

Swiss Soft Days

38th edition

Fribourg 02.10.2026

Adolphe Merkle Institute, University of Fribourg
Chemin des Verdiers 4, 1700 Fribourg

Sponsored by



Local organizers: Adam Burbidge
Hans-Jörg Limbach
Veronique Trappe

PROGRAM

09.30-09.55	Registration / Coffee	
09.55-10.00	Welcome	
10.00-10:35 <i>invited</i>	T. Bereau <i>University of Heidelberg</i>	Resolution as a variable: navigating chemical space and bridging scales
Session chair: Hans-Jörg Limbach (AMI Fribourg)		
10:35 – 10:50	M. Nedyalkova <i>Uni Fribourg</i>	One Fluorine, many fates: Protein-selective interaction landscape of 926 PFAS
10:50 - 11:05	M.Stehrenberger <i>Uni Fribourg & ZAHW</i>	Automated in-column functionalisation of stationary phases for ion chromatography
11:05 - 11:20	L.Rabut <i>Uni Fribourg</i>	Solvent-driven control of structure in short Fmoc peptide hydrogels
11:20 - 11:35	F.Bortoletto <i>AMI Fribourg</i>	Tailoring Cu(I)-Iodide Hybrids Emission with Planar Optical Microcavities
11:35 - 12:00	Sound bites	Selected Posters
12:00 – 13:30	Lunch / Poster Session	
13:30 – 14:15 <i>Invited</i>	A. Fernandez-Nieves <i>University of Barcelona</i>	Many fire-ant systems
Session chair: Urs Gasser (PSI)		
14:15 – 14:30	M. Le Bec <i>ETH Zürich</i>	Shaping nematic order in bacterial films with single-cell resolution patterning
14:30 – 14:45	T. Peshkovsky <i>ETH Zürich</i>	Spatiotemporally resolved refractive index imaging
14:45 – 15:00	S. Gowen <i>ETH Zürich</i>	Observing local plasticity in depletion colloidal gels
15:00 – 15:15	D. Natali <i>EPF Lausanne</i>	4D-printable shape morphing double network granular elastomers
15:15-15:45	Coffee / Poster Session	
Session chair: Cornelia Palivan (Uni Basel)		
15:45 – 16:00	R. Ollivier <i>EPF Lausanne</i>	Tensegrity-inspired force asymmetric network materials: programming mechanics beyond
16:00 – 16:15	S. van Kesteren <i>ETH Zürich</i>	Adaptive rewiring in self-assembled particle networks
16:15 – 16:30	D. Grimm <i>EMPA</i>	A click host-guest macromer hydrogel from cold water fish gelation: correlating material properties with network design
Closing		

Number		Posters
1	V. Jakobs <i>ETH Zürich</i>	Effect of particle surface topography on buckling of particle-laden interfaces
2	L. Woolley <i>ETH Zürich</i>	Impact of surface asperities on stress bearing properties of linear colloidal aggregates
3	N. Windbacher <i>ETH Zürich</i>	Hydrodynamics of Golfball Particles in Dense Suspensions
4	E. Perler <i>ETH Zürich</i>	Freeze structuring as an enabler for processing complex food systems
5	M. Scherer <i>ETH Zürich</i>	Understanding Freeze-Fracture in Soft Model Hydrogels
6	A. Bach <i>ETH Zürich</i>	Addressing multicomponent complexity in freeze structuring of food colloids
7	M. Rutsch <i>Uni Basel</i>	Confining Geometry Governs Dynamics in Lipidic Mesophases
8	E. Mégroz <i>Uni Fribourg</i>	SAXS and SANS Guided Design of Biomimetic Lipid Nanoparticles
9	E.M. Mollica <i>ETH Zürich</i>	Bacterial motility effects on leaf surface exploration
10	L. Rinaldi <i>EPF Lausanne</i>	Shark centra-inspired biomineralized granular hydrogels
11	G. Mazzotta <i>Uni Fribourg</i>	Magnetite NPs for Production of Anisotropic Mesoporous Materials
12	G. Cocchi <i>EPF Lausanne</i>	Nacre-Inspired CaCO ₃ Composites via Enzymatic Mineralization
13	R. Gervasone <i>ETH Zürich</i>	Aperiodic Orientational Order in Optothermally-Aggregated Colloids
14	P. Bertsch <i>Uni Fribourg</i>	Universal adsorption of proteins at oil-water interfaces: A tool for mapping novel plant-based proteins
15	Z. Zhang <i>ETH Zürich</i>	Investigation of the structure and digestion of plant protein-stabilized interfaces in vitro
16	L.-H. Lin <i>ETH Zürich</i>	From Adsorption to Network Formation: Can Plant Proteins Stabilize the Oil-Water Interface?
17	N. Gray <i>ETH Zürich</i>	Adaptive Hydrogels with Spatiotemporal Stiffening Using pH-Modulating Enzymes

18	C.-E. Choi <i>Western University.</i>	Metal–Organic Framework-Reinforced GelMA Hydrogels as 3D-Printable Soft Biomaterials for Bone Repair
19	U. Altuntas <i>EPF Lausanne</i>	Loading-Ratio-Dependent Cyclic Softening and Energy Dissipation in Double-Network Elastomers with Distinct Architectures
20	M. Steinacher <i>ETH Zürich</i>	3D Printing of Living Bioluminescent Mechanosensors
21	B. Pierucci <i>Uni Fribourg</i>	Towards the development of an electric organ to power implantable devices: block copolymer membranes for energy conversion
22	P. Zumsteg <i>ETH Zürich</i>	Interferometric Validation of Misalignment Errors in Narrow-Gap Parallel-Plate Rheometry
23	S. Burkule <i>EMPA</i>	Combining FCS and SAXS for Traceable Nanoparticle Characterisation

INVITED CONTRIBUTIONS

Resolution as a variable: navigating chemical space and bridging scales

Tristan Bereau

Institute for Theoretical Physics. University of Heidelberg

Soft matter has no single correct resolution to work at: interaction energies of the order of the thermal energy leave no gap in the relaxation spectrum to cut at. Resolution becomes a variable of the problem, and two distinct coarse-grainings follow — a compositional one, over which chemistries a model represents, and a configurational one, over which degrees of freedom it retains. Along the first, a hierarchy of bead-type alphabets charts chemical space by free energies computed from a transferable force field; that landscape is smoother at coarse resolution, so multi-level Bayesian optimisation can search coarse and refine upward. Along the second, Split-Flows constructs a probabilistic transport map between resolutions that returns a normalised density, and with it the mapping entropy — the entropic term of the coarse-grained free energy.

Many fire-ant systems

Alberto Fernandez-Nieves

Department of Condensed Matter Physics. University of Barcelona
Catalan Institution for Research and Advanced Studies (ICREA)

Experiments with fire-ant columns reveal similarities and differences with granular columns. For granular columns, we will show that narrowing the column diameter can result in novel behavior relative to how we think of wider columns, which were studied more than a century ago by German engineer Janssen; the key is the force-chain structure. We will then show that fire-ant columns also exhibit force chains. However, as an active granular system, there are apparent fluctuations and activity within the system. In 2D, these effects become most noticeable and manifest in the form of non-linear activity waves that propagate along the vertical direction. Ultimately, these waves reflect the existence of activity cycles, whereby the fire-ant system changes from “active”, where all the ants move, to “inactive”, where a large fraction of the ants cluster and remain stationary. Our findings indicate that the “inactive” states can be thought of resulting from a motility-induced attraction reflecting the social interactions between the ants.

ORAL CONTRIBUTIONS

One Fluorine, Many Fates: Protein-Selective Interaction Landscapes of 926 PFAS

Baptiste Birbaum, Marco Lattuada, [Mira Nedyalkova](#)

Department of Chemistry, University of Fribourg

Environmental Significance

PFAS environmental and health relevance cannot be inferred from persistence or fluorinated-chain length alone. This study maps predicted interaction preferences of 926 PFAS across eight human proteins, combining flexible docking, DFT descriptors, chemometrics and explainable machine learning to identify PFAS–protein combinations warranting prioritized experimental assessment.

Abstract

This study maps predicted protein preference for 926 PFAS across eight human protein structures, identifying which constitutional, electronic, charge and geometry descriptors govern these patterns. Docking scores were integrated with 59 descriptors and OECD structural categories; for 704 compounds with complete profiles, within-target normalization defined predicted preferred proteins, with 76.0% of assignments stable across normalization methods.

Target-specific classifiers showed useful discrimination under random and PFAS-type-held-out validation. Stable permutation importance identified H/C and F/C ratios, fluorine mass fraction, oxygen content, polarizability, rotational constant A and atomic polar tensor charge as recurrent contributors — indicating predicted protein preference reflects a balance of fluorination, headgroup polarity, charge distribution and geometry, not fluorine content alone.

As reference PFOA, PFNA and PFDA were not consistently prioritized for PPAR α and pose coordinates were unavailable, the landscape is presented as a reproducible source of testable PFAS–protein hypotheses rather than confirmed biological selectivity.

Automated in-Column Functionalisation of Stationary Phases for Ion Chromatography

Manuel Stehrenberger

University of Fribourg and Zurich University of Applied Sciences

Stationary phases for ion chromatography are mostly polymeric particles based on polystyrene-divinylbenzene copolymers [1]. While these particles exhibit exceptional chemical stability in alkaline measuring eluents, they tend to form secondary interactions with polarisable ions such as nitrate or bromide [2]. To minimise these interactions, the hydrophobic particles are coated with a hydrophilic layer of grafted polymer [3]. These functionalisations are particularly labour-intensive for defined step-growth graftings of AA and BB monomers. Up to 15 consecutive functionalisation steps are required to produce the desired ion exchanger and epoxide/amine functionalisations have already been tested for automated in-column functionalisations [4,5]. To further investigate the possibility of in-column functionalisation, columns were automatically functionalised on a standard Metrohm ion chromatograph. These reactions included oxa- and aza-Michael additions, amide synthesis by N,N'-carbonyldiimidazole, methylations, hydrolysations and epoxide ring-opening reactions. The attachment of mini-columns in front of the raw chromatographic columns made it possible to analyse up to ten consecutive grafting reactions. Additionally, these mini-columns also enabled the investigation of column heterogeneity, and ultimately proved the axially homogeneous grafting of divinyl sulfone to poly(styrene-co-divinylbenzene) particles with a hydroxyl surface. Despite aiming to graft functional layers by forming alkaline-stable functional groups such as ethers or secondary amines, almost all of the columns exhibited a total loss of chromatographic capacity during repeated measurements by anion-chromatography with carbonate eluents. It was eventually proven that the presence of residual carboxylic acids on the poly(styrene-co-divinylbenzene) particles with a hydroxyl surface caused the stability issues. To prove this, these particles were investigated using chemical reactions such as amide formation and epoxide ring opening, as well as treatments such as thorough washing of the synthesised columns with aqueous and organic solvents. The residual carboxylic acids lead to the formation of an ester-bound grafting, which eventually resulted in the loss of quaternary ammonium ions by during anion chromatography measurements.

- [1] Liu et al., Journal of Chromatography A 2021, 1653, 462313
- [2] Yuchi, Analytical Sciences 2014, 30, 51–57
- [3] Zatirakha, Smolenkov, Shpigun, Analytica Chimica Acta 2016, 904, 33–50,
- [4] Buszewski et al., Journal of Separation Science 2011, 34, 601–608
- [5] Pohl & Srinivasan, Talanta 2018, 184, 338–346

Solvent-driven control of structure in short Fmoc peptide hydrogels

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Antimicrobial peptides (AMPs) have strong potential to combat microbial resistance [1,2]. However, their limited shelf life, susceptibility to degradation, and the high cost of synthesizing larger peptide sequences remain major obstacles to clinical translation [2]. Short Fmoc-phenylalanine-based peptides have recently gained attention for their intrinsic antimicrobial activity and their ability to self-assemble into hydrogels under physiological conditions [3,4]. Nevertheless, the mechanisms governing their self-assembly, particularly in complex solvent environments, remain poorly understood, limiting their rational design as functional biomaterials.

Here, we investigate the structure-function relationships in Fmoc-dipeptide systems by investigating how solvent conditions govern self-assembly and the resulting material properties. We systematically vary peptide concentration, pH, ionic strength and DMSO content to investigate their role on the supramolecular structure. Ionic strength and pH modulate electrostatic interactions, while DMSO modifies peptide self-assembly by altering solvation and weakening hydrogen bonding, providing complementary routes to tune assembly pathways.

Small-angle X-ray scattering (SAXS), combined with rheology and electrophoretic mobility measurements, reveals the formation of nanostructured dipeptide hydrogels with tuneable structural and viscoelastic properties. These observed structural and rheological properties are strongly influenced by solvent composition, demonstrating how formulation parameters govern supramolecular organization across multiple length-scales.

By establishing structure–function relationships in Fmoc-dipeptide systems, this work provides a framework for the rational design of tunable peptide hydrogels with defined structural and mechanical properties.

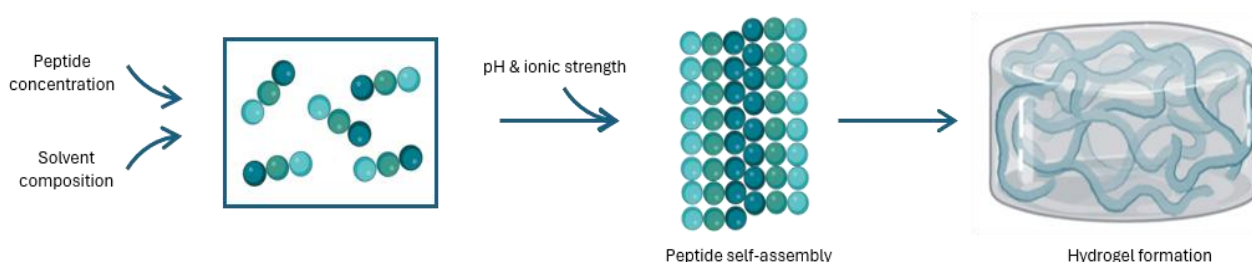


Figure 1- From formulation to Fmoc-dipeptide gel structure and viscoelastic properties. Created with <https://BioRender.com>

- [1] M. Saubenova, A. Rapoport, Z. Yermekbay and Y. Oleinikova, *Fermentation*, 2025, **11**, 36.
- [2] C. Bucataru and C. Ciobanasi, *Microbiological Research*, 2024, **286**, 127822.
- [3] N. Chauhan and Y. Singh, *ACS Biomater. Sci. Eng.*, 2020, **6**, 5507-5518.
- [4] Z. Ahmadi, S. Yadav, A. K. Kar, D. Jha, H. K. Gautam, S. Patnaik, P. Kumar and A. K. Sharma, *Biomaterials Advances*, 2022, **133**, 112633.

Tailoring Cu(I)-Iodide Hybrids Emission with Planar Optical Microcavities

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Cu(I)-iodide hybrid materials have emerged as a versatile class of luminescent coordination compounds that combine structural diversity with highly tunable photoluminescence, spanning a wide range of the visible spectrum. The combination of efficient photoluminescence, stimuli-responsive behaviours, and the low cost and earth abundance of copper and iodide, has generated significant interest in these materials for a broad range of applications, including sensing (1), X-ray detection (2), and light-emitting devices (3), offering an alternative to luminescent systems based on expensive precious metals or rare-earth elements.

However, Cu(I)-iodide hybrids typically exhibit broad emission bands, which limit their use in advanced technological applications requiring narrow spectral profiles, such as high-resolution displays, low-threshold lasers, optical communications, and wavelength-selective photonic devices.

In this work, we address this limitation by engineering the optical environment around the emitter rather than modifying the emitter itself. Planar optical microcavities, consisting of alternating layers of high- and low-refractive-index materials, generate photonic bandgaps, i.e., spectral regions in which light propagation is forbidden for selected wavelengths and angles of incidence. Introducing an engineered defect layer within this structure creates a resonant optical mode that can selectively reshape the emission of an embedded emitter (4), (5).

Luminescent Cu(I)-iodide hybrid materials are integrated into a fully solution-processed planar hybrid microcavity, where they serve as the emissive material embedded in the defect layer (Fig. 1a). The Cu(I)-iodide hybrid clusters are formed directly inside the cavity via ligand evaporation, enabling efficient *in-situ* growth. Coupling the intrinsically broad emission of the Cu(I)-iodide hybrid to the cavity resonance leads to pronounced spectral narrowing and enhanced emission intensity (Fig. 1b). These results demonstrate the potential of optical cavity engineering as a versatile strategy for tailoring the emission of Cu(I)-iodide hybrid materials towards applications requiring spectrally narrow light sources.

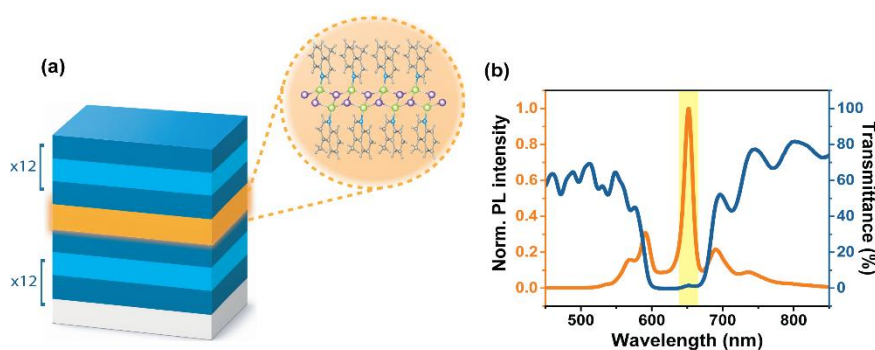


Fig. 1 (a) Scheme of the solution-processed optical microcavity containing luminescent Cu(I)-iodide clusters in the cavity layer; (b) Transmittance and photoluminescence (PL) spectra of the complete microcavity, showing spectral overlap between the cavity mode and the reshaped Cu(I)-iodide clusters emission.

(1) Y. Yu et al., Chem. Commun., 2014, 50, 1444.

(2) J. Chen et al., Chem. Sci., 2025, 16, 1106.

(3) Y. Li et al., Chem. Mater., 2023, 35, 1318.

(4) H. Megahd et al., Opt. Mater. X, 2022, 13, 100130.

(5) P. Lova et al., Adv. Opt. Mater., 2018, 6, 1800730.

Shaping nematic order in bacterial films with single-cell resolution patterning

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When growing on a surface, *B. subtilis* bacteria proliferate as cell chains[1] (elongating filaments of constant width) which can locally align with each other upon contact. At high cell density, such microbial population can self-organise in liquid-crystalline domains of aligned cell filaments delimited by topological defects (*Figure 1*). Powered by cell growth, chaotic flows of cells emerge forming what can be described as an active nematic phase[2]. Here we investigate the dynamics emerging within such 2D bacterial colonies by harnessing the precision of capillary assembly methods[3]. By patterning *B. subtilis* spores with controlled initial spatial configuration at single-cell resolution - namely their positions and orientations, we aim to shape the dynamics and final morphologies of monolayer biofilms. While orthogonally seeded spores lead to chaotic dynamics, seeding them with parallel orientations yields films with high nematic order across millimetres, which subsequently synchronously buckle upon further growth. Our observations are captured by numerical simulations and a model that describes the buckling dynamics starting from the mechanical properties of individual filaments.

By programming local cell orientation with single-cell precision, we finally harness nematic alignment to create macroscopic bacterial films with local optical anisotropy, via structural colouration and light polarisation (*Figure 2*). Our findings demonstrate that initial conditions play a key role and offer exciting opportunities to control the spatio-temporal organisation of bacterial assemblies towards addressing open biological questions and realising living materials with tailored properties.

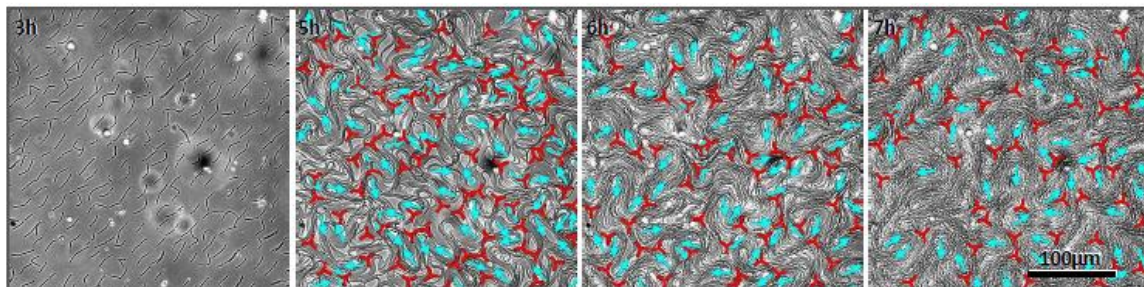


Figure 1. Active nematic phase emerging from a 20µm-spaced patterned array of B. subtilis spores growing between PDMS and agarose. Microscopy images at 3h, 5h, 6h and 7h with +1/2 topological defects as cyan arrow and -1/2 as red trefoil symbols.

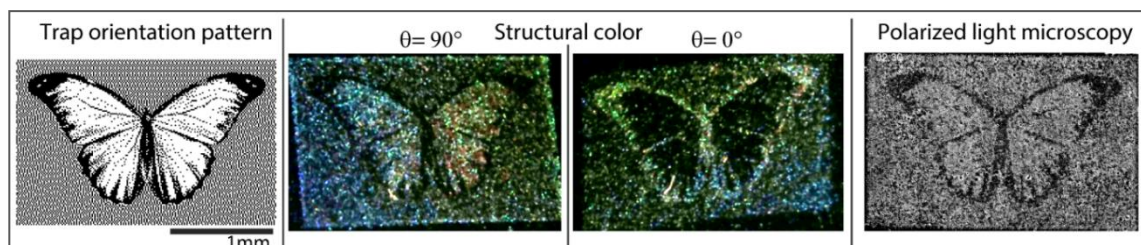


Figure 2. Local control of optical anisotropy to produce an image in structural colour and polarized light with bacterial films using 2D trap orientation pattern with black and white pixel oriented orthogonally.

- [1] J. van Gestel, H. Vlamakis, R. Kolter, *PLOS Biology*. 13, e1002141 (2015).
- [2] Y. I. Yaman, E. Demir, R. Vetter, A. Kocabas, *Nat Commun*. 10, 2285 (2019).
- [3] S. Ni, L. Isa, H. Wolf, *Soft Matter*. 14, 2978–2995 (2018).

Spatiotemporally Resolved Refractive Index Imaging

Taieesa Peshkovsky [1], Stefan Andreas Schmid [1,2], David Taylor [2], Robert W. Style [1], Lucio Isa [1], Federico Paratore [1]

[1] Department of Materials, ETH Zürich

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Chemical concentration gradients at the microscale are omnipresent, shaping fundamental processes in a wide range of systems from cell signaling to transport phenomena. Despite their ubiquity, visualizing chemical gradients typically requires the addition of labels, such as fluorescent dyes, for optical readout. Because dyes bleach, or may interfere with the processes of interest, i.e. up to inducing toxicity for biological systems, alternative, label-free approaches are sought after. For systems that lack optical contrast, interferometric methods are a label-free solution that relate refractive index (RI) to a compound's identity or concentration *in situ*. I will present here a tool that expands on the principles of Fabry-Pérot interferometry to two dimensions to obtain RI mapping within a microfluidic chip. By tracking fringes of equal chromatic order our tool achieves a RI resolution of $1\text{e-}5$ refractive index units per image pixel, for instance sensitive to 1 mM changes in concentration of NaCl. The tool, which we named RIO for refractive index observer, mounts onto any microscope and I will report its resolution and RI precision, as well as demonstrate its potential by quantifying dynamically evolving concentration gradients of dissolved NaCl in a microfluidic channel. We envisage that RIO will give unprecedented visibility to a broad range of microscale phenomena, for example thermophoresis and colloidal chemotaxis.

Observing Local Plasticity in Depletion Colloidal Gels

Pierre Lehericey, Savannah Gowen, Peter Derlet, Jan Vermant

ETH Zürich

Yield-stress materials, those that transition from solid-like to fluid-like behavior under applied stress, are abundant in our society with applications ranging from food products to construction materials [1, 2]. However, the nature of yielding remains difficult to predict or resolve, particularly as it relates to a material's microstructure. In the present work we provide a direct observation of microscopic colloidal gel network dynamics under shear using a rheo-confocal microscope [3]. These experiments probe local plastic rearrangements as precursors to material yielding by monitoring non-affine motion in depletion gels ranging from dense structures at 45% volume fraction to stringy gels at 20% volume fraction. We find extreme value statistics similar to those present in glassy systems [Fig.1].

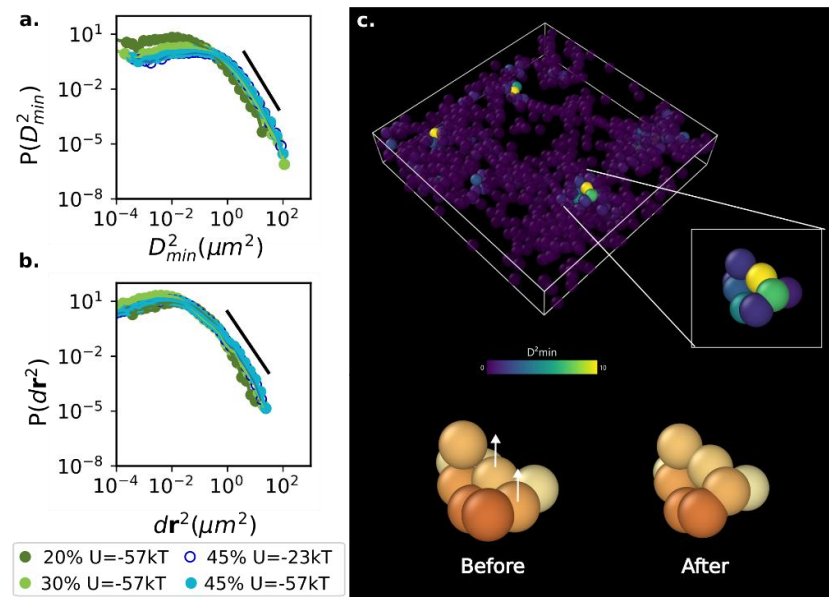


FIG. 1. Characterization of non-affine particle motion. **a.** The probability density of D_{min}^2 , the local non-affine motion, is shown for each gel. The distributions are characterized by a power law decay at high values that appear remarkably similar between gels of different concentrations. The line marks a slope of -2.5. **b.** The probability distribution of $d\vec{r}^2$, the particle non-affine displacement relative to the global affine displacement. All formulations show similar distributions with a power law decay here denoted by the black line with slope -2.25. **c.** An example of the spatial distribution of non-affine events measured by D_{min}^2 for gel formulation $\phi = 20\%$, $U_{dep} = -57kT$ is above. Below is an example of a cluster before and after a rearrangement is shown.

- [1] Bonn, Daniel, et al. "Yield stress materials in soft condensed matter." *Reviews of Modern Physics* 89.3 (2017): 035005.
- [2] Nelson, Arif Z., et al. "Designing and transforming yield-stress fluids." *Current Opinion in Solid State and Materials Science* 23.5 (2019): 100758.
- [3] Colombo, Gabriele, et al. "Ultrafast imaging of soft materials during shear flow." *Korea-Australia Rheology Journal* 31.4 (2019): 229-240.

4D-Printable Shape Morphing Double Network Granular Elastomers (DNGEs)

Daniele Natali, Esther Amstad

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email: daniele.natali@epfl.ch*

The growing relevance of soft robotics within materials science has, in the recent years, driven increasing interest in the development of soft, yet load-bearing and responsive materials that can be processed into customized shapes. Double network granular elastomers (DNGEs), composed of crosslinked microparticles interconnected through a second interpenetrated elastomeric network combine toughness with load-bearing properties.¹ To prepare DNGEs, the microparticles are swelled in the precursors' solution of the second network before being centrifugated to induce a critical packing density of the microparticles, a process named jamming (*Figure 1a*). In the jammed state, swelled microparticles present the behaviour of a shear-thinning ink (*Figure 1b*) thus allowing the processability through direct ink writing (DIW)-based 3D printing. The properties of DNGEs can be tuned as a function of the nature of networks' precursors. In this context, smart DNGEs present a new class of elastomers that is particularly promising for soft robotics. In this contribution, I will demonstrate how thermo-sensitive shape-morphing behaviour can be introduced in DNGEs by employing click photo-induced thiol-ene reaction of crystallizable monomers. The crystallization of polymeric domains are exploited for the fixation of different temporary shapes, while the original shape of samples is recovered heating above the material's melting transition (*Figure 1c*). Semicrystalline domains thus consent to combine the enhancement of the mechanical properties with the obtainment of thermo-sensitive shape-memory properties, introducing a novel elastomeric material suitable for load-bearing applications and capable to generate active force upon heating (*Figure 1d*). Mechanical properties of the DNGEs are tuned by regulating the amount of crosslinker both in the microparticles and in the second network. Moreover, DIW enables the printing of multi-materials manufactures, affording optimization and tailoring of mechanical and shape-memory properties also through the design of the items. Shape-memory DNGEs, thus step into the field of 4D-printing as promising smart materials for applications in soft robotics.

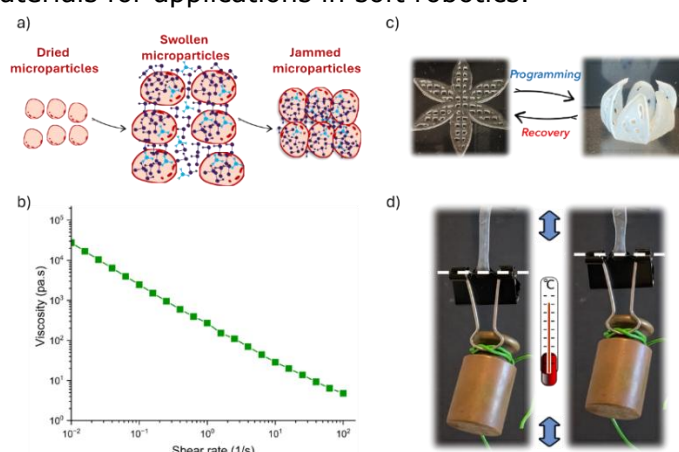


Figure 1. a) steps for the preparation of the shear-thinning ink: first the microparticles are let swell in the solution of second network precursors before being jammed to generate the printable ink; b) flow curve of the ink showing shear-thinning behavior; c) shape-memory properties of 3D-printed DNGEs; d) load-bearing and active force demonstration of shape-morphing DNGEs: the materials can be programmed to bear and lift loads when activated through heating.

[1] E. Baur, B. Tiberghien, E. Amstad. *Advanced Materials*. 3D Printing of Double Network Granular Elastomers with Locally Varying Mechanical Properties, 36, 2313189, 2024.

Tensegrity-inspired Force-Asymmetric Network Materials: Programming Mechanics Beyond Geometry and Topology

Roxane Ollivier and Sangwoo Kim

Mechanics of Soft and Biological Matter Laboratory (MESOBIO), EPF Lausanne

Network-based materials offer a broad range of tunability in mechanical properties. While most studies have focused on how network geometry, connectivity, and topology govern linear and non-linear mechanical responses and rigidity transitions, the role of heterogeneity in constituent properties remains largely unexplored. Here, we introduce a tensegrity-inspired approach that exploits force asymmetry at the bond-element level to expand the tunability of material properties. For this, we combine conventional linear springs with cables and struts, which respond only to tension and compression, respectively, into disordered networks. We find that varying the composition of these three elements, without controlling their detailed spatial arrangement, substantially broadens the range of accessible mechanical properties, including independent control of bulk and shear moduli, shifts in rigidity transitions, negative Poisson's ratio [1], strain stiffening and softening, and strain-induced rigidity [2]. Interestingly, prestress, a defining feature of classical tensegrity, can suppress rather than enhance this tunability by weakening the force-asymmetric character of individual bonds [3]. Our results establish constituent-level force asymmetry as an orthogonal design axis for programming the mechanics of disordered networks, complementary to conventional approaches based on geometry and topology.

[1] Goodrich, C. P., Liu, A. J., & Nagel, S. R. (2015). The principle of independent bond-level response: Tuning by pruning to exploit disorder for global behavior. *Physical review letters*, 114(22), 225501.

[2] Arzash, S., Shivers, J. L., Licup, A. J., Sharma, A., & MacKintosh, F. C. (2019). Stress-stabilized subisostatic fiber networks in a ropelike limit. *Physical Review E*, 99(4), 042412.

[3] Bose, A., Vermeulen, M. F., Storm, C., & Ellenbroek, W. G. (2018). Self-stresses control stiffness and stability in overconstrained disordered networks. *arXiv preprint arXiv:1812.00611*.

Adaptive rewiring in self-assembled particle networks

Steven van Kesteren

ETH Zürich

The ability to reorganize and rewire connections is a key property underlying learning in biological brains [1]. Yet, despite the promise of neuromorphic computing for more efficient, brain-inspired computers, current hardware remains largely based on static silicon architectures [2]. Soft materials such as colloidal gels, in contrast, naturally combine network structures with dynamic, reconfigurable connections, but lack the computational functionality needed to process information. In this talk, I will present recent experimental results demonstrating how information can be stored and processed through connections between colloidal particles [3-4]. I will then show, through simulations and experiments, how the structure and connectivity of colloidal gels can be trained and optimized to improve their performance on simple machine-learning tasks [5]. Together, these results point toward a new class of computing systems in which the material itself can reorganize its structure and connectivity to adapt to the task at hand.

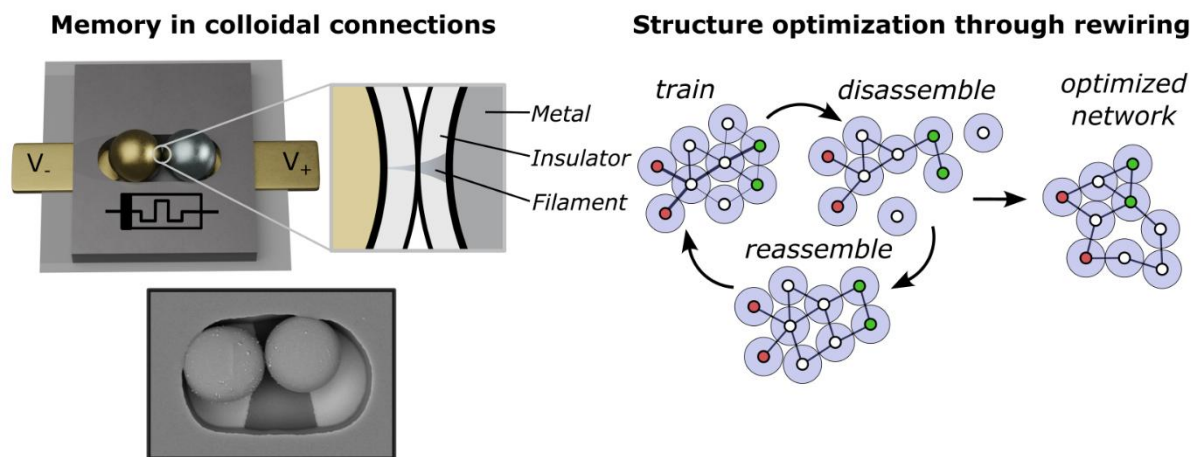


Figure 1. Information can be stored in the conductivity between two colloids by voltage-induced bridging with conductive wires. Such colloidal memory can build colloidal gels that train their structure by selectively breaking and reforming connections with the weakest conductivity.

1. Li, J., Bauer, R., Rentzeperis, I. & van Leeuwen, C. Adaptive rewiring: a general principle for neural network development. *Front Netw Physiol* **4**, 1410092 (2024).
2. Mehonic, A. *et al.* Roadmap to neuromorphic computing with emerging technologies. *APL Mater.* **12**, 109201 (2024).
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A Click Host-Guest Macromer Hydrogel from Cold Water Fish Gelatin: Correlating Material Properties with Network Design

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Hydrogel behavior is often described by bulk rheological characterization, reporting storage (G') and loss modulus (G'') and their ratio, i.e. the damping factor ($\tan \delta = G''/G'$). However, that does not necessarily capture what a cell experiences, especially in the case of dynamic hydrogels.⁽¹⁾ Herein, we developed a dynamic click host-guest supramolecular (CHGM) hydrogel based on cold water fish gelatin (cfGel) and compared it to different hydrogels with related network design elements (Fig. 1). We assessed the contributions of bond type, precursor preparation history and gel formation mechanism to the gel properties. Covalent bonds (chemical) vs. supramolecular interactions (physical) are incorporated with step-growth (SG) vs. chain-growth (CG) polymerization into cfGel networks. The formulations for comparison to CHGM (physical, SG) were a click gel (chemical, SG), a host-guest macromer gel (HGM, physical, CG) and methacrylated cfGel (GelMA, chemical, CG). A pre-equilibration time of 24 h for the precursor solution was found to have a different effect on HGM than CHGM but was irrelevant for chemical gels. Further, despite indiscernible bulk rheological characteristics, CHGM displayed unusual swelling behavior and faster cell spreading compared to the click gel. Thus, similar bulk rheological behavior does not necessarily predict similar cell response.

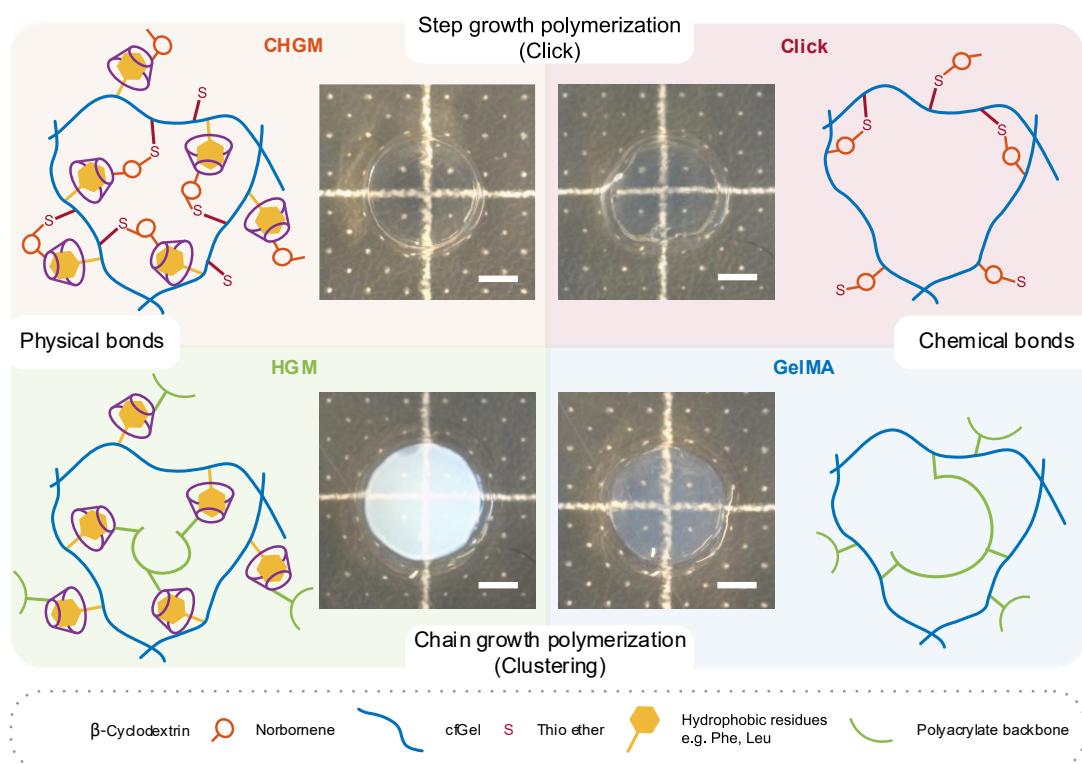


Fig. 1: Contextualization of CHGM hydrogel in design space of bond type and crosslinking mechanism. Scheme of structures and digital images of hydrogels. Scale bar 2mm.

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POSTER CONTRIBUTIONS

1) Effect of particle surface topography on buckling of particle-laden interfaces

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Applications such as emulsion and foam stabilisation, as well as the fabrication of interfacial materials rely on the mechanical behaviour of particle-laden interfaces. Upon compression, these interfaces exhibit complex mechanical responses, arising from the interplay between particle-particle interactions, particle-interface interactions, and the imposed boundary conditions. Particle surface topography alters particle behaviour at interfaces, including contact angle, lateral capillary interactions and particle assembly, thereby influencing the structure and mechanical response of the resulting interfacial layer [1]. In this study, the effect of particle surface topography on the compression and buckling behaviour of silica microparticles at an air-water interface is investigated. Langmuir trough experiments compare monolayers consisting of smooth spherical particles, particles with a corrugated, concave surface topography, and particles decorated with discrete protruding surface asperities [1][2]. Surface pressure-area isotherms characterise the response of these particle monolayers during compression, while microscopy captures the accompanying structural changes and the onset of buckling. The aim is to characterise how differences in particle surface topography influence the buckling behaviour and mechanical response of compressed interfacial layers.

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2) Impact of surface asperities on stress bearing properties of linear colloidal aggregates

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When stress is applied to a colloidal network, yielding initially localizes at the weakest points, typically the cluster-cluster connections. While the overall stress-bearing capacity of the network is dictated by these weakest links, it also depends heavily on the stress distribution among individual strands that govern network compliance. At this physical limit, particle contacts can no longer be accurately described by classical DLVO theory. To investigate these micro-mechanical limits, we employ time-shared optical tweezers to assemble linear aggregates of silica particles featuring discrete surface asperities [2]. Subsequently, these aggregates were deformed using a beam-bending approach. These experiments reveal a complex interplay between contact forces, geometrical constraints, and locked-in stresses. This results in a broad distribution of maximal bending moments that a linear aggregate can support prior to a localized plastic event. Consequently, these findings challenge the assumption that a colloidal network can be described by a single friction coefficient.

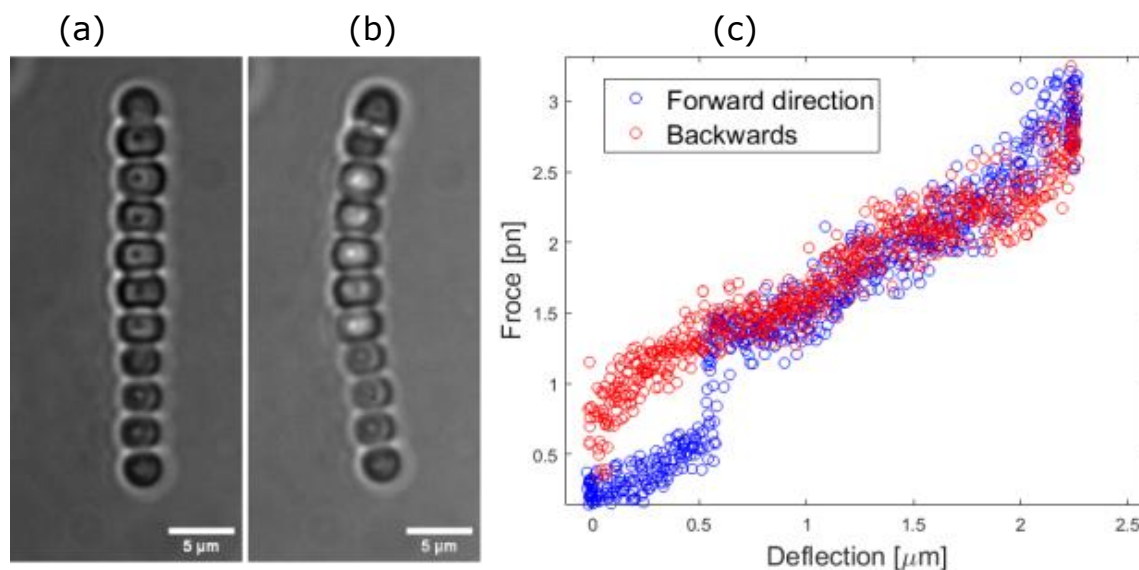


Fig 1 a.) Typical linear aggregate in a undeformed state, b.) aggregate in a deformed state, c.) Force-Deflection curve of a typical linear aggregate bending experiment

[1] J. P. Pantina and E. M. Furst, *Langmuir* 22, 5282–5288 (2006)

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3) Hydrodynamics of Golfball Particles in Dense Suspensions

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Dense colloidal suspensions exhibit shear thickening at high stresses, ranging from a continuous increase in viscosity (CST) to a discontinuous jump (DST), however the microscopic mechanism governing the transition between these regimes remains poorly understood. Current models attribute thickening to a crossover from lubricated, frictionless particle contacts to frictional boundary contacts under stress, framing this transition almost exclusively in terms of the volume fraction and its distance to jamming (1). This leaves the role of particle-level surface interactions underexplored, especially for rough topographies.

Here we introduce a hydrodynamic timescale, governing the interplay between lubrication film drainage and asperity-mediated contact, as an additional control parameter for the shear thickening transition. We use rough, golfball-like particles as a model system whose surface topography allows for this timescale to be tuned directly, which is shown with hydrodynamic squeeze-film simulations. This approach maps single-particle lubrication dynamics onto the rheological response of a dense suspension, offering new insight into how surface topography controls shear thickening.

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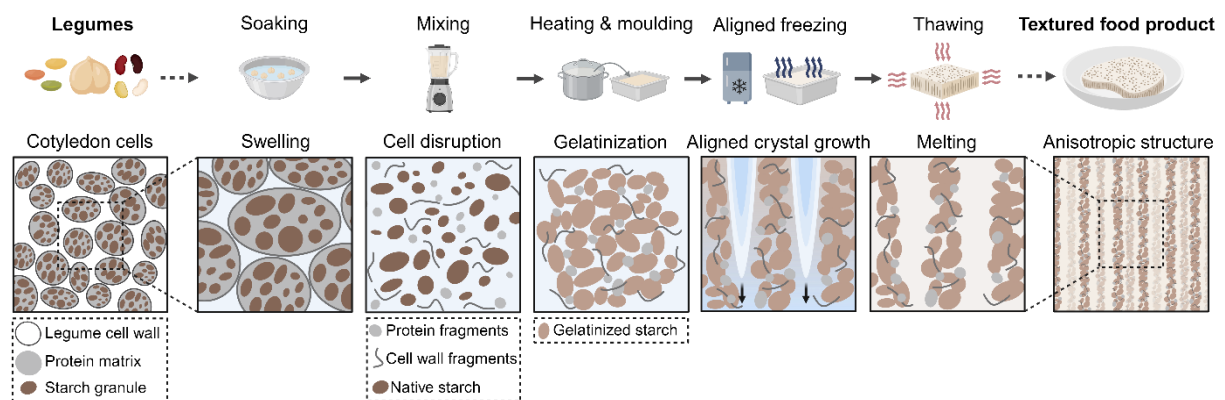
4) Freeze structuring as an enabler for processing complex food systems

Elin Perler, Andrea Bach, Lenja S. Lemcke, Patrick A. Rühls

Department of Health Sciences and Technology, Institute of Food, Nutrition, and Health/
ETH Zürich, Switzerland

Legumes are a sustainable, nutrient-rich, and affordable food source, yet their full potential remains underutilized due to limitations in conventional processing methods, which often fail to incorporate the whole raw material or deliver desirable textures. Here, we introduce freeze structuring (FS) as a novel, mild processing approach to engineer structure and texture in minimally processed legume-based systems. During freezing, controlled ice crystal formation induces a spatial reorganization of biopolymeric components, generating hierarchical structures across multiple length scales. When freezing is applied directionally under a defined thermal gradient, fibrous and anisotropic architectures emerge. Simultaneously, freeze-induced local concentration effects promote enhanced network formation and gel strengthening.

Compared with conventionally cooled references, directionally freeze-structured materials exhibit higher viscoelastic moduli, increased hardness, and pronounced directional texture. These process-structure-property relationships are consistently observed across a diverse range of legume systems, such as lentils, soybeans, chickpeas, and common beans, demonstrating the broad applicability of FS across different legume types and compositions. Overall, these results reposition freezing from a passive preservation step to an active structuring tool, enabling texture design through controlled ice templating and concentration phenomena. Building on established freezing technologies, freeze structuring offers a scalable, clean-label approach with strong relevance for both fundamental food structure research and industrial legume processing.



Bach, A., Perler, E., Lemcke, L.S. *et al.* Freeze structuring unlocks minimal-processing strategies for legume texturization. *npj Sci Food* **10**, 258 (2026).

<https://doi.org/10.1038/s41538-026-00991-5>

5) ..Understanding Freeze-Fracture in Soft Model Hydrogels

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Freezing-induced damage in soft, porous materials is a widespread problem that is still poorly understood, but which impacts many disciplines such as geology, and material and food sciences [1]. There are two key challenges that have made it hard to make progress on this problem. Firstly, most samples of interest are not transparent, so it is hard to directly visualize freezing damage processes. Secondly, materials like food, tissue and clay have complex fracture properties, and so they break in complex ways. Thus, although freezing damage strongly resembles a fracture process, it has been challenging to directly apply fracture mechanics to understand it.

Here, we develop a model freezing system, using transparent hydrogels. When we freeze these gels at a constant rate, we observe the formation of beautifully periodic, ice-filled cracks (Fig. 1). By bringing order into the damage process, we now have an excellent testbed to understand freeze-fracture. We find that the cracks depend on certain parameters such as temperature gradient, freezing speed and sample geometry thickness, and explain this dependence with a simple fracture mechanics model to our system. However, while fracture mechanics describes many of our experimental observations, there are some surprising discrepancies - such as the observed crack tips being much larger than expected from theory. Our results demonstrate the great potential for understanding fundamental questions in freeze damage by applying well-established concepts from fracture mechanics.

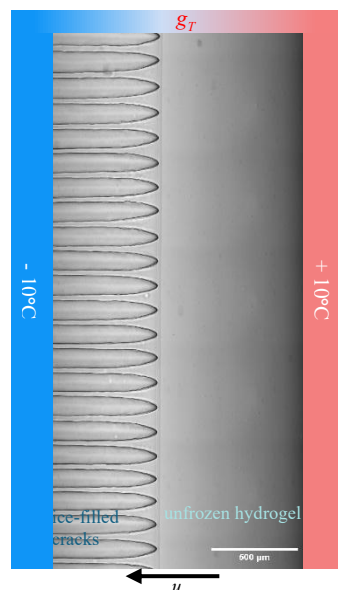


Figure 1: Microscope image of ice-filled cracks in a PEGDA hydrogel growing inside a temperature gradient, while the sample moves at a constant speed u .

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6) Addressing multicomponent complexity in freeze structuring of food colloids

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ETH Zürich

Freeze structuring (FS) is a promising technique for engineering porous food structures through controlled ice crystal formation. FS's scalable, straightforward process enables precise control over pore morphology by manipulating ice crystal formation in suspensions through material and process parameters. However, food systems are inherently complex, heterogeneous, and polydisperse mixtures of polysaccharides, proteins, and fats. Unlike well-studied single-component systems, the interactions within multi-component mixtures during FS are challenging, limiting the broader adoption of FS for food systems.

In this work, we investigate how material parameters influence structural outcomes across scales, from microscale porosity to macroscale mechanical properties. We focus on solid loading and water-material interactions as key drivers of structure formation and propose viscosity as an accessible, potentially predictive parameter for morphology control. By enabling the direct structuring of complex food mixtures without pre-purification, we aim to position FS as a practical tool for efficient, nutritious, and scalable food design.



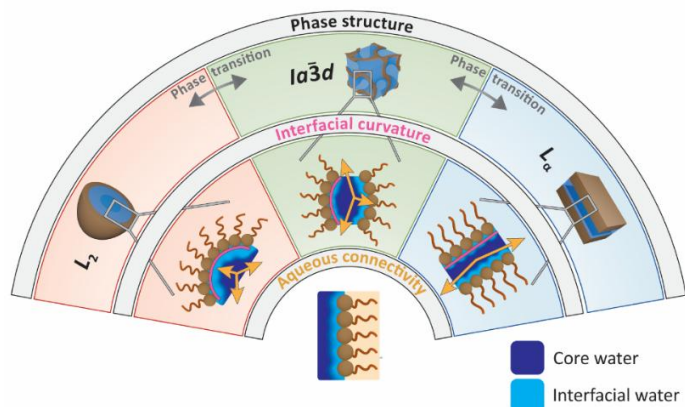
Bach, A. & Rühs, P. A. Addressing multifactorial complexity in freeze structuring of food colloids. *Curr. Opin. Colloid Interface Sci.* **79**, 101941 (2025).

7) Confining Geometry Governs Dynamics in Lipidic Mesophases

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In biological and advanced nanomaterial environments, water and other non-aqueous solvents often exist in confined settings, with their dynamics tightly governed by the surrounding interfaces [1]. Although confinement size is known to be an important factor, how confining geometry itself shapes solvent behavior remains less understood [2,3]. Lipidic mesophases (LMPs) offer an ideal model system for probing soft confinement, as they offer a range of self-assembled phase structures with nanometer-sized solvent-domains [4]. Depending on composition and temperature, these mesophases transition from structures with planar interfaces to curved interfaces with interconnected solvent channels, and ultimately to highly curved, isotropic phases, such as the lamellar (L_a), cubic $Ia\bar{3}d$, and reverse micellar (L_2) phases, respectively. Using a combination of X-Ray Scattering and Calorimetry, we show that phase transitions require only modest enthalpic energy input yet produce abrupt changes in both lipid and solvent dynamics, as probed by complementary spectroscopic techniques: In both water- and glycerol-based LMPs, conductivity increases as the system moves towards more fluid phases and solvent-connectivity is increased. As interfacial curvature decreases toward planar geometries, hydrogen-bonding strength increases, revealing dynamically different interfacial and core water populations, while lipid tails pack more tightly. Together, these findings establish a clear geometric principle: interfacial curvature and solvent connectivity jointly control the packing of lipids, hydrogen-bonding, solvent dynamics, and charge transport in lipidic mesophase, providing a conceptual framework for the rational design of lipid-based systems [5,6].



Integrative schematic linking geometry to interfacial curvature and aqueous connectivity, which then govern the dynamics within lipidic mesophases.

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8) SAXS and SANS Guided Design of Biomimetic Lipid Nanoparticles

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Self-assembled structures at lipid–water interfaces play a central role in biological systems. These ordered phases can solubilize polar, nonpolar, and amphiphilic components, making them attractive for applications in nutrient and drug delivery. The project focuses on developing pH-responsive interfaces of oleic acid and dioleoylphosphatidylcholine (DOPC) that can be exploited for functional applications. The rational design of the self-assembled structures depends on a molecular-level understanding of structural response mechanisms. Beyond molecular composition, surface interactions, spatial confinement and hierarchical structuring play a decisive role in directing the functional behavior of these materials.

This presentation demonstrates pH- and composition-responsive lipid/water interfaces formed by dispersed oleic acid/DOPC self-assemblies in excess water. Using in situ SAXS and SANS, combined with selective deuteration and solvent-contrast variation, we analyze the formation of self-assembled structures with temporal and compositional resolution. Supported by numerical data modeling, we map the distribution of molecules within these systems, aiming to understand self-assembly mechanisms and create a multi-dimensional phase diagram with detailed structural assignments at the mesoscale.

The structural transformations are interpreted within the critical packing parameter framework and correlated with intermolecular interactions. Building on these findings, we propose advanced design principles for creating adaptive, biomimetic nanomaterials with potential for application in nutrient and drug delivery.

9) Bacterial motility effects on leaf surface exploration

Edoardo Maria Mollica, Giovanni Stefano Ugolini¹, Benjamin Daniel², Tommaso Redaelli¹, Francesco Carrara¹, François Peaudecerf⁵, Lucio Isa³, Andrea Carminati⁴, Eleonora Secchi¹, Julia Vorholt², Roman Stocker¹

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** presenting author*

The aerial surfaces of plants support diverse microbial communities essential to plant function and survival. The factors that determine where bacteria first attach and grow on plant leaves remain poorly understood. While microbial colonization of the phyllosphere—leaf, stem, and flower surfaces—has been widely studied, most work has focused on later stages shaped by biological and chemical interactions. Here, we isolate the physical contribution by recreating realistic leaf topographies in microfluidic devices and examining bacterial behavior in the absence of biological and chemical cues. We show that purely hydrodynamic interactions with the surface are sufficient to trap motile bacteria in epidermal grooves, guiding early spatial distribution.

Our microfluidic device, developed using two-photon nanolithography and PDMS molding, allows high-resolution imaging of bacterial behavior under controlled conditions. We observed that motile bacteria, including *E. coli* and native phyllosphere isolates such as *Pseudomonas syringae*, preferentially accumulate in grooves between epidermal cells. *E. coli* and *P. syringae* cells were respectively 39% and 22% more likely to be trapped in grooves than on cell tops. Over several hours, these regions also hosted significantly larger colonies, with *E. coli* colony area being 50% greater in grooves than on cell tops. These findings, paired with mathematical models, illuminate how bacterial motility and hydrodynamic interactions shape microbial colonization patterns on plant surfaces. More broadly, they contribute to our understanding of how topographical features influence microbiome assembly in living systems. By enabling controlled, high-resolution observation, our method allows for a mechanistic understanding of biological phenomena that are otherwise difficult to disentangle in vivo.

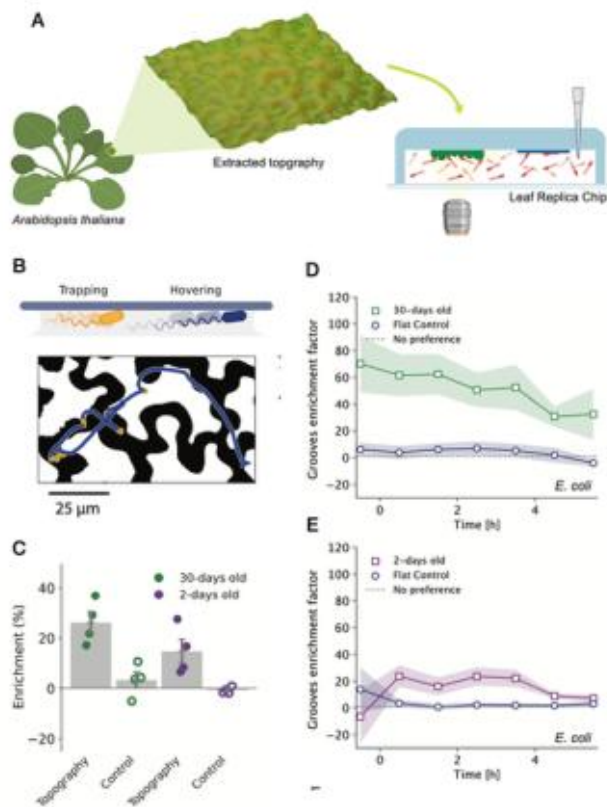


Figure 1. Physical trapping of motile bacteria in leaf surface grooves. (A) Fabrication pipeline of the Leaf Replica Chip: a topographic scan of a real *Arabidopsis thaliana* leaf (left) is converted into a microfluidic device reproducing its epidermal surface geometry (right). (B) Top: schematic of bacteria interacting with the leaf-replica surface. Bottom: a representative single-cell trajectory from microscopy, overlaid on the segmented topography map, illustrating trapping and hovering behavior over epidermal grooves. (C) Groove trapping enrichment (%) for *E. coli* on mature (green) and juvenile (purple) leaf-replica surfaces, relative to flat controls. (D) Time evolution of groove enrichment during attachment on old surfaces (green) and their corresponding flat controls (blue). (E) As in (D), for young surfaces (purple) and their corresponding flat controls (blue).

10) Shark centra-inspired biomineralized granular hydrogels

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The vertebral centra of sharks consist of mineralized cartilage with stiffnesses comparable to mammalian trabecular bones ranging from 10s to 100s of MPa (1, 2, 3). During the free-swimming motion of sharks, the centrum undergoes millions of compression cycles to strains up to 3-8% (2, 3). Also, shark centra toughness is positively correlated with its stiffness. By contrast, biological materials generally display an increase in brittleness with increased stiffness, resulting in a lower toughness (3). This unusual set of mechanical properties is remarkable when considering that, unlike bones, cartilage does not show evidence of remodelling mechanism to help accommodate the accumulation of microdamage during cyclic loading (2).

Synchrotron microcomputed tomography studies revealed that the microstructure of shark centra consists of mineralized trabeculae with features down to the 10s of μm (1). It is composed of two continuous and interconnected collagen networks; one is mineralized while the other remains unmineralized. Although the hierarchical complexity of shark centra is suggested to participate in the accommodation of cyclic loading (1), the centra microstructure needs further investigation to understand how it impacts the macroscopic mechanical properties.

A key difficulty in the design of hydrogels for load-bearing application in tissue engineering is to reach similar toughness as their biological counterparts without sacrificing their stiffness and strength (4,5). Therefore, this field could benefit from new insights on the effect of microstructure on shark centra mechanics.

I will present a 3D printable granular hydrogel system that can be converted into calcium-phosphate-based composites. I will present methods to control their microstructure and thereby their mechanical properties.

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11) Magnetite NPs for Production of Anisotropic Mesoporous Materials

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Lyotropic liquid crystals (LLCs) are mesophases, a state of matter with a behaviour between liquids and solids, which are formed when amphiphiles such as surfactants are dissolved in water at specific concentrations and temperatures. Depending on the latter, LLCs can manifest into different phases, including bicontinuous cubic, hexagonal and lamellar.

In recent years, LLCs have been widely exploited as templating agents to fabricate mesoporous inorganic materials that retain the original structure of the templating system (1), for catalysis, drug delivery, pollutant adsorption and chromatography. In particular, the hexagonal LLCs are extensively used, consisting of cylindrical micelles packed into randomly oriented domains of hexagonal arrays (2), therefore lacking a long-range anisotropic order.

Imposing a preferred overall orientation remains a major challenge; however, the resulting templated porous materials could benefit from enhanced mass transport and reduced pressure drop. Although several strategies have been explored to orient such domains (2), these attempts have not yet been translated into the preparation of monoliths with anisotropic porosity.

Here, we propose a strategy to fill this gap using LLCs containing polymerisable oils, which swell the lipophilic domains (3) of a reverse hexagonal (H_2) phase. Remarkably, these "swollen" LLCs can host hydrophobic magnetite nanoparticles (MNPs) (4). Under a static magnetic field, such MNPs-doped LLCs are expected to align parallel to the field, thereby providing anisotropic templates. We investigate H_2 phases containing MNPs dispersed in a polymerisable oil (i.e., methyl methacrylate), which is then photopolymerised. Upon polymerisation in a magnetic field, and after surfactant removal, porous, anisotropic monoliths can be obtained.

Preliminary results demonstrated the formation of MNPs-doped H_2 systems, their domains alignment under a static magnetic field, and the retention H_2 of the hexagonal structure after polymerisation of a tert-butyl methacrylate-based systems. As next steps, optimisation of the composition will be considered, and tests will be carried out in magnetic fields to produce anisotropic materials retaining both macroscopic alignment and hexagonal periodicity. Once obtained, the resulting monoliths can be tested to assess the effect of anisotropy on mass transfer compared with analogous isotropic samples.

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12) Nacre-Inspired CaCO₃ Composites via Enzymatic Mineralization

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Nature creates strong and tough materials such as nacre through highly efficient, low-energy processes. Nacre exemplifies how a hierarchical architecture of polygonal aragonite tablets interlaced with a biopolymeric matrix can dissipate energy effectively, resulting in an unusual combination of stiffness and toughness [1]. Synthetic materials with similar compositions often display inferior mechanical performance despite relying on energy-intensive fabrication steps, including high-temperature sintering. Recent work in our laboratory has investigated the reinforcement of soft granular gels through mineralization [2]. However, the resulting structures remain limited in load-bearing capability because strength and toughness are difficult to unite within a single synthetic system.

Here, we will introduce enzyme-containing hydrogel microfragments that will be co-printed with enzyme-free counterparts to create layered, nacre-like architectures. These structures will undergo controlled mineralization to yield composites that achieve combinations of stiffness, toughness and fatigue resistance similar to nacre, while being fabricated entirely at room temperature through benign and energy-efficient processes. We will further show that their structure, mineral content and mechanical properties can be tuned over a broad range by adjusting the ratio of enzyme-active to enzyme-inactive fragments and by modulating the CaCO₃-polymer interface. Such bioinspired hybrid composites hold significant potential due to their tunable mechanical properties and hierarchical design, offering a promising pathway toward advanced materials that bridge the gap between strength and toughness.

Keywords: microgels, 3D printing, enzymatically induced mineralization, nacre

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13) Aperiodic Orientational Order in Optothermally-Aggregated Colloids

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In the present work we exploit optically-induced thermal gradients to achieve stoichiometrically-controlled manipulation of bi-disperse micrometric colloidal particles in a strongly confined 2D geometry right under the microscope. By compacting mixtures in conditions where size ratio and concentration are such to allow the formation of 2D quasicrystals from nonadditive hard-disks, we do see the local formation of square-triangle tiled regions with strong 12-fold orientational correlations spanning many nearest neighbours. We then compare our results with MD simulations mimicking the same out-of-equilibrium compaction process adopted experimentally, backing our results.

We then inquire over the possible forms of orientational ordering that may or may not be attained by compacting hard sphere colloids through an external force; specifically, we show how 12-fold symmetry is possible for a specific choice of particle size ratio, while no 8-fold symmetry can be achieved under the constraint of strict compactness.

Lastly, we verify via simulation that, by removing the compacting thermal force while keeping the particles constrained within a given boundary, the whole system self-assembles in a long-range correlated quasicrystal according to what predicted by the self-assembly diagram in reference [1].

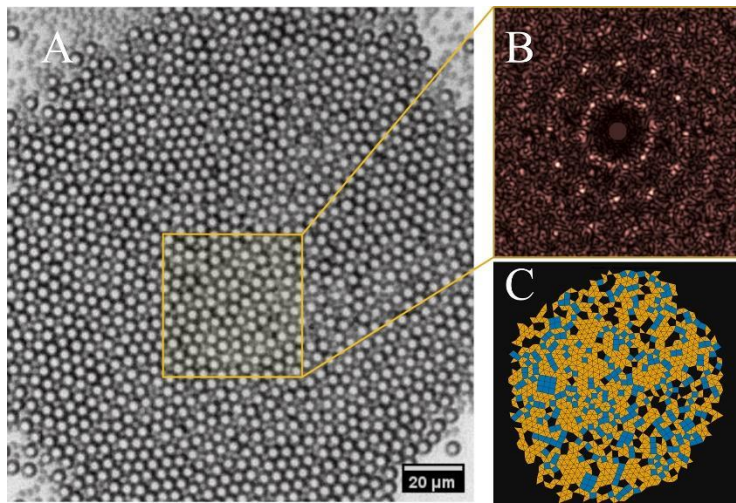


Figure 1: (a) Image of a close-packed aggregate obtained from bi-disperse colloidal particles. (b) Partial structure factor of the large particles contained in the highlighted square region. (c) Square-triangle tiling of the aggregate.

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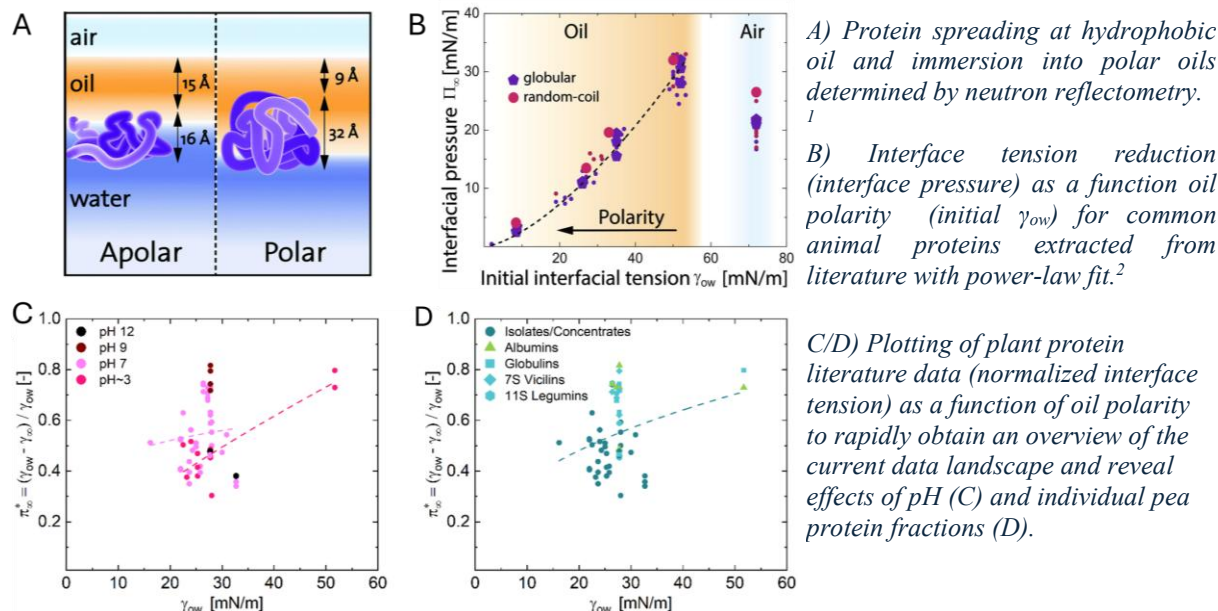
14) Universal adsorption of proteins at oil-water interfaces: A tool for mapping novel plant-based proteins

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The adsorption of proteins to fluid-fluid interfaces is a crucial process in physiology and the formulation of food, pharmaceutical and cosmetic products. At fluid oil-water interfaces, protein adsorption and associated structural rearrangements depend on the thermodynamic stability of the protein and hydrophobicity (inverse polarity) of the oil phase. Proteins stretch out more in the interfacial plane at hydrophobic oils, while they immerse deeper in polar oils with limited structural rearrangements¹ (see Figure A). As a consequence, the reduction of oil-water interface tension γ_{ow} by proteins as a function of oil polarity follows a universal power-law that describes previously published protein adsorption data² (see Figure B). In light of the importance of shifting from traditional animal-based (dairy, egg, serum) to more sustainable plant-based proteins, we have applied this novel method (alternate subphase tensiometry, AST) to map the current data landscape of plant protein adsorption³. We plotted the interface tension reduction by plant proteins as a function of oil polarity of published data from more than 60 studies. AST allows standardized plotting of literature data in uniform graphs, providing a rapid overview of the present data and pinpointing current gaps. Furthermore, grouped data can be readily singled out to identify promising protein fractions and effects of processing conditions such as pH, ionic strength, or pretreatments (showed exemplarily for pea proteins in Figures C and D). Hence, AST is a powerful tool to summarize the existing data landscape, identify research gaps and particularly promising protein fractions, and ultimately predict the interfacial performance of plant proteins for interfacial stabilization.



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15) Investigation of the structure and digestion of plant protein-stabilized interfaces in vitro

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Human lipid digestion begins at the interface of oil and water by interfacial adsorption of lipases. Tailoring the available surface area for lipase activity can lead to specific lipid sensing in the body, thus, tailored satiety hormone release.^[1, 2] Therefore, we aim to explore the effects of plant proteins as the surface-active materials to modulate the gastric stability of oil-in-water emulsions.

Interfacial shear rheology was used to investigate the layer evolution during gastric in vitro digestion steps. Medium-chain triglyceride oil (MCT) was used for the oil phase. β -lactoglobulin (β -lg), soy protein concentrate (SPC) and rapeseed protein concentrate (RPC) were used for preparing protein solutions at pH 2. Interfacial storage G_i' and loss G_i'' moduli of adsorbed layers were measured over time at constant oscillation at 20 °C. Simultaneous subphase exchange was performed, based on the methodology described by Bertsch *et al.*^[3]. The subphase was a protein solution initially. After having equilibrated states, 0.4 mg/ml pepsin was injected into the subphase. This technique allows insights into viscoelastic layer evolution under various gastric conditions and thus an estimation of the emulsion destabilization process in the stomach.

Pepsin digestion behavior differed among proteins. For β -lg, interfacial moduli decreased rapidly after pepsin addition, indicating protein hydrolysis and network breakdown. The layer was fully degraded after one hour, followed by peptide rearrangement and partial network recovery. In contrast, SPC and RPI showed slower degradation, with G_i' decreasing faster than G_i'' . Complete breakdown ($G_i' < G_i''$) occurred after approximately 28 hours for SPC and 3 hours for RPI. These results suggest that plant protein-stabilized interfaces exhibit higher resistance to enzymatic digestion than animal protein-stabilized interfaces.

These findings provide fundamental information for designing plant-protein-based lipid emulsions to modify lipid digestion.

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16) From Adsorption to Network Formation: Can Plant Proteins Stabilize the Oil-Water Interface?

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Emulsions are ubiquitous in multiphase food systems and are characterized by high interfacial contact area of oil and water. The most common food emulsion stabilizers are animal-derived proteins. Recently, sustainability concerns are driving the move towards plant-based alternatives. However, this "protein transition" is challenged by the complex interfacial structuring, unfolding behavior and low solubility of plant proteins.

Their strong sensitivity to pH, ionic strength and oil subphases further complicates their stability at interfaces (1). To successfully create stable, sustainable and green emulsions and foams, fundamental understanding of plant protein interfacial behavior is essential. In this study, we investigated the interfacial behavior of pea, lentil, and faba bean proteins and their fractions at various oil–water interfaces by combining complementary techniques to characterize the full adsorption process from bulk to interface.

Drop tensiometry measures adsorption kinetics and interfacial tension reduction. Interfacial shear rheology coupled with a protein injection system observes dynamic viscoelastic interfacial layer formation. Small-angle neutron and X-ray scattering (SANS/SAXS) elucidate the molecular structure of adsorbed proteins on a nanoscale. Albumins adsorb rapidly and reduce interfacial tension more efficiently at short times, whereas globulins form more viscoelastic interfacial layers (interfacial storage modulus > loss modulus). We could show that SANS measurements at the oil match point show a broad correlation feature (q 0.1-0.3 $1/\text{\AA}$), which may be attributed to protein–protein interactions in the continuous phase and/or structuring at the oil–water interface.

This integrated approach provides insight into plant protein interfacial adsorption, network formation, and emulsion structure. These findings contribute to comprehensive and fundamental understanding of plant protein techno-functionality, supporting the design of stable, sustainable emulsions and foams.

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17) Adaptive Hydrogels with Spatiotemporal Stiffening Using pH-Modulating Enzymes

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Mechanical responses in biological systems rely on the chemomechanical transduction of reaction-diffusion processes into structural transitions. While synthetic hydrogels can emulate this autonomy via enzymatic reactions, the underlying transduction mechanisms remain poorly understood. This study investigates a pH-responsive polyacrylamide-alginate hydrogel incorporating the acidifying enzyme glucose oxidase. This enzyme enables acidifying wavefronts propagating at 15-44 $\mu\text{m}/\text{min}$ that trigger calcium-mediated crosslinking via the dissociation of pH-responsive Ca-EDTA complexes. Due to the slow kinetics the system offers, a significant kinetic lag was observed in the resulting mechanical wave, which propagates at only 12 $\mu\text{m}/\text{min}$ and yields a 2.1-fold increase in stiffness. This decoupling demonstrates that mechanical transduction, rather than chemical signaling, serves as the system's rate-limiting step. Furthermore, our findings highlight the energetic load imposed by the mechanical transition on the enzymatic system. Consequently, our system provides valuable mechanistic insights essential for the further development of synthetic adaptive materials.

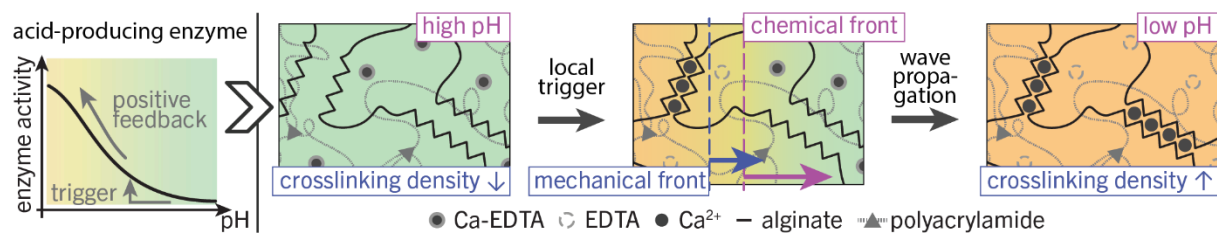


Figure 1. Schematic of the enzymatically-driven adaptive hydrogel. Locally triggering the acid-producing enzyme glucose oxidase, initiates a positive feedback loop which generates a sustained chemical wave. The resulting pH-switch induces a localized increase in crosslinking density, translating the chemical signal into a mechanical wave. This mechanical wave lags behind the chemical wave and yields a global increase in stiffness.

18) Metal–Organic Framework-Reinforced GelMA Hydrogels as 3D-Printable Soft Biomaterials for Bone Repair

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Hydrogels provide a versatile soft-material platform for tissue engineering because their mechanical properties, microstructure, and biological functionality can be independently engineered. However, commonly used hydrogel matrices such as gelatin methacrylate (GelMA) provide a permissive cellular environment but possess limited intrinsic bioactivity and mechanical strength for bone-regenerative applications.

Here, we developed a metal–organic framework (MOF)-reinforced GelMA nanocomposite hydrogel in which zinc-based ZIF-8 nanoparticles were incorporated into the polymer network to simultaneously modulate material properties and introduce biologically active functionality. The resulting composite was engineered for digital light processing (DLP)-based 3D bioprinting, enabling rapid fabrication of defined hydrogel architectures.

Incorporation of ZIF-8 substantially altered the mechanical response of the GelMA network, increasing the compressive modulus from 52.14 ± 19.42 kPa to 128.13 ± 19.46 kPa, while maintaining cytocompatibility and improving printability. Beyond mechanical reinforcement, the porous MOF phase served as a functional reservoir within the soft polymer matrix, supporting controlled molecular release. Vancomycin incorporated into the nanocomposite showed sustained release with a maximum cumulative release of $87.52 \pm 1.60\%$.

Importantly, ZIF-8-containing hydrogels promoted osteogenic differentiation of human adipose-derived mesenchymal stem cells, demonstrating that the dispersed inorganic nanophase could simultaneously influence the physical and biological properties of the hydrogel environment. The nanocomposite formulation was also compatible with coating of metallic implant surfaces, highlighting its adaptability across different geometries and fabrication strategies.

Together, these findings demonstrate how incorporating functional porous nanoparticles into a soft polymer network can couple mechanical reinforcement, controlled molecular transport, additive manufacturing, and cellular regulation within a single material system. This particle–hydrogel approach provides a modular strategy for engineering multifunctional soft biomaterials for regenerative medicine.

Keywords: soft materials, nanocomposite hydrogels, metal–organic frameworks, GelMA, 3D bioprinting, bone regeneration

19) Loading-Ratio-Dependent Cyclic Softening and Energy Dissipation in Double-Network Elastomers with Distinct Architectures

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Elastomers can soften during repeated deformation well before visible cracks appear. We examine how a granular network architecture changes this prefracture response. Conventional double-network elastomers (DNEs) contain two molecularly interpenetrating networks: a stiff, sacrificial first network and a soft, extensible second network (1). In double-network granular elastomers (DNGEs), the first network is instead confined to jammed microparticles connected by the continuous second network (2). We subject initially uncracked, compositionally matched DNEs and DNGEs to 1000 displacement-controlled cycles over several maximum stretches and loading ratios. Both architectures show rapid initial loss of maximum stress followed by slower continued softening. Normalizing the transient response reveals a shared qualitative evolution, but systematic effects of loading ratio, chemistry, and architecture remain. Under matched loading conditions, DNGEs generally dissipate more energy and a larger fraction of the applied work than DNEs. They also tolerate a broader range of cyclic conditions without visible cracking or premature failure, even when their accumulated stress loss is comparable to or greater than that of DNEs. These results show that macroscopic stress loss alone does not measure cyclic durability. By separating stiff particle regions from a softer interparticle network, the granular architecture accommodates internal mechanical evolution and continued deformation while sustaining high energy dissipation.

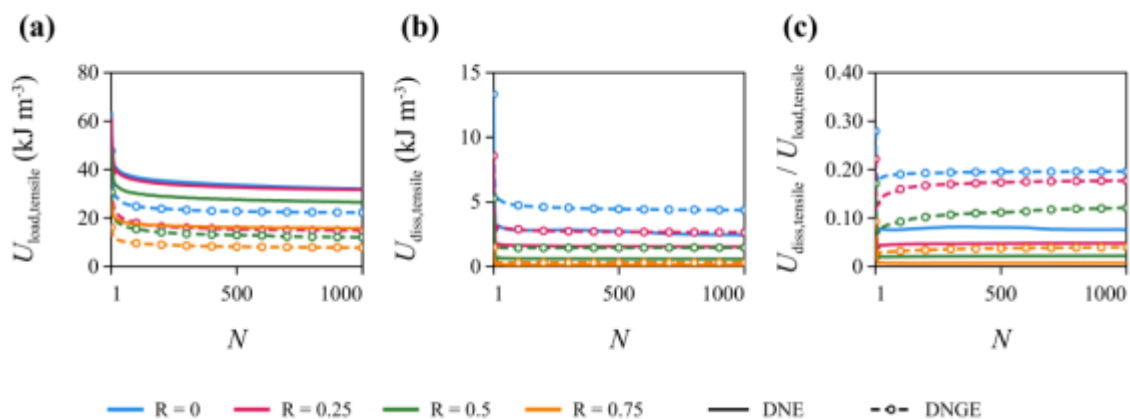


Figure 1 Evolution of tensile energy measures for chemistry A at $\lambda_{\text{max}} = 1.5$ under different loading ratios R. (a) Tensile loading energy density, $U_{\text{load,tensile}}$. (b) Tensile dissipated energy density, $U_{\text{diss,tensile}}$. (c) Fraction of the tensile loading energy dissipated during each cycle, $U_{\text{diss,tensile}} / U_{\text{load,tensile}}$. Increasing R narrows the cyclic stretch excursion and reduces the absolute loading and dissipated energies. DNGEs retain a greater dissipated energy and a greater dissipated fraction than DNEs. Colors identify R; solid lines represent DNEs and dashed lines with open circles represent DNGEs

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20) 3D Printing of Living Bioluminescent Mechanosensors

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Engineered living materials (ELMs) harness the biological activity of microbes to produce and degrade materials or provide them additional functionality. As many microorganisms have developed highly efficient metabolisms, ELMs can often be produced with minimal resources and at ambient conditions. The microbial biological activity of interest can be a simple enzymatic reaction or a more complex cascade of reactions that are difficult to reproduce synthetically. *Pyrocystis lunula* are unicellular marine dinoflagellates that developed an efficient pathway to sense a mechanical stimulation and transform it into a visual reporter through bright bioluminescence in the visible range. ELMs containing these dinoflagellates can harness their biological activity and report a mechanical trigger through the emission of light. However, the incorporation of dinoflagellates into solid objects of defined shapes remains challenging.

We address these challenges by embedding dinoflagellates into biocompatible hydrogels with suitable mechanical properties while keeping them viable and metabolically active to show bioluminescence. Analysis of mechanical tests of dinoflagellate-loaded gels revealed that a critical strain and strain rate need to be applied to the gel to trigger bioluminescence. To further characterize the optical response of the embedded cells, we recorded detailed emission spectra of single colonies that indicate distinct peaks of wavelengths in the range from blue to green light. Moreover, we extended the complexity in shape of the produced ELMs by embedding dinoflagellates in a photocurable resin that was printed via digital light processing (DLP). These printed objects showed bright bioluminescence when mechanically deformed. To benefit from the sensitivity and short response time of the dinoflagellates, we demonstrate the potential of such responsive materials by fabricating a bioluminescent stress sensor. The force sensor is able to detect and differentiate small compressive stresses and report them visually and even detectable by eye. Such devices are attractive options for optics-based mechanosensing, signalling, illumination, and soft robotic applications.



Figure: 3D-printed hydrogels loaded with dinoflagellates rendering them mechanoluminescent.

Reference: Rani Boons, Mathias Steinacher et al., Light-based 3D printing of mechanoluminescent living gels loaded with dinoflagellates. Sci. Adv. 12, eadz0017(2026). DOI: [10.1126/sciadv.adz0017](https://doi.org/10.1126/sciadv.adz0017)

21) Towards the development of an electric organ to power implantable devices: block copolymer membranes for energy conversion

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Electric fish such as Torpedo rays and electric eels can transform metabolic energy into powerful electrical discharges. Inspired by this natural phenomenon, we aim to develop implantable artificial electric organs capable of powering active biomedical devices, including artificial muscles and pacemakers. (1,2) We recently investigated the possibility of harvesting energy from ion gradients using ultrathin ion-selective membranes formed through the self-assembly of amphiphilic block copolymers (BCPs). (3)

In this work, our strategy focused on fabricating molecularly thin BCP membranes with macroscopic areas for enhanced power generation. Conventional bilayer membranes, typically formed by folding or painting, produce ultrathin structures only over areas of hundreds of micrometers, rarely reaching 1 mm². However, achieving meaningful current output from ion gradients requires significantly larger active membrane areas. To overcome this limitation, we introduced a toluene-displacement method that enables the formation of ~35 nm-thin BCP membranes across areas ranging from 0.1 to 10 cm², representing an increase of several orders of magnitude. (3) This liquid-liquid interfacial assembly yields robust, molecularly defined membranes suitable for energy conversion applications.

We also demonstrated that ion selectivity could be tuned by incorporating ion carriers such as valinomycin, which selectively transports potassium ions. (3) However, the energy-harvesting efficiency remains limited by the slow diffusion of the carrier within the hydrophobic domains of the membrane. To address this, we are currently exploring the incorporation of pore-forming molecules to create controlled ionic channels, thereby enhancing ion transport and, therefore, electrical current.

This approach is promising for the development of high-performance artificial electric organs and opens new avenues for autonomous bioelectronic systems, including soft robotics, active prosthetics, and long-lasting implantable devices.

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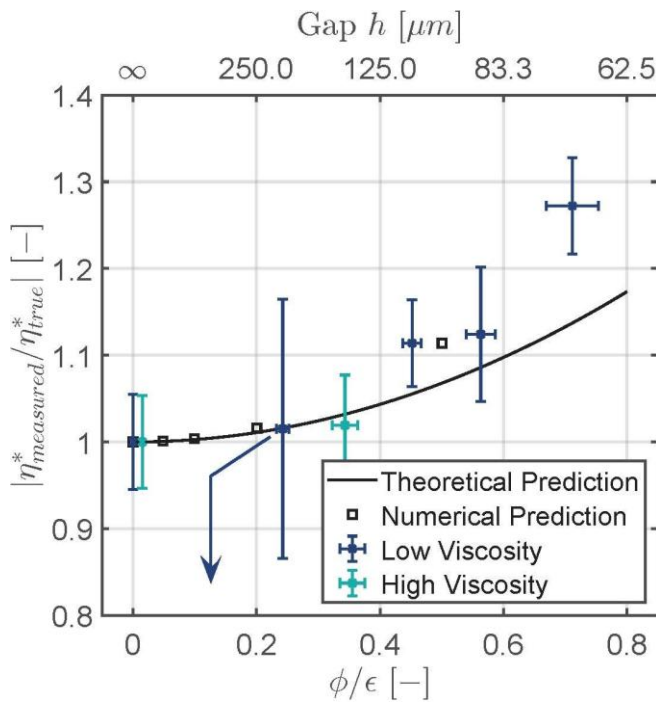
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22) Interferometric Validation of Misalignment Errors in Narrow-Gap Plate Rheometry

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Narrow-gap parallel-plate rheometry is highly sensitive to plate nonparallelism, as small tilt angles distort the flow field and introduce systematic errors in the measured viscosity. Although analytical and numerical models have quantified this effect, direct experimental validation has remained limited. Here, we integrate a Fizeau-type interferometer into a commercial rheometer to measure plate tilt *in situ* while determining the rheological response of Newtonian viscosity standards under controlled misalignment. The resulting error is governed by the dimensionless tilt ϕ/ϵ , where ϕ is the plate tilt angle and ϵ is the average gap-to-radius aspect ratio. For small tilt parameters, $\phi/\epsilon < 0.4$ the measured viscosity errors agree closely with analytical predictions based on perturbation theory [1]. At larger misalignment, the analytical approximation increasingly underestimates the error, while the measurements follow the finite-tilt numerical predictions. Measurements with fluids of different viscosities, together with scaling estimates, indicate that inertial and meniscus-related contributions are not dominant. These results provide direct experimental validation of the predicted rheometric error caused by plate nonparallelism, establish the practical range of the small-tilt approximation, and demonstrate the importance of accurate plate alignment in narrow-gap rheometry.



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23) Combining FCS and SAXS for Traceable Nanoparticle Characterisation

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Nanoparticles are used increasingly by industries in healthcare, semi-conductor/ energy and consumer products. However, there are currently no standardized and validated measurement methods for number concentration and particle density¹. Knowing the number concentration and particle density is important not only for the research and development of new nanomedicines and other new technologies, but also for personal safety, environmental safety and regulatory compliance². Furthermore, to make reliable measurements with ensemble methods, the absolute number concentration and particle density are often required as input parameters. In this work, we successfully measured three nanoparticles selected as reference material candidates using fluorescence correlation spectroscopy (FCS) and small angle x-ray scattering (SAXS). The number concentration values determined from FCS are used as input for particle density measurements using SAXS. The measured number concentrations showed good agreement, in terms of order of magnitude, with values obtained using complementary characterization techniques within the ConcenSus consortium members. Hence, this work demonstrates that FCS and SAXS are promising tools for traceable and reliable measurements of particle number concentration and particle density. This work contributes to the development of standardized metrological methods for nanoparticle characterization and making industries more sustainable.

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