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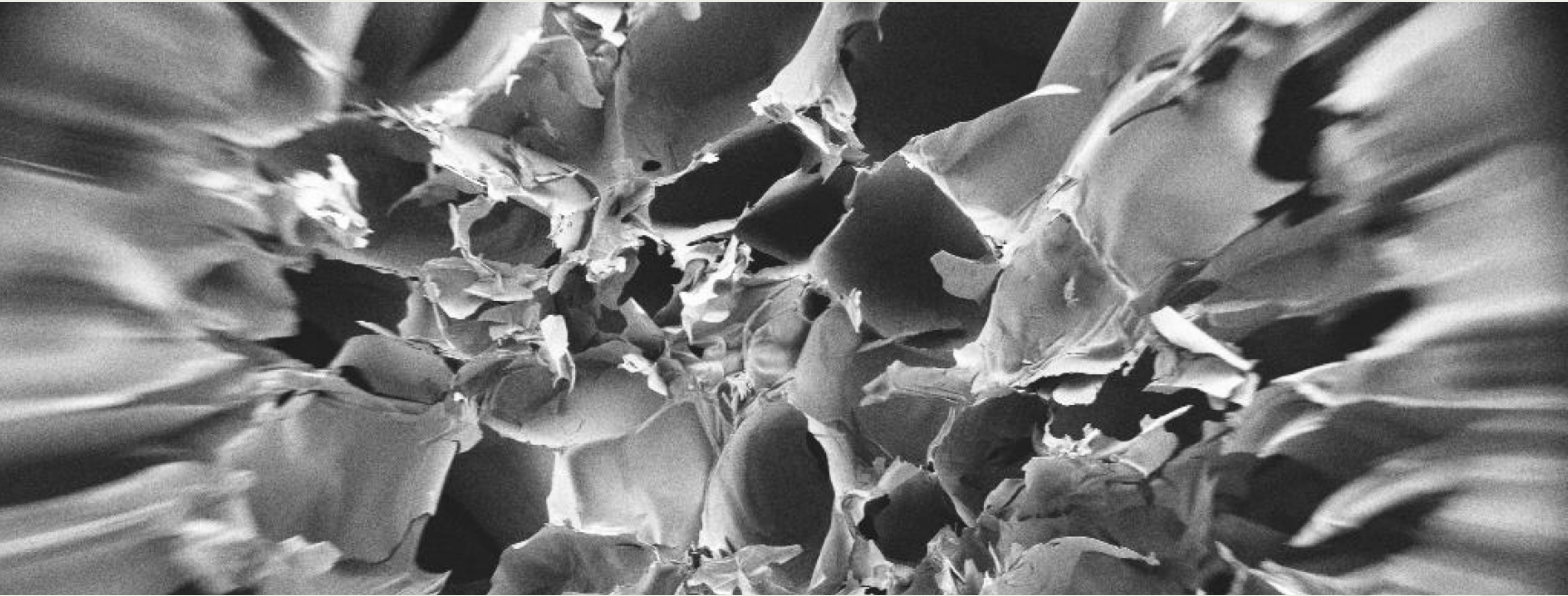
Center for Development, Demonstration and Training for Carbon-Free Technologies



Functional Hydrogels for Energy Applications

Superaerophobic Electrode Coatings

Vojtěch Škopek, Filipa A. Andre Vicente, Blaž Likozar, Ilja Gasan Osojnik Črnivec*

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Scientists 4Future Slovenia

European Commission

SEAL OF EXCELLENCE

aris

CarbNETs

ENFiber COST Action CA24111

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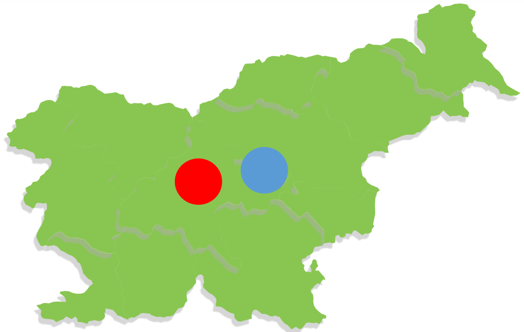
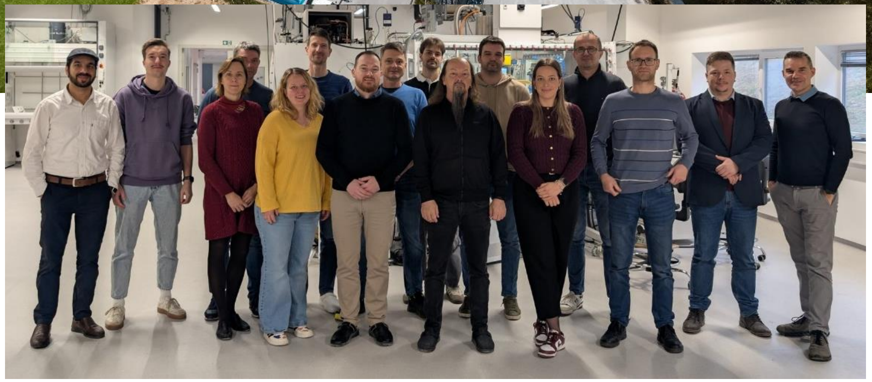
National Institute of Chemistry (NIC)
Ljubljana, Slovenia



Center for development, demonstration and training for zero carbon technologies Kisovec, Slovenia

Undergoing full renovation

Fully operational in 2026, 32 mio EUR investment



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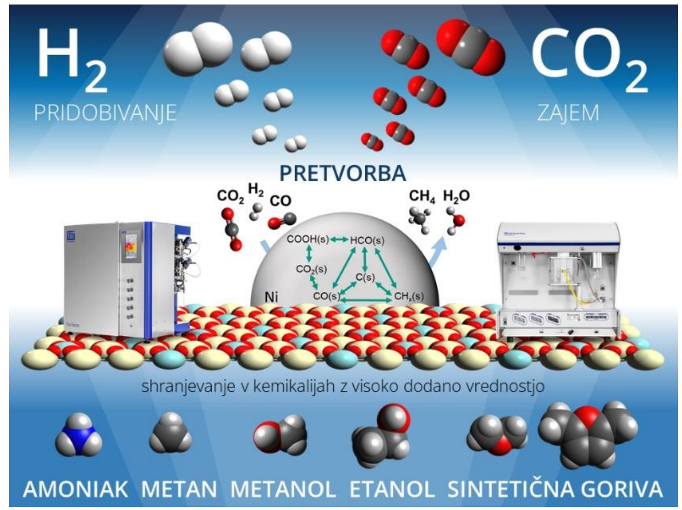
L52 Laboratory for Demonstration of H_2 and CO_2 Technologies



Chemical engineering for alternative energy, fine chemical production, decarbonisation and energy intensive industries, at industrially relevant operating conditions.

MATERIALS	**catalysts, sorbents, electrodes, membranes**
CATALYSIS	**gas to gas, gas to liquid standard, HT, HP**
ELECTROLYSIS	**AEM, PEM, water, hybrid**

including support to cross-cutting biological processes and waste utilisation challenges

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NATIONAL INSTITUTE OF CHEMISTRY

L52 Laboratory for Demonstration of H_2 and CO_2 Technologies
Prof. Dr. Ilja Gasan Osojnik Črnivec, gasan.osojnik@ki.si

Resilience and Energy Efficiency
Opportunities in decarbonization

Green Hydrogen

for sustainable industrial processes

HyBReED
SI H_2 and battery
RRI – TRL 3-6

ENERGY CARRIER

substitution of fossil energy carriers
SI: glass ✓, ceramic, lime, metallurgic – aluminum, (steel)
long-haul transport: ships, trucks, …

HEAT RECOVERY

utilization of high temperature industrial heat

ELECTROLYSIS & BIOMETHANE

standalone production of hydrogen
SI: glass and chemical industry

FEEDSTOCK

substitution of fossil hydrogen sources
methanol, ethanol, jet fuel, ammonia etc.

Carbon Capture

supporting H_2 technologies and biomass recovery

CarbNETs
CO_2 heat &
water

NOVEL SORBENTS & TECH

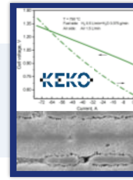
(CO_2 composition, process heat, gas purity)

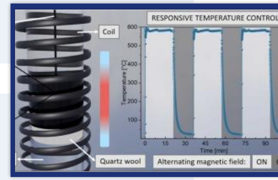
FEEDSTOCK

fuels, polymers, advanced ceramics/minerals

Water Security

supporting decarbonization





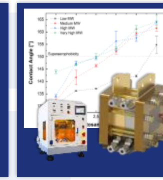
ELECTROLYSIS

Water treatment and alternative water sources

BIOBASED MATERIALS

Biobased sorbents for emerging pollutants
and hazardous gasses removal

Biobased PFAS-free advanced coating
and polymer adhesive alternatives

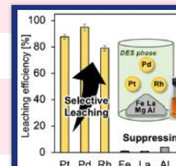


NOVEL PROCESSES

Residual water production
High pressure electrolysis

Critical Raw Materials

value chains for high added value materials



ADVANCED NANOMATERIALS

novel selective recovery and/or separation of metals

PHOSPHOROUS RECOVERY

novel solvents and electrochemical extraction systems
SI value chain: sludges to technical agents, electrolytes,
electrodes and absorbent producers.

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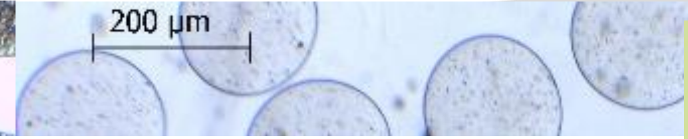
Features of bio-based hydrogels for protection and delivery



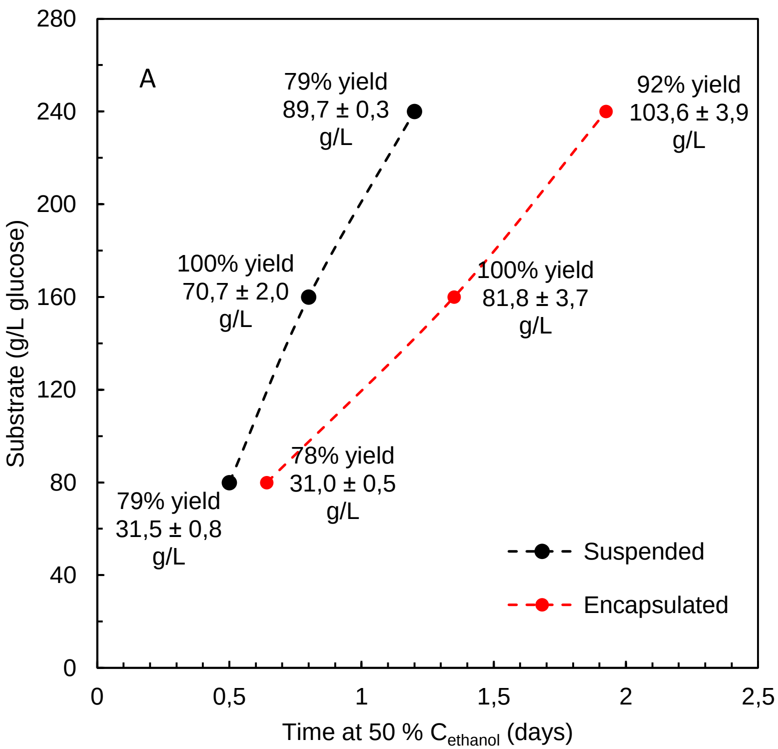
Adverse growth conditions

S. cerevisiae

high gravity conditions

growth medium: YPD @ 8 to 32 wt. % glucose

V_d = 50 mL, T_d = 24 °C, t_{50} shown on graph



Industrial culture collection UL BF

https://doi.org/10.3390/molecules26247484

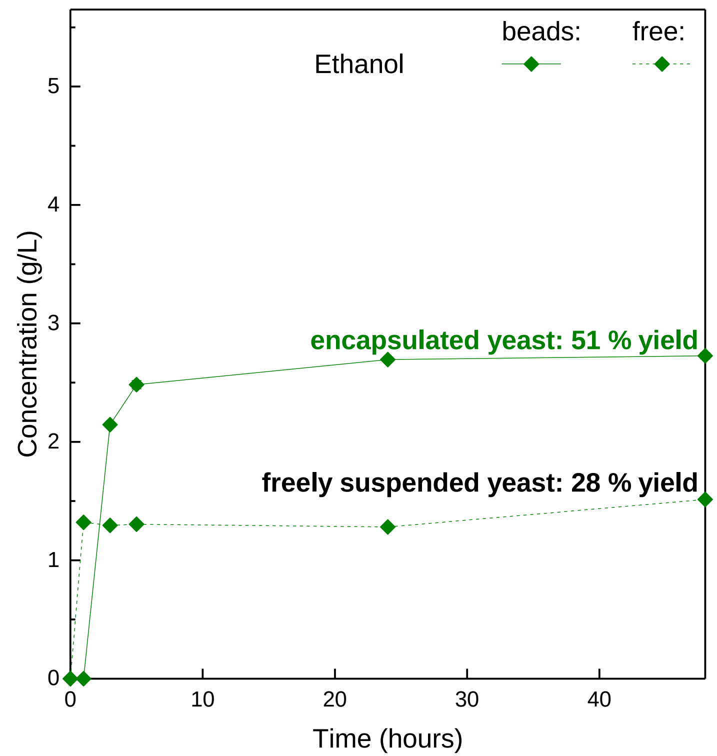
K. Marxianus

presence of organic acids

growth medium: modified MRS

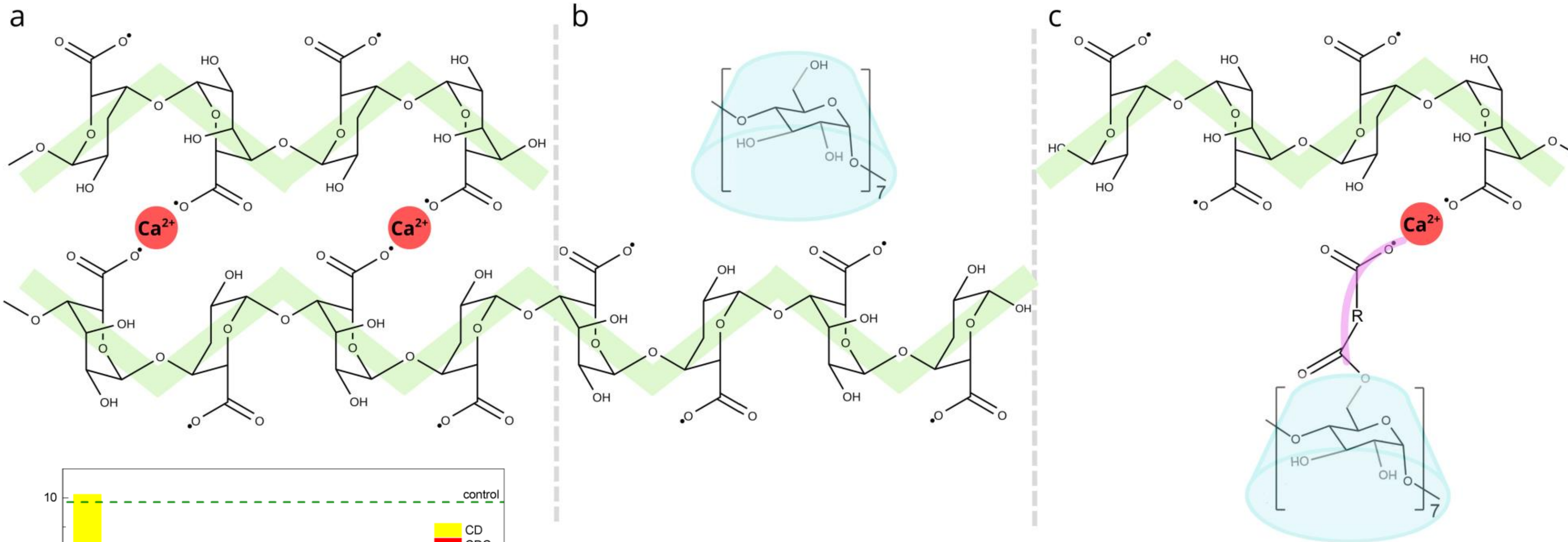
with 1 wt. % lactose, 1 wt. % lactic acid

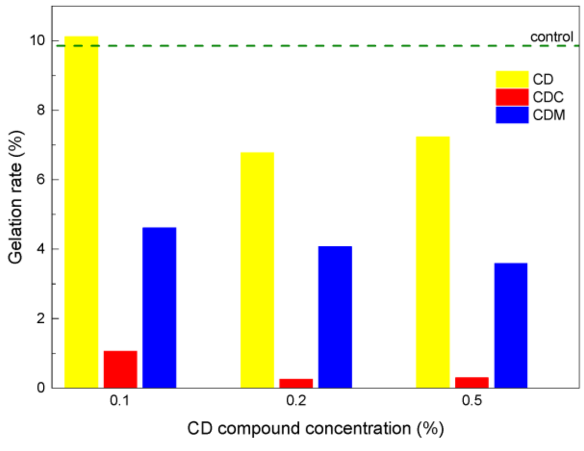
V_d = 50 mL, T_d = 38 °C, t_f = 48 hours

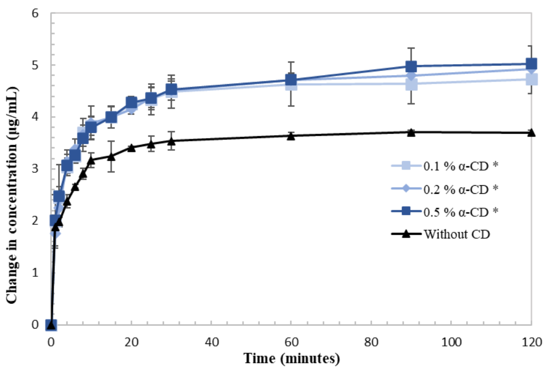


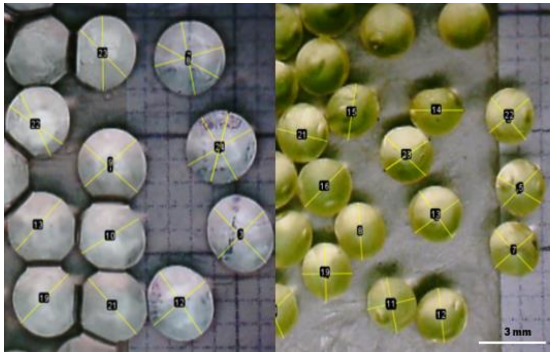
Gel porosity modulation

Alginate gel with
β-cyclodextrin inclusion









Cyclodextrin reduces solution viscosity (not shown), crosslinked gel deformation resistance (G') and increase flow (G'').
https://doi.org/10.3390/gels11110875

Cyclodextrin improves the rate and capacity for hydrophobic compounds integration (example for curcumin).
--in press--

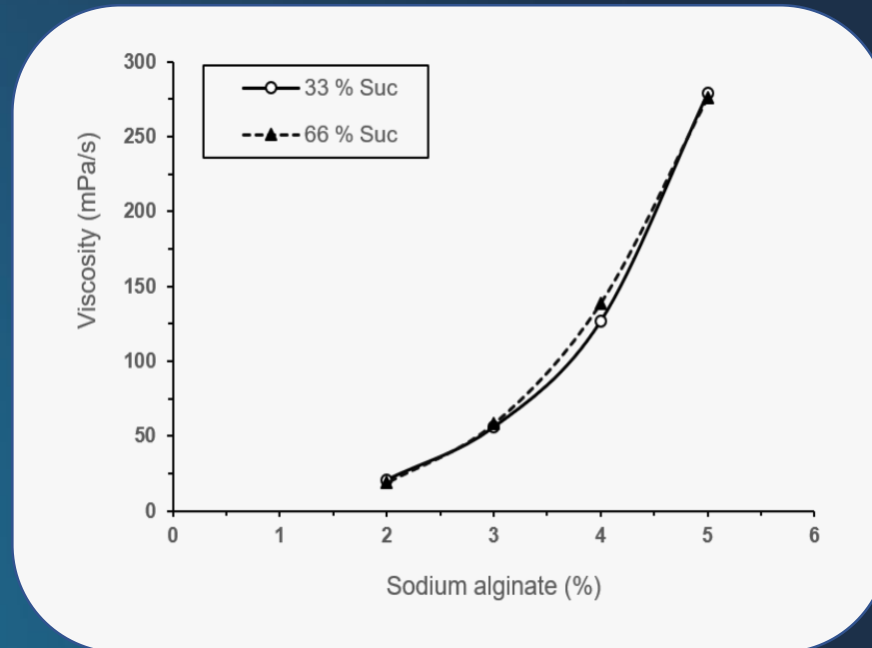
Tuning hydration

Alginate-based edible inks

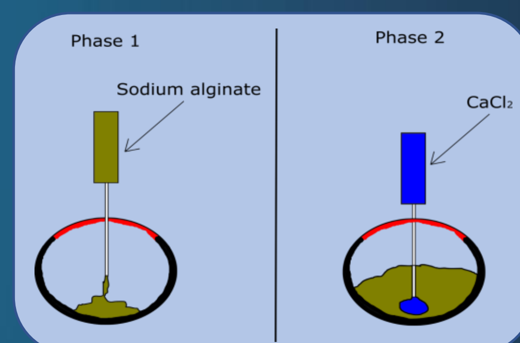
- Good stability in powdered and gel form
- Good encapsulation properties for gut delivery
- Vegan acceptable

Recipe takes in account:

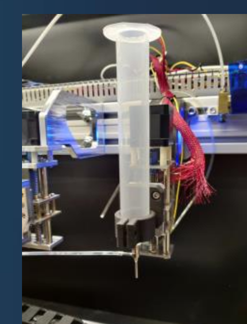
- Fast ion induced gelation (Ca^{2+})
- Fast solubility/hydration period in cold water (minutes at no/minimal mixing instead hours at intensive agitation)
- Versatile entrappment (also hydrophobic instead of only hydrophillic)
- All materials EFSA and FDA approved for food consumption



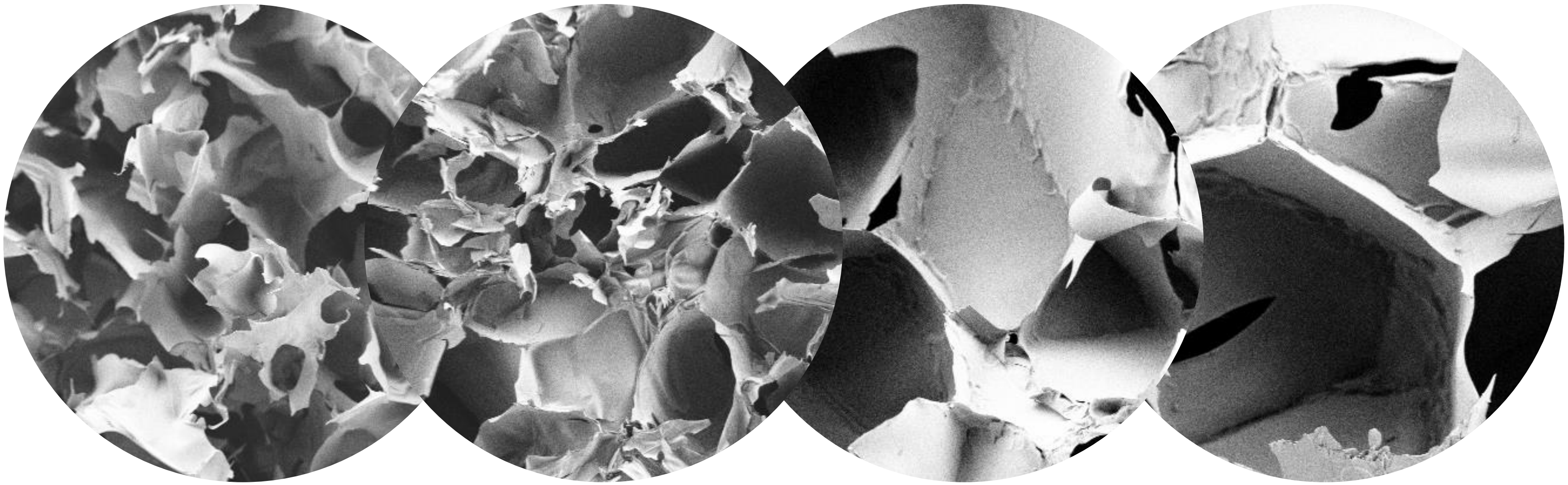
Viscosity of rapidly dissolving alginate matrix



Extrusion steps for the gelation of Na-alginate



Printing nozzle inside the machine



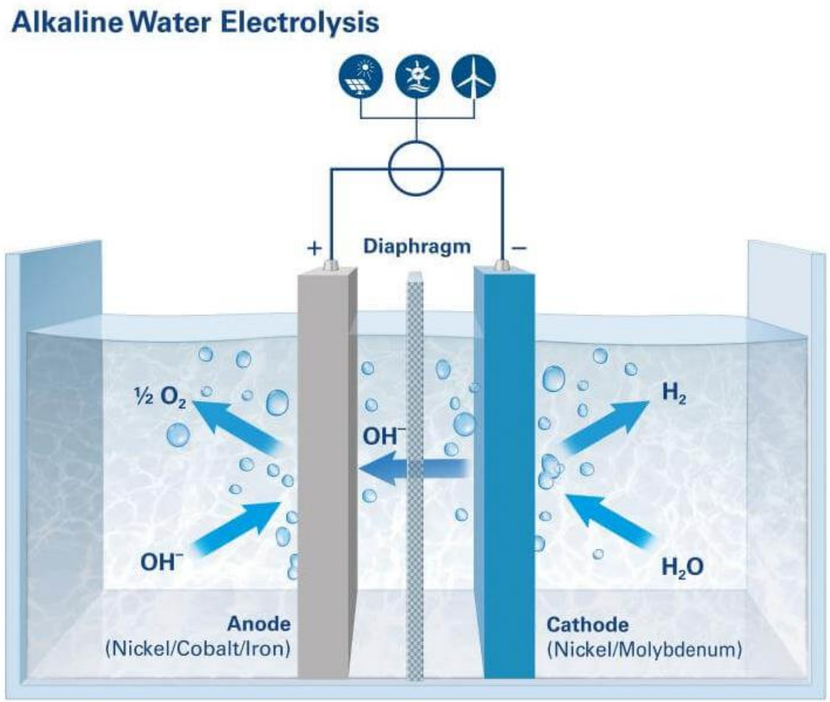
Functional coatings

Hydrogen

Versatile energy carrier

- the highest **energy content** per mass
- 15x lighter than air
- **Power-X** to for surplus energy

Storage and **transport** challenges, **on demand** production is beneficial.

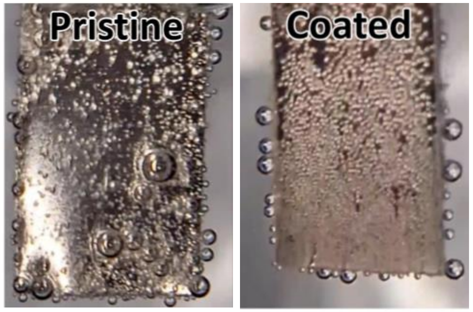


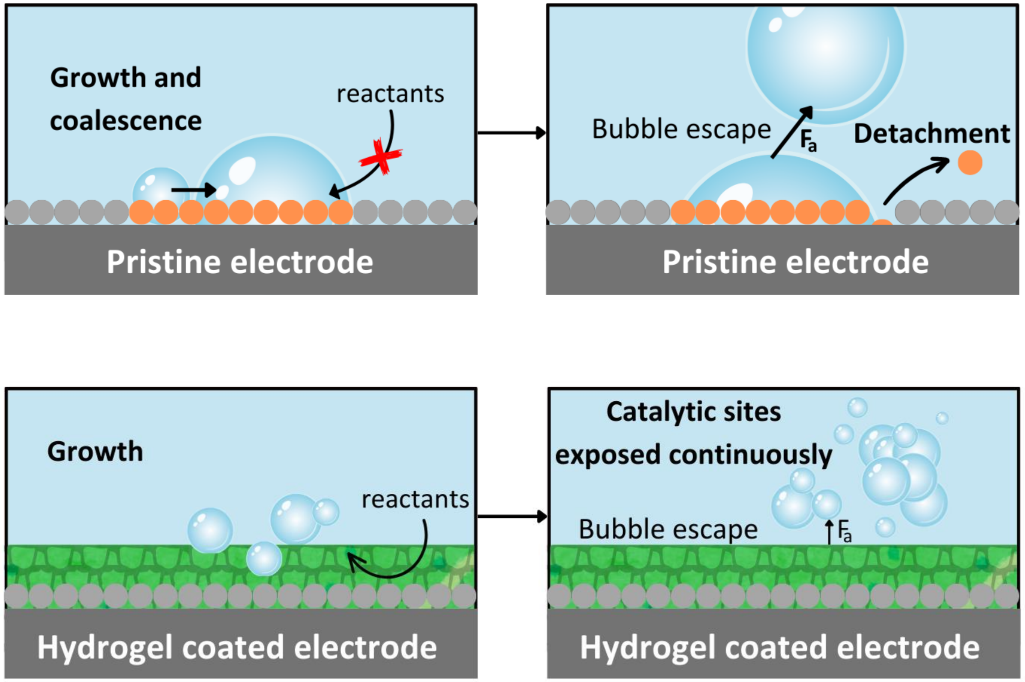
Water electrolyisis

- produces 99.99% **pure hydrogen**
- **green hydrogen** with PV/wind
- room temperature and ambient pressure
- Industrial feedstock
- can feed directly into fuel cells

Challenges in hydrogen evolution reaction (HER)

- **high energy consuption**
- **noble metals** as electrodes (e.g., Pt)
- gas bubble at electrodes **reduce efficiency** by blocking active sites
- new alternatives required to boost HER performance





SUPERAEROPHOBIC COATINGS[1]
- improved bubble detachment
- reduced overpotential
- overall boost in efficiency

However, **toxic** and **expensive**:
- **M13 virus** with specific coditions[2]
- Fossil based and persistent (polyallylethylamine, polyethyleneimine)[3]
- toxic crosslinker (glutaraldehyde)

[1] BAE, M. et al. Superaerophobic Polyethyleneimine Hydrogels for Improving Electrochemical Hydrogen Production by Promoting Bubble Detachment. In *Advanced Energy Materials* . 2022. Vol. 12, no. 29, s. 2201452. .
[2] JEON, D. et al. Superaerophobic hydrogels for enhanced electrochemical and photoelectrochemical hydrogen production. In Science Advances . 2020. Vol. 6, no. 15, s. eaaz3944. .
[3] KANG, Y. et al. Versatile, Stable, and Scalable Gel-Like Aerophobic Surface System (GLASS) for Hydrogen Production. In *Advanced Functional Materials* . 2024. Vol. 34, no. 2. .

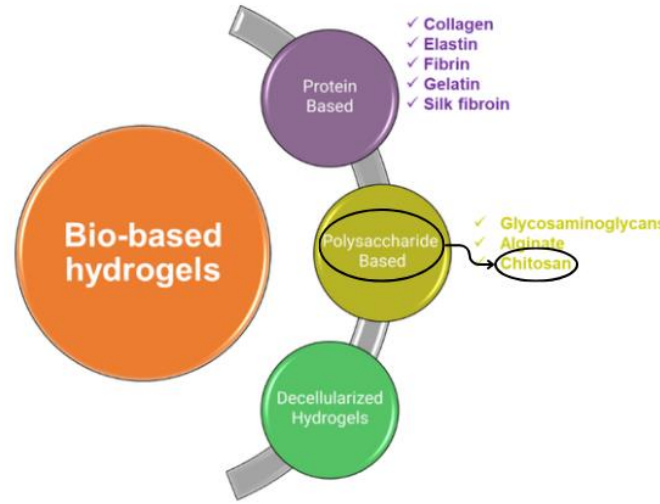
Towards alkaline resistant properties

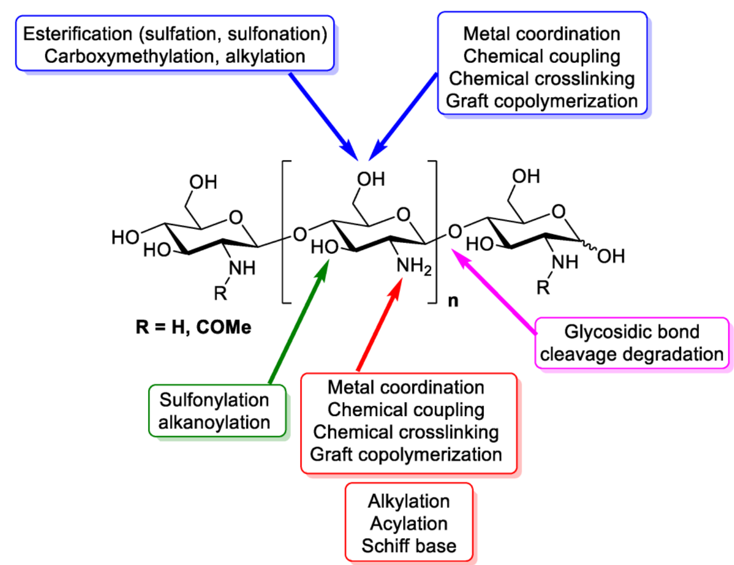
Chitosan

- Derived from chitin
- Only natural cationic polysaccharide
- Biocompatible, adhesive, modifiable
- High number of hydroxy and amino groups to achieve high hydrophilicity

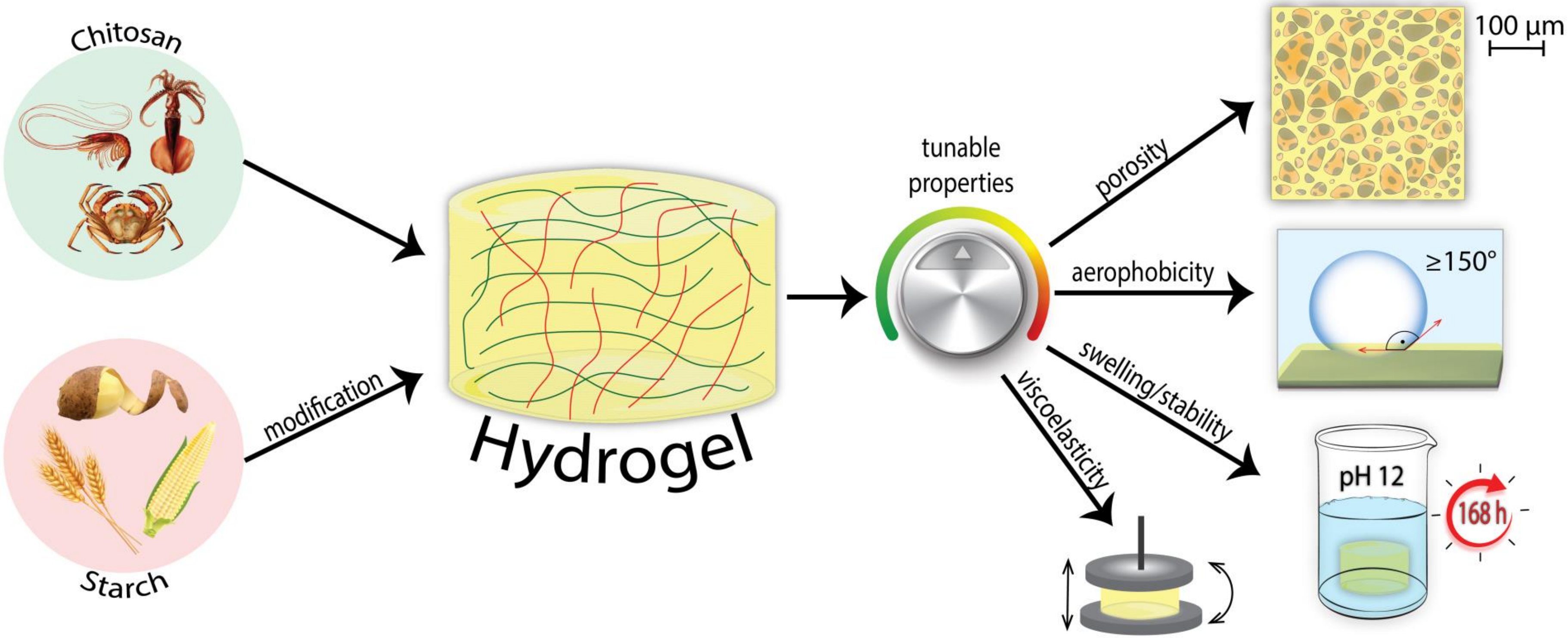
limitations

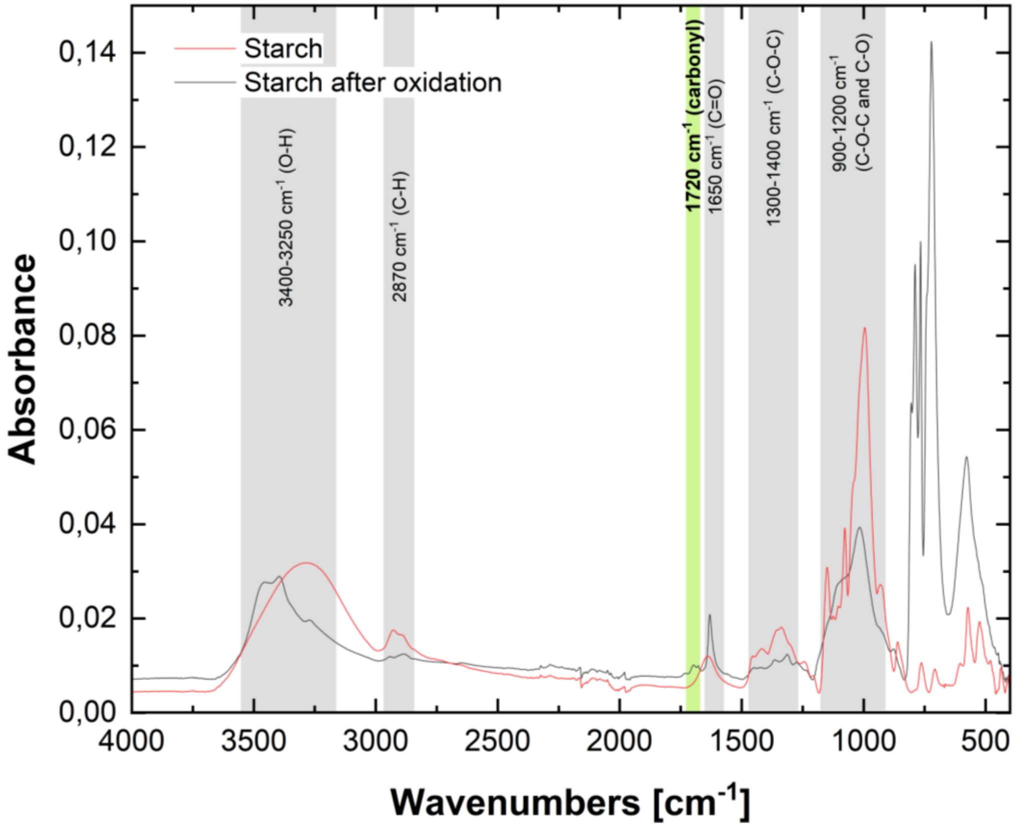
- Common crosslinkers are usually toxic (glutaraldehyde, glyoxal) or expensive (genipin)
- Searching for non-toxic and abundant alternatives



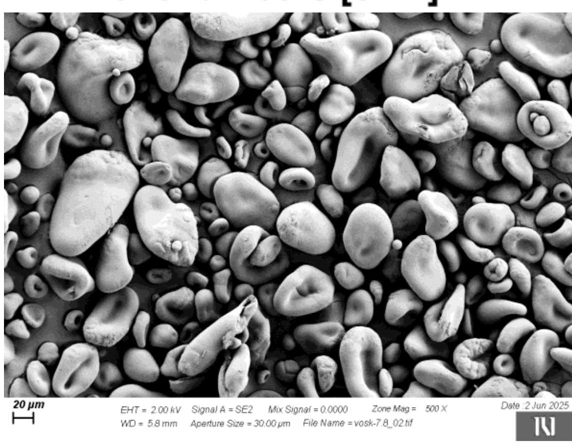


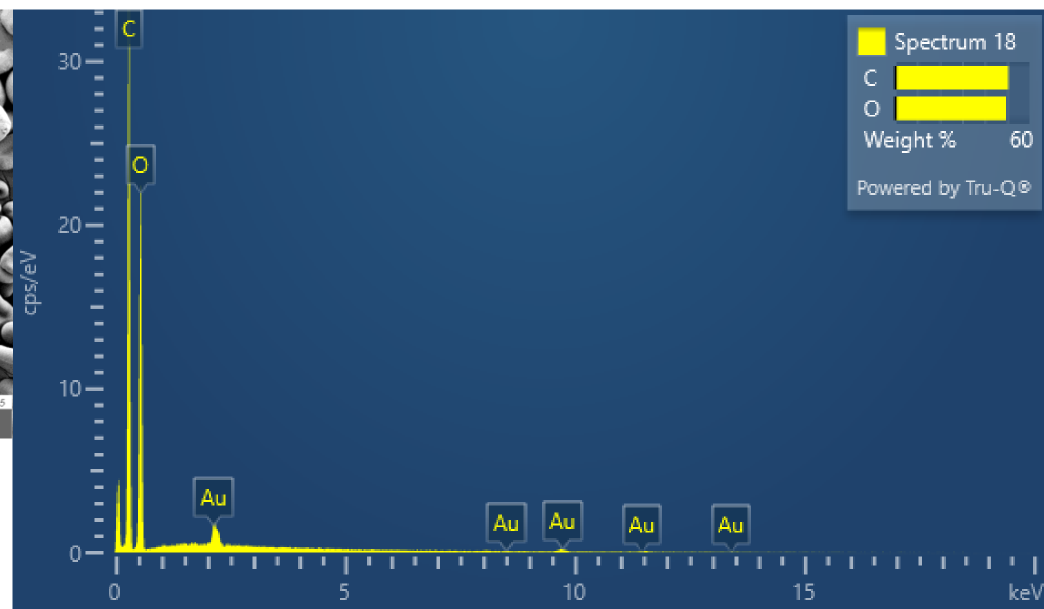
Designing required material properties





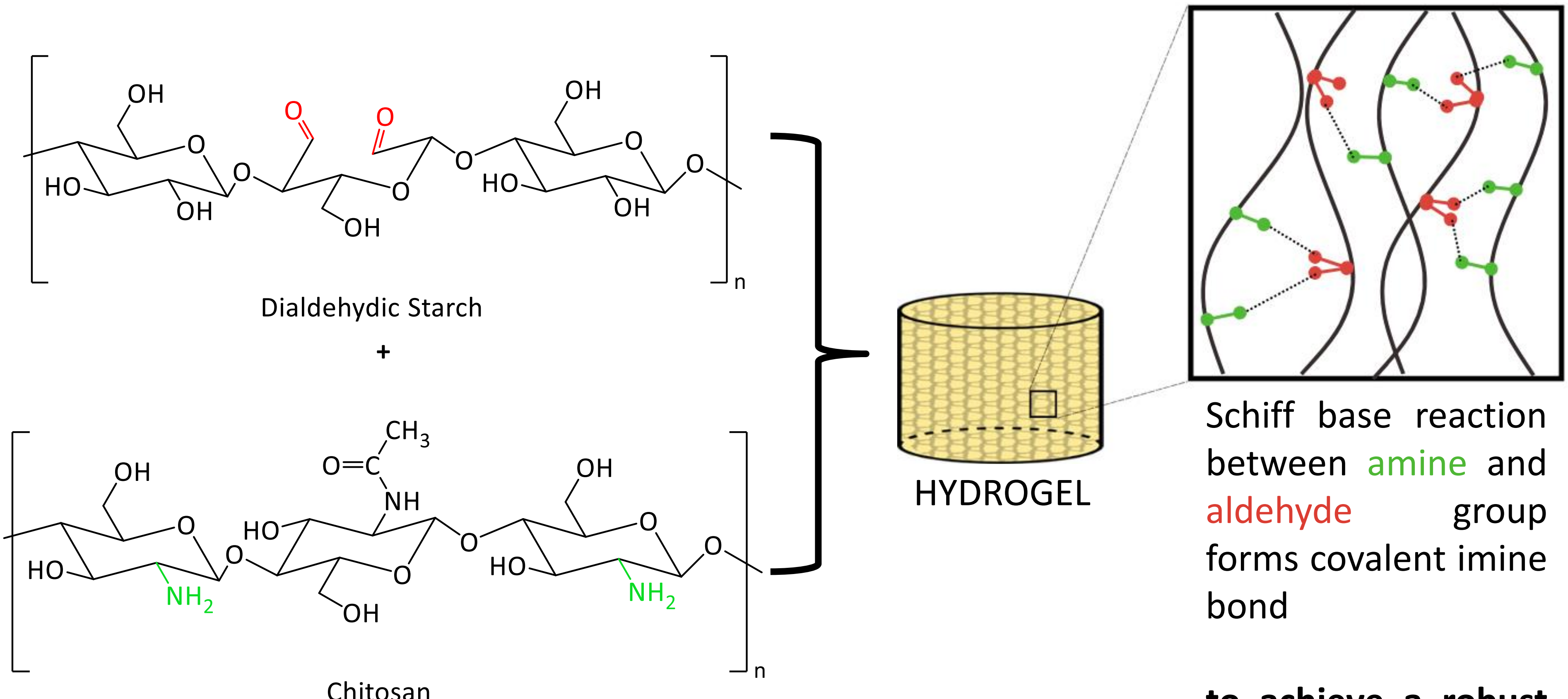
- **FTIR spectra**
  - Confirming creation of new aldehydic group





- **Elemental surface composition**
  - Confirming preparation of pure crosslinker

Hydrogel synthesis

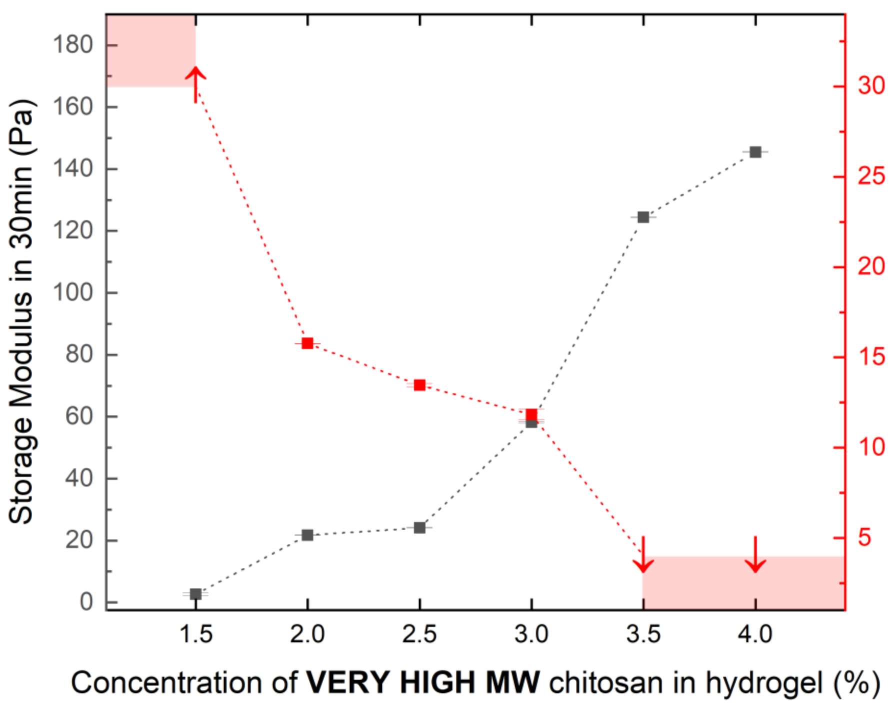


Schiff base reaction between amine and aldehyde group forms covalent imine bond

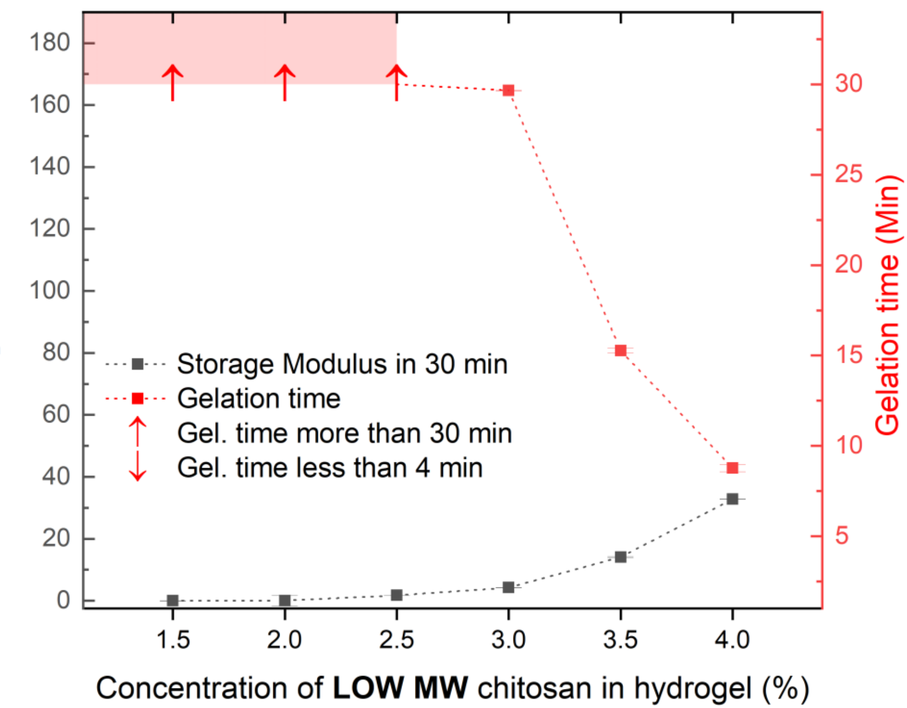
to achieve a robust crosslinked gel

Viscoelasticity and gelation tuning

- Tunability with changing **polymer concentration** and **molecular weight**
- With the right tuning **rapid gelation** (under 4 min)



VS.



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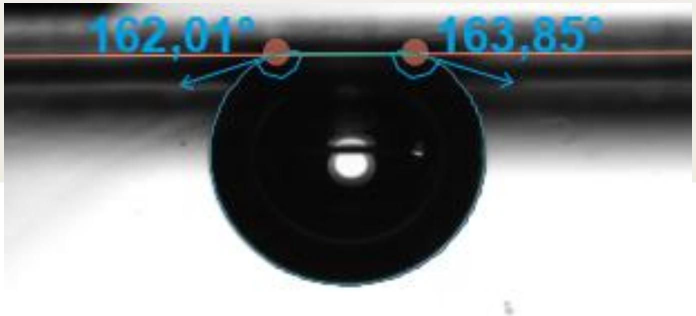
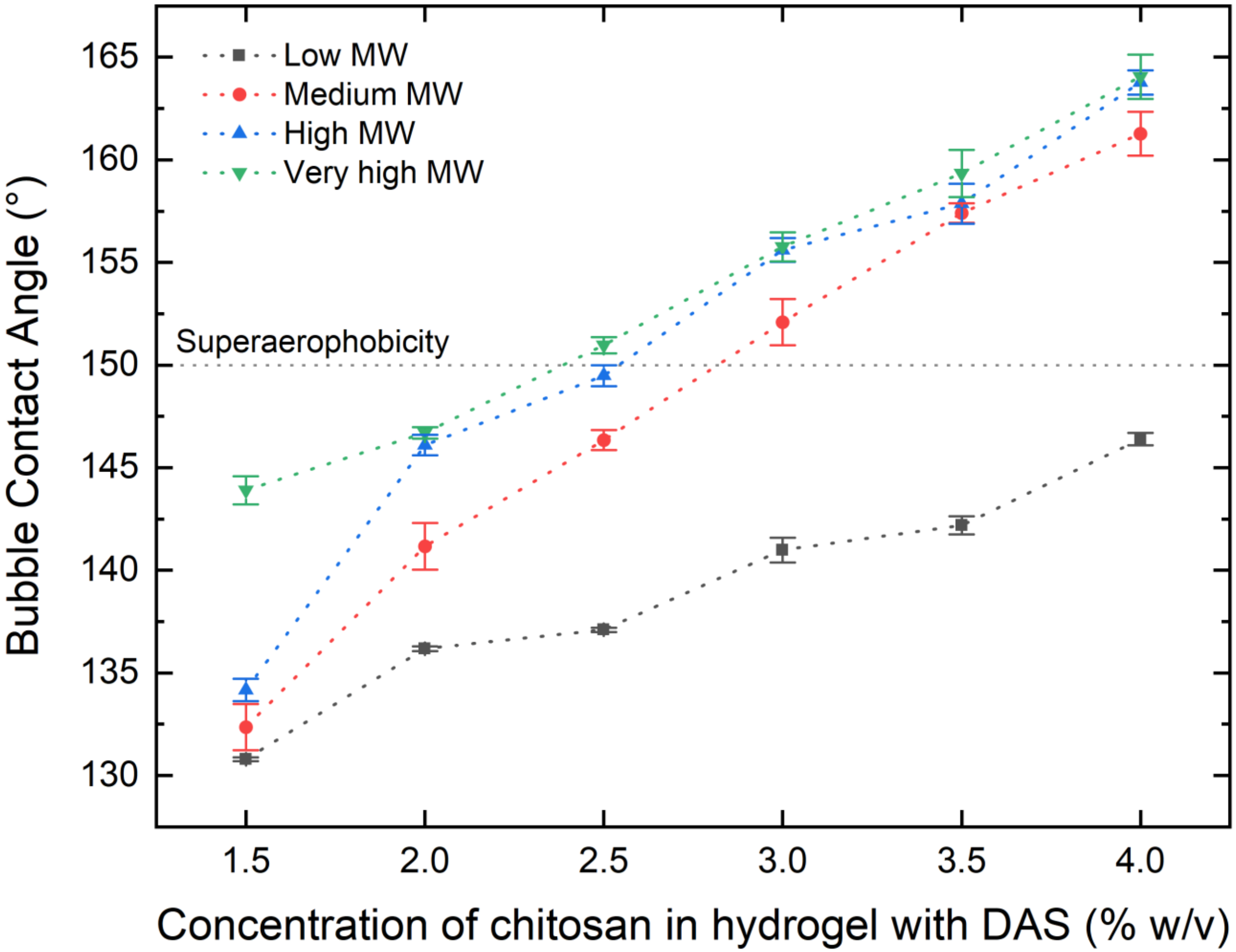


Bubble contact angle

Captive bubble method

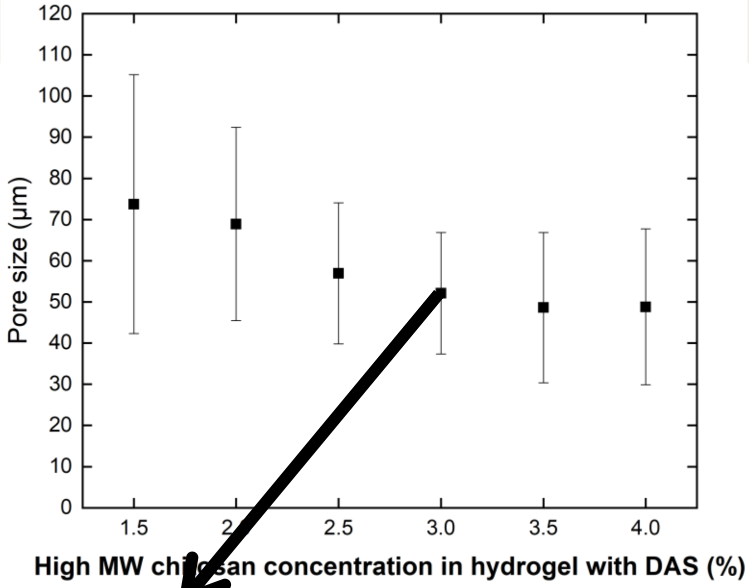
Contact angles between air bubble and hydrogel film under the water

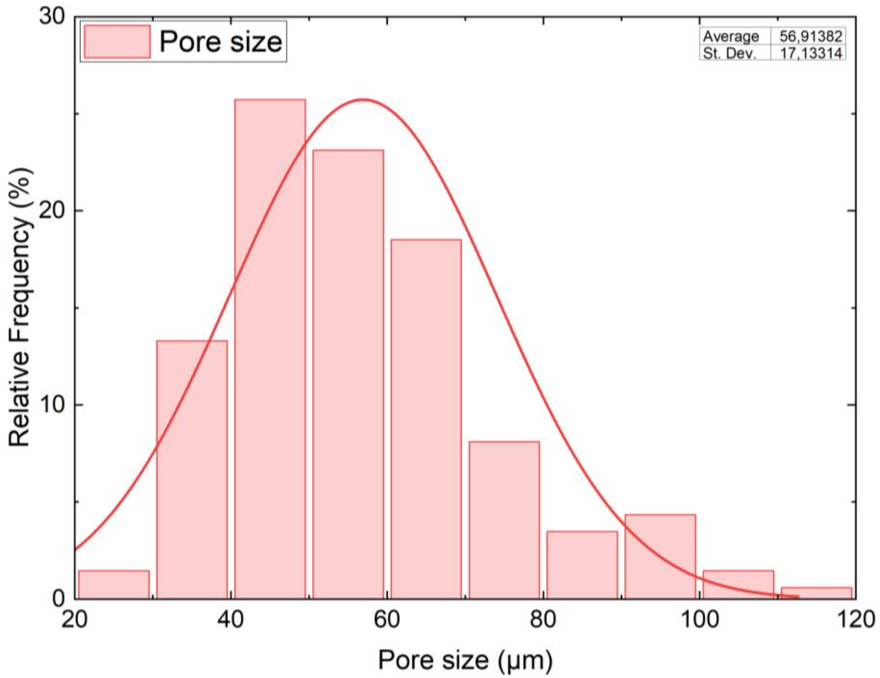
Superaerophobicity @150° and above

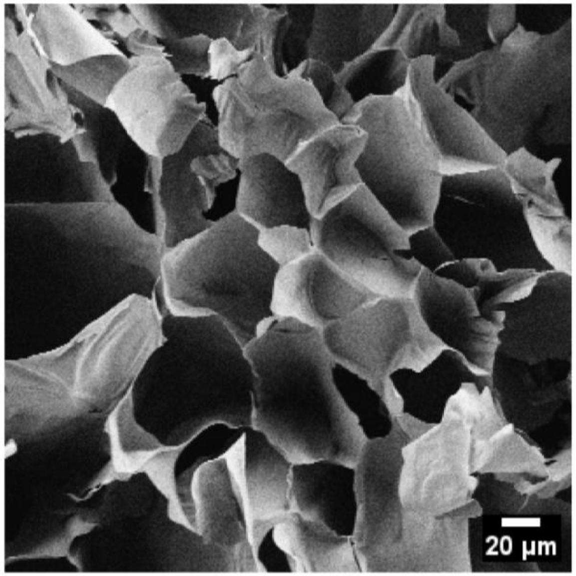


Pore size distribution

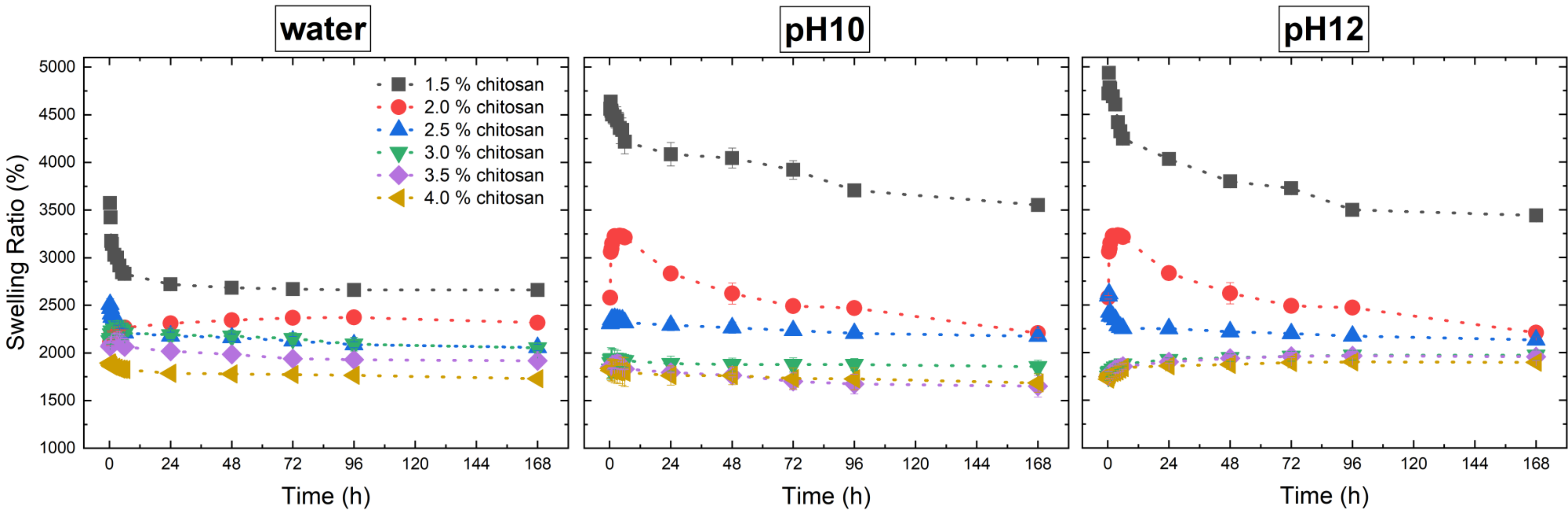
- open **porous 3D structure**
- pore diameters ranging **10-100 µm**







Stability in alkaline environment

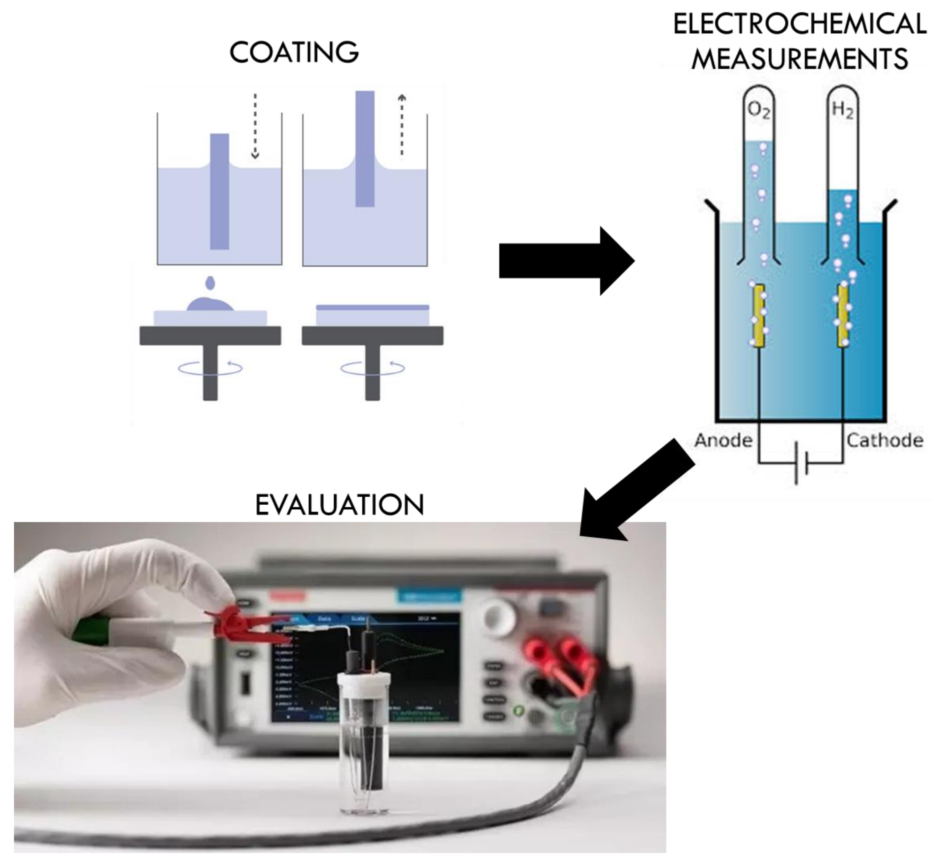


Stable swelling behavior over period of **7 days**

Conclusions and further steps

- Hydrogels are customizable well defined chemical environments.
- Shown for **chitosan/DE starch** – **excellent alkaline stability**, **superaerophobicity** ($\alpha \geq 165°$).
- **Fibers** to **sustainable hydrogels** to replace **synthetic and PFAS-based ingredients**, particularly for emerging applications of **solid-liquid-gas interfaces** in **harsh alkaline-resistant environments:**

- energy production and storage
- corrosion protective coatings
- environmental absorbents and sensors







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6 – 9 September 2026

Bled, Slovenija

Abstract submission

May 15, 2026

Early bird registration

July 15, 2026




Accompanying workshop: **Fibre101**

10 – 11 September

details follow…

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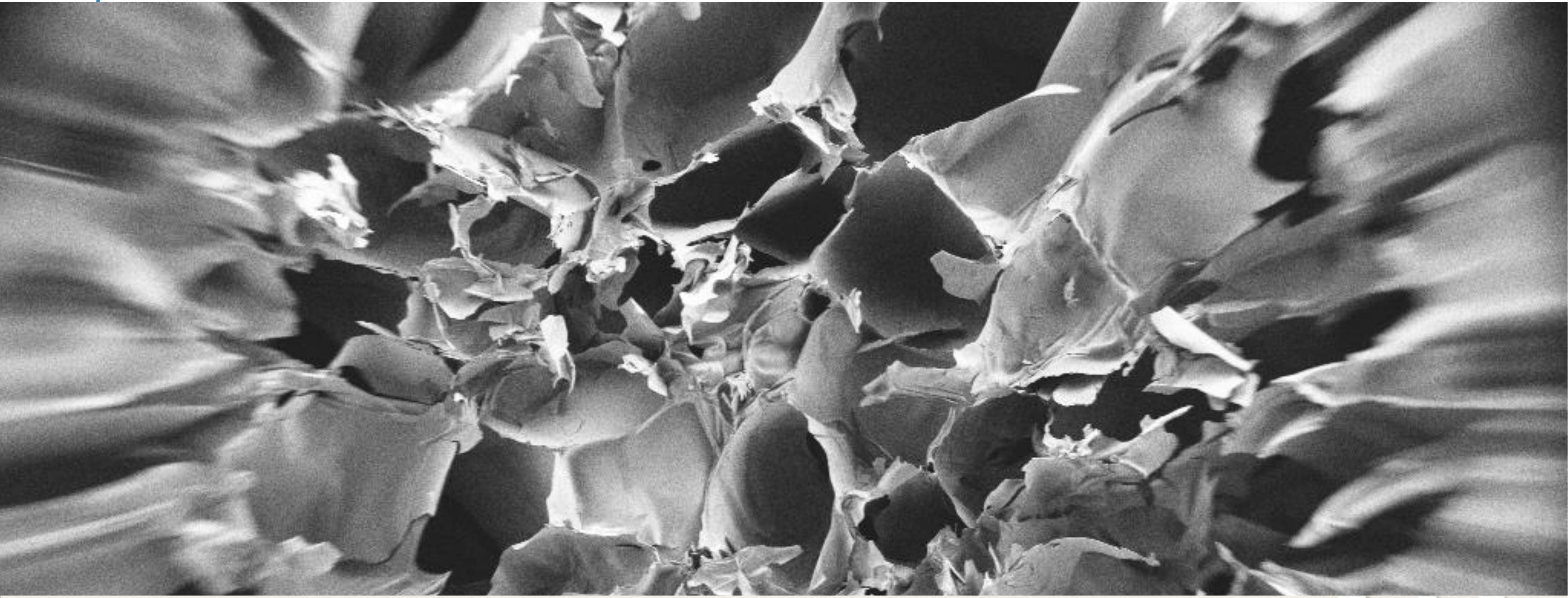

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SUPERAEROPHOBIC ELECTRODE COATINGS

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