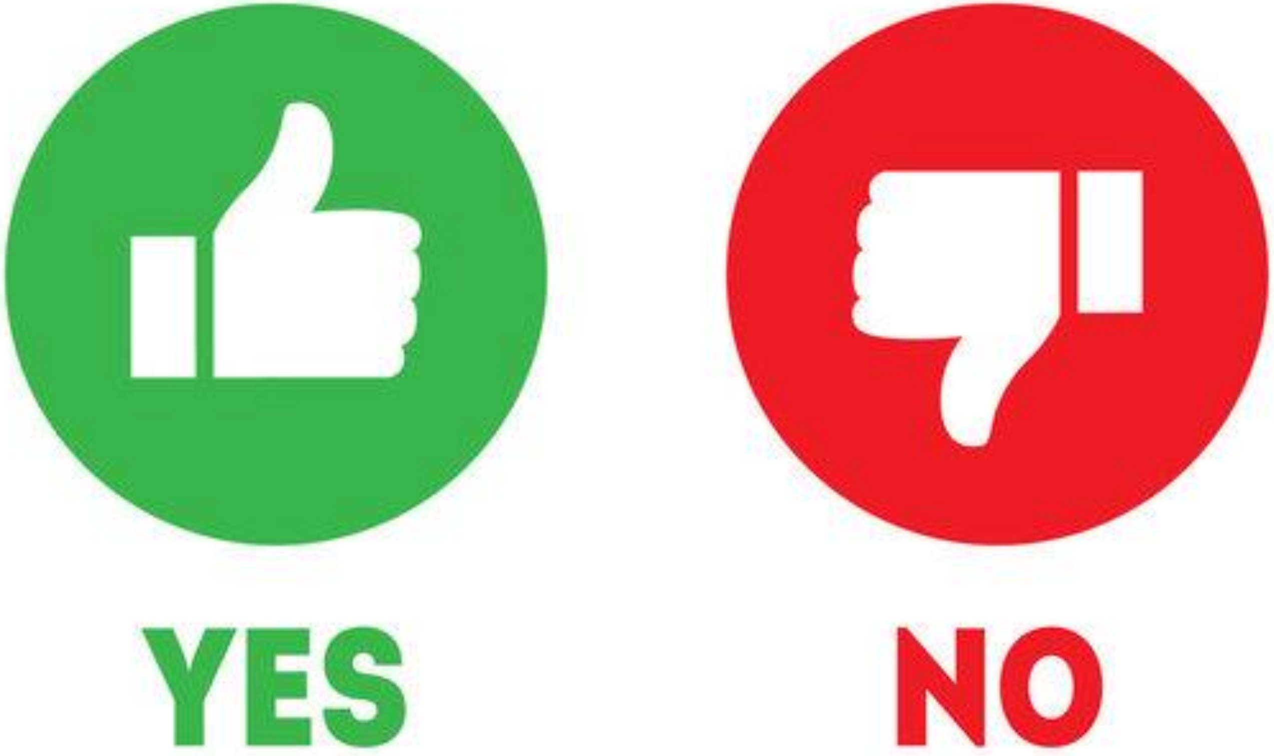
Writing a "good" methods section

The purpose is to provide enough detail that a competent worker could repeat the experiment. Many of your readers will skip this section because they already know from the Introduction the general methods you used. However careful writing of this section is important because for your results to be of scientific merit they must be reproducible. Otherwise your paper does not represent good science.

Goals:

- Exact technical specifications and quantities and source or method of preparation
- Describe equipment used and provide illustrations where relevant.
- Chronological presentation (but related methods described together)
- Questions about "how" and "how much" are answered for the reader and not left for them to puzzle over
- Discuss statistical methods only if unusual or advanced
- When a large number of components are used prepare tables for the benefit of the reader
- Do not state the action without stating the agent of the action

Did you like this paper? Why or why not?



Takeaways

- An even better idea of ELMs
- Using ELMs to help solve an important problem
- A general understanding of cyanobacteria, its role in oxygenating the atmosphere, and its potential role in decarbonizing the atmosphere
- Stopping emissive activities is critical, capturing CO_2 when emissive activities occur is critical, actively lowering CO_2 in atmosphere is also important
- Not one answer, most likely (and hopefully soon or now), different technologies will be implemented at scale
- We are now sooo experts on MICP and cyanobacteria… well, at least we know the words…