Civil and
Environmental
Engineering

Technological Advances in Food Security and Food Safety

Benedetto Marelli

Sustainability Masterclass

How do
we feed
(sustainably
and safely)
10 billion people?

Population, urbanization and food

We will add 2 billion people by 2050

In 2021, > 1 billion people suffered from food insecurity

In 2020, ¼ of households experienced food insecurity in the US.   circa 10% food cost increase in 2022

37% of all anthropogenic gas emissions come from food production

>30% of food is wasted, 3rd larger GHG producer after China and US – 25% of freshwater loss

48 M/year people get sick, and 3,000 people die from a foodborne illness every year in the US

Food safety incidents cost $7B/year in the US

UN 2019 Special Report on Climate Change and Land
US EPA 2017 Sources of Greenhouse Gas Emissions
FAO 2017 Water for Sustainable Food and Agriculture
MIT Program on Global Change – Report N. 254
UN FAO 2015 Status of the World's Soil Resources

Biomaterials-based Innovation for Food Security

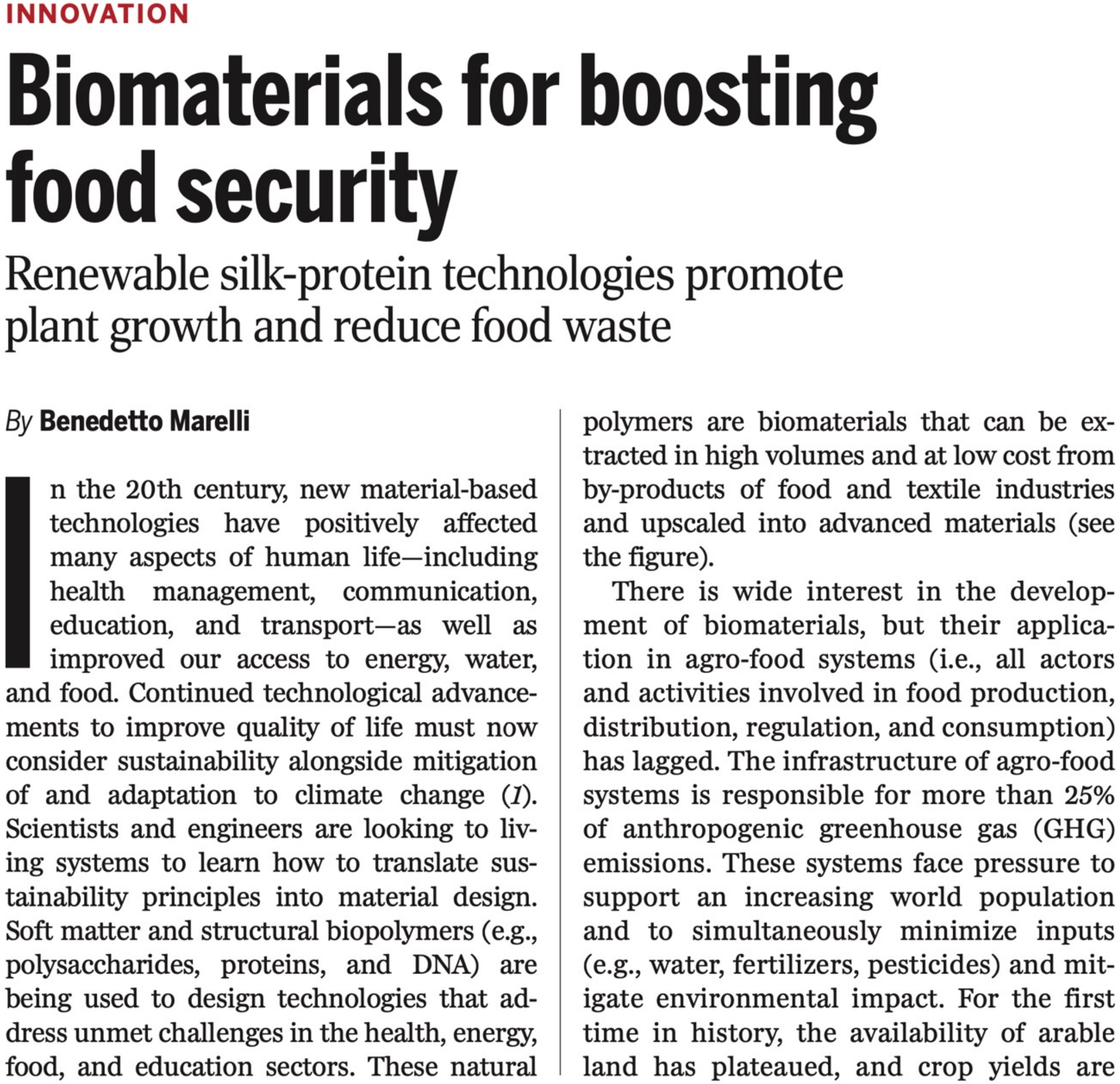
PRIZE ESSAY

GRAND PRIZE WINNER

Benedetto Marelli

Benedetto Marelli received undergraduate degrees from Politecnico di Milano and a PhD from McGill University. After completing his postdoctoral fellowship at Tufts University, he started his laboratory in the Department of Civil and Environmental Engineering at the Massachusetts Institute of Technology in late 2015. His research focuses on nanomanufacturing of structural biopolymers to engineer a new generation of advanced materials that can be interfaced with food and plants. **www.science.org/doi/10.1126/science.abo4233**

BII | Prize for
Science | Innovation



INNOVATION

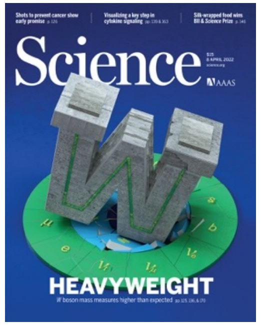
Biomaterials for boosting food security

Renewable silk-protein technologies promote plant growth and reduce food waste

By **Benedetto Marelli**

In the 20th century, new material-based technologies have positively affected many aspects of human life—including health management, communication, education, and transport—as well as improved our access to energy, water, and food. Continued technological advancements to improve quality of life must now consider sustainability alongside mitigation of and adaptation to climate change (*1*). Scientists and engineers are looking to living systems to learn how to translate sustainability principles into material design. Soft matter and structural biopolymers (e.g., polysaccharides, proteins, and DNA) are being used to design technologies that address unmet challenges in the health, energy, food, and education sectors. These natural polymers are biomaterials that can be extracted in high volumes and at low cost from by-products of food and textile industries and upscaled into advanced materials (see the figure).

There is wide interest in the development of biomaterials, but their application in agro-food systems (i.e., all actors and activities involved in food production, distribution, regulation, and consumption) has lagged. The infrastructure of agro-food systems is responsible for more than 25% of anthropogenic greenhouse gas (GHG) emissions. These systems face pressure to support an increasing world population and to simultaneously minimize inputs (e.g., water, fertilizers, pesticides) and mitigate environmental impact. For the first time in history, the availability of arable land has plateaued, and crop yields are



Marelli, Science, **376**, 2022

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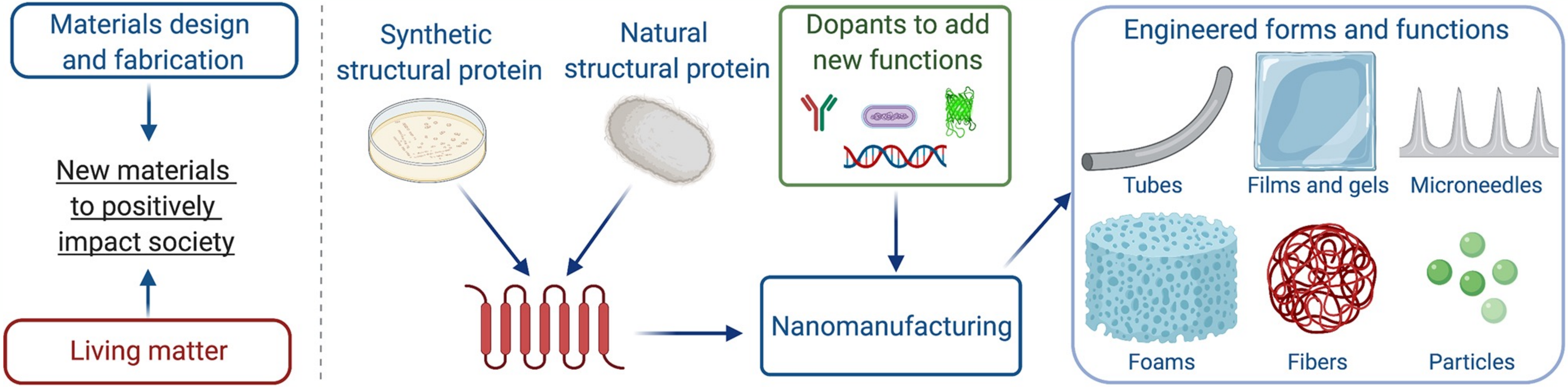
Biomaterials-based Innovation for Food Security



Biomaterials can be designed to be interfaced with food and plants

Merits: edibility, nontoxicity, biodegradation

Requirements: scalable, ease of manufacturing, retrofit existing techniques

Massachusetts Institute of Technology

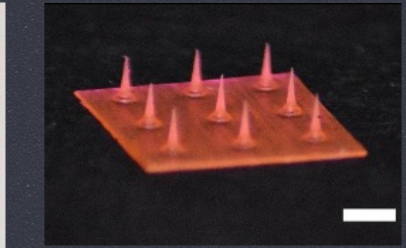
Sun et al. [Marelli], MRS Comm, **11**, 2021 Marelli [Marelli], Science, **376**, 2022 Sun et al. [Marelli], Adv Func Mater, **2201930**, 2022


100
APPROX
80

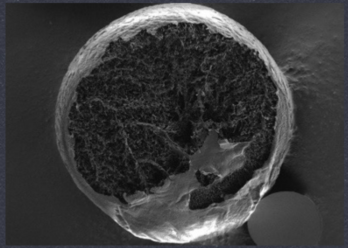
Silk fibroin – form factors

Monoliths

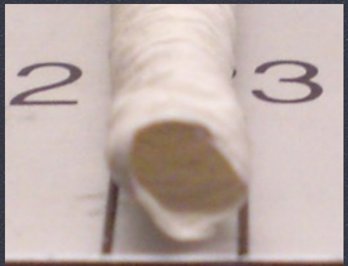
Microneedles



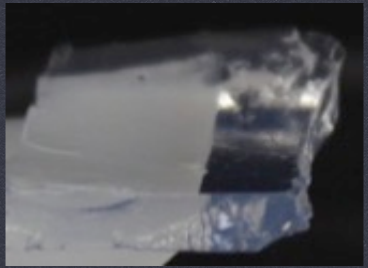
Particles



Tubes



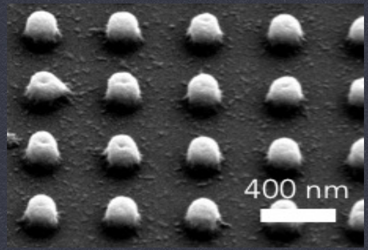
Gels



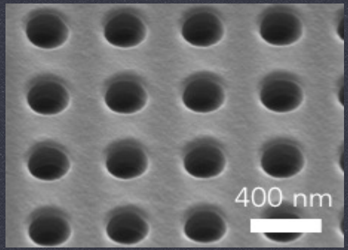
Films

Inkjet prints

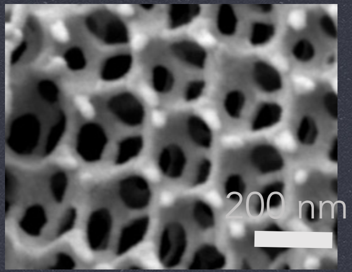
Nanopillars



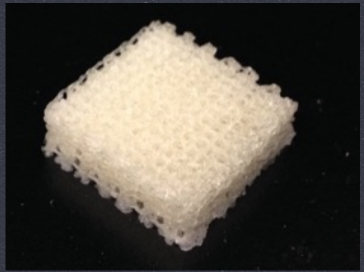
Nanoholes



Photonic crystals



3d prints



Aerogels

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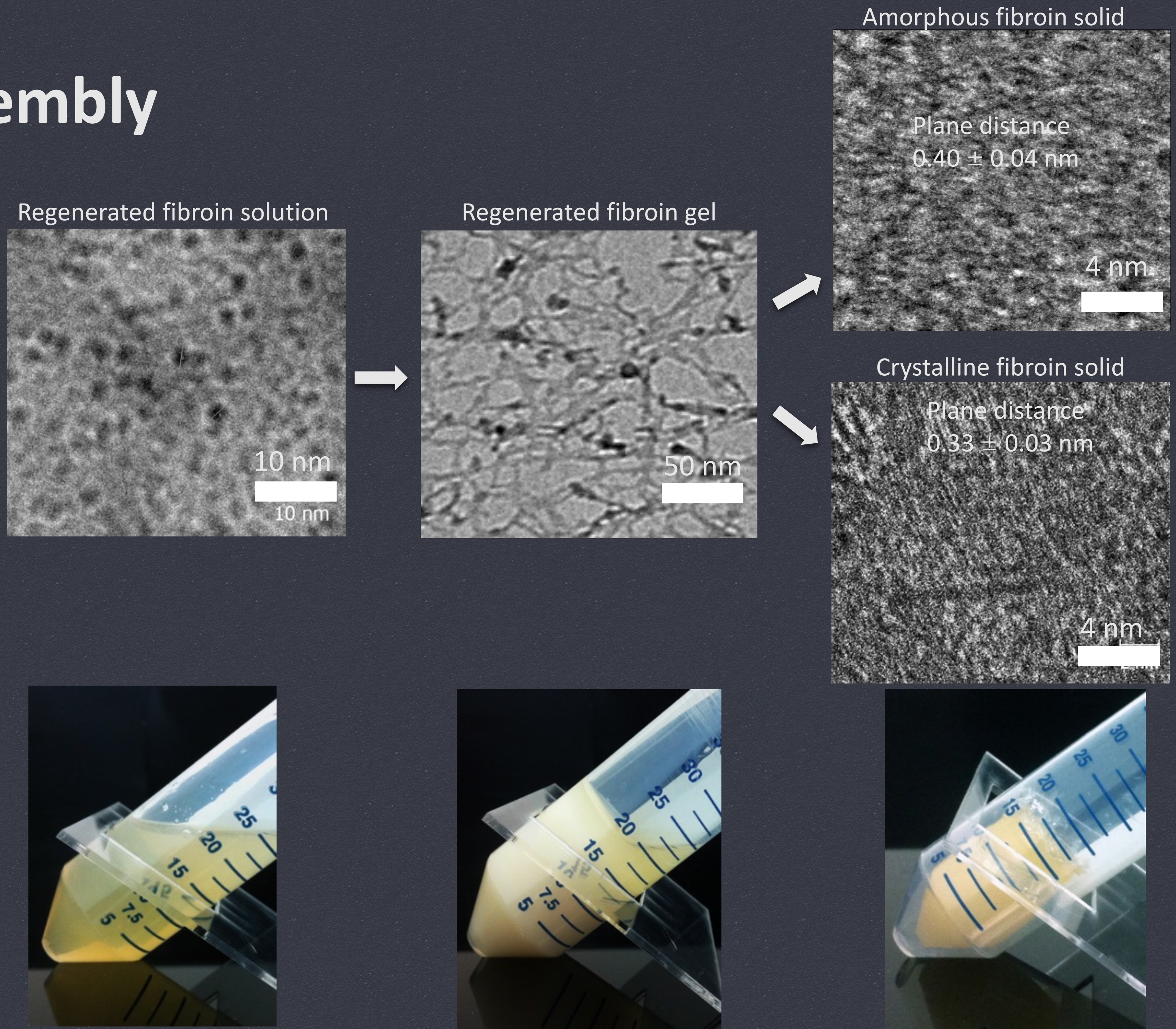
Polymorphic assembly



Regenerated fibroin solution

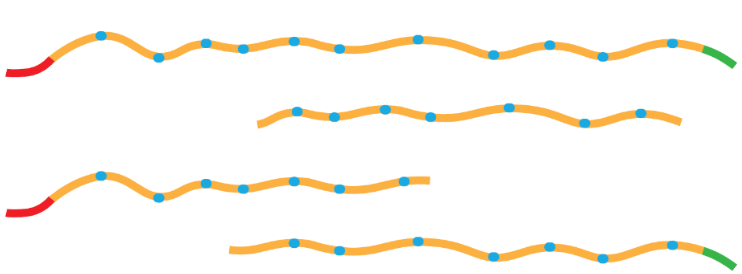
Regenerated fibroin gel

Amorphous fibroin solid

Crystalline fibroin solid

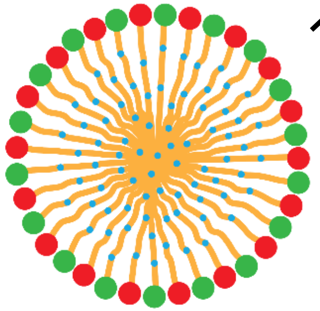
Marelli et al, PNAS, 2017
Sun and Marelli, Nat. Comm., 2019

Driving disorder to order transitions

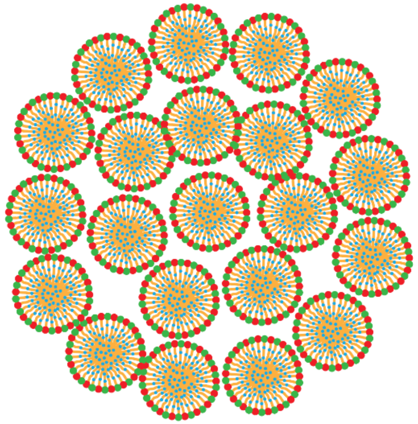


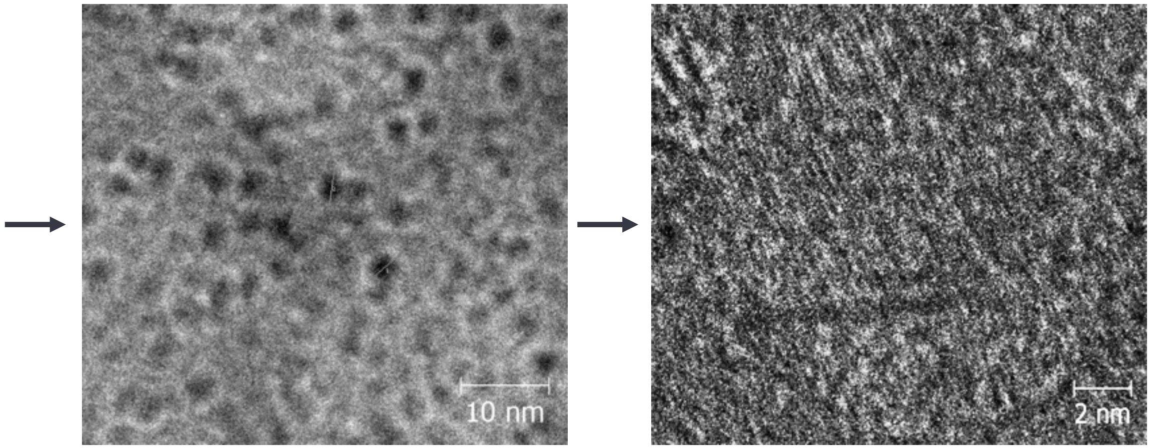
- 🟥 N-terminal
- 🟧 hydrophobic domain (GAGAGS)
- 🟦 hydrophilic domain (nonrepetitive)
- 🟩 C-terminal

Silk fibroin chains



Micelle assembly of silk fibroin in water due to the hydrophilic-hydrophobic multi-block copolymer structure.

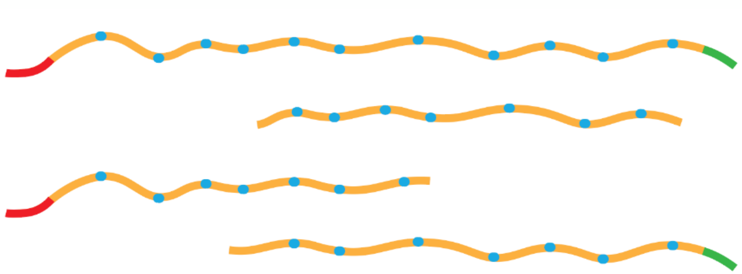




Inputs: water removal, pH, T, P, shear stress, electric field

?

Driving disorder to order transitions



🟥 N-terminal
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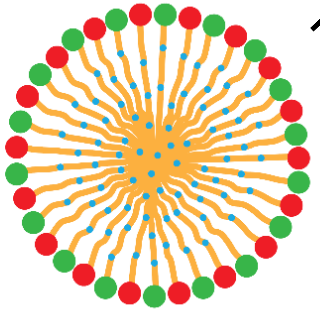
🟦 hydrophilic domain (nonrepetitive)
🟩 C-terminal

Silk fibroin chains



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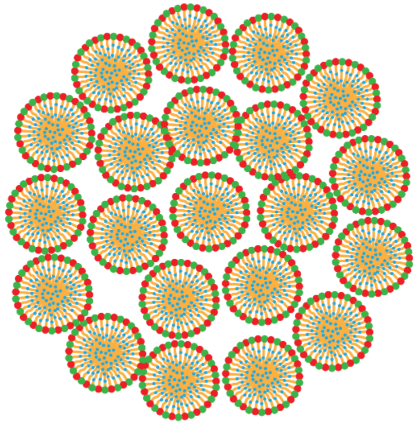
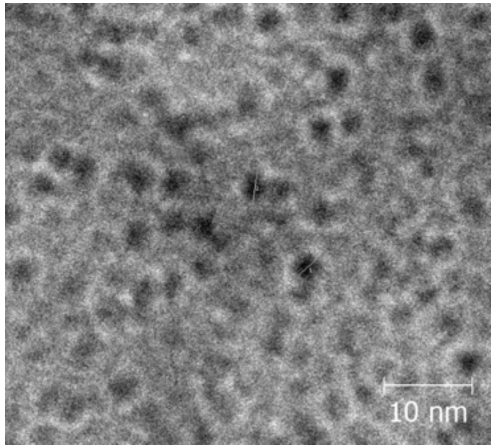
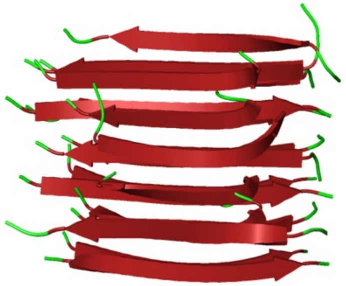


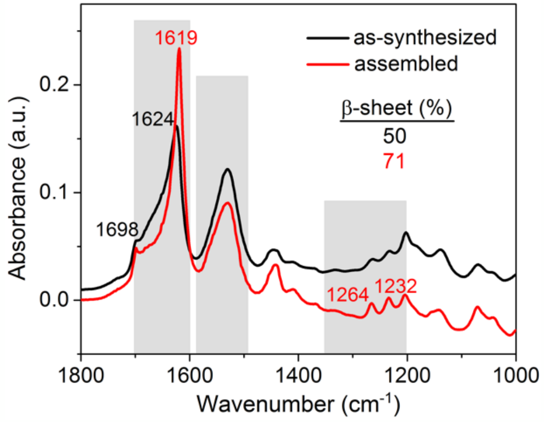


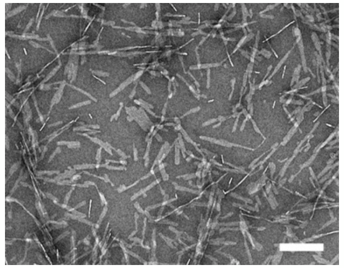
Inputs: water removal, pH, T, P, shear stress, electric field

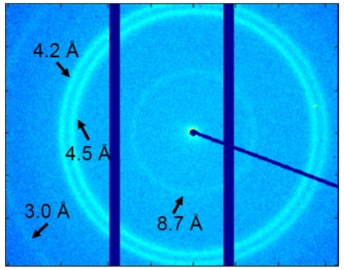
?

Highly-ordered β-sheet nanoparticles



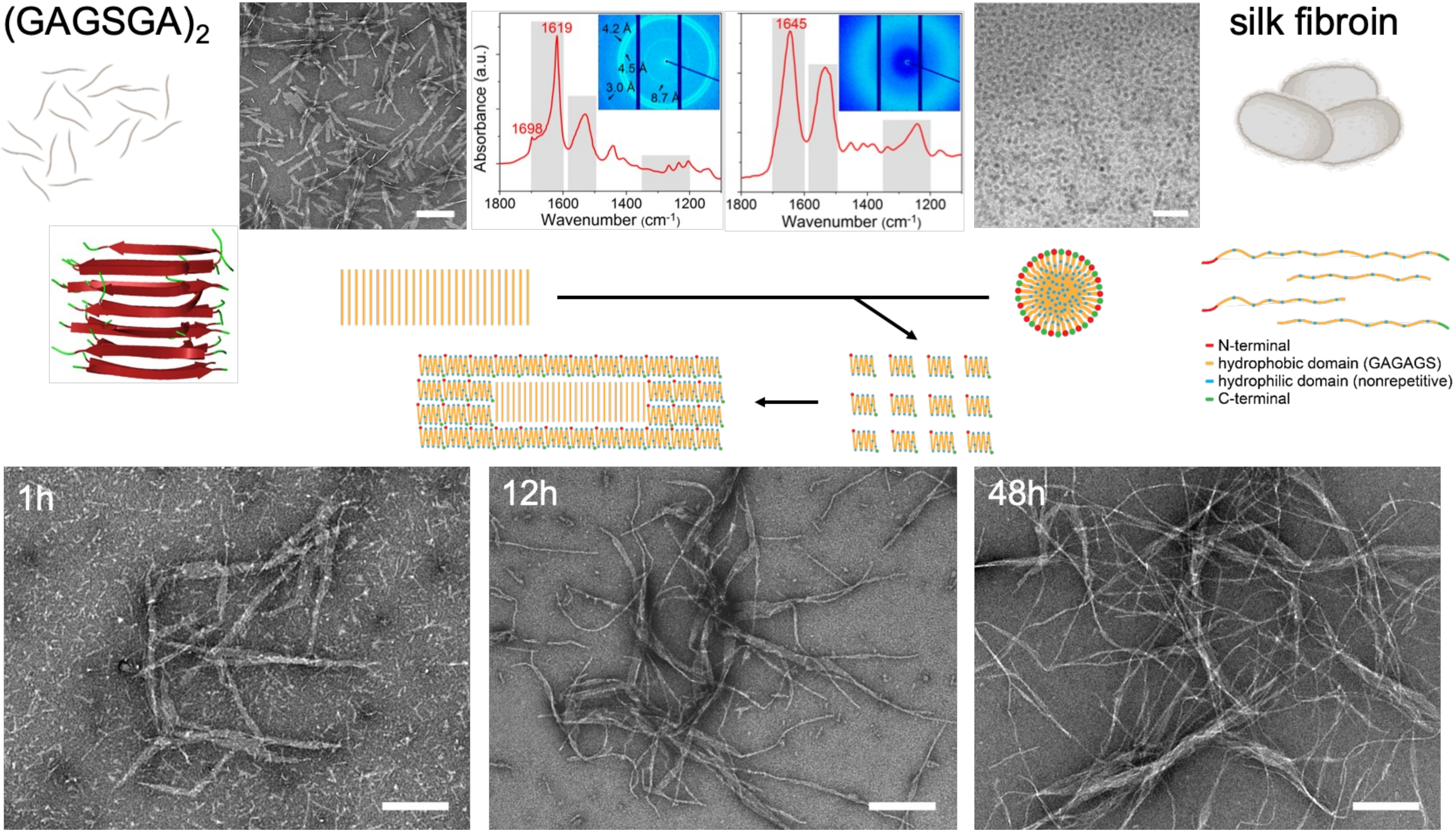






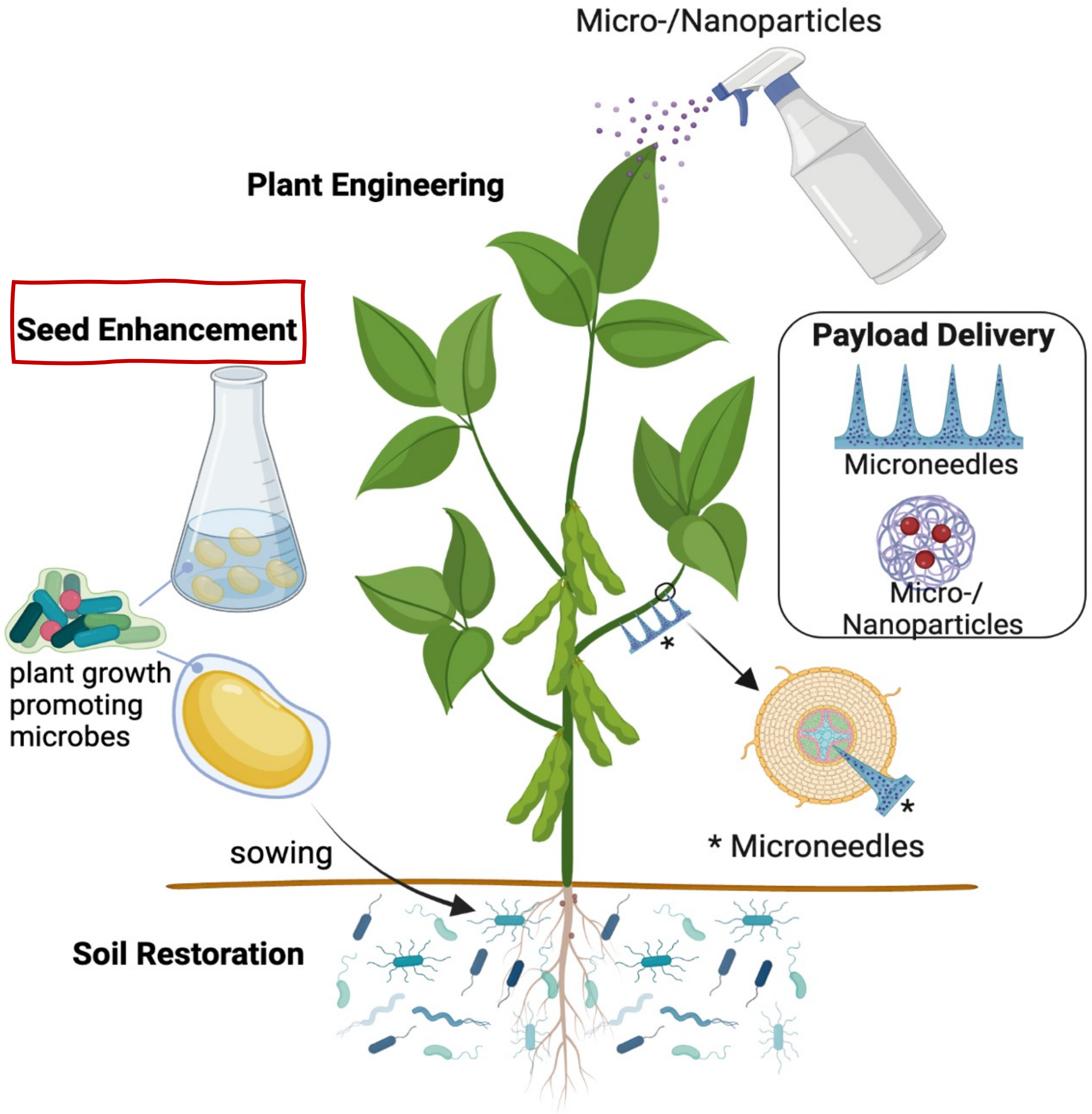
Sun and Marelli, Nat. Comm., 2020

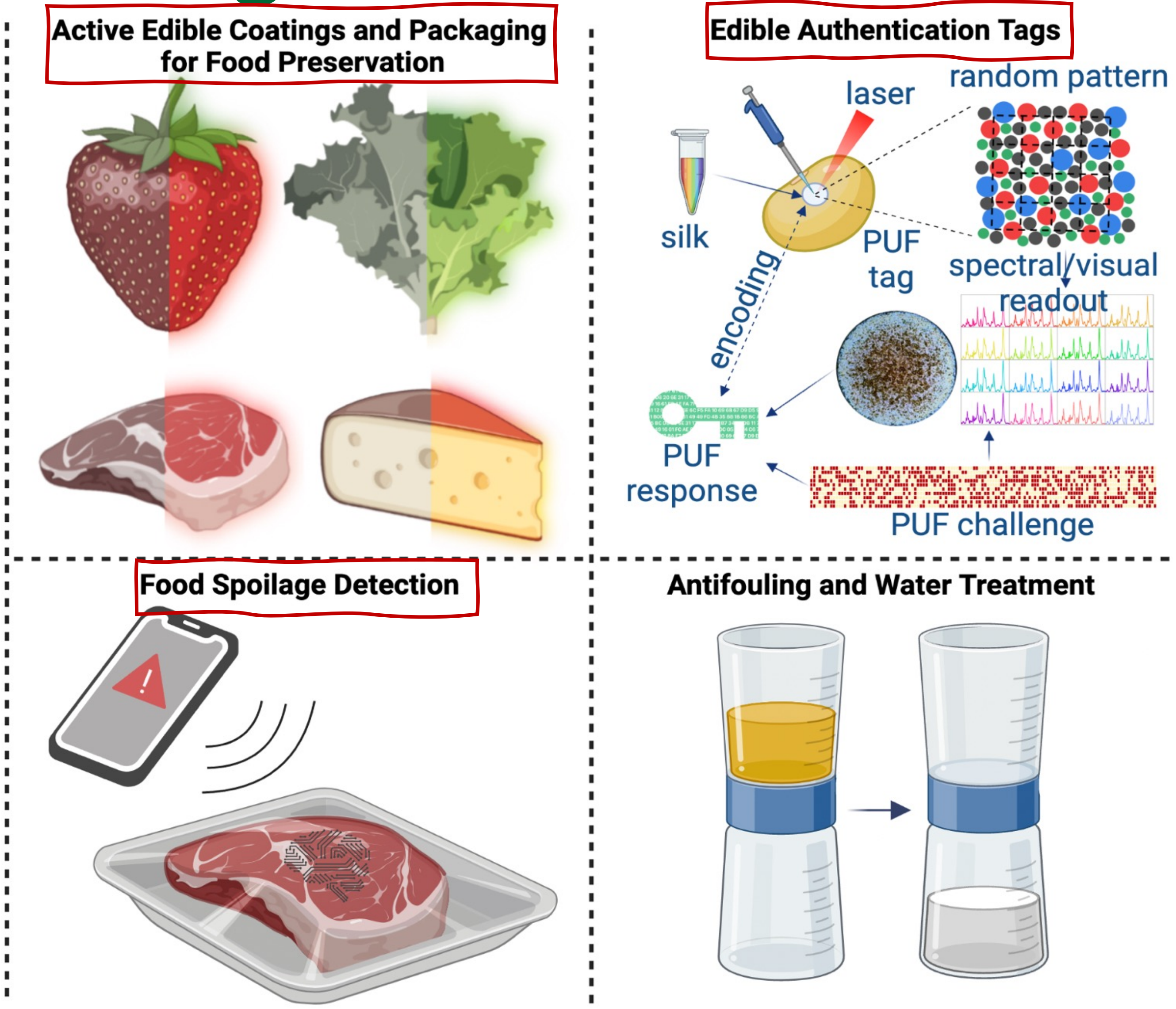
Templated disorder to order transitions



Sun and Marelli, Nat. Comm., 2020

And once we know how to grow silk materials….





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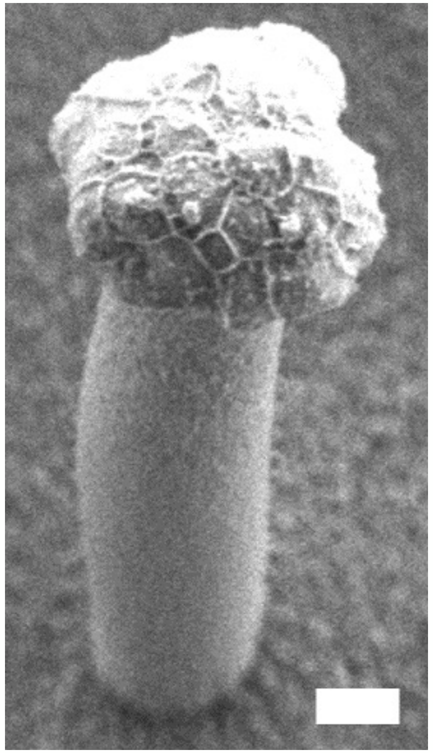
Sun et al. [Marelli], MRS Comm, **11**, 2021

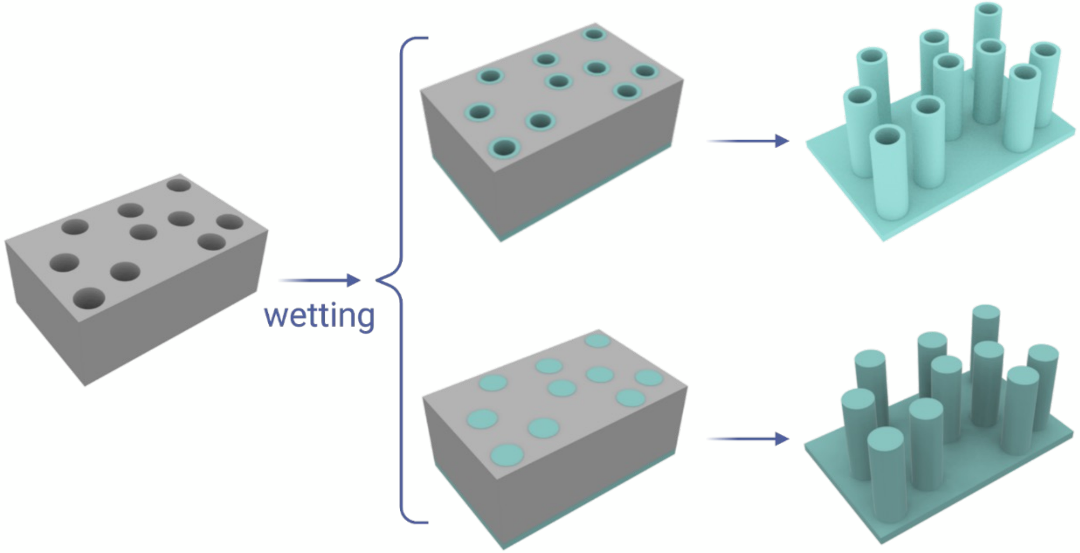
Marelli [Marelli], Science, **376**, 2022

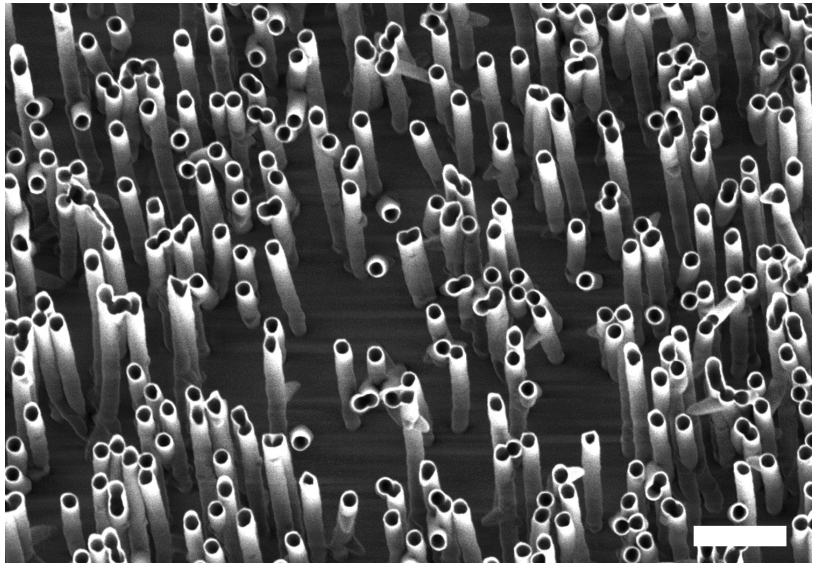
Sun et al. [Marelli], Adv Func Mater, **2201930**, 2022

Large-Scale, Proteinaceous Nanotube Arrays with Programmable Hydrophobicity, Oleophilicity, and Gas Permeability



Sun and Marelli Nano Lett. 2023





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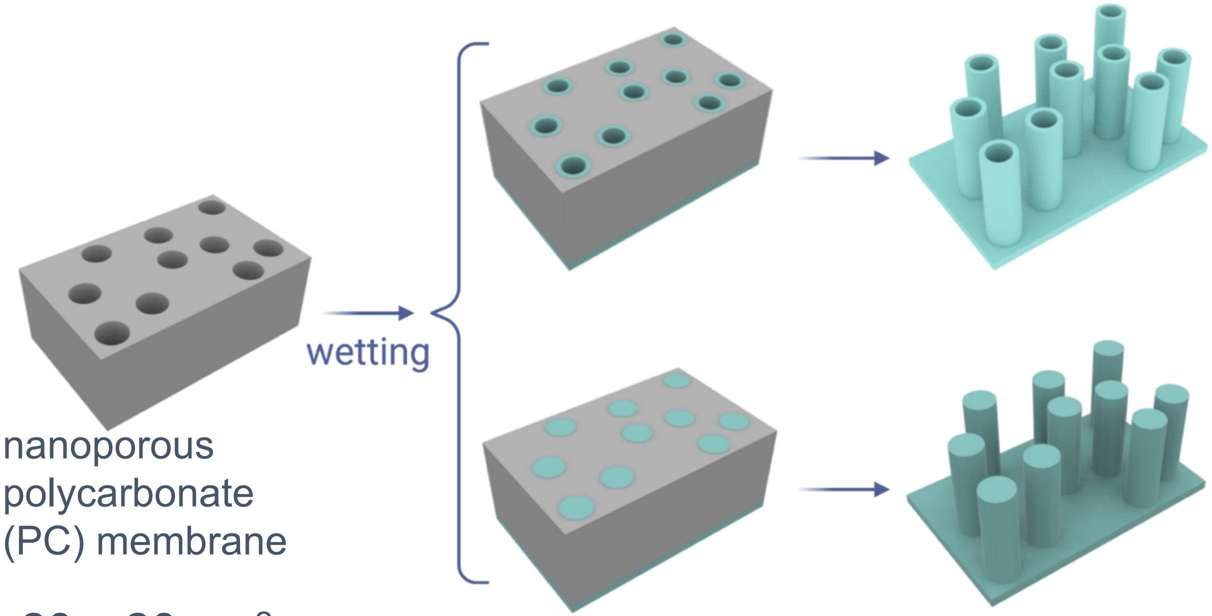
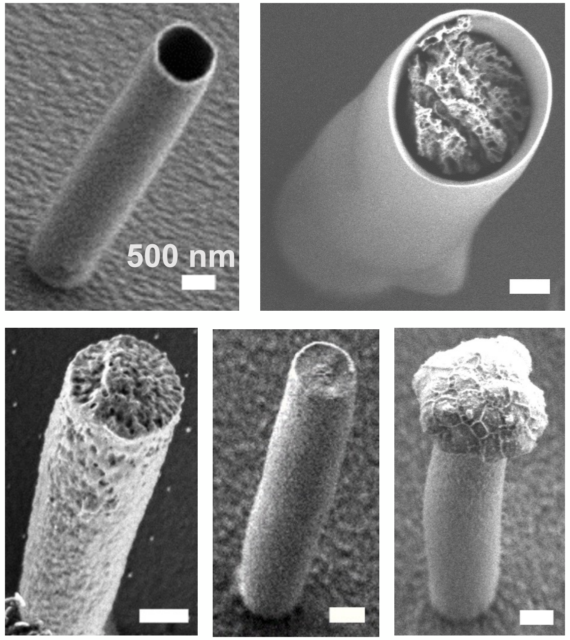
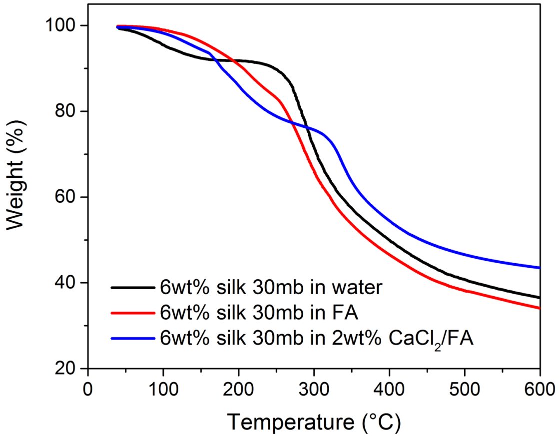
Silk Nanotube/pillar fabrication through nanoconfinement

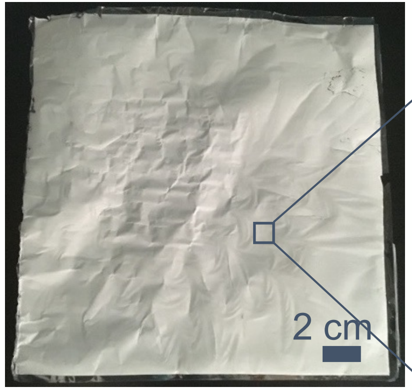


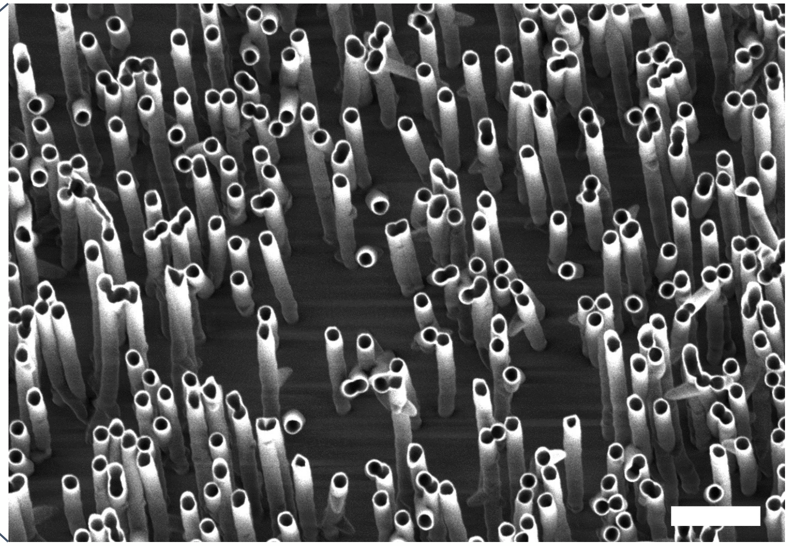
nanoporous polycarbonate (PC) membrane

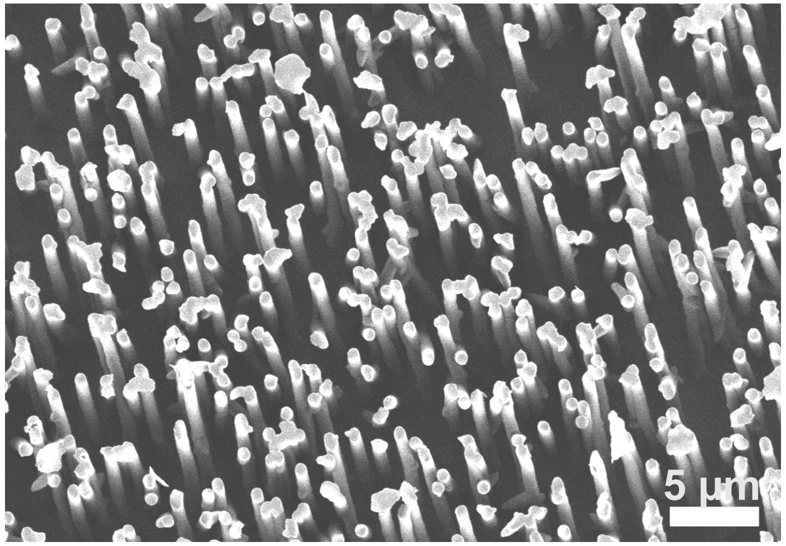




20 x 20 cm^2 array

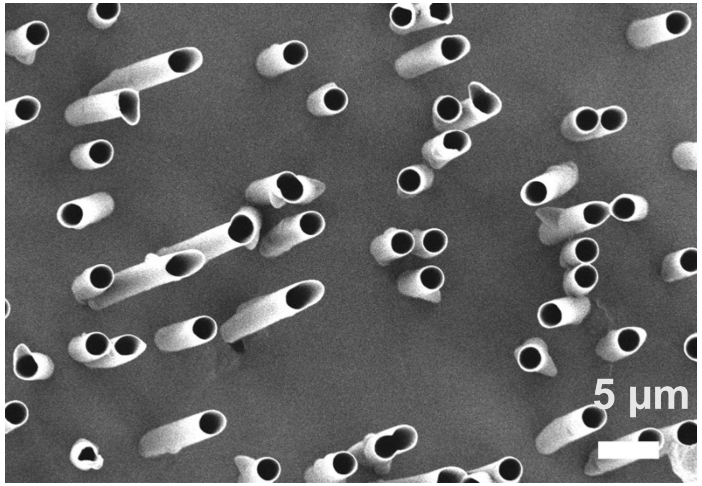




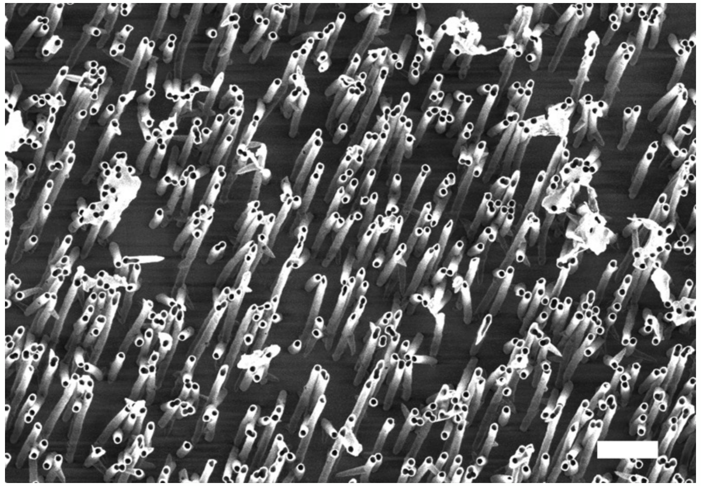


Control over size, density, morphology & silk polymorphs

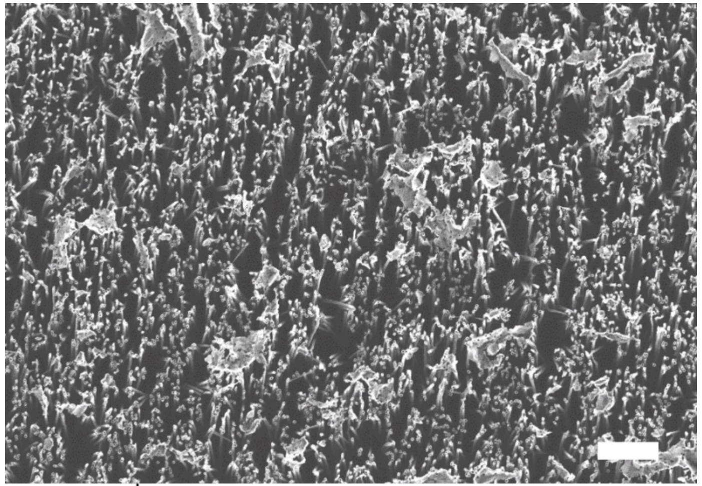
Φ=2 µm, ρ=2x10^6 pores/cm^2



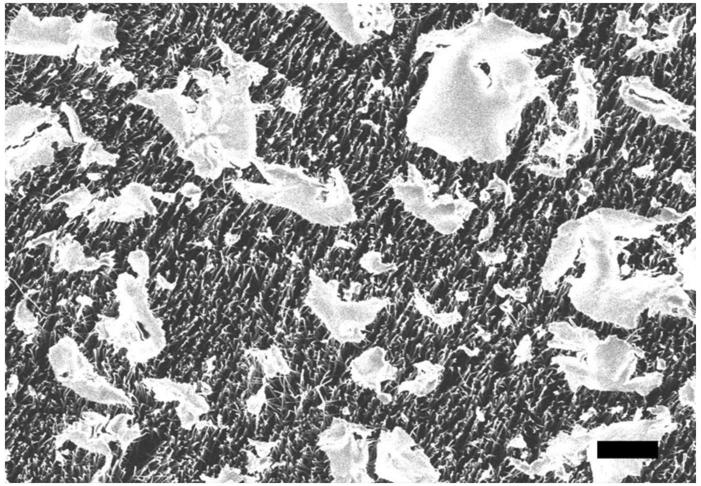
Φ=600 nm, ρ=3x10^7 pores/cm^2



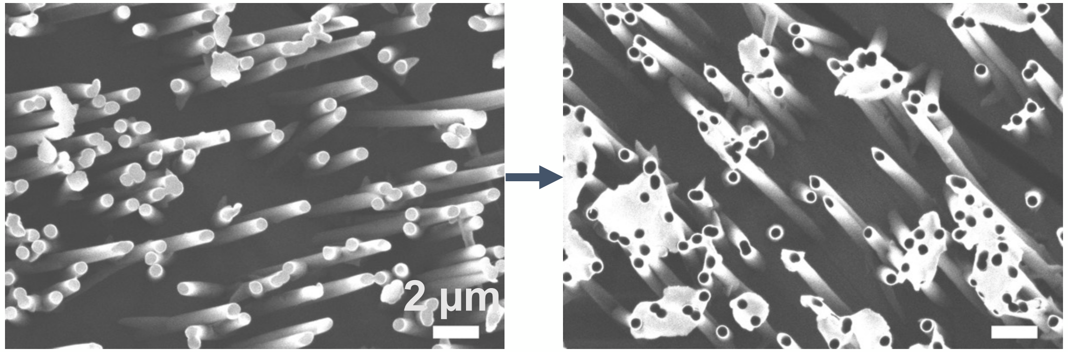
Φ=200 nm, ρ=3x10^8 pores/cm^2



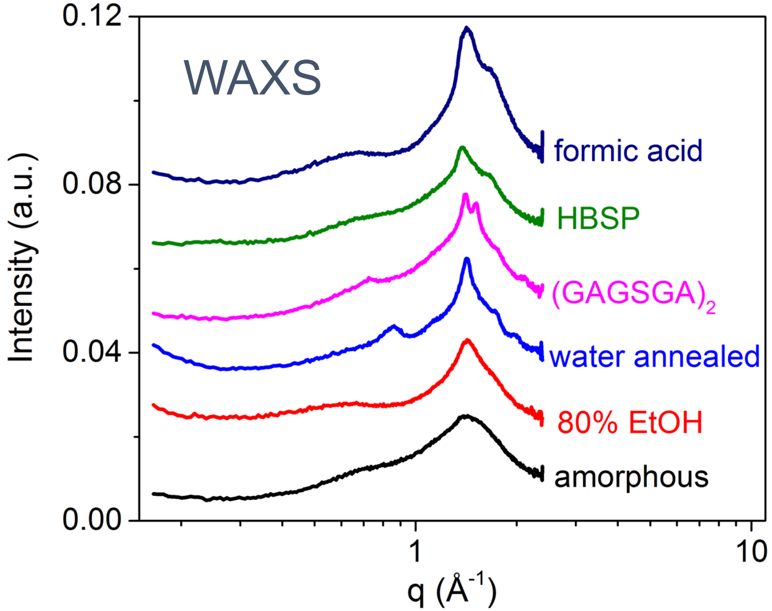
Φ=50 nm, ρ=6x10^8 pores/cm^2



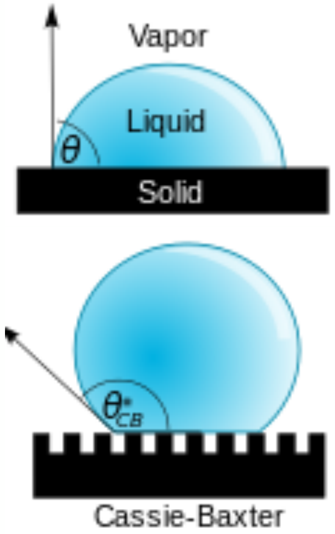
pillar to tube transition by water-annealing

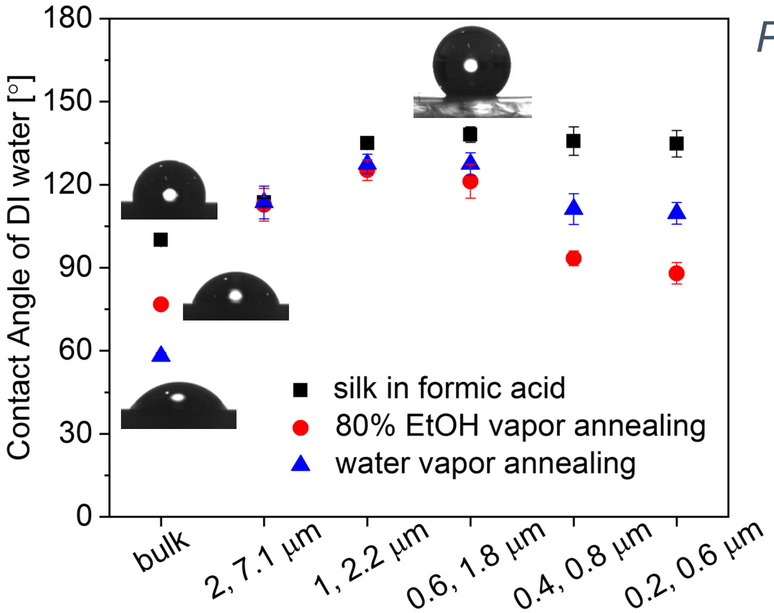


Variation in silk conformation

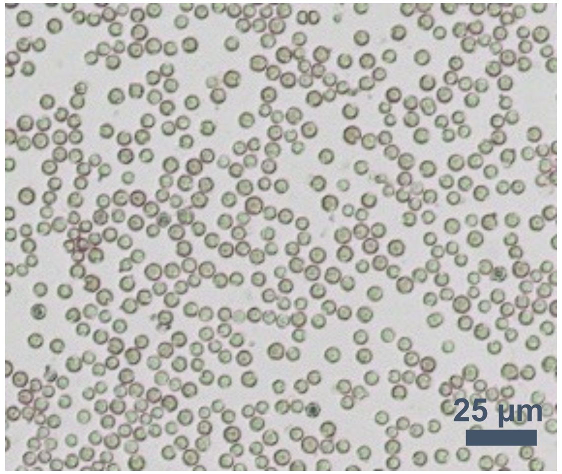


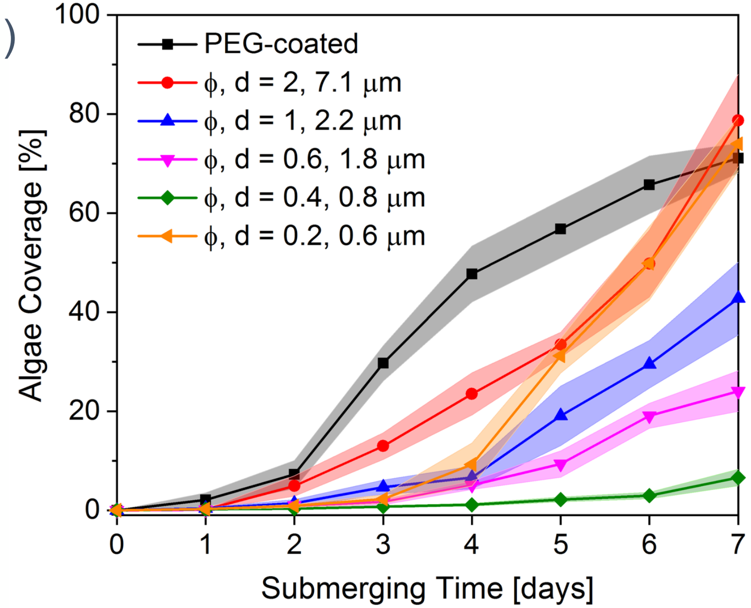
Super-hydrophobicity and Anti-fouling



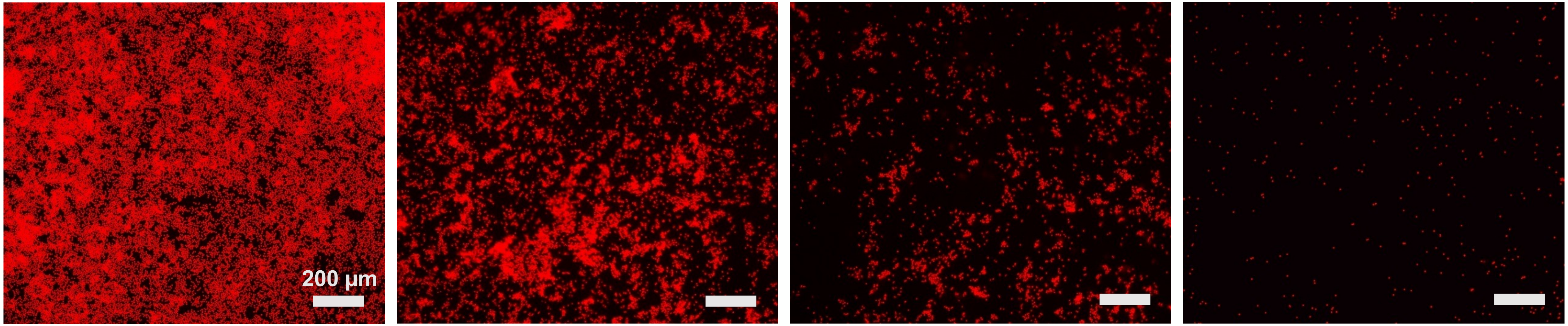


Porphyridium cruentum (~4 μm)





Algae coverage Day 7

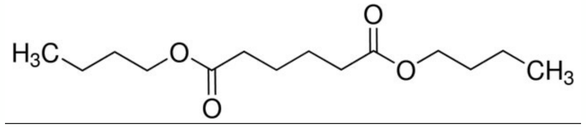

PEG-coated

ϕ, d = 1, 2.2 μm NT

ϕ, d = 0.6, 1.8 μm NT

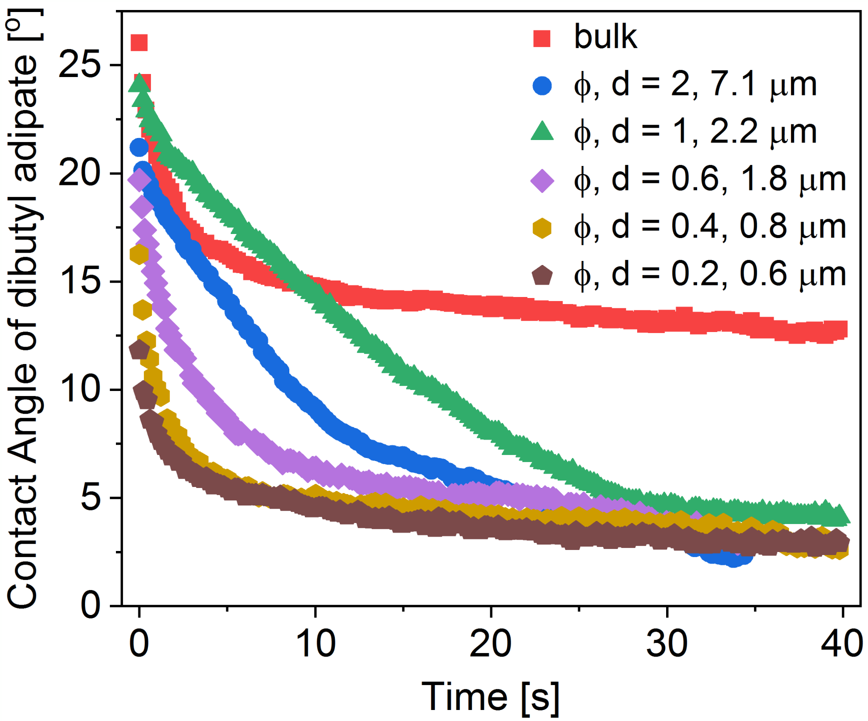
ϕ, d = 0.4, 0.8 μm NT

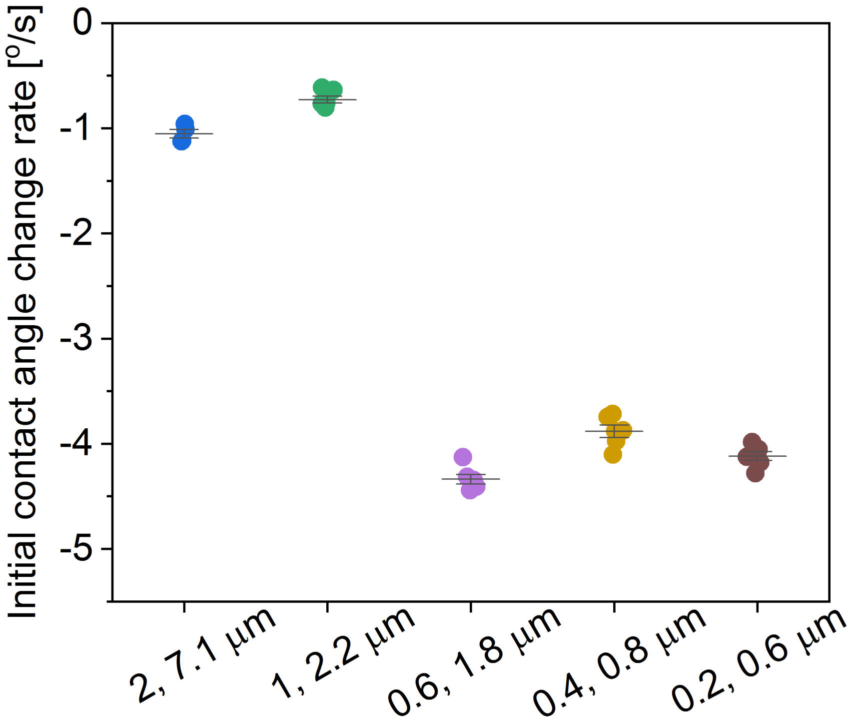
Superoleophilicity



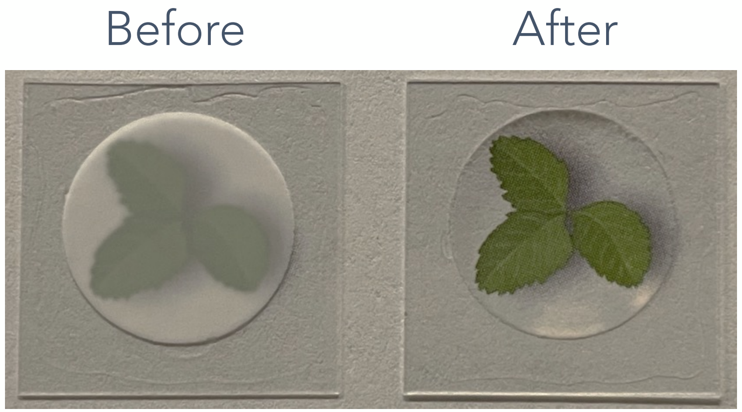
Dibutyl Adipate

Wetting of DA on 1μm NT array

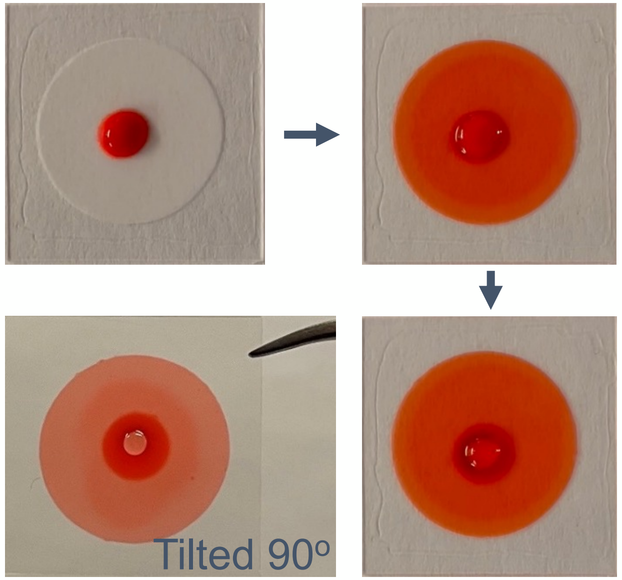


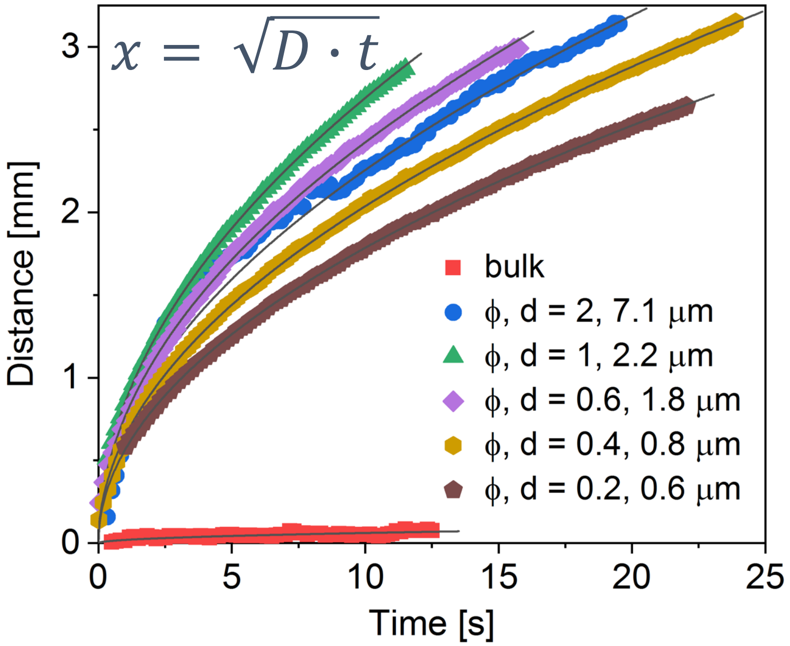


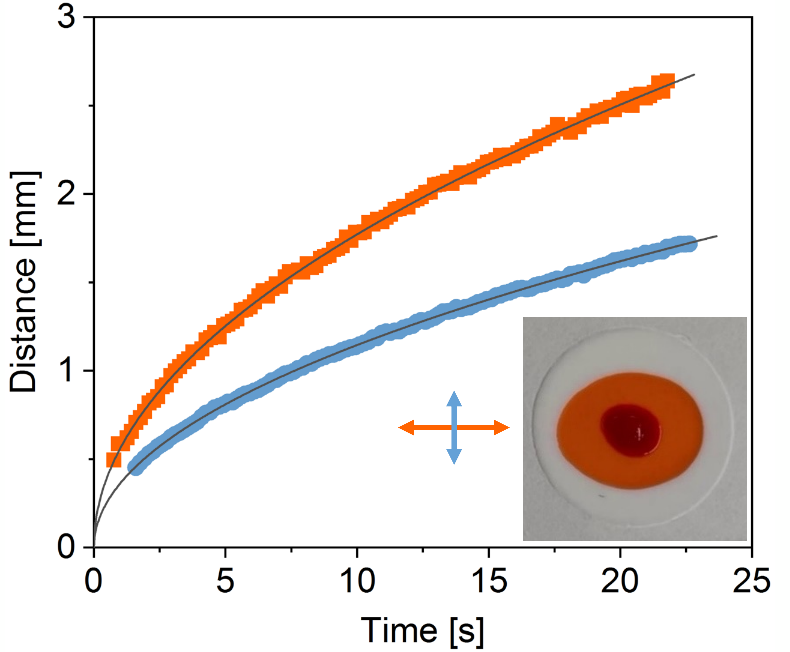
Infiltration by refractive index oil (RI=1.55)

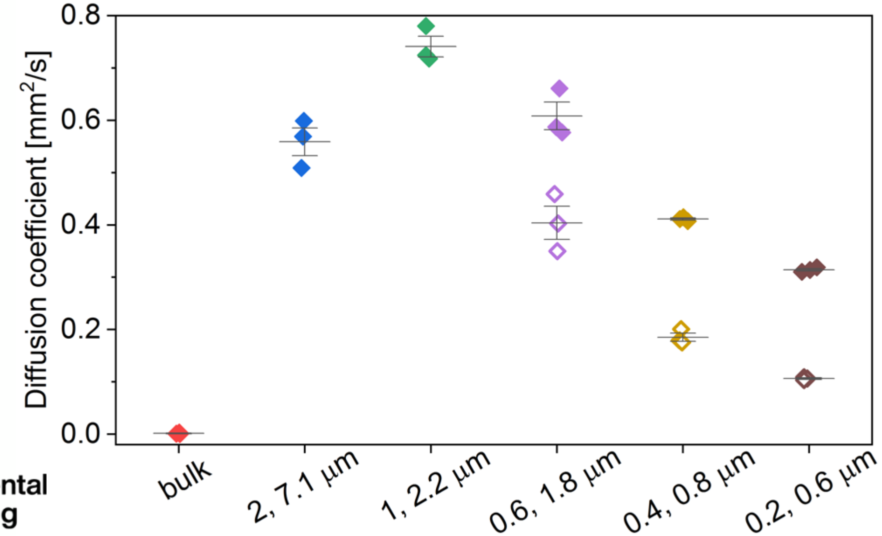


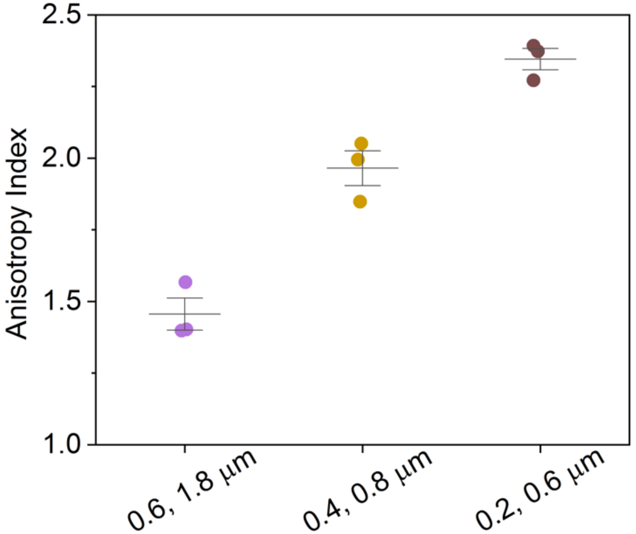
Oil extraction from oil-water emulsions

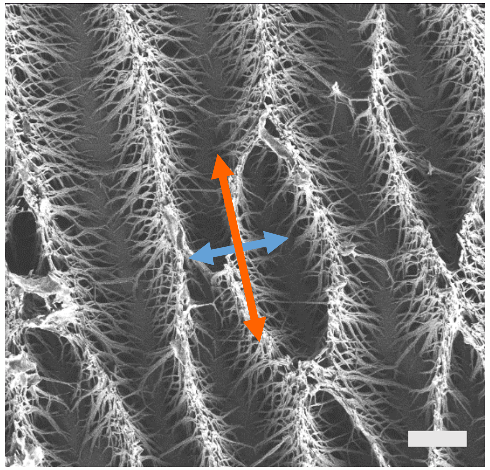




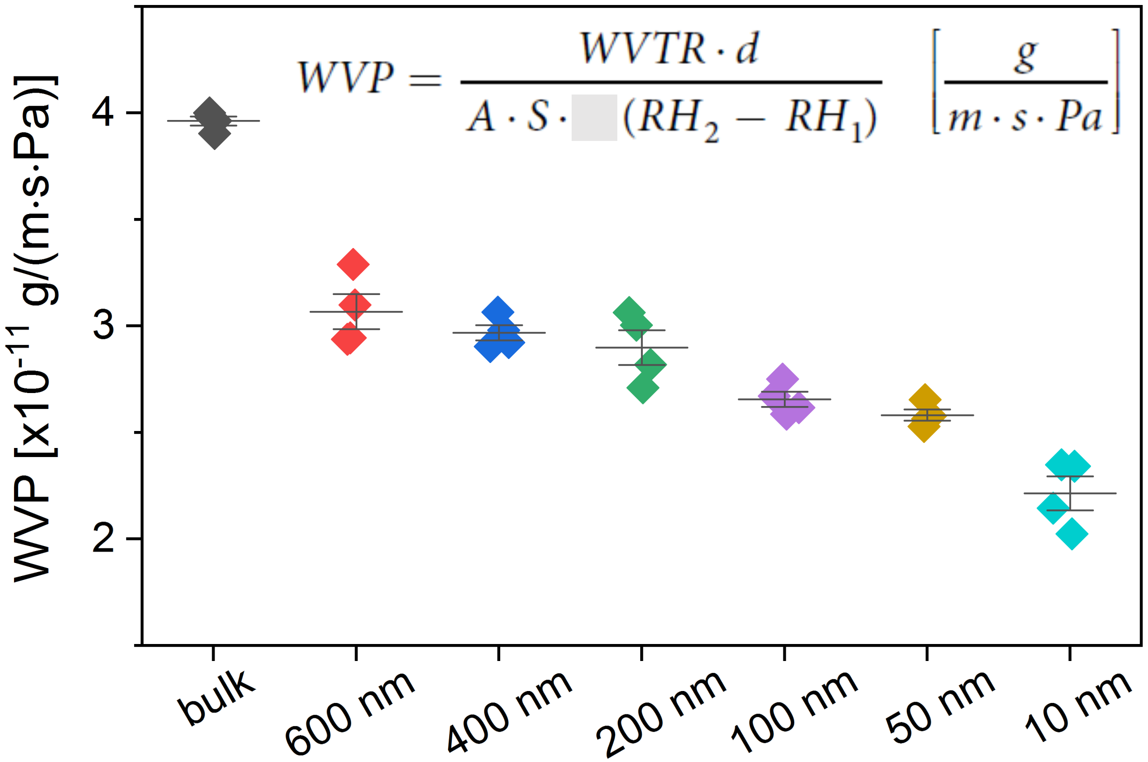




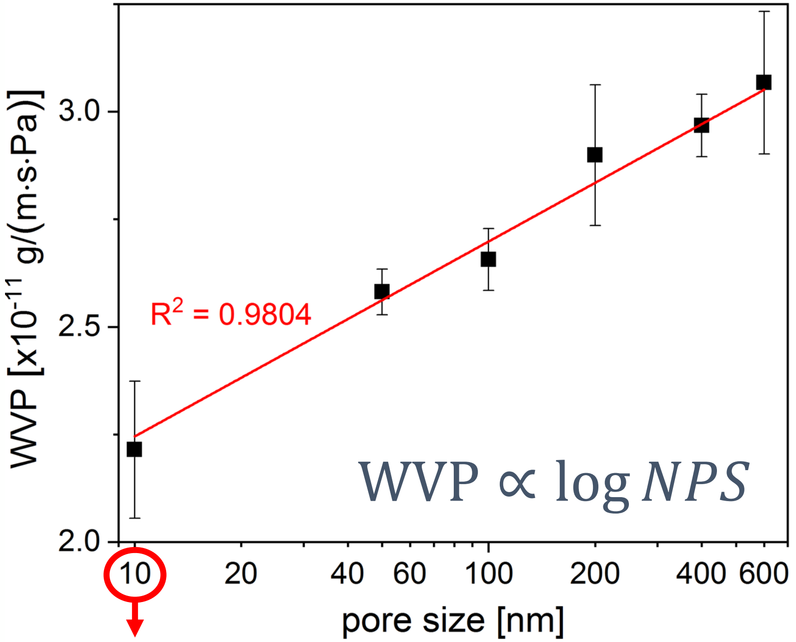


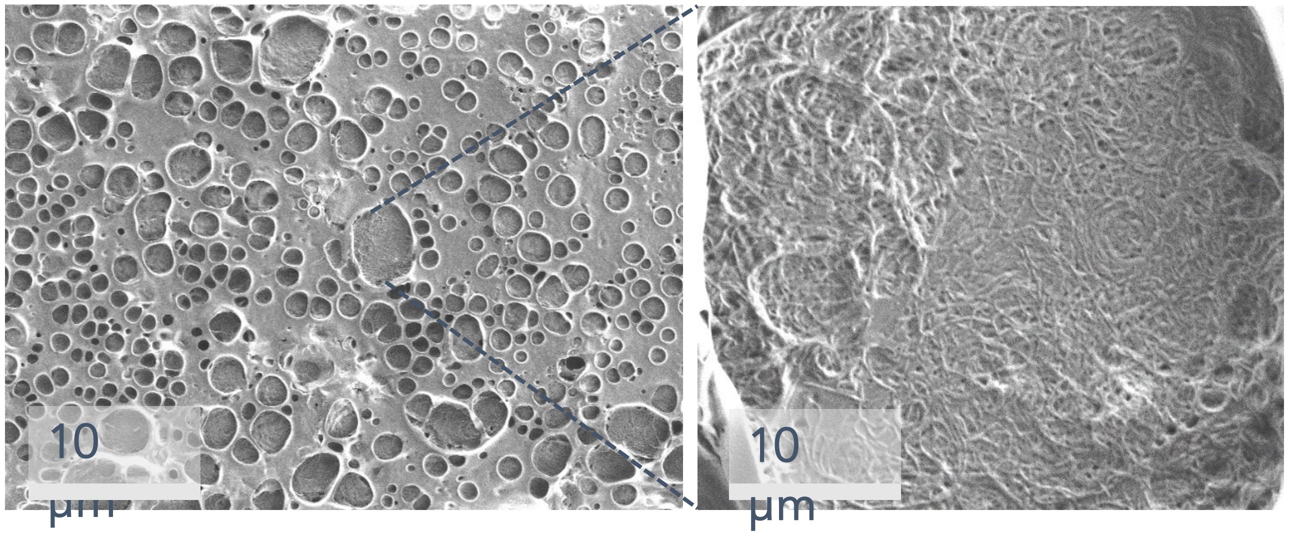


Improved gas barrier performance



$$WVP = \frac{WVTR \cdot d}{A \cdot S \cdot (RH_2 - RH_1)} \quad \left[\frac{g}{m \cdot s \cdot Pa}\right]$$



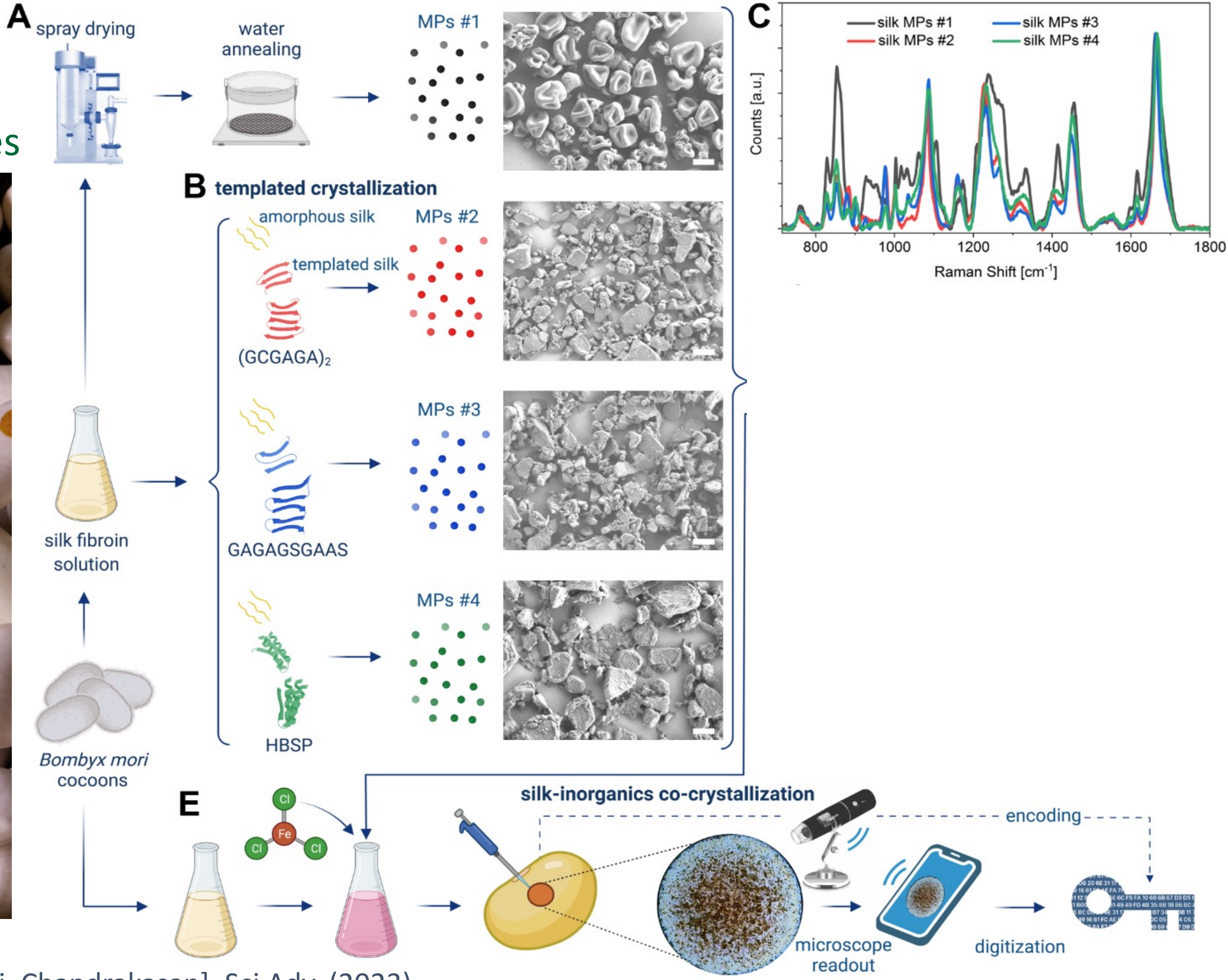


- Nanotube membranes show lower WVP than bulk
- Linear decrease of WVP w.r.t. the logarithm of the nominal pore size (NPS) of nanotube membranes
- Hierarchical pore structures contribute to lower WVP

Edible Physical Unclonable Functions

Edible Physical Unclonable Functions

- 70% of agricultural products are counterfeited in emerging countries



Massachusetts Institute of Technology

Sun et al. [Marelli, Chandrakasan], Sci Adv, (2023)

Edible Physical Unclonable Functions

Challenge: Authentication methods suffer from poor performance and are too complex to be used in rural areas

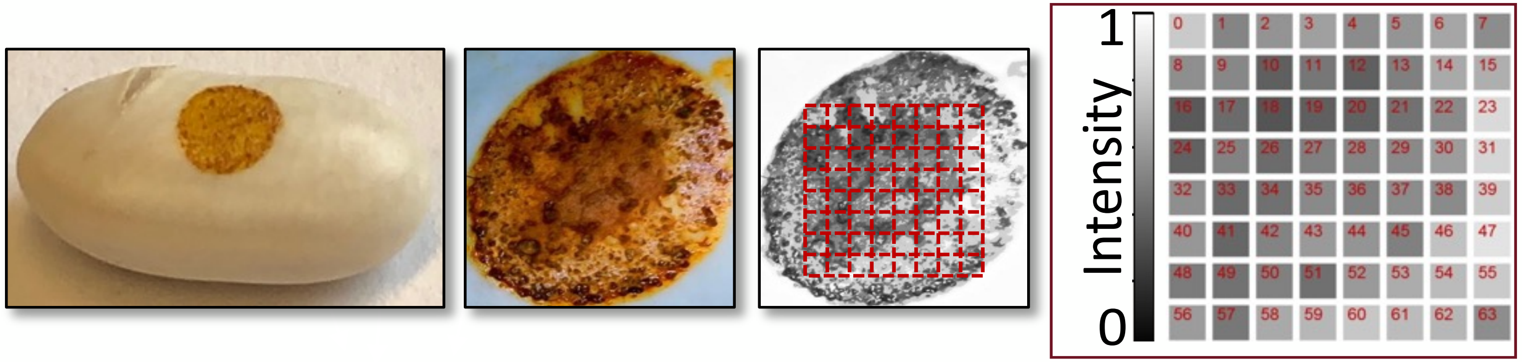
Solution: Silk-based, visual physical unclonable functions

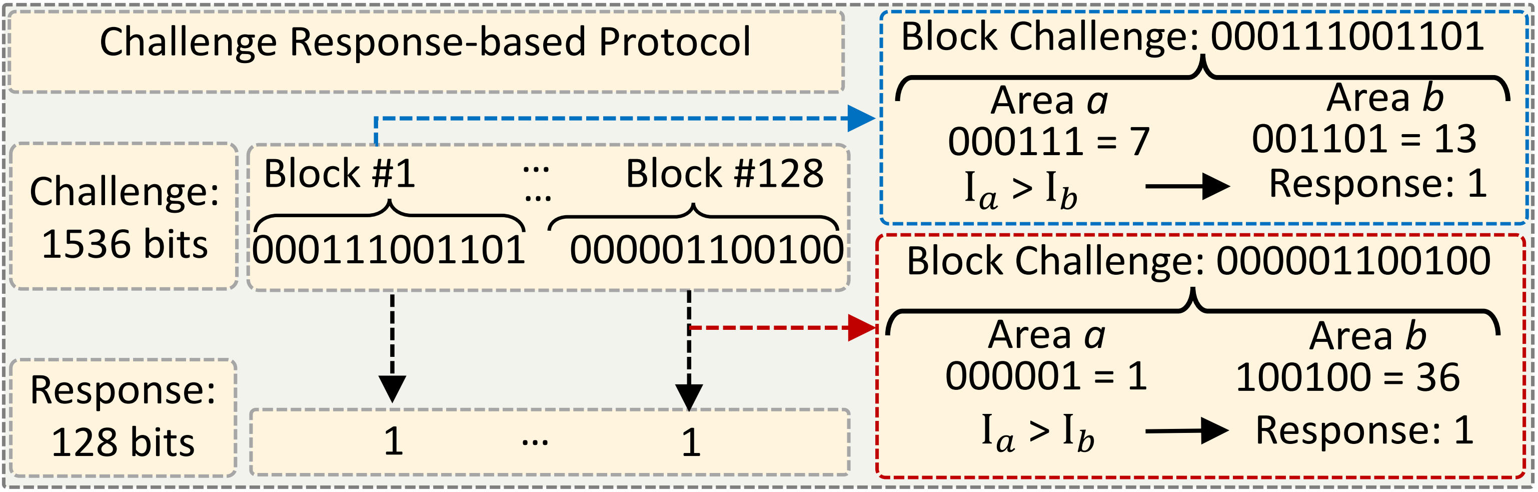
Rapid formation on complex surfaces of tags that cannot be tampered and embed unique, random patterns

Edible and biodegradable, yet resistant to humidity and friction

- Interrogation with a cell-phone or portable Raman spectrometer enables 128-bit cryptographic key

- Silk PUF passes all standard NIST tests





Challenge Response-based Protocol

Challenge: 1536 bits

Block #1 … Block #128

000111001101 000001100100

Response: 128 bits

1 … 1

Block Challenge: 000111001101

Area *a* 000111 = 7

Area *b* 001101 = 13

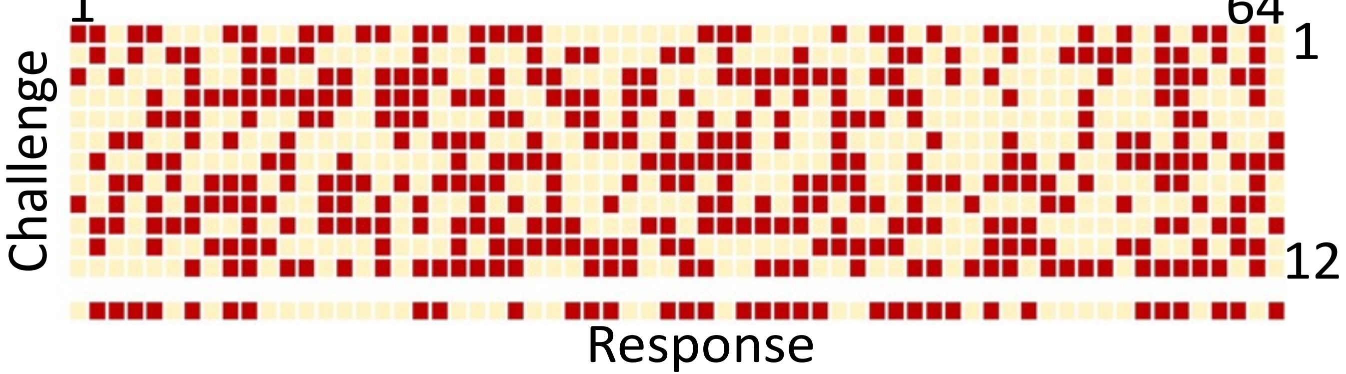
$I_a > I_b$ → Response: 1

Block Challenge: 000001100100

Area *a* 000001 = 1

Area *b* 100100 = 36

$I_a > I_b$ → Response: 1



The bits 1 and 0 are represented by 🟥 and ☐ colors respectively

Massachusetts Institute of Technology

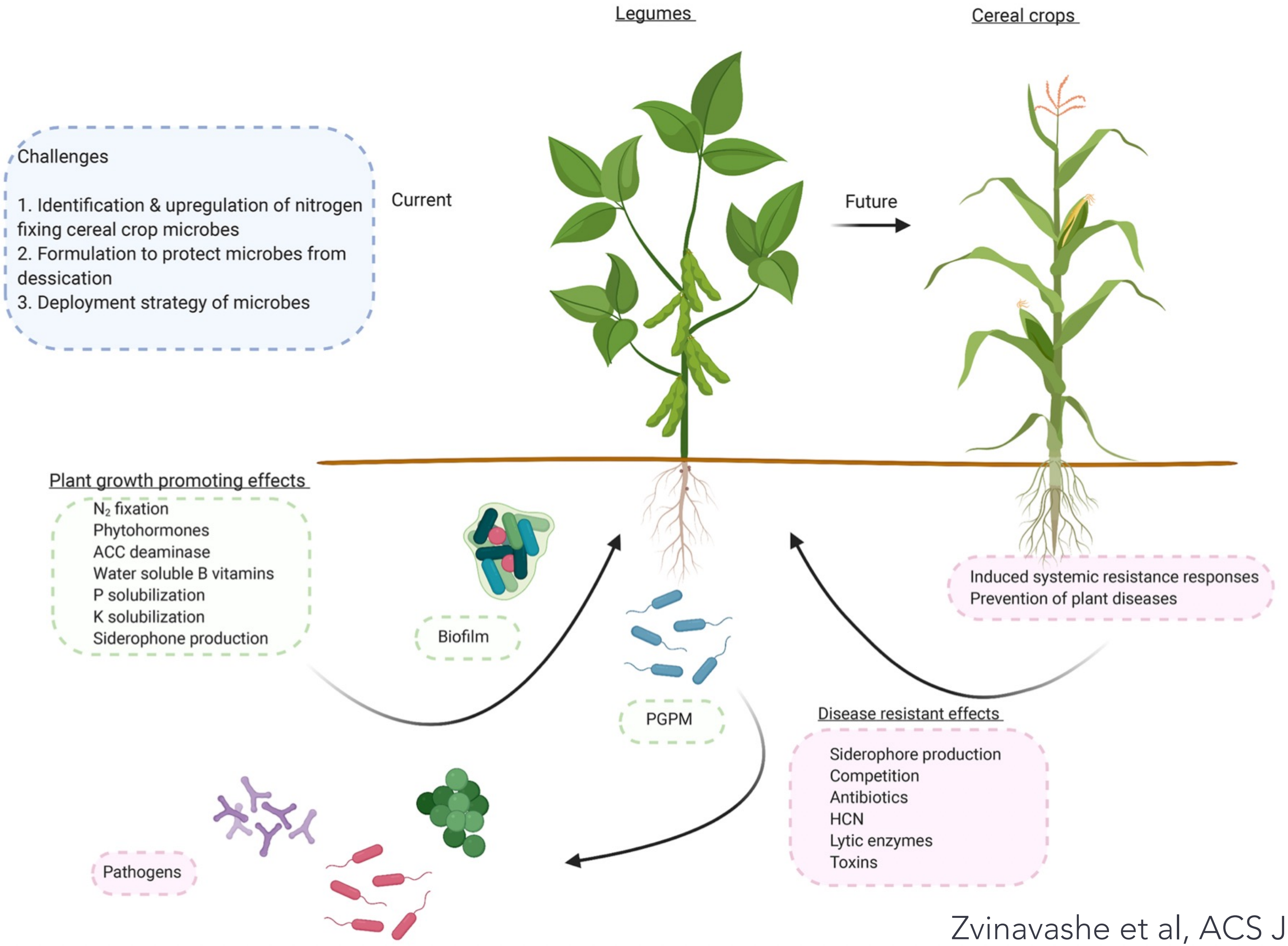
Engineering of seed microenvironment

Engineering of seed microenvironment

- No more arable land
- 3% of world energy is spent in synthesizing nitrogen fertilizers
- Phosphate fertilizers production will peak in 2033, causing shortage afterwards
- Biofertilizers (plant growth-promoting microbes) fix nitrogen, solubilize phosphate, mitigate stressors and increase plant health
- Translation is hinder by low viability in anhydrous conditions
- 90% of agrochemicals go off-target

Zvinavashe et al, Nature Food, 2021 Zvinavashe et al, ACS J. Agric. Food Chem, 2021

Engineering of seed microenvironment



Legumes

Cereal crops

Challenges

1. Identification & upregulation of nitrogen fixing cereal crop microbes
2. Formulation to protect microbes from dessication
3. Deployment strategy of microbes

Current

Future

Plant growth promoting effects

- N_2 fixation
- Phytohormones
- ACC deaminase
- Water soluble B vitamins
- P solubilization
- K solubilization
- Siderophone production

Biofilm

PGPM

Induced systemic resistance responses
Prevention of plant diseases

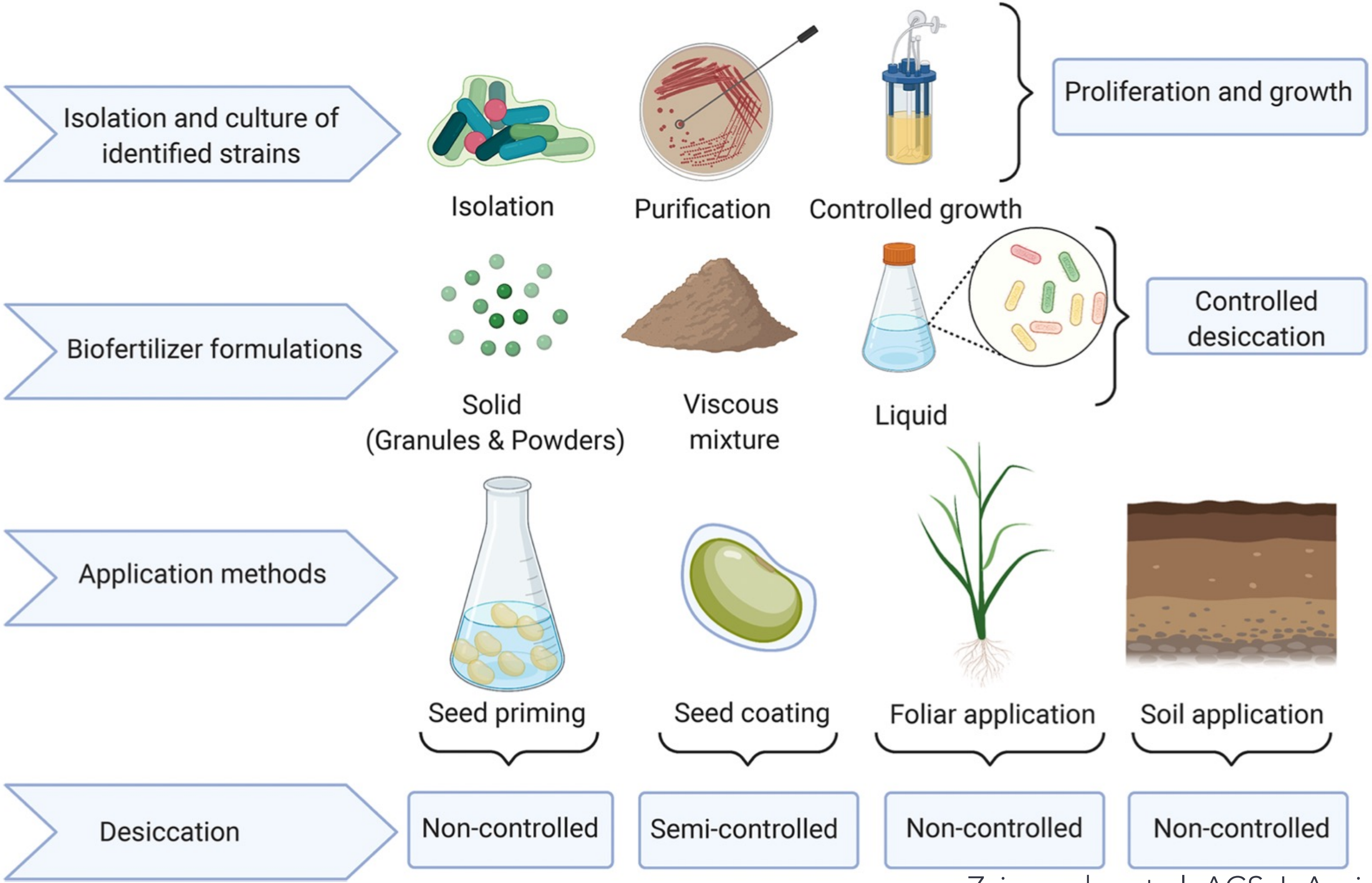
Disease resistant effects

- Siderophore production
- Competition
- Antibiotics
- HCN
- Lytic enzymes
- Toxins

Pathogens

Zvinavashe et al, ACS J. Agric. Food Chem, 2021

Engineering of seed microenvironment



Isolation and culture of identified strains

Isolation

Purification

Controlled growth

Proliferation and growth

Biofertilizer formulations

Solid (Granules & Powders)

Viscous mixture

Liquid

Controlled desiccation

Application methods

Seed priming

Seed coating

Foliar application

Soil application

Desiccation

Non-controlled

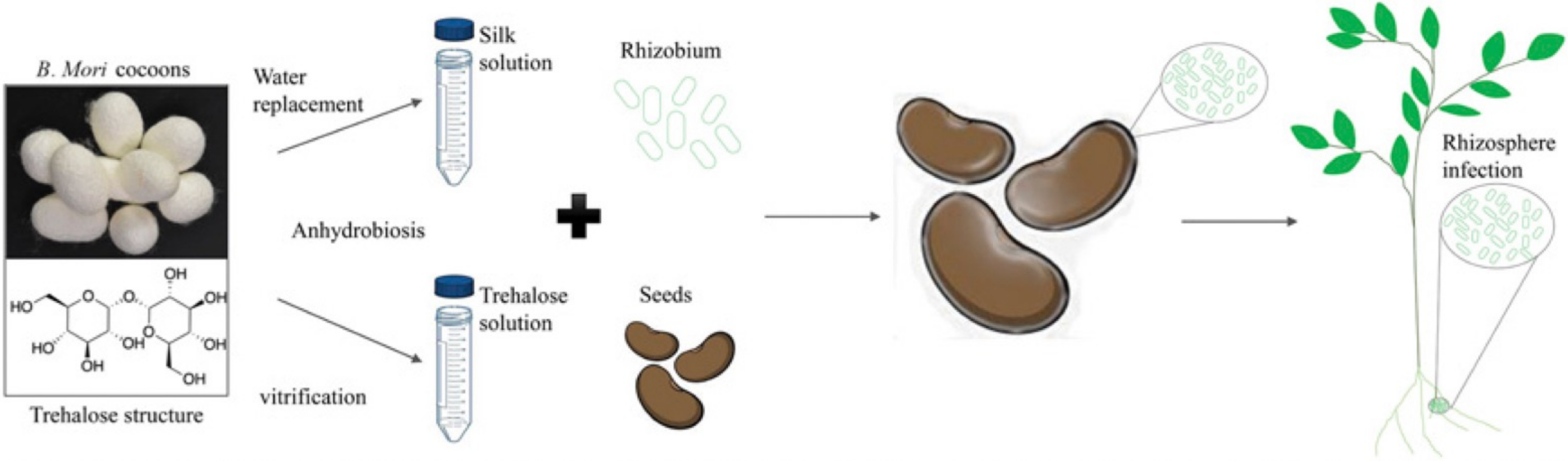
Semi-controlled

Non-controlled

Non-controlled

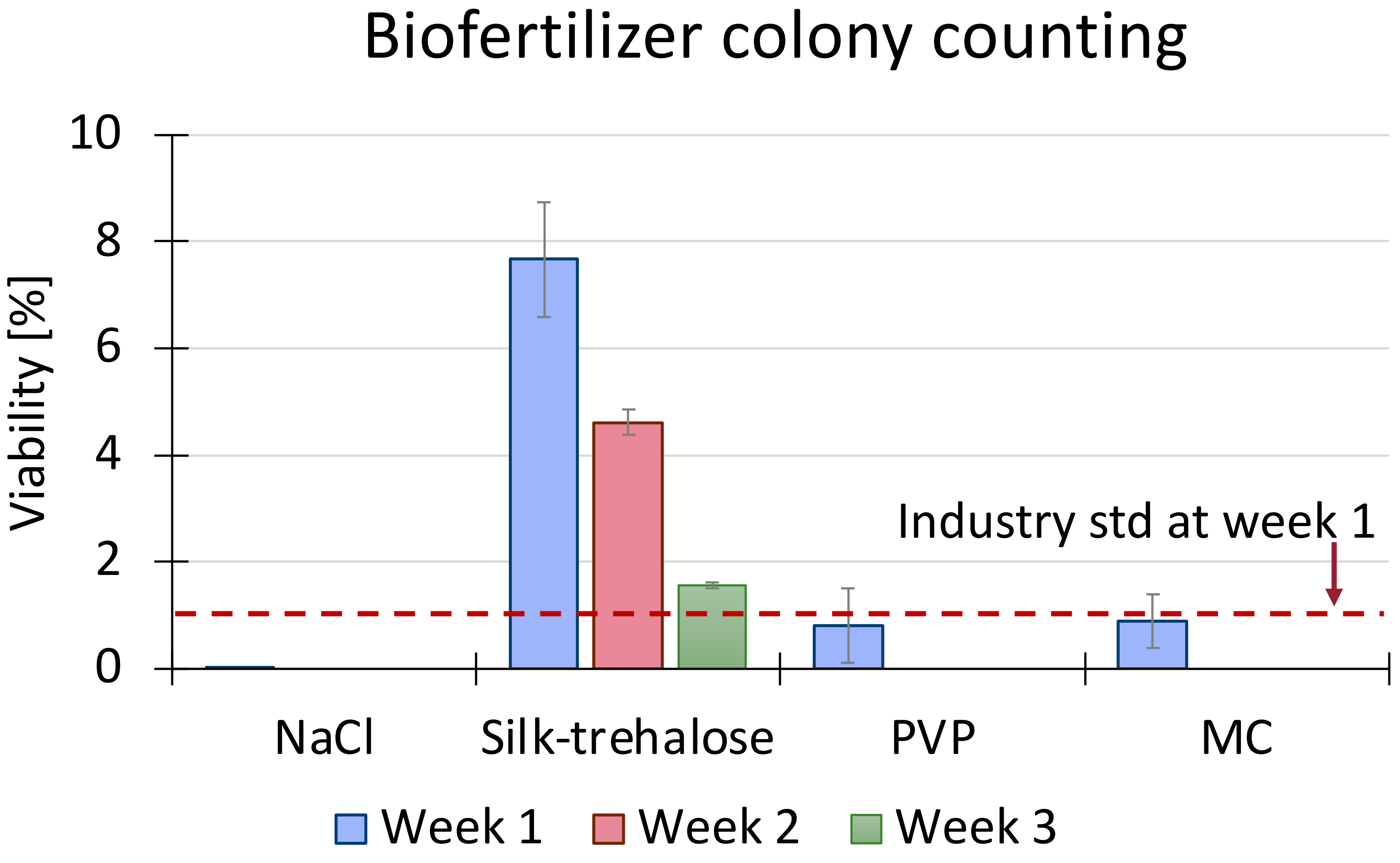
Zvinavashe et al, ACS J. Agric. Food Chem, 2021

Engineering of seed microenvironment



Zvinavashe et al, PNAS, 2019

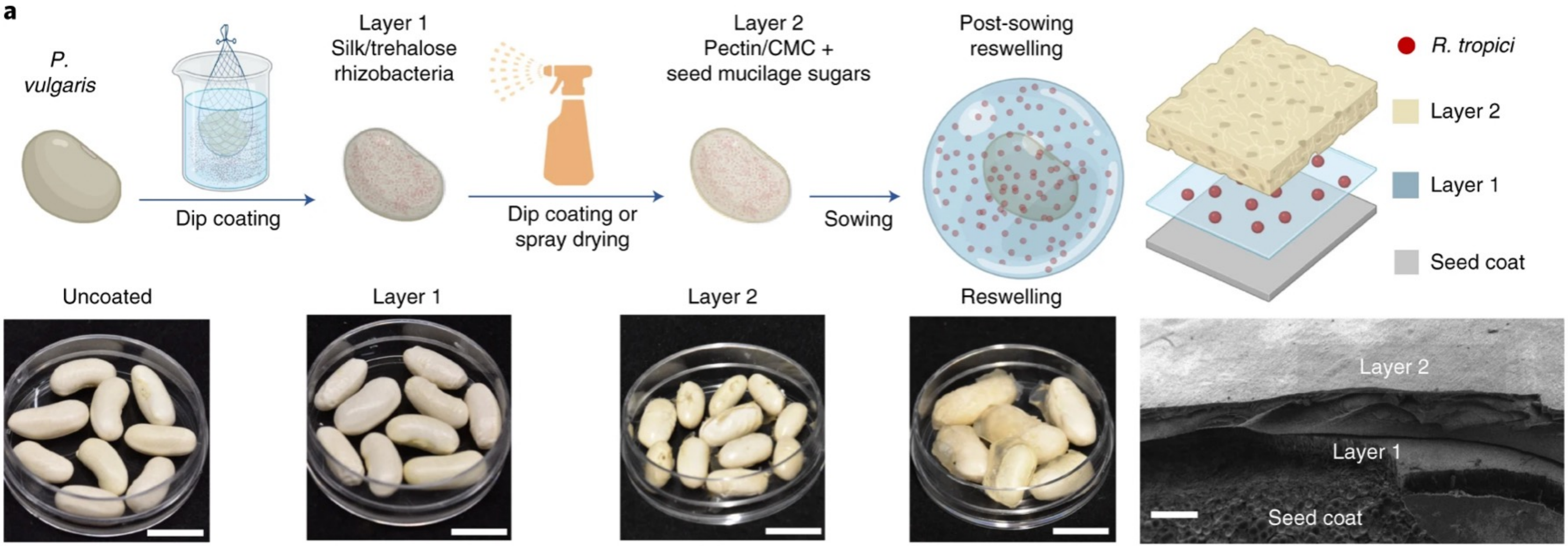
Engineering of seed microenvironment



PVP – $(C_6H_9NO)_n$ - polyvinylpyrrolidone
MC – methylcellulose

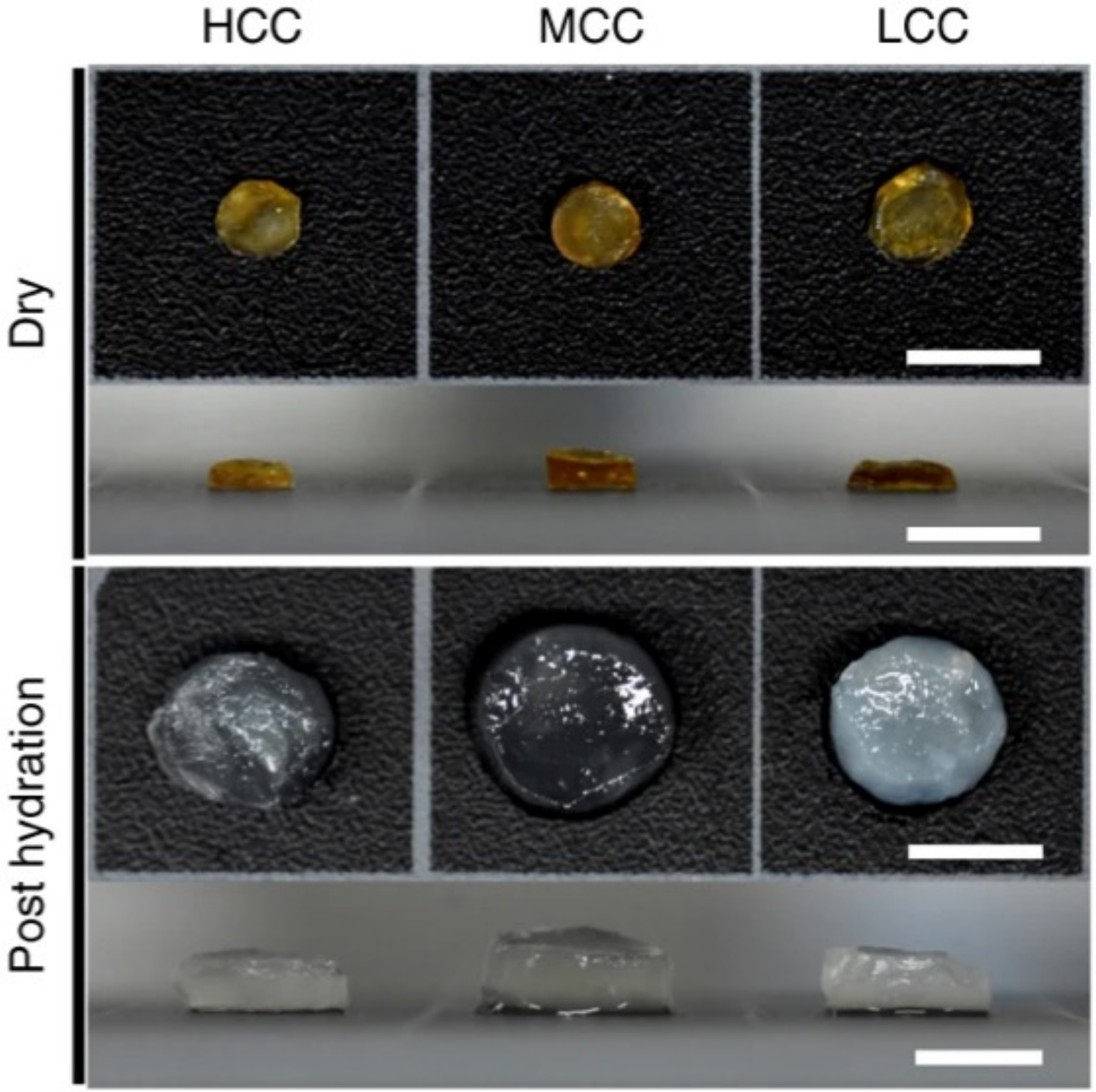
Zvinavashe et al, PNAS, 2019

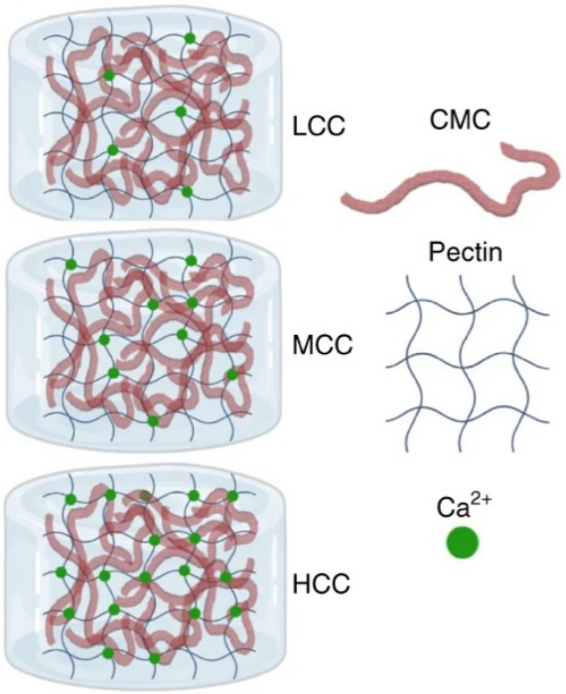
Engineering of seed microenvironment

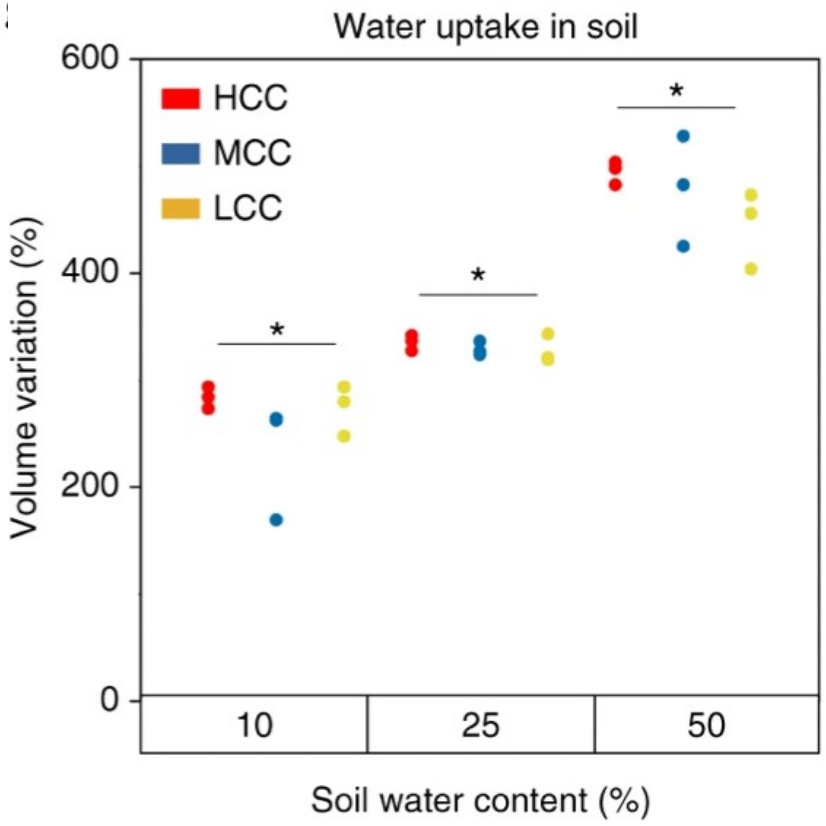


Zvinavashe et al, Nature Food, 2021

Engineering of seed microenvironment

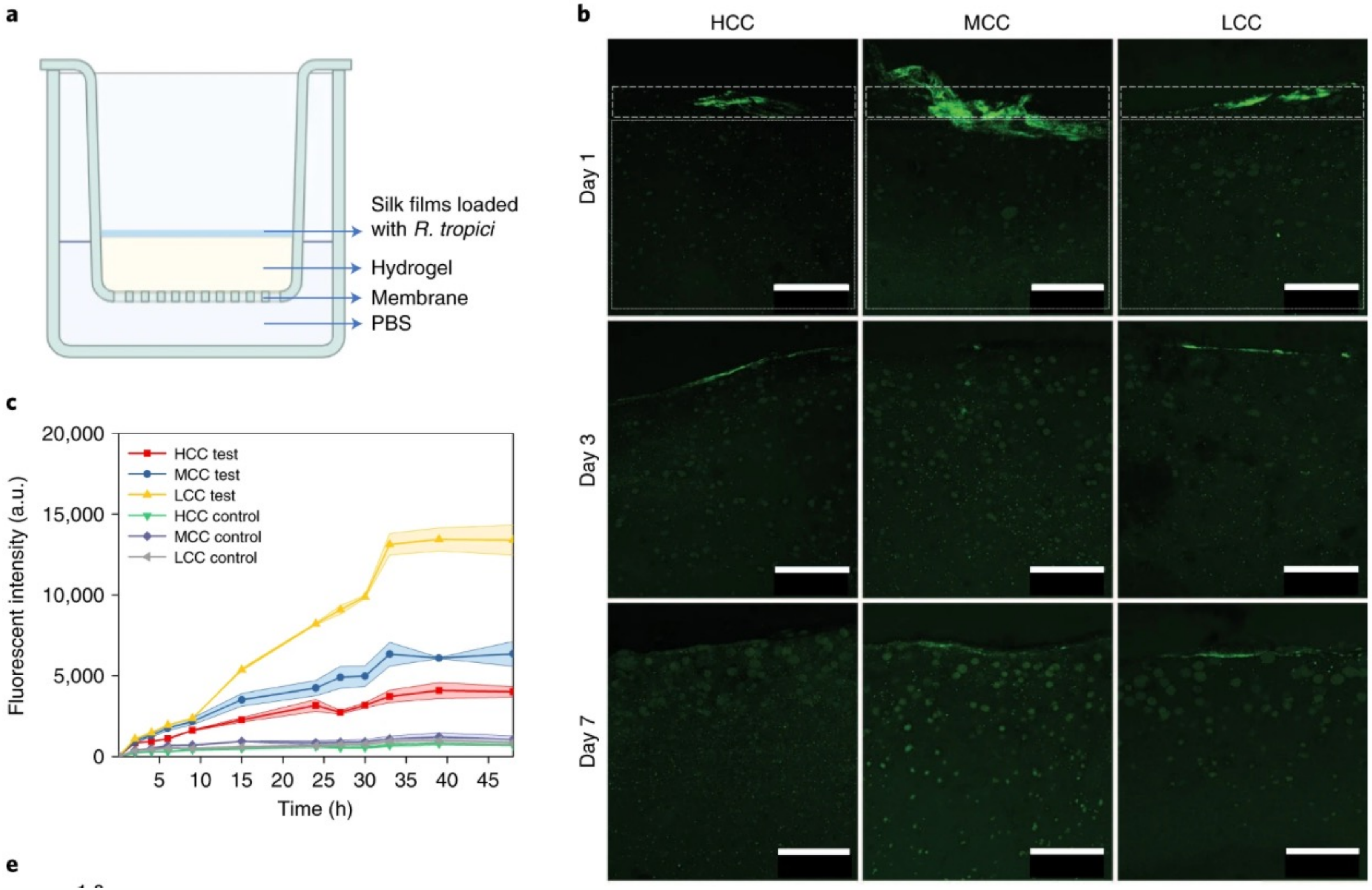






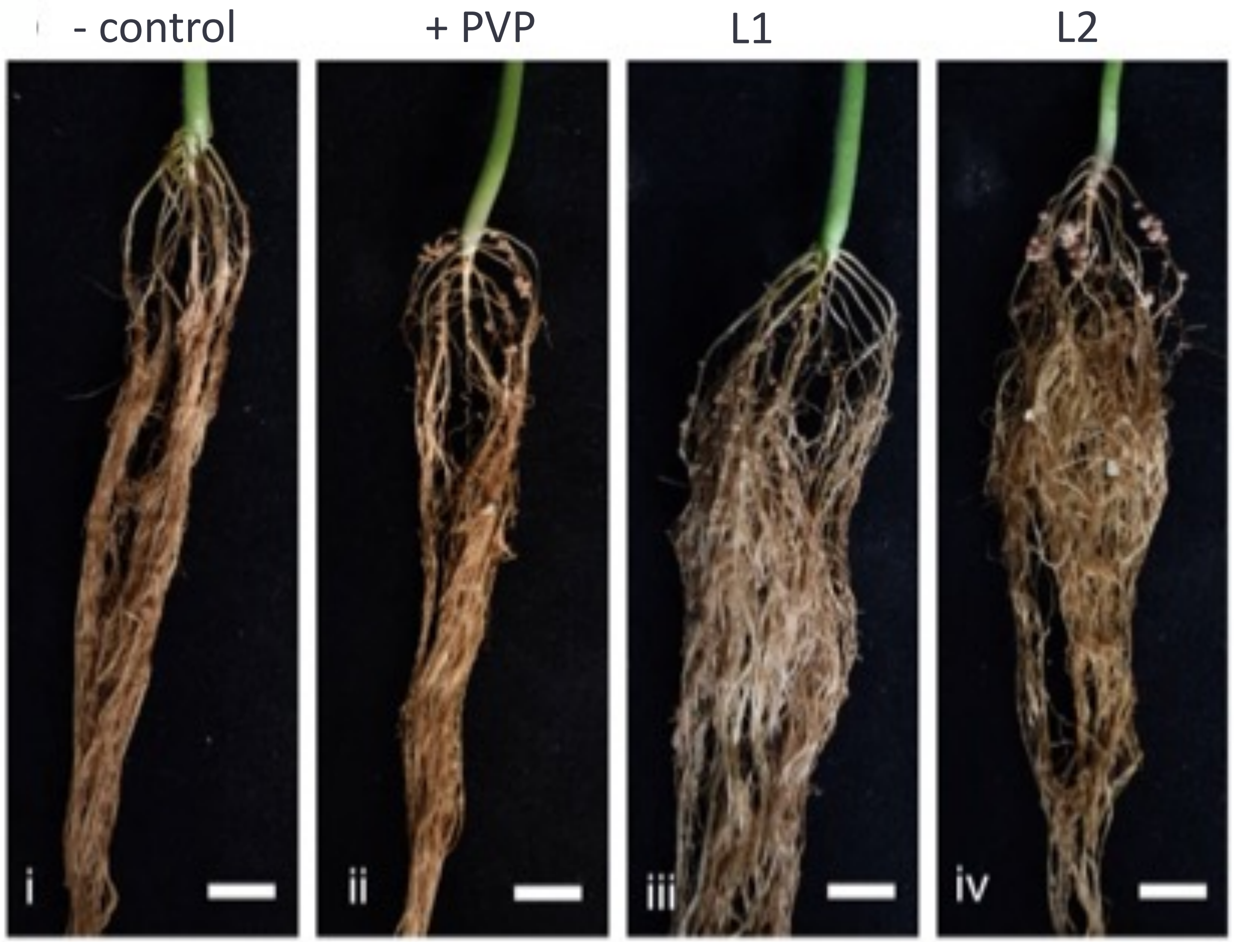
Zvinavashe et al, Nature Food, 2021

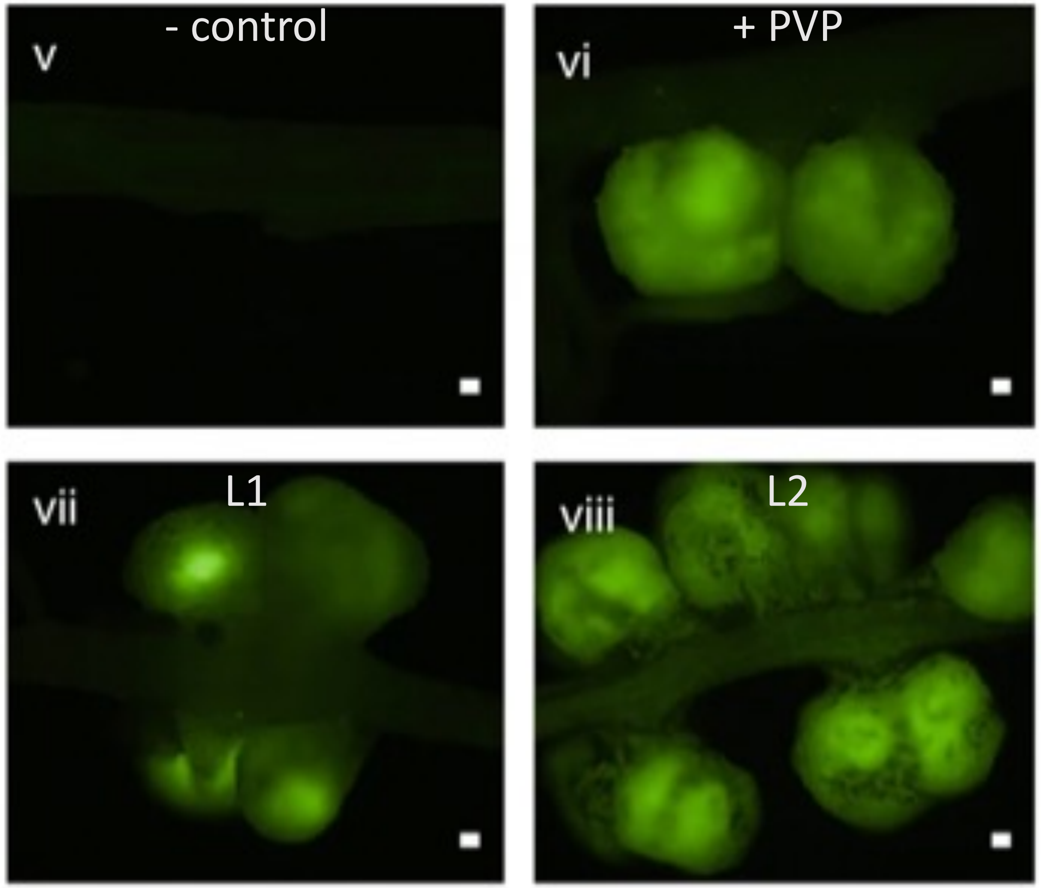
Engineering of seed microenvironment



Zvinavashe et al, Nature Food, 2021

Engineering of seed microenvironment



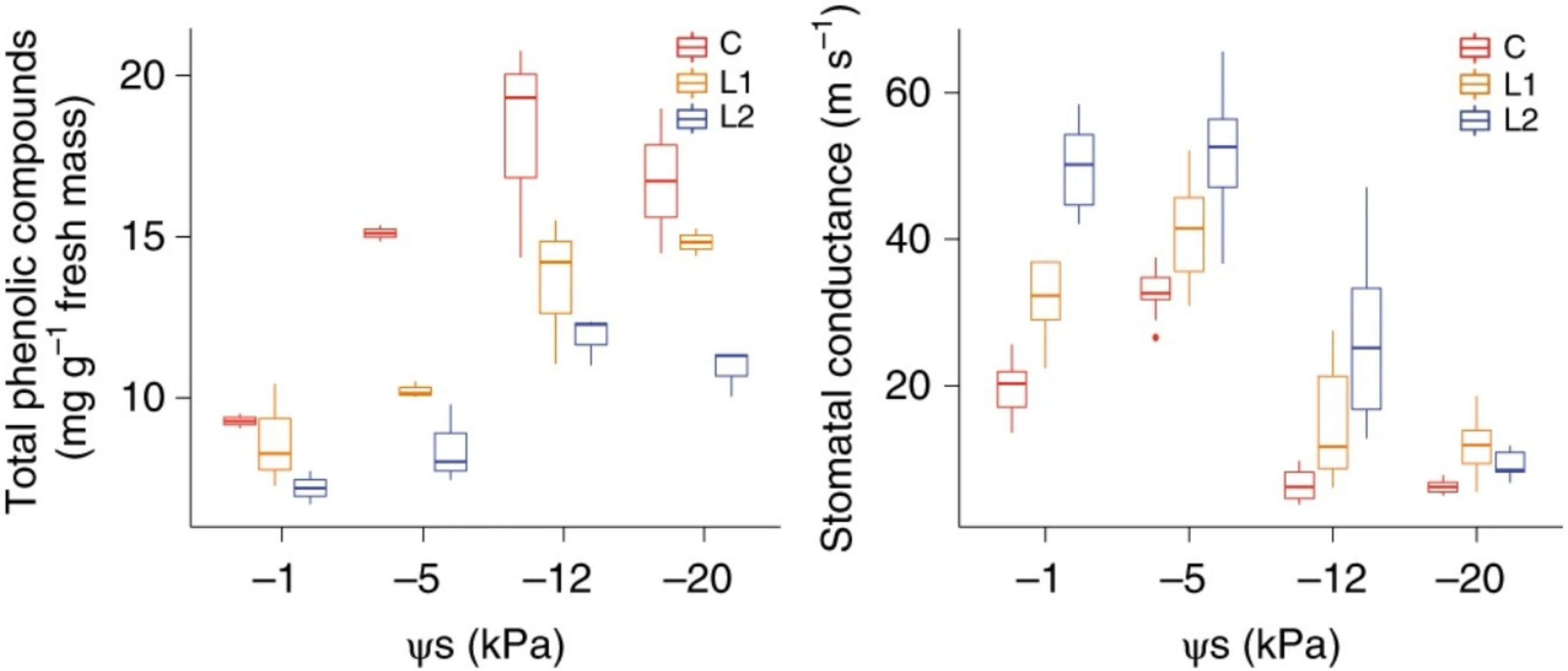


Zvinavashe et al, Nature Food, 2021

Engineering of seed microenvironment

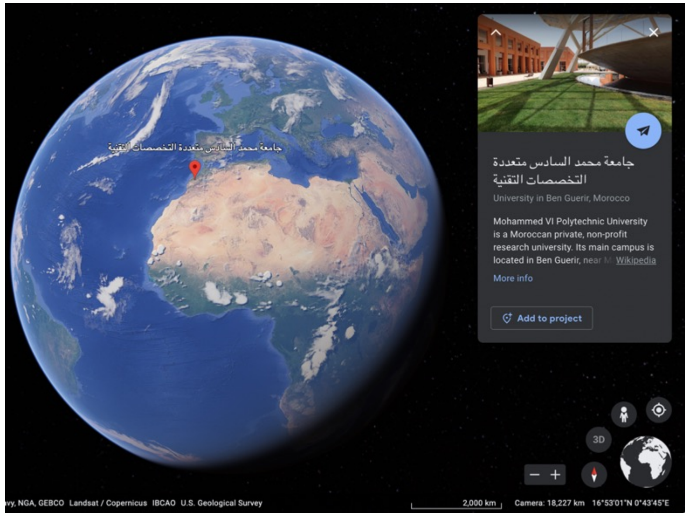
No coating

Coated



Zvinavashe et al, Nature Food, 2021

Engineering of seed microenvironment



جامعة محمد السادس متعددة التخصصات التقنية

University in Ben Guerir, Morocco

Mohammed VI Polytechnic University is a Moroccan private, non-profit research university. Its main campus is located in Ben Guerir, near M Wikipedia

Seeds planted in saline soil. Coated seeds on the (left) and control (uncoated) seeds on the right of each image.

Saline soil obtained from Hiadna-Morocco

Zvinavashe et al, PNAS, 2019


Coimbra
Madrid
Castellón de la Plana
Salerno
Portugal
Toledo
Cáceres
Spain
Valencia
Balearic Sea
Sardegna
Tyrrhenian Sea
Cagliari
Lisbon
Palma
Badajoz
Messina
Palermo
Alicante
Trapani
Catania
Córdoba
Elche
Sicilia
Syracuse
Marsala
Seville
Huelva
Albufeira
Murcia
Tunis
تونس
Annaba
عنابة
Algiers
مدينة الجزائر
Granada
Almería
Faro
Málaga
Malta
Setif
سطيف
Gibraltar
Alboran Sea
Batna
باتنة
Tebessa
تبسة
Biskra
بسكرة
Oujda
وجدة
Rabat
الرباط
Fes
فاس
Tunisia
Tripoli
طرابلس
El Oued
الوادي
Meknes
مكناس
Casablanca
الدار البيضاء
Safi
أسفي
Ghardaia
غرداية
Ouargla
ورقلة
Essaouira
الصويرة
Marrakesh
مراكش
Beni-Mellal
بني ملال
Agadir
أكادير
Tiznit
تزنيت
Timimoun
تيميمون
In Amenas
عين أمناس
Adrar
أدرار
Algeria
Awbari
أوباري
In Salah
عين صالح
Aoulef
أولف
Illizi
اليزي
Reggane
رقان
Murzuq
مرزق

The end of the mouldy fruit bowl? Scientists discover microscopic silk covering to keep food fresh

A Silky Solution to the Problem of Wasted Food?

By DANIEL AKST

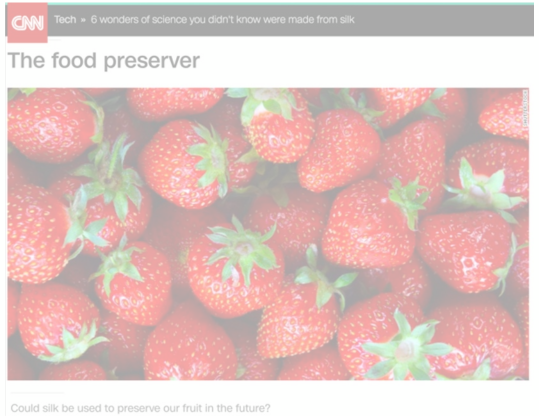
May 19, 2016 2:27 p.m. ET

Food waste is a big problem, and produce is particularly vulnerable. Largely due to spoilage, 40-50% of the world's fruit and vegetable output is wasted, according to a U.N. estimate, along with a great deal of labor, water and energy.

Silk Fibroin as Edible Coating for Perishable Food Preservation

This One Surprising Trick Might Keep Fruit Fresh for Longer

Olivia B. Waxman @OBWax May 6, 2016

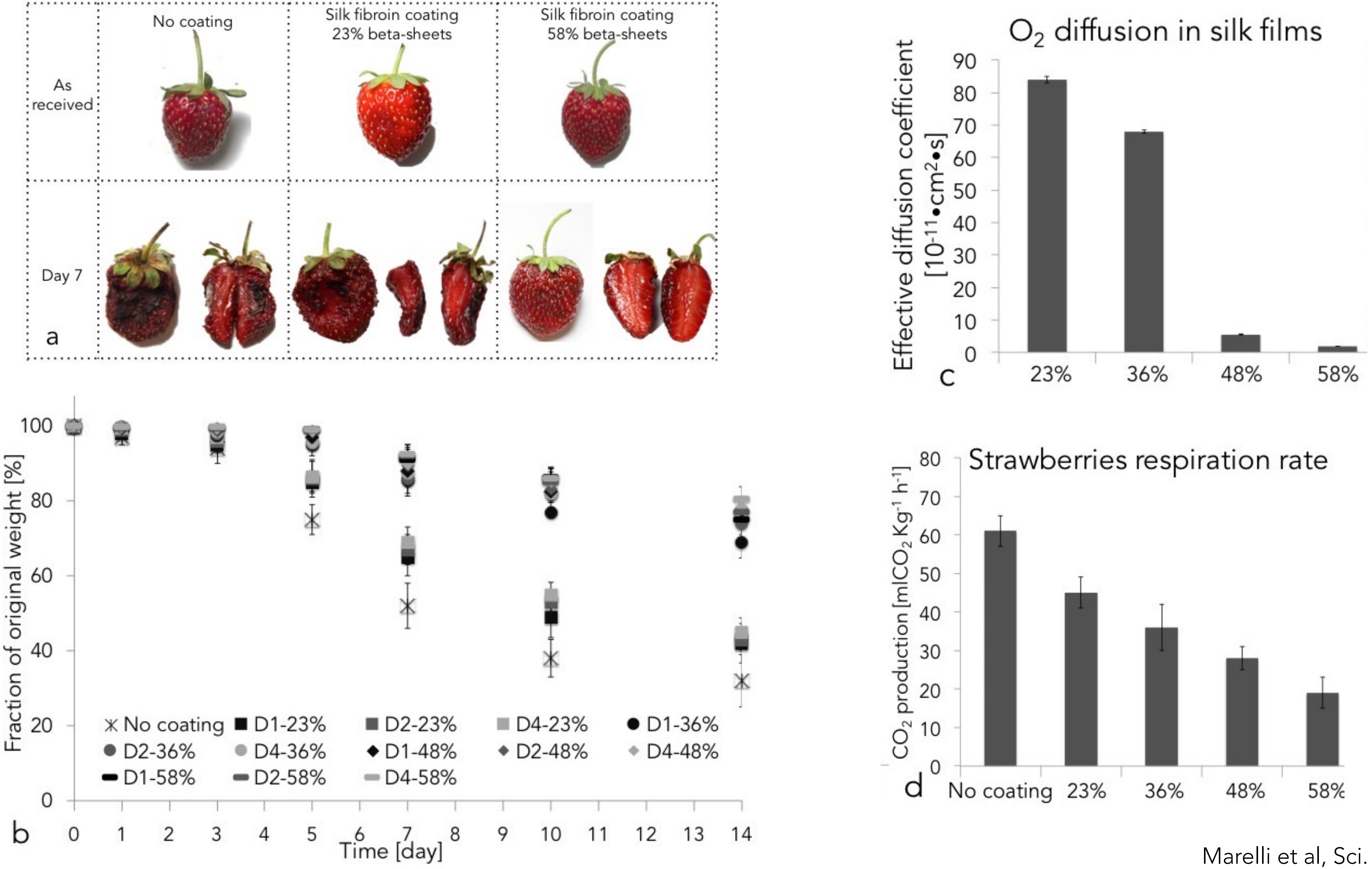


The food preserver

Could silk be used to preserve our fruit in the future?

Marelli et al, Sci. Rep. , 2016


100
APPROX.
80
60
40
20



Marelli et al, Sci. Rep. , 2016

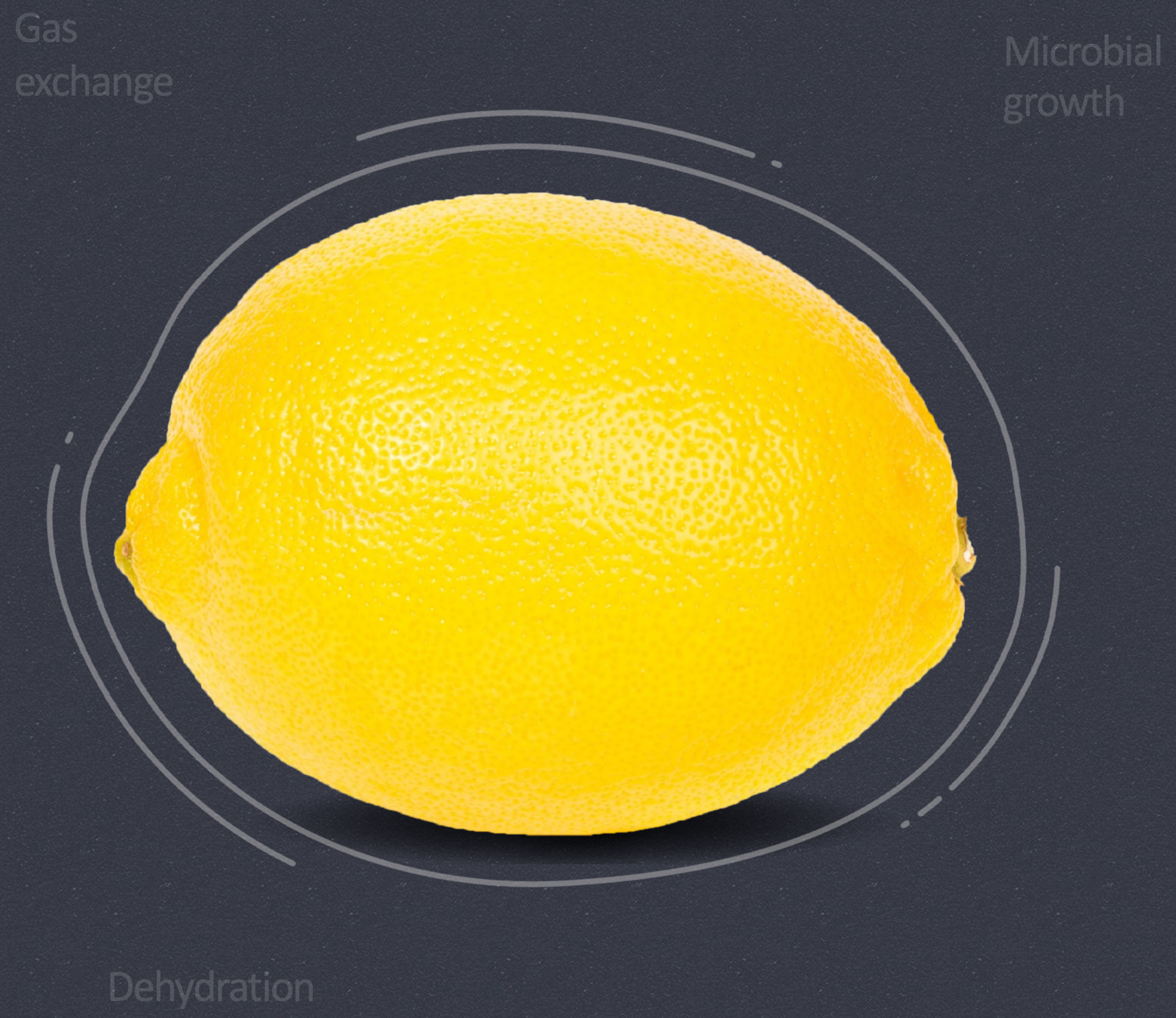
Silk directly addresses why food goes bad.

Gas exchange

Microbial growth

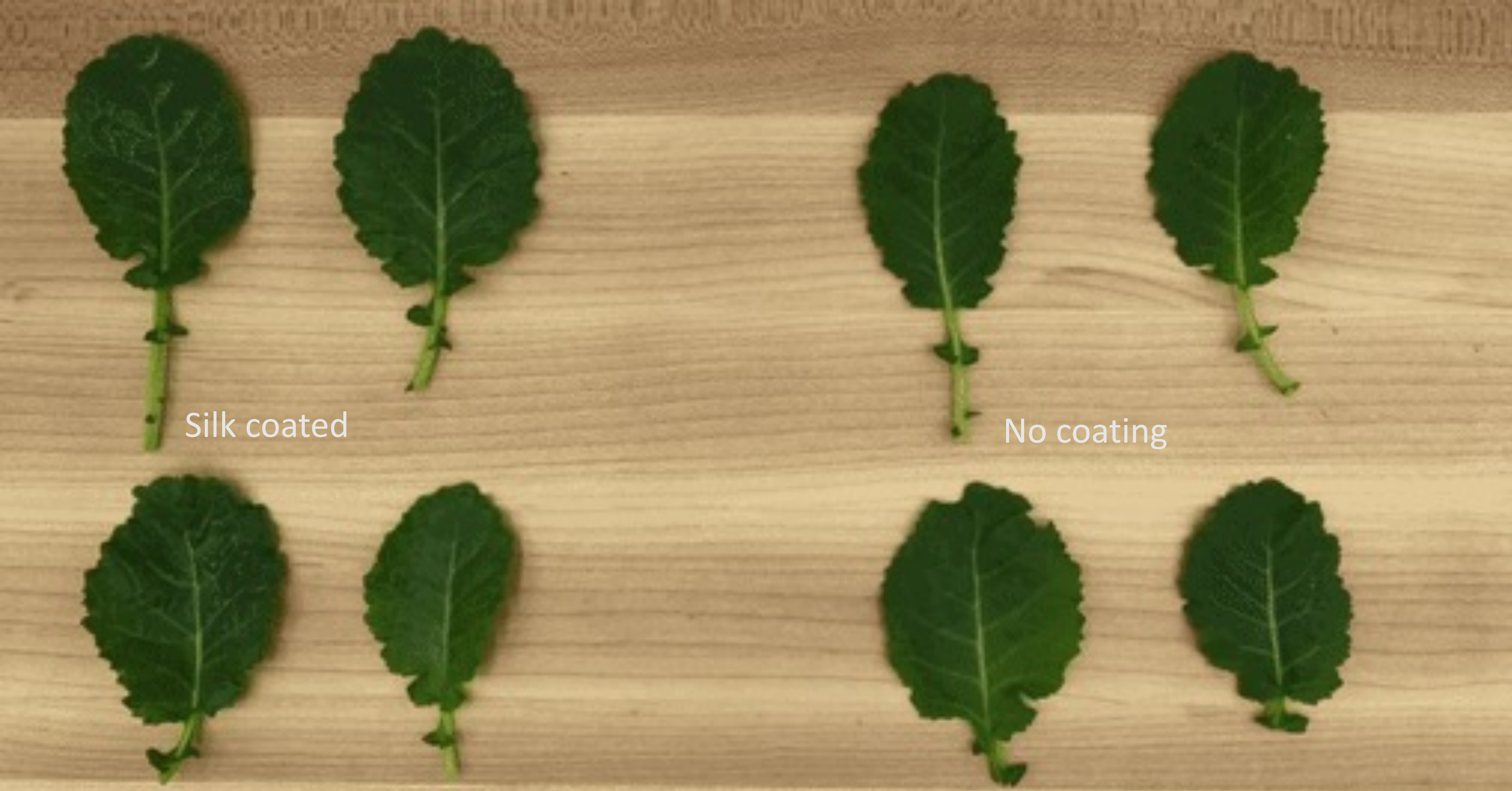
Dehydration

Through a natural and edible protective layer.



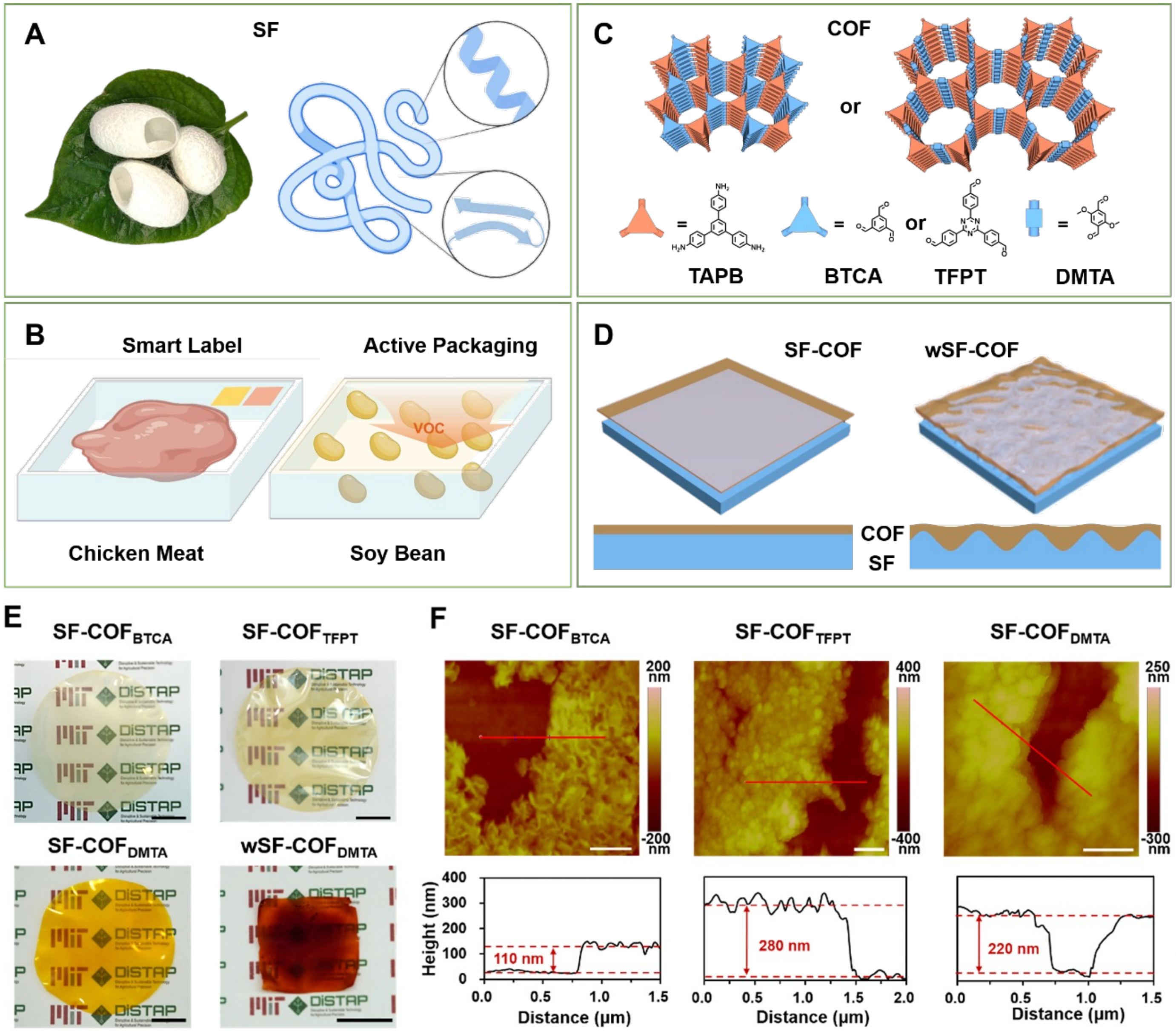
mori™

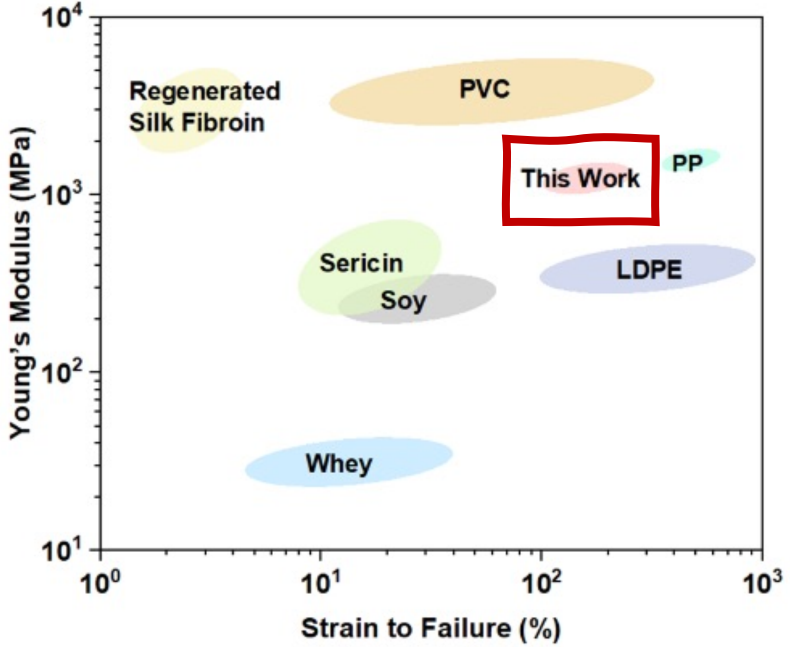
More food.
Less waste.

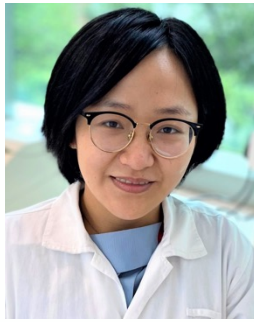


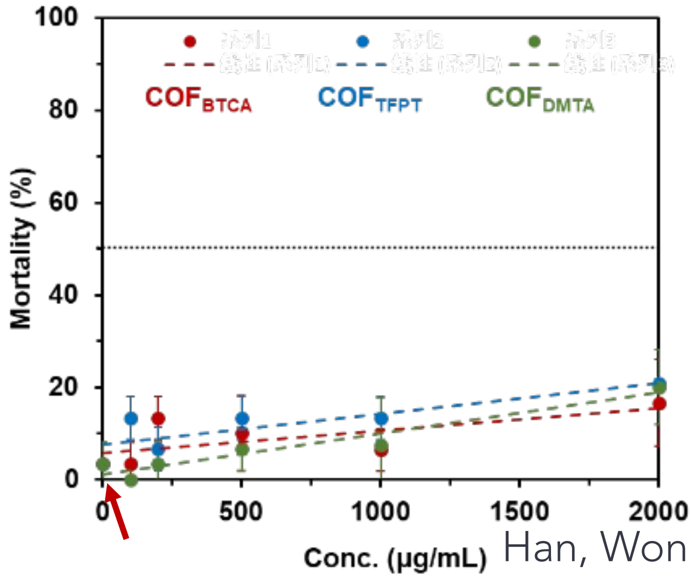
World Economic Forum 2021 Technology Pioneers – Science AAAS Prize for Innovation

Silk-Covalent Organic Framework climate-specific packaging



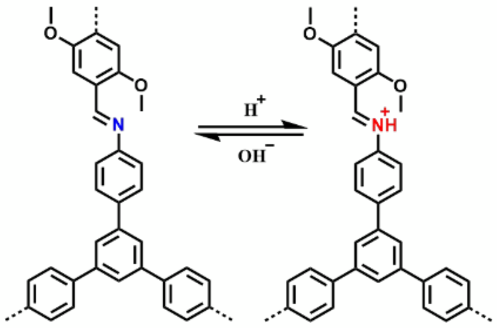


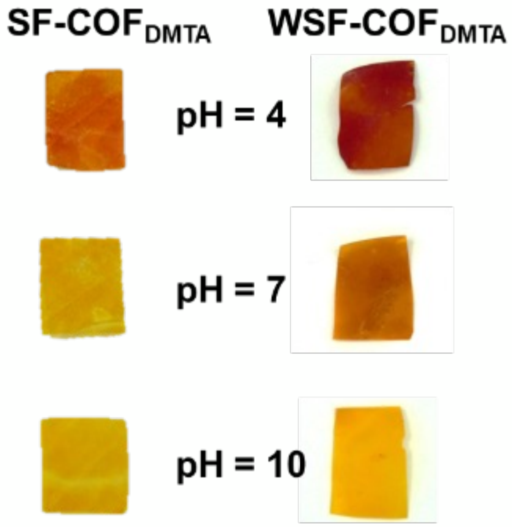


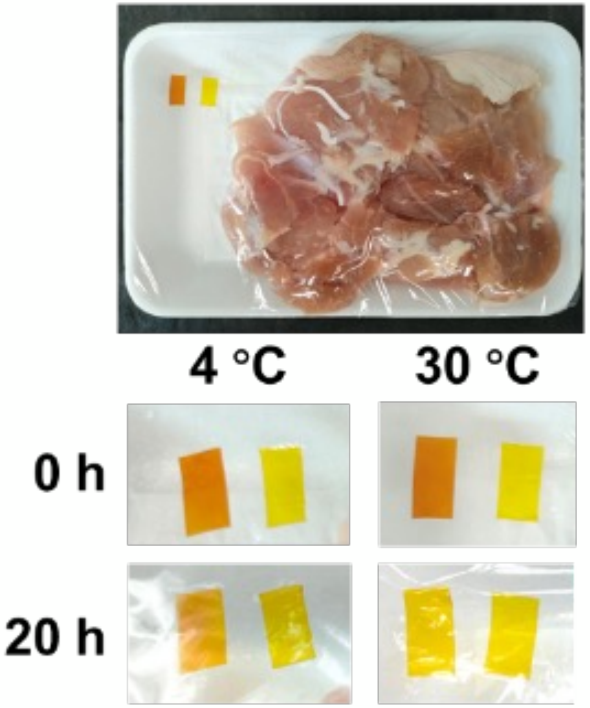


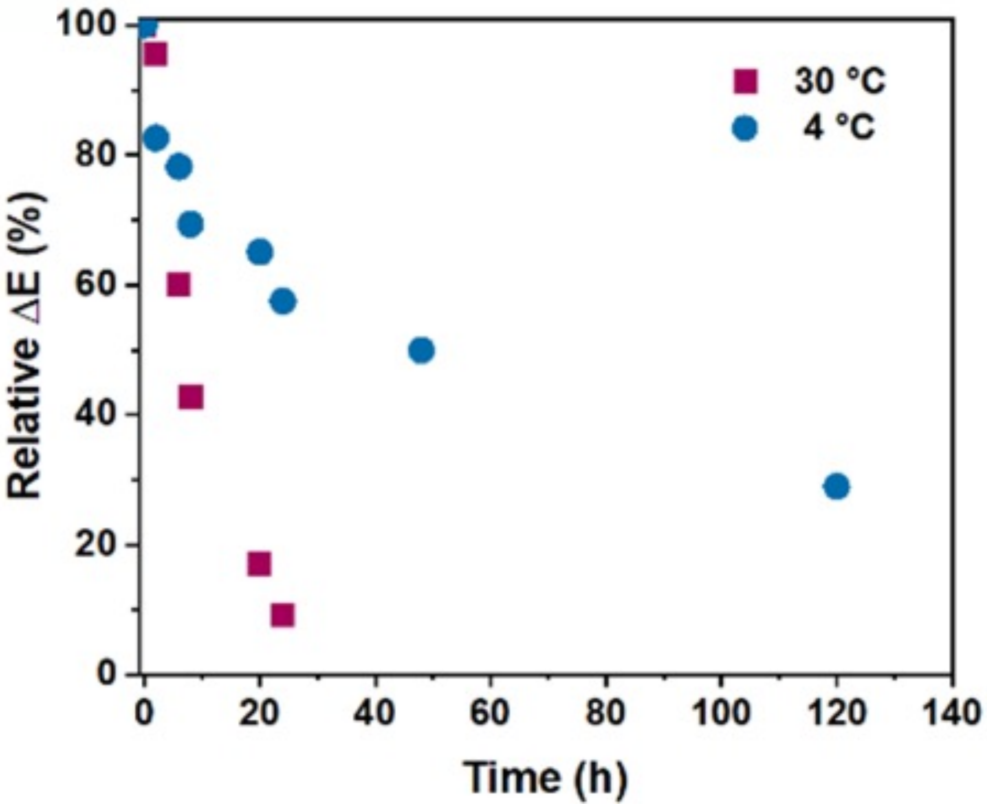
Han, Wong et al, submitted

Silk-Covalent Organic Framework climate specific packaging



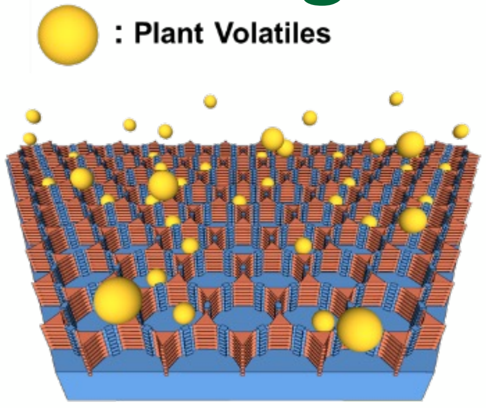


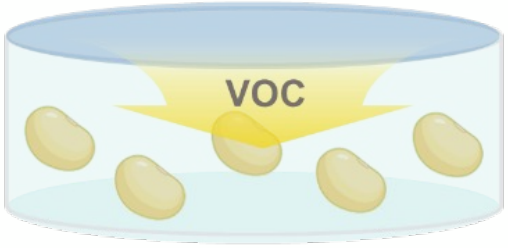


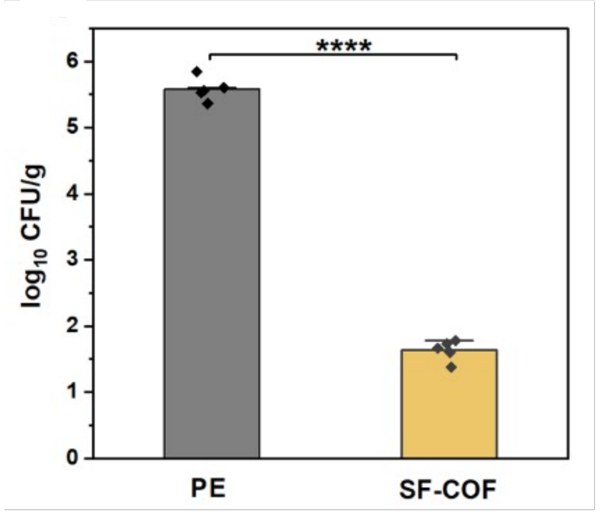


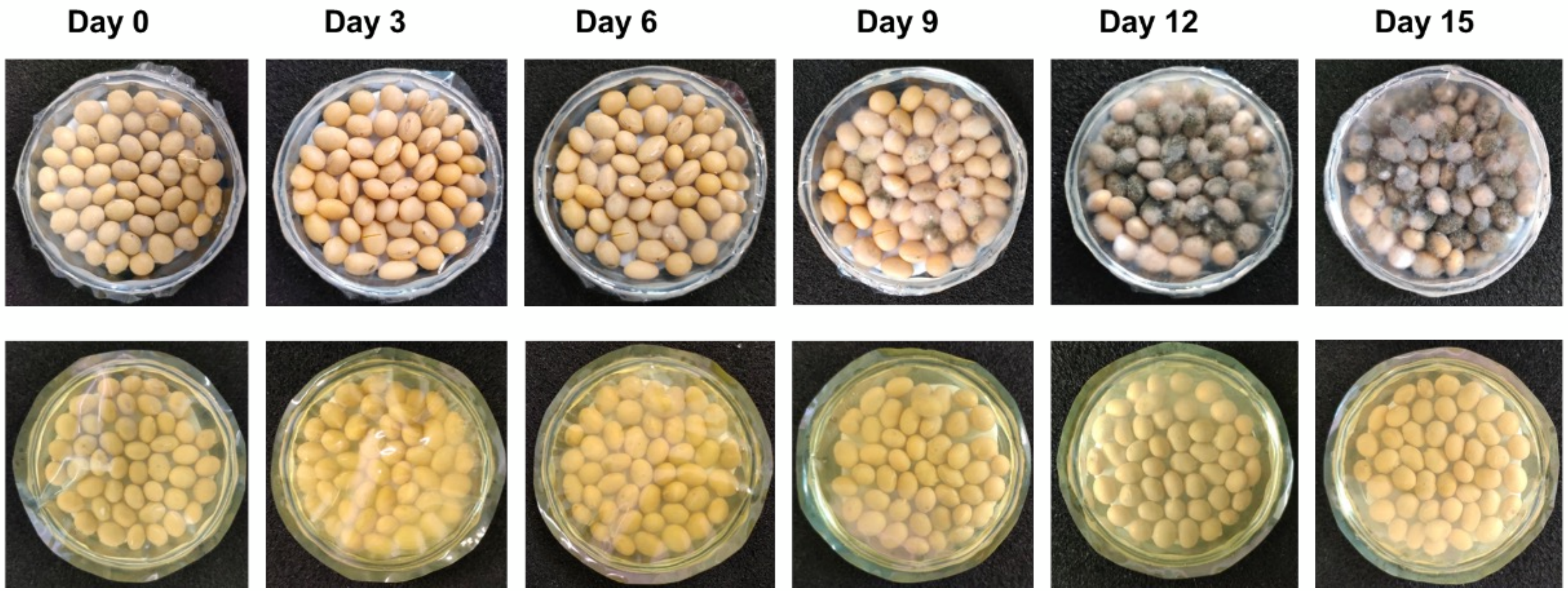
Han, Wong et al, submitted

Silk-Covalent Organic Framework climate-specific packaging



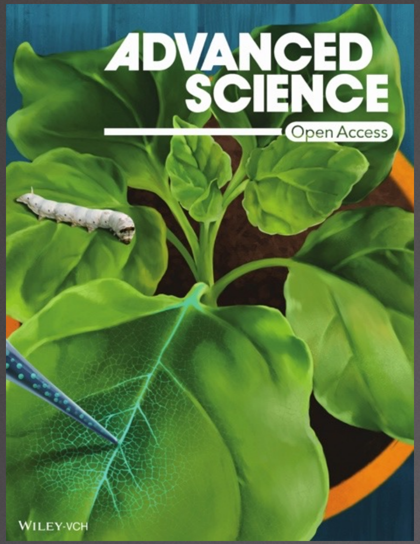






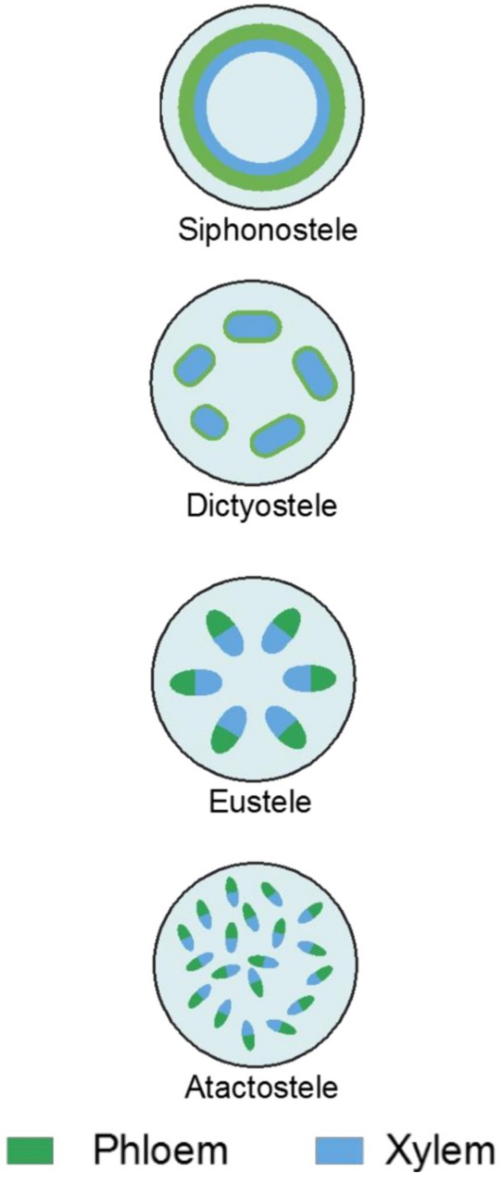
Han, Wong et al, submitted

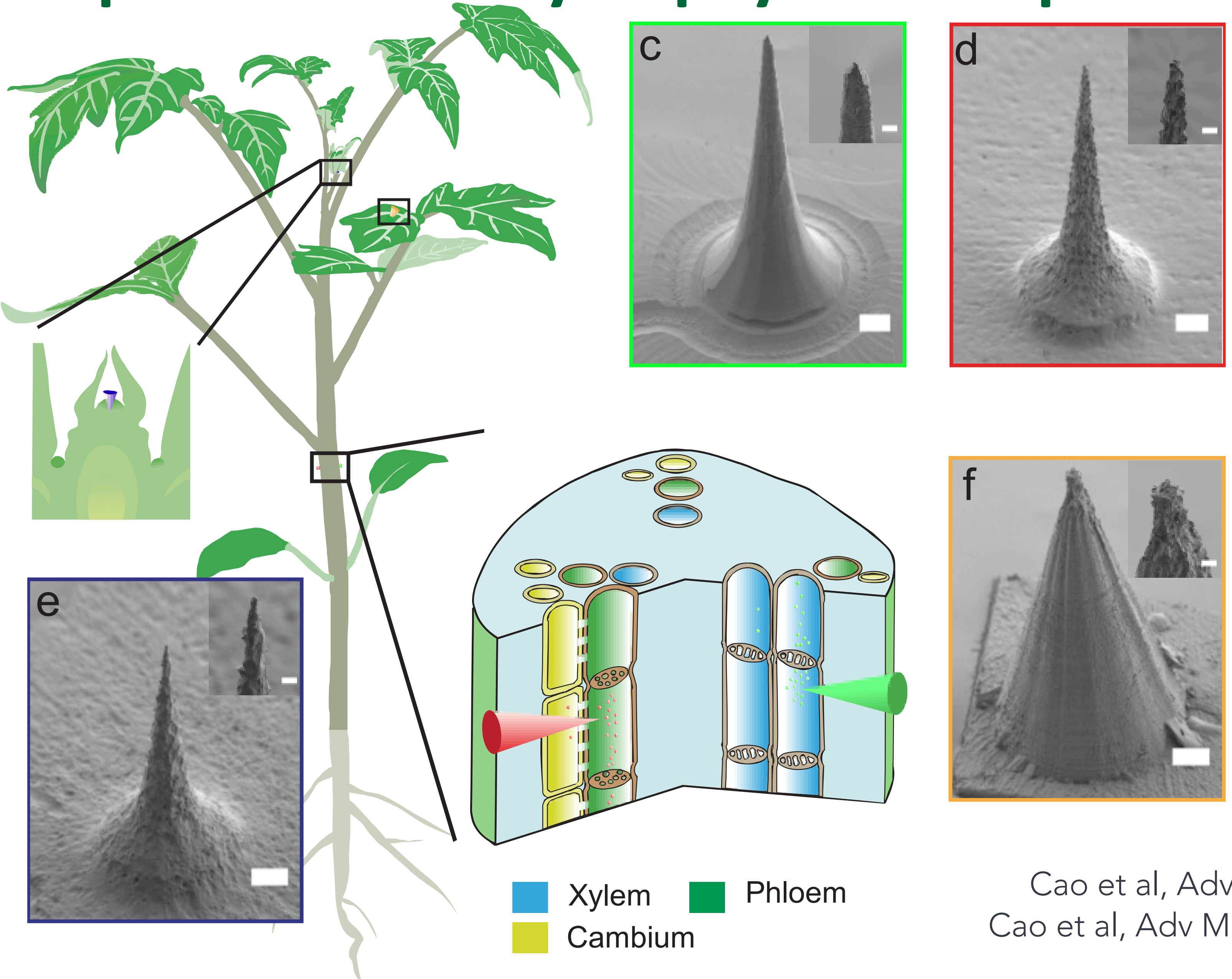
Drug Delivery in Plants Using Microneedles



Cao et al, Adv. Mater., 2023 ; Cao et al, Adv. Sci., 2020

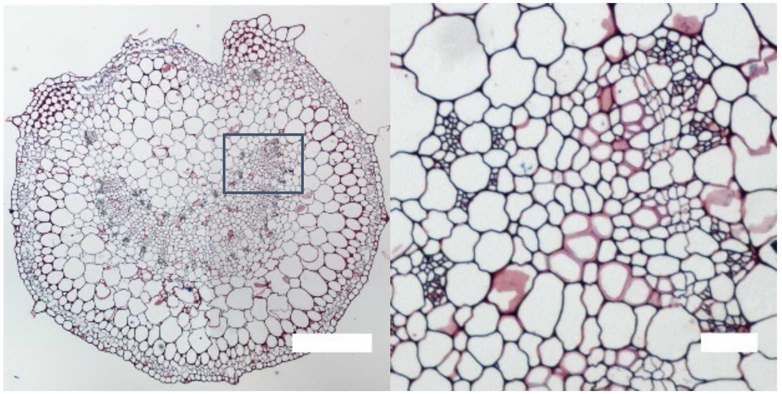
Multiscale and precise delivery of payloads in planta

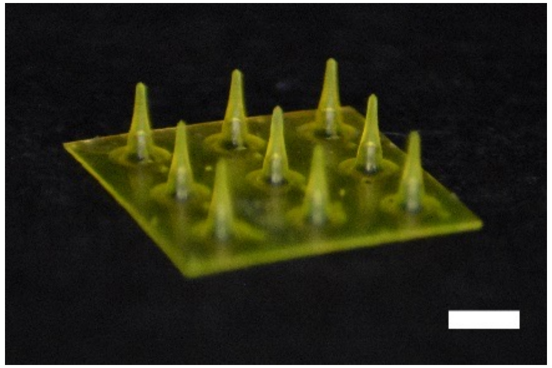


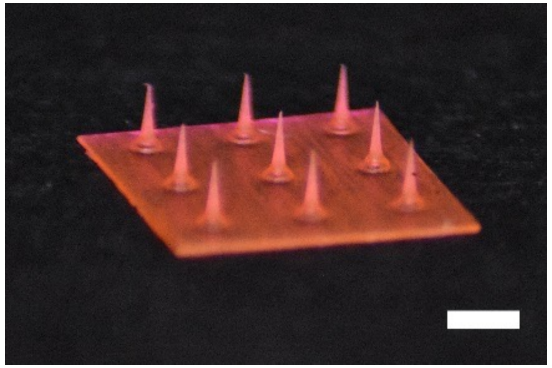


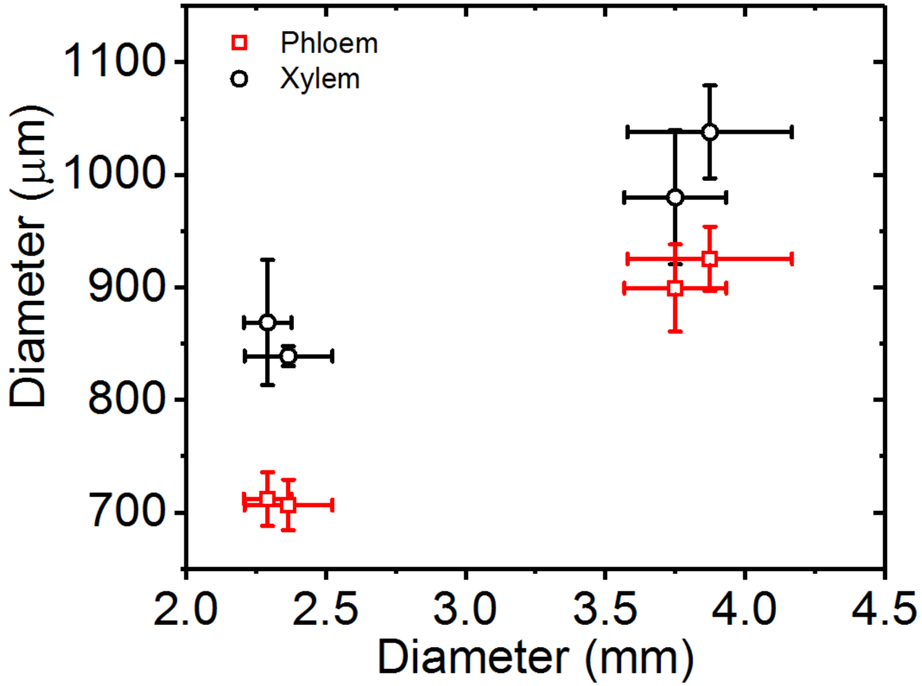
Cao et al, Adv Sci, 2020
Cao et al, Adv Mater, 2023

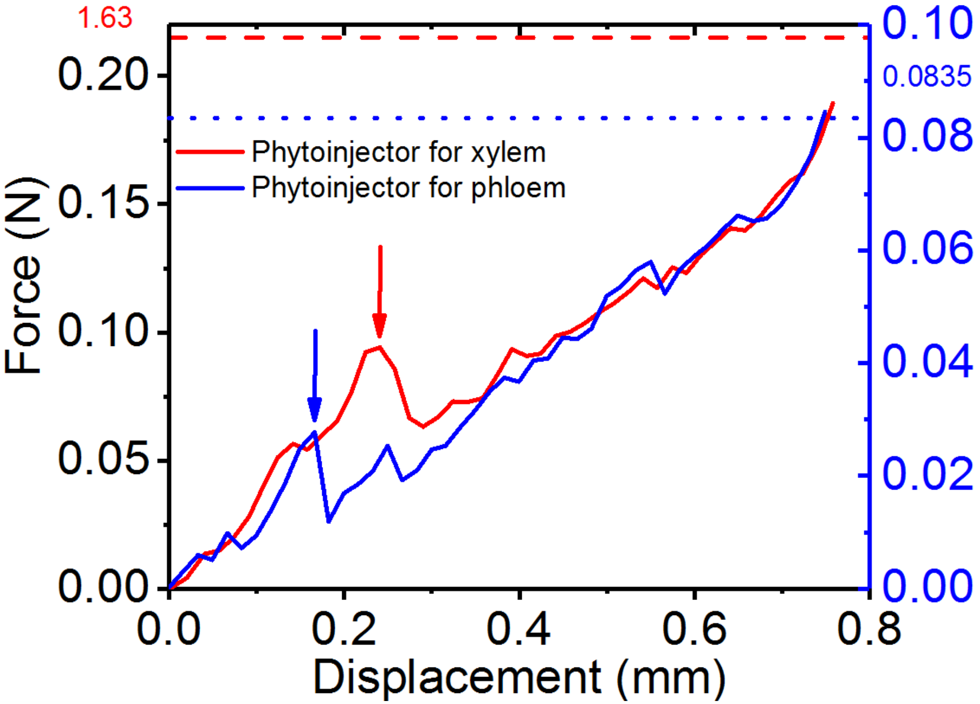
Multiscale and precise delivery of payloads in planta





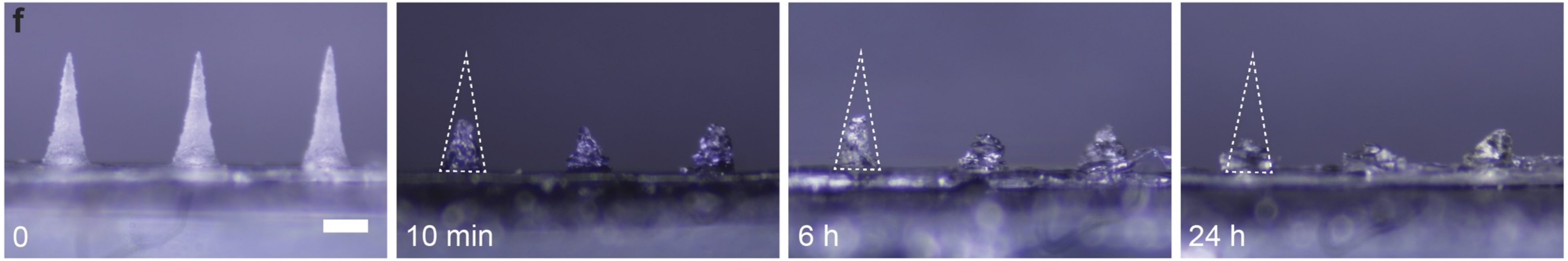




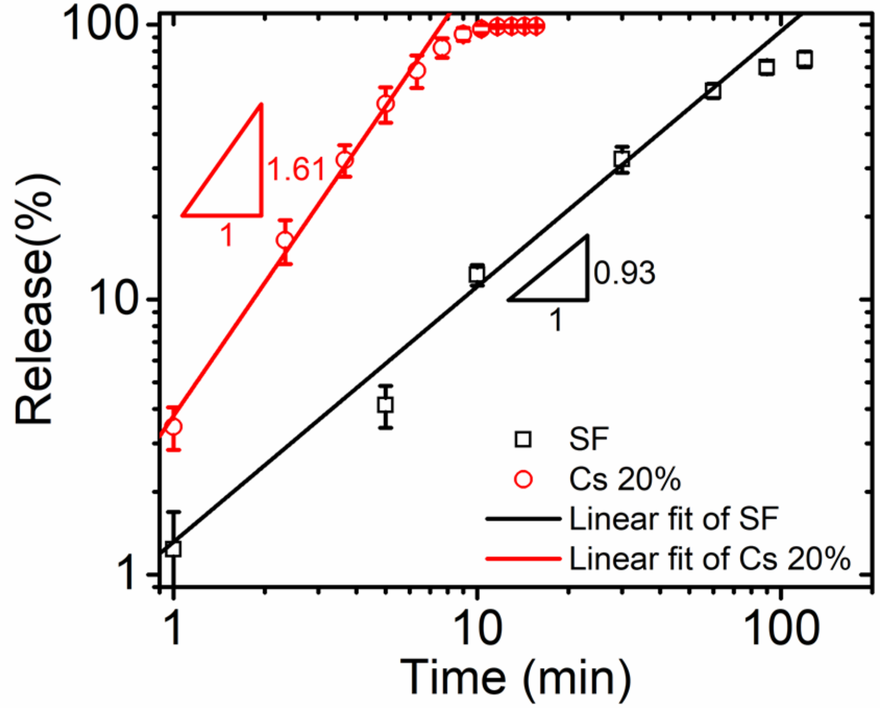


Cao et al, Adv Sci, 2020

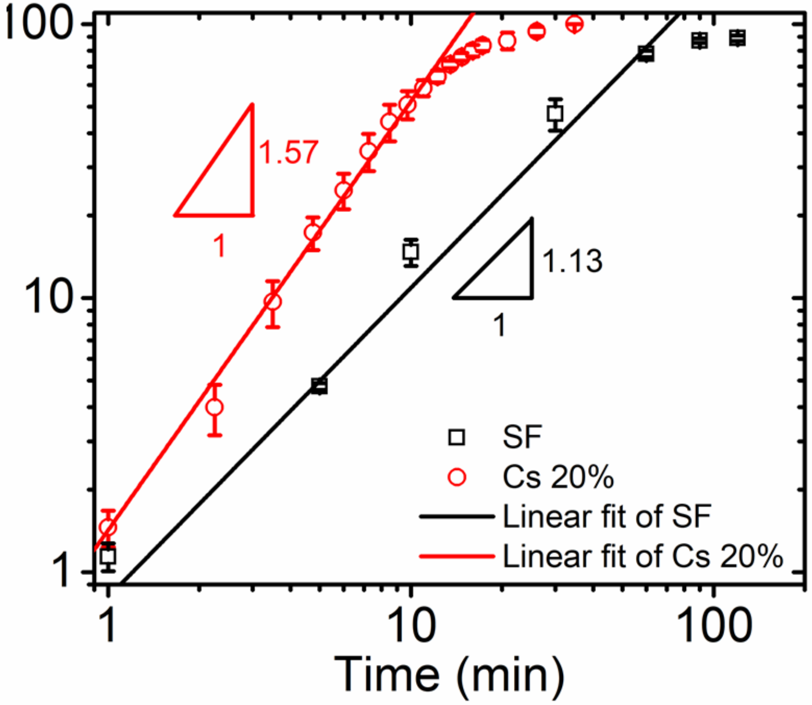
Multiscale and precise delivery of payloads in planta



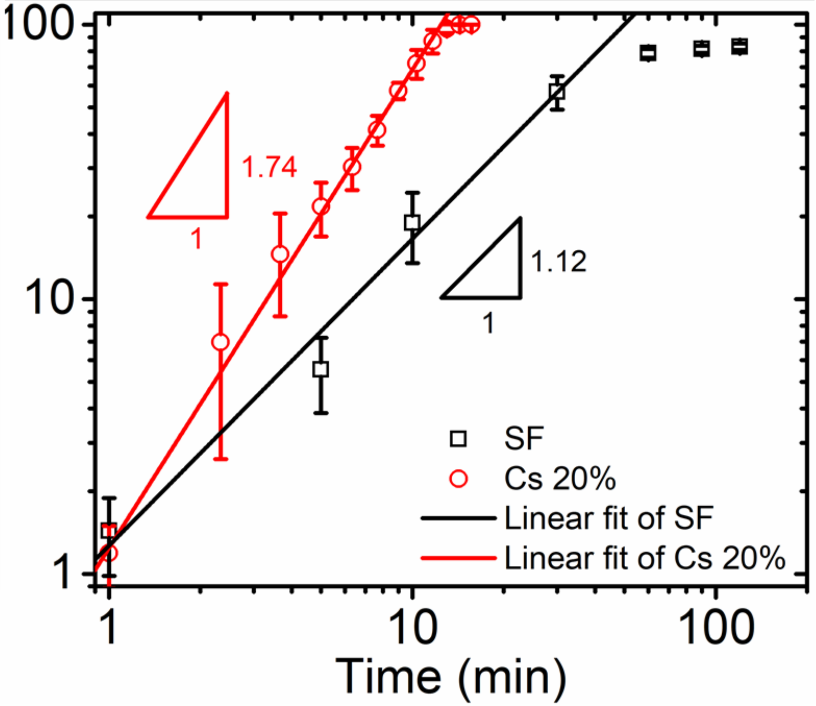
Rhodamine 6G



Azoalbumin



Agrobacterium



$$\frac{M_t}{M_\infty} = kt^n$$

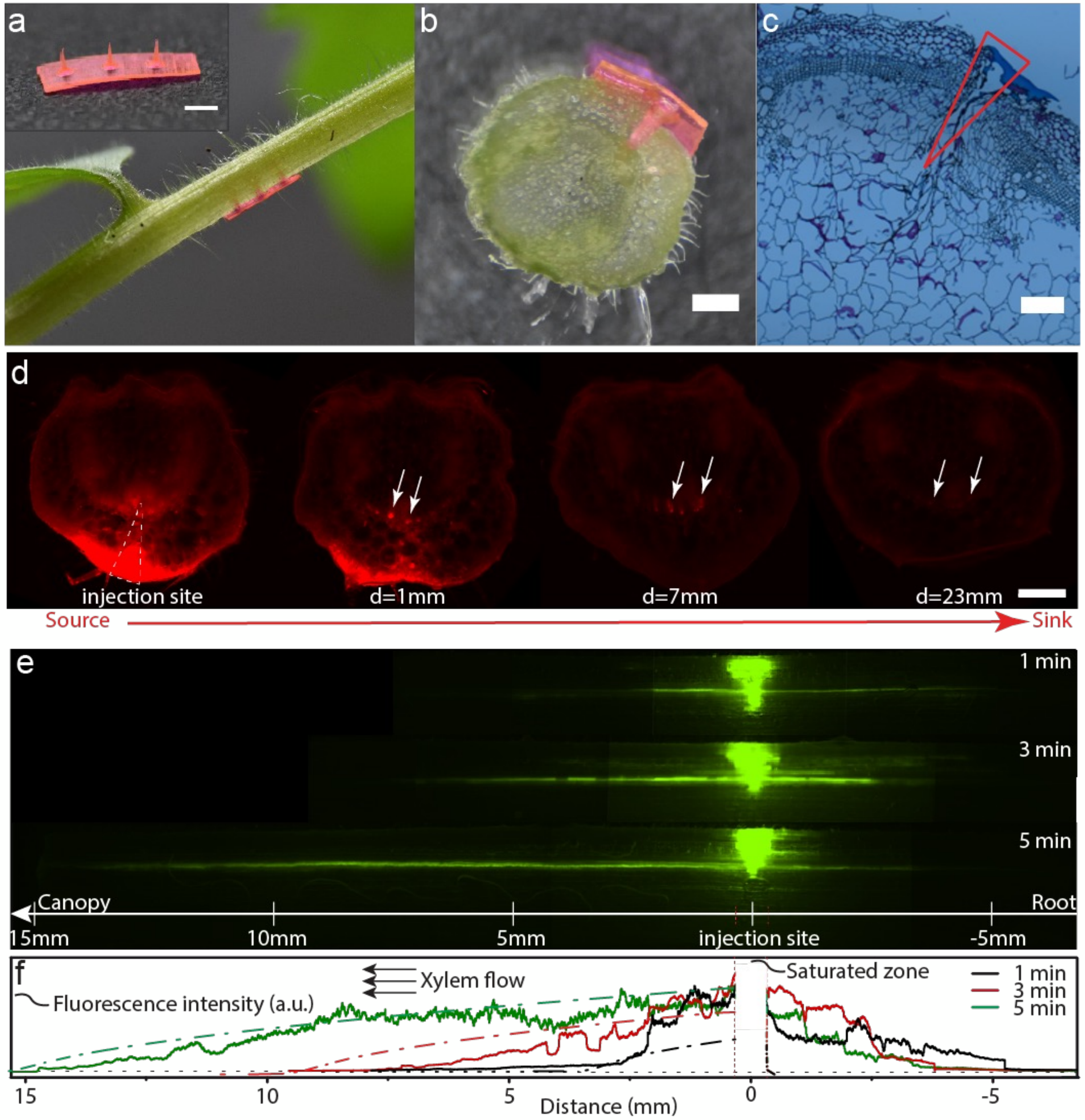
Cao et al, Adv Sci, 2020

Cao et al, Adv Mater, 2022

Multiscale and precise delivery of payloads in planta

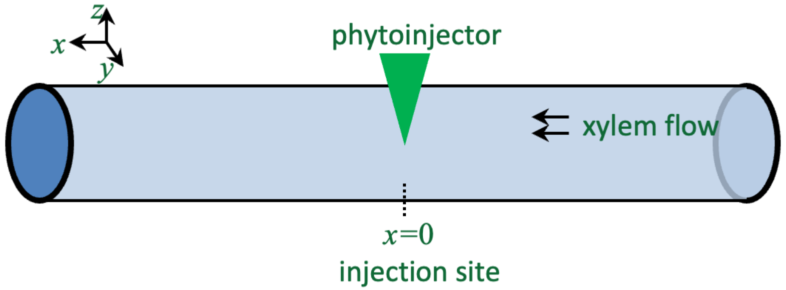
Cao et al, Adv Sci, 2020

Multiscale and precise delivery of payloads in planta



Cao et al, Adv Sci, 2020

Multiscale and precise delivery of payloads in planta



convection-diffusion equation for incompressible fluid without source or sink

$$\frac{\partial c}{\partial t} = \nabla \cdot (D \nabla c) - \boldsymbol{v} \cdot \nabla c$$

1-dimension

$$\frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2} - u \frac{\partial c}{\partial x}$$

$\mathrm{IC{:}}\ (\mathrm{x}, 0) = 0$

$\mathrm{BCs{:}}\ \mathrm{c}(0, \mathrm{t}) = \mathrm{c}_0(\mathrm{t}),\ \mathrm{c}(\infty, 0) = 0$

Concentration distribution

$$c(x,t) = \frac{|x|}{\sqrt{4\pi D}} e^{\frac{ux}{2D} - \frac{u^2 t}{4D}} \int_0^t \frac{c_0(\tau)}{\sqrt{(t-\tau)^3}} e^{\frac{u^2 \tau}{4D} - \frac{x^2}{4D(t-\tau)}} d\tau$$

$\mathrm{c}_0(\tau)$ determined by mass conservation:

$$M_t = M_\infty k t^n = \int_{-\infty}^{+\infty} c(x,t)dx \qquad (M_t < 0.6 M_\infty)$$

$M_t < 0.6 M_\infty$ is required by power law release.

Phytoinjector is a point source but is considered via mass conservation instead of a source.

Upon all payloads released

$$M_\infty = \int_{-\infty}^{+\infty} c(x,t)dx$$

We here only focus on the release period where

$$M_t < 0.6 M_\infty$$

It is hard to get an analytical solution for the integral equation. So we tried a numerical method.

Cao et al, Adv Sci, 2020

Multiscale and precise delivery of payloads in planta

By Taylor series (n denotes time and i is position)

$$\left(\frac{\partial c}{\partial t}\right)_i^n = \frac{c_i^{n+1} - c_i^n}{\Delta t} + O(\Delta \mathrm{t})$$

$$\left(\frac{\partial c}{\partial x}\right)_i^n = \frac{c_{i+1}^n - c_{i-1}^n}{2\Delta x} + O(\Delta x^2)$$

$$\left(\frac{\partial^2 c}{\partial x^2}\right)_i^n = \frac{c_{i+1}^n - 2c_i^n + c_{i-1}^n}{\Delta x^2} + O(\Delta x^2)$$

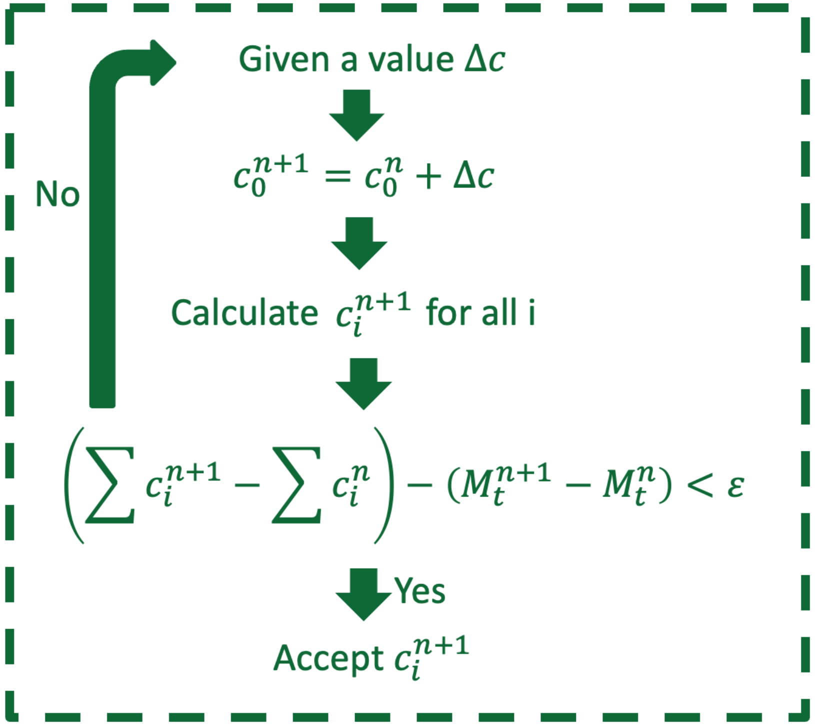
$$\frac{\partial c}{\partial t} = D\frac{\partial^2 c}{\partial x^2} - u\frac{\partial c}{\partial x}$$

$$\frac{c_i^{n+1} - c_i^n}{\Delta t} = D\frac{c_{i+1}^n - 2c_i^n + c_{i-1}^n}{\Delta x^2} - u\frac{c_{i+1}^n - c_{i-1}^n}{2\Delta x} + O(\Delta t, \Delta x^2)$$

$$c_i^{n+1} = c_i^n - \frac{u\Delta t}{2\Delta x}(c_{i+1}^n - c_{i-1}^n) + \frac{D\Delta t}{\Delta x^2}\left(c_{i+1}^n - 2c_i^n + c_{i-1}^n\right)$$

$c_\infty^n = 0$

To determine $\mathrm{c}_0(\mathrm{t})$, we used mass conservation.



Given a value Δc

$c_0^{n+1} = c_0^n + \Delta c$

Calculate c_i^{n+1} for all i

$$\left(\sum c_i^{n+1} - \sum c_i^n\right) - (M_t^{n+1} - M_t^n) < \varepsilon$$

Accept c_i^{n+1}

Constants:

$D = 4{\times}10^{-10} m^2/s$ (small dye molecule, ~600Da)

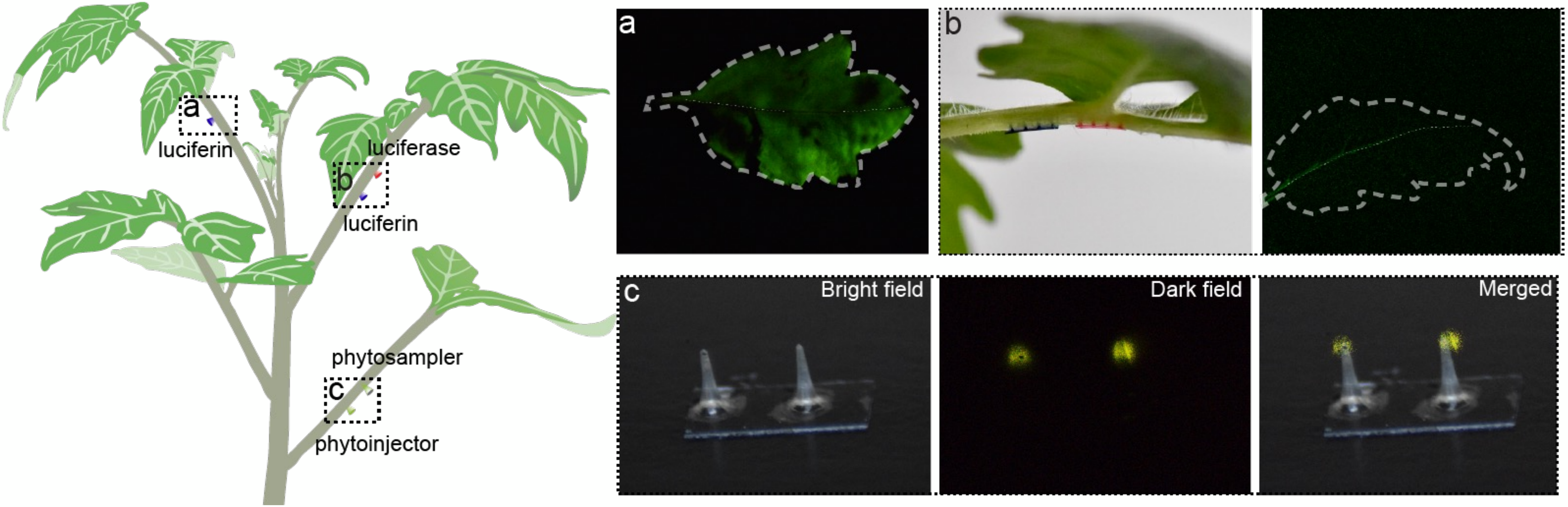
$u = 5{\times}10^{-5} m/s$ (based on observation)

$k = 0.038$ (power law release, time unit minute)

$n = 1.61$ (power law release)

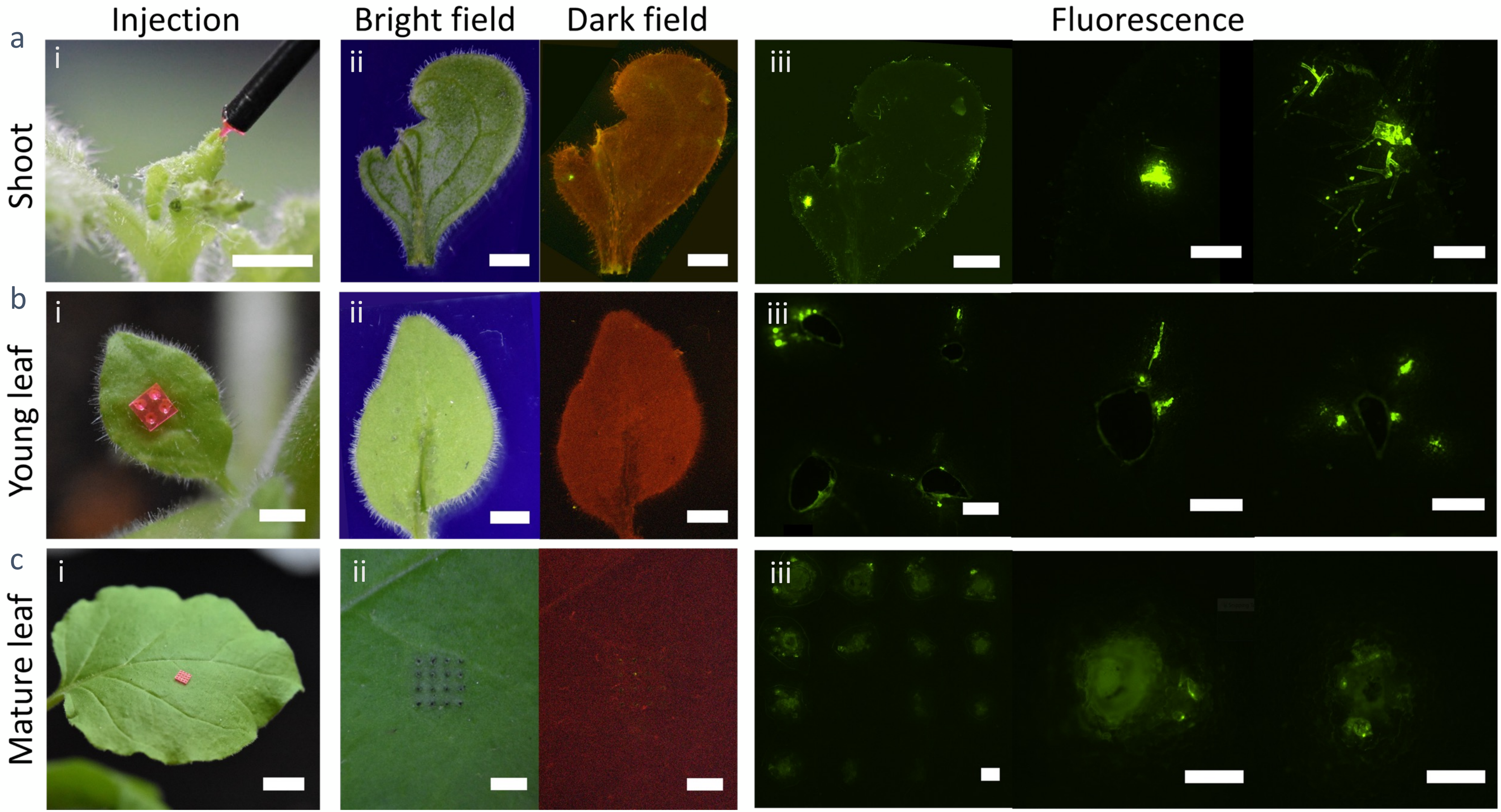
Cao et al, Adv Sci, 2020

Multiscale and precise delivery of payloads in planta



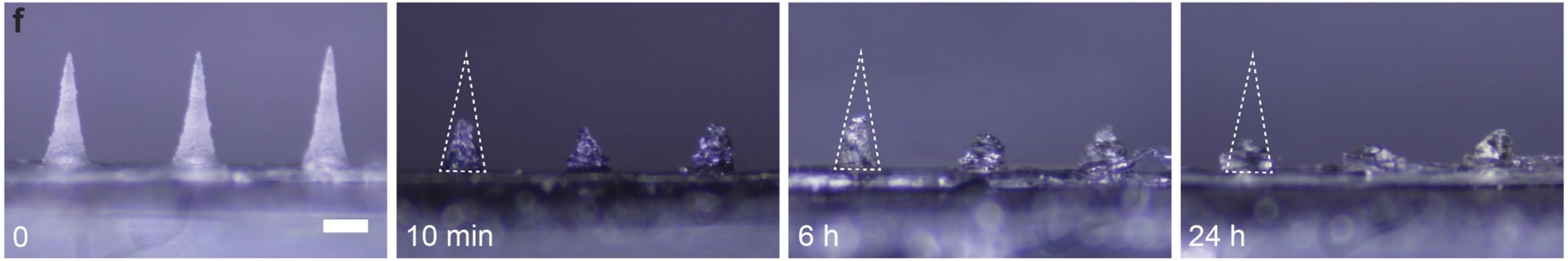
Cao et al, Adv Sci, 2020

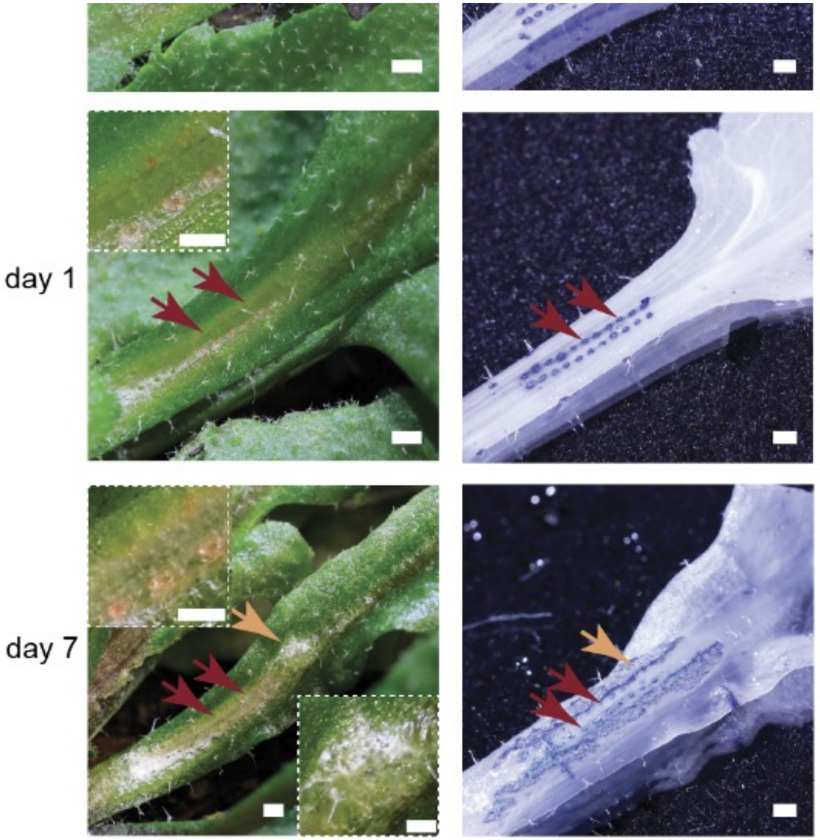
Multiscale and precise delivery of payloads in planta

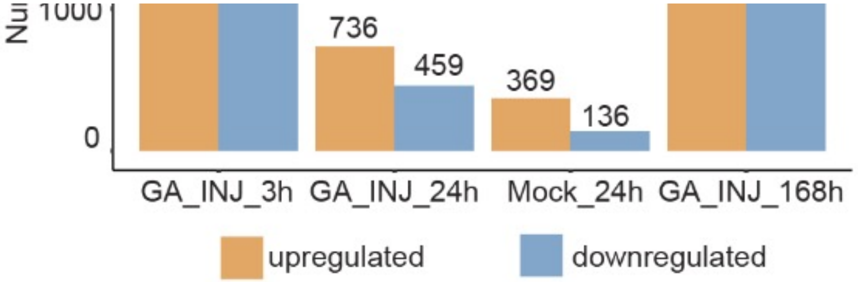


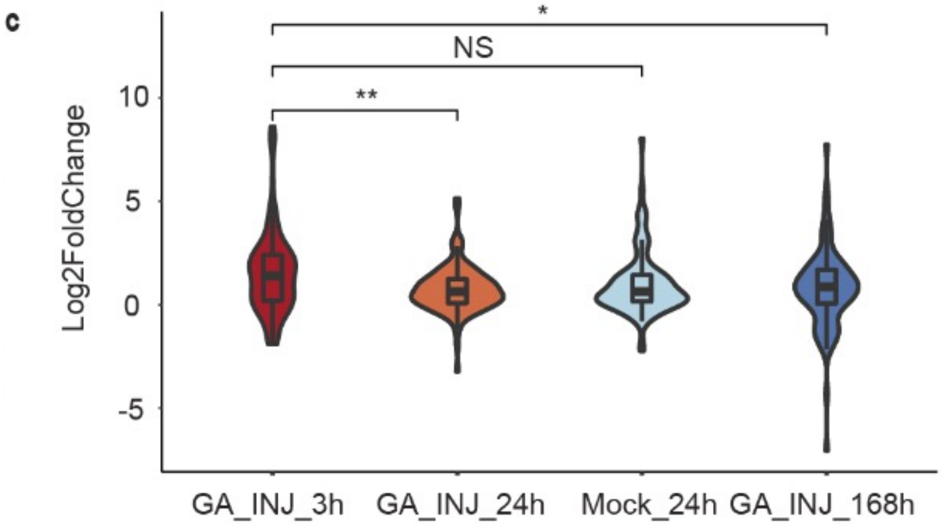
Cao et al, Adv Sci, 2020

Wounding response induced by microneedles





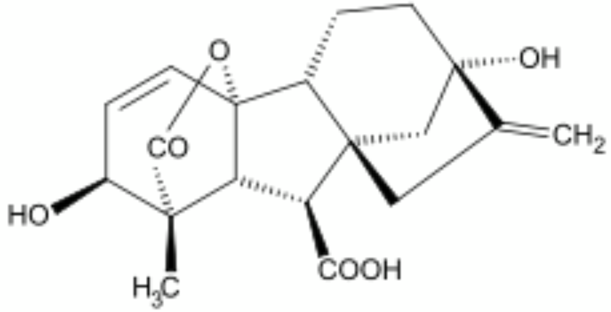




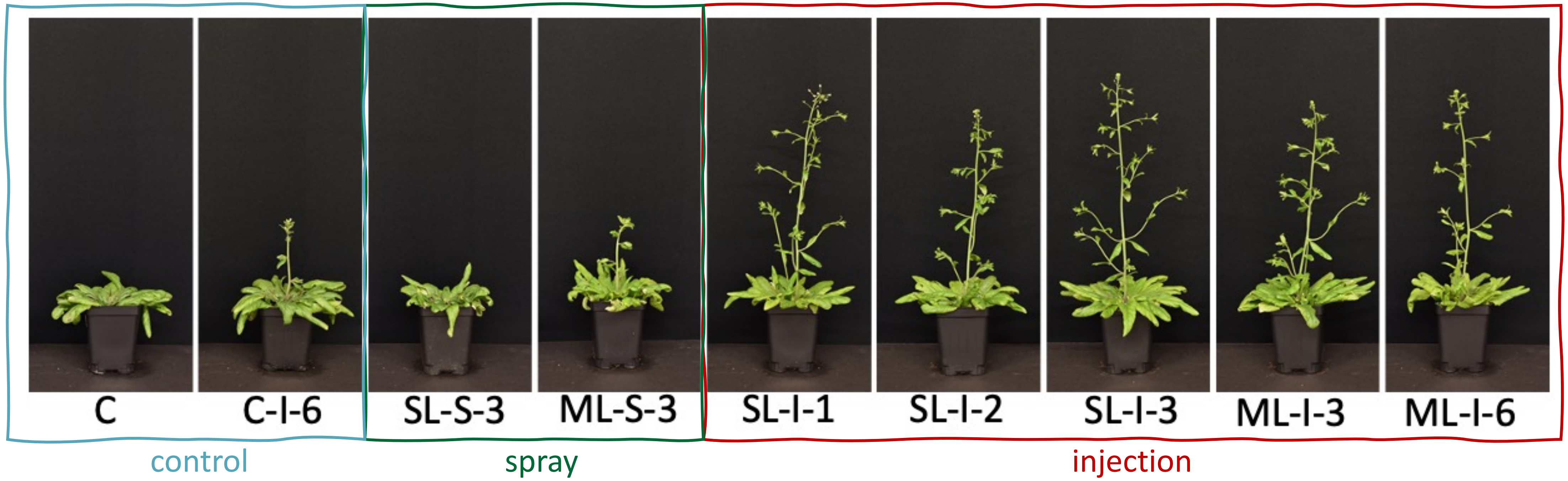
Changes in expression of 103 wounding response genes found in response to wounding GO:0009611 term.

Cao et al, Adv Mater, 2022

Delivery of hormones in planta - GA



Gibelleric acid



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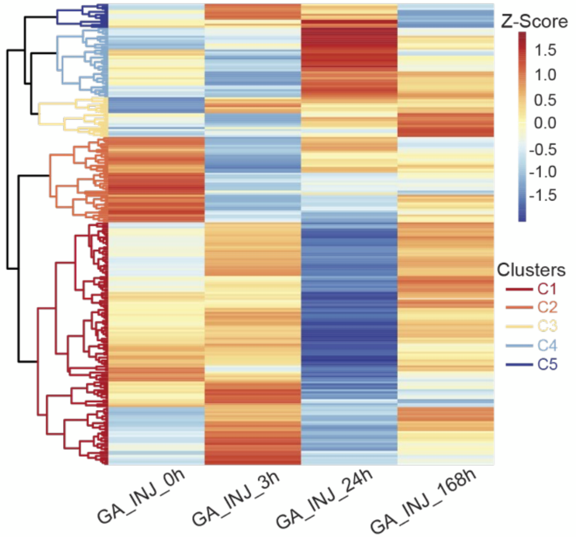
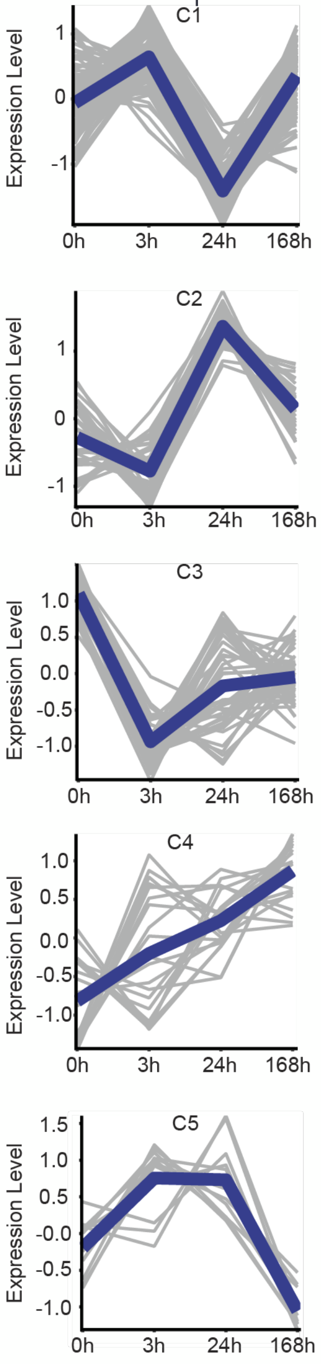
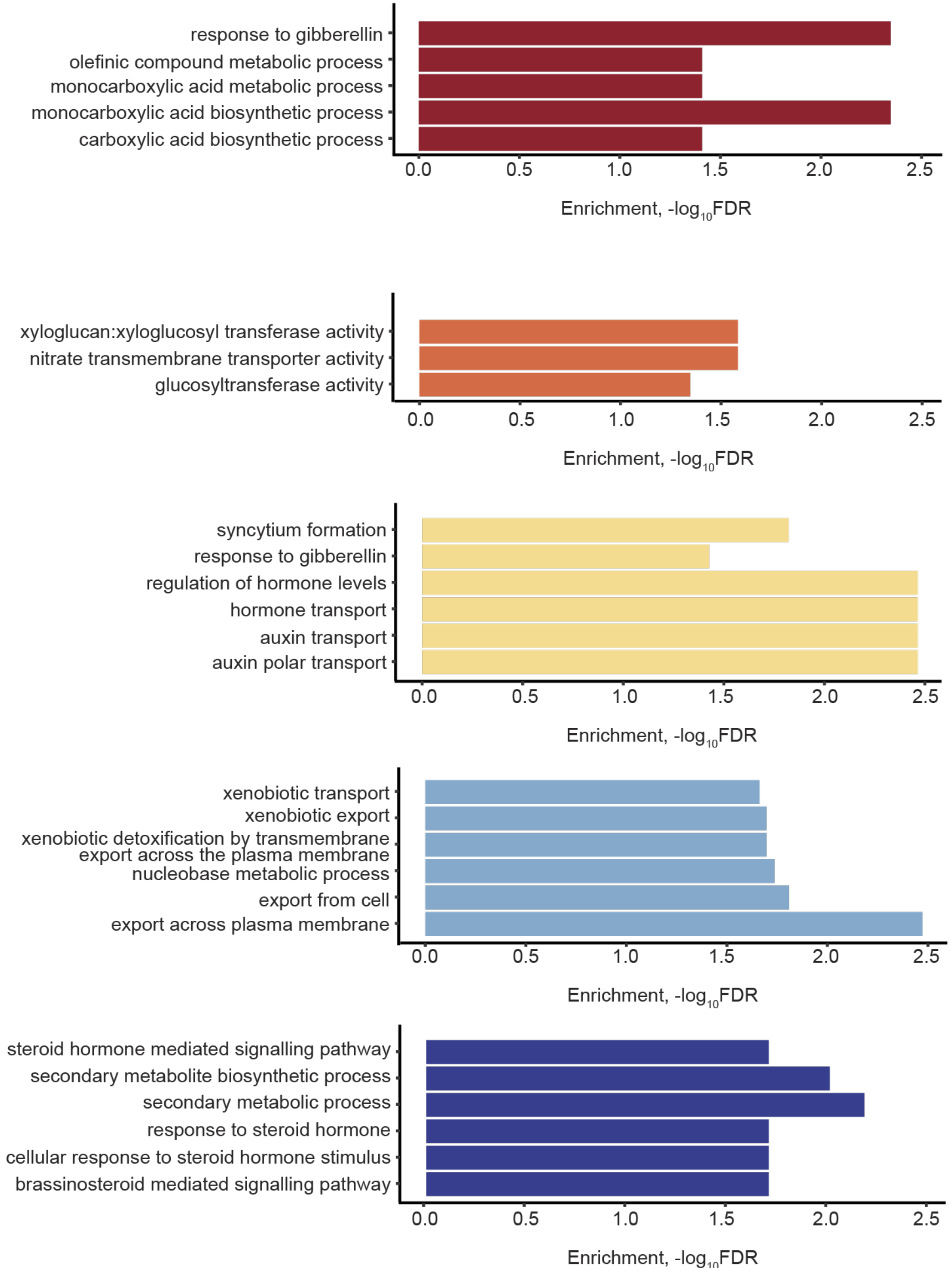
GO enrichment analysis



Z-scored expression level



Top 6 enriched GO terms (FDR<0.01)



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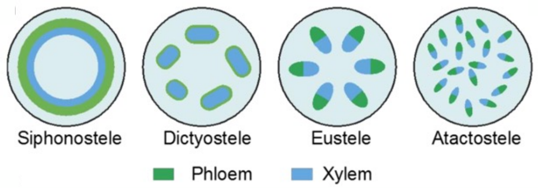
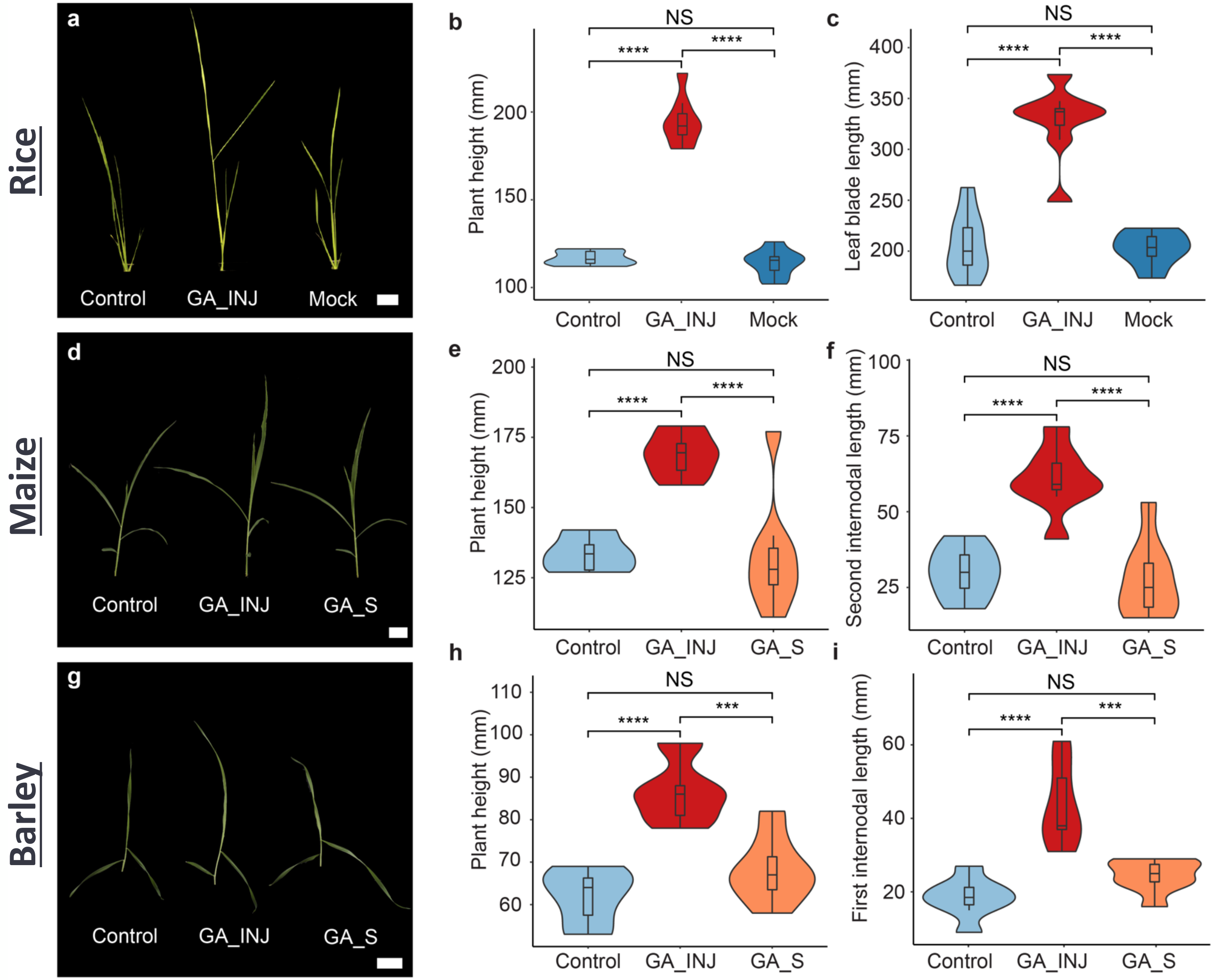
GA Delivery in planta





Cao et al, Adv Mater, 2022

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