Bijels by STRIPS: A complex new form of liquid matter

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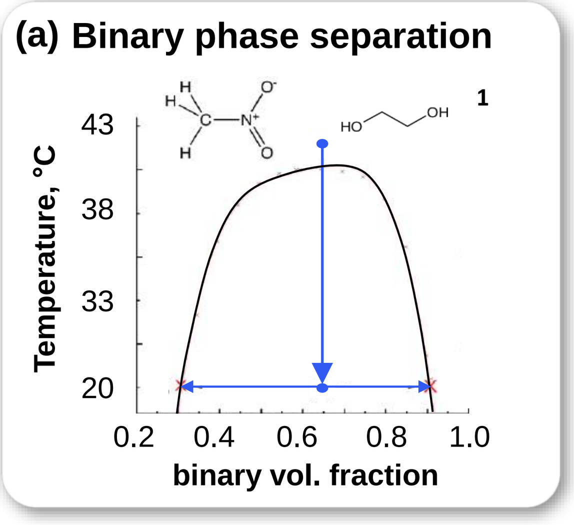
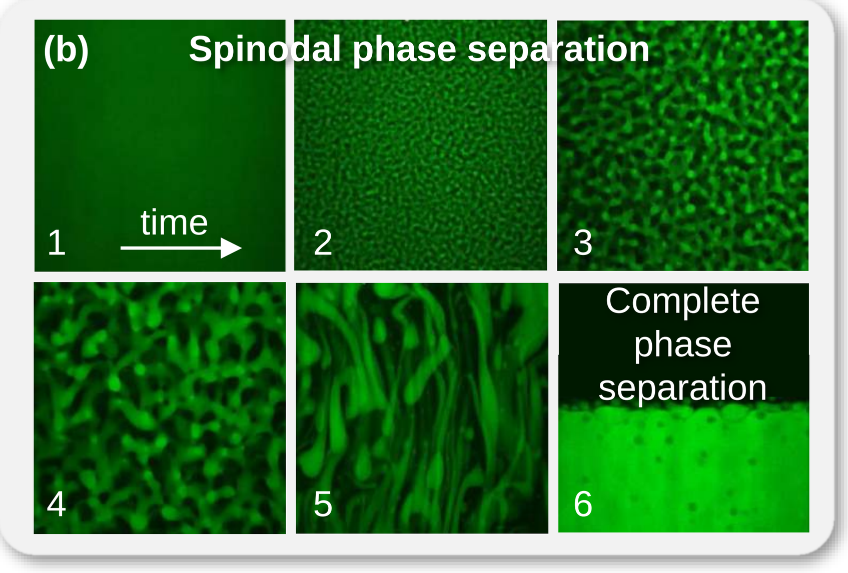
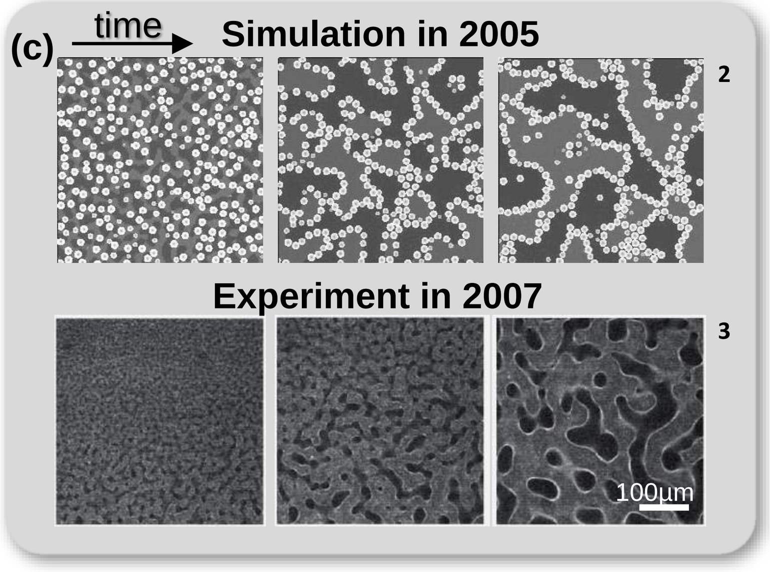
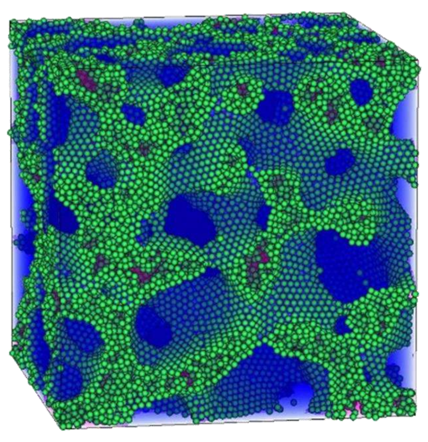
1. Bicontinuous interfacially jammed emulsion (Bijel)

Bijels are a new class of soft materials that are formed by phase separation of immiscible liquids. The binary phase diagram in **(a)** shows the temperature dependent mis-cibility of 2 liquids. Above 40°C the two liquids can be mixed. Rapidly cooling this warm mixture along the blue arrow induces a spinodal phase separation as shown in **(b)**. An interconnected liquid-liquid channel network forms, which coarsens into 2 completely separated phases. To make a bijel the phase separation has to be arrested with colloidal particles in the mixture, as was first demonstrated in computer simulations in the year 2005 **(c)**.



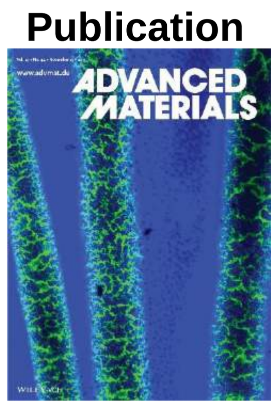






The particles attach strongly to the interface between the 2 liquids and form a densely packed layer. This layer is interfacially jammed an stabilizes a bicontinuous fluid network (first demonstrated experimentally in 2007). This poster describes an advanced method of making bijels introduced by me in 2015.

Publication



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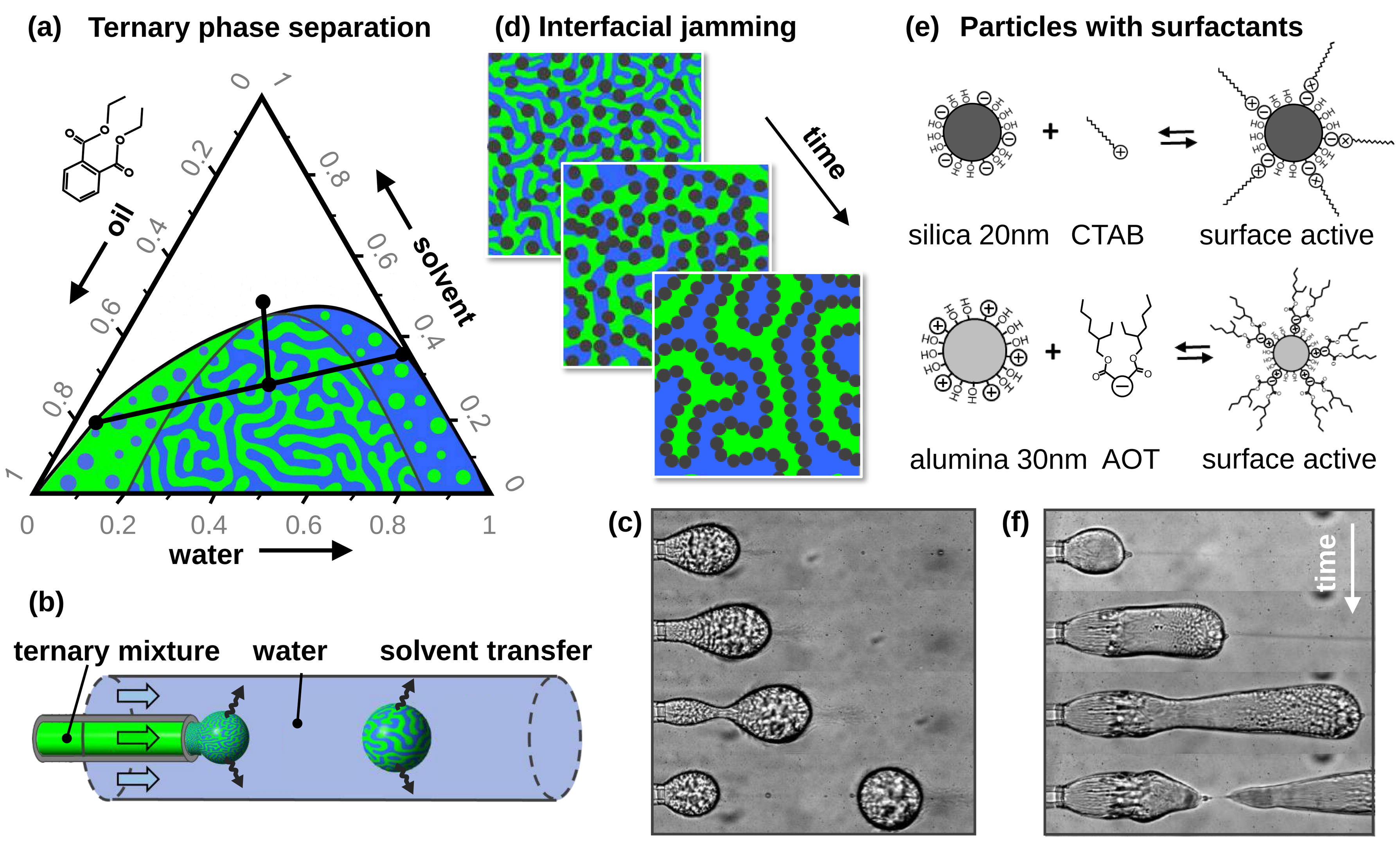
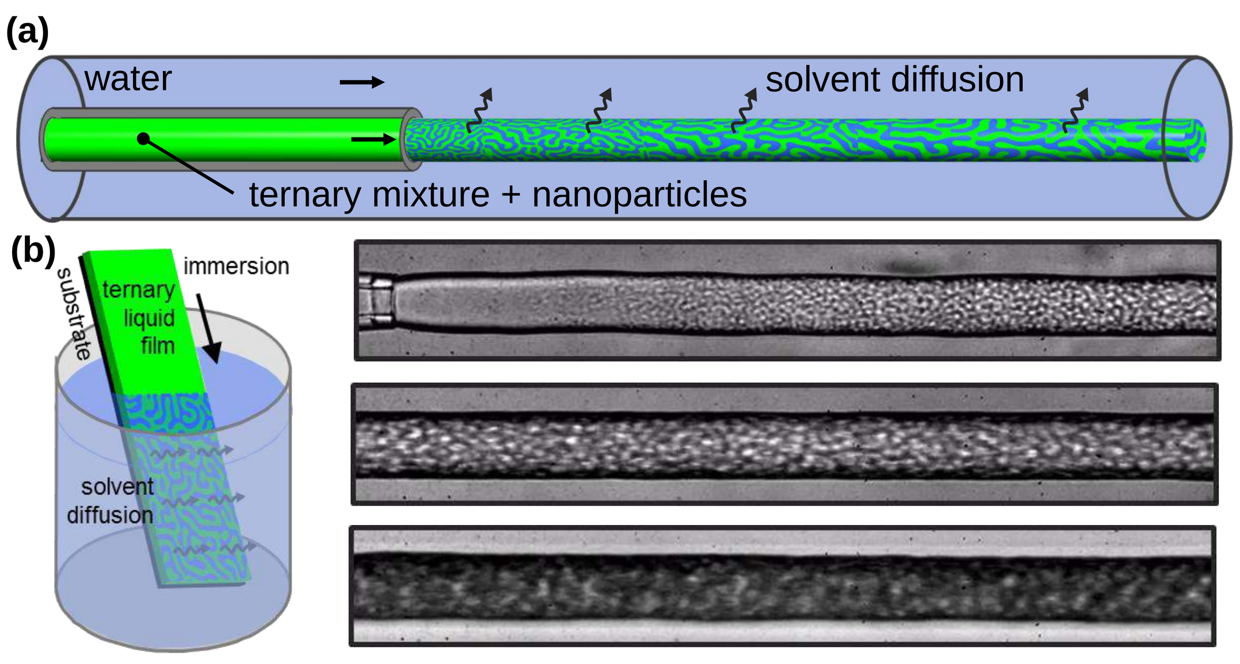
2. Solvent Transfer Induced Phase Separation (STRIPS)



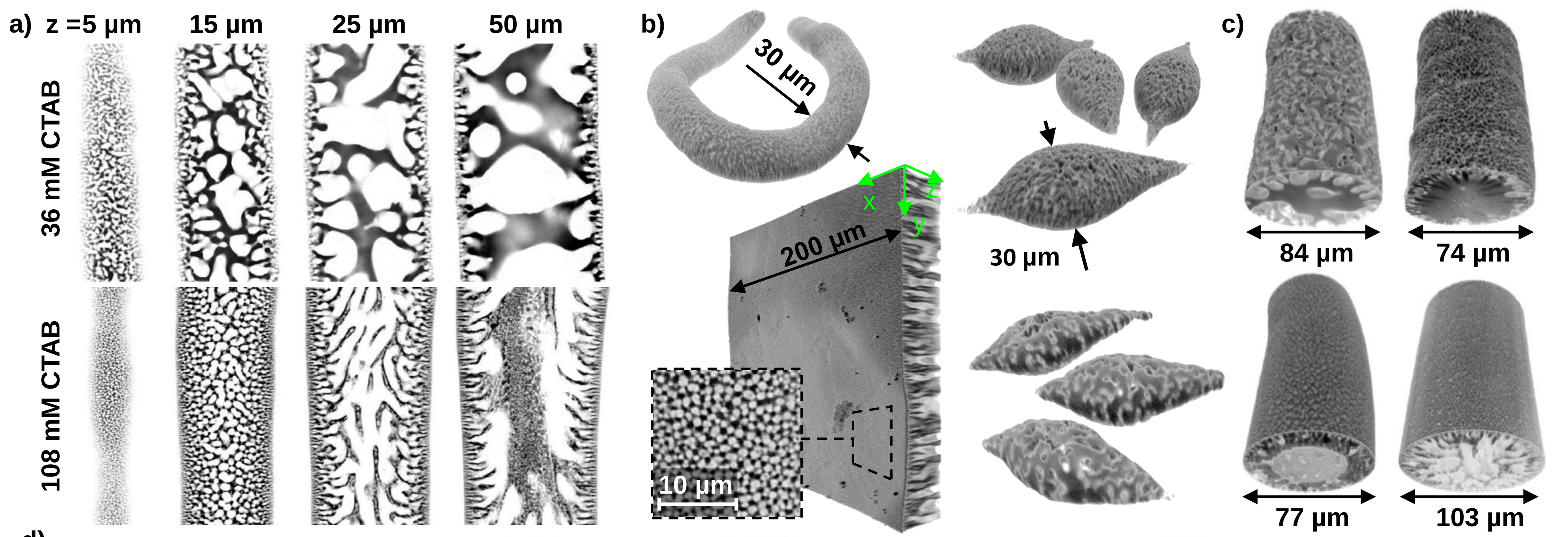
Instead of binary, we use ternary phase separation **(a)**: This approach facilitates the combination of many different pairs of immiscible liquids that cannot be mixed by raising the temperature. We inject a homogeneous mixture of oil, water and a solvent into a water stream **(b)**. Phase separation occurs in the so formed droplets because the solvent diffuses into the water stream, leaving immiscible water and oil behind. The spinodal patterns are clearly visible under the microscope **(c)**. Introducing surface active nanoparticles to the ternary mixture allows for the formation of bijel droplets **(d)**. To this end we make the nanoparticles surface active by combining oppositely charged particles and surfactants **(e)**. The surfactants adsorb on the particles and make them partially hydrophobic. With the nanoparticles the droplet pinch off looks very different **(f)**. The droplet are viscoelastic (like toothpaste) and pinch off as irregularly shaped objects. Interfacial particle jamming causes the liquid mixture to have mechanical properties.

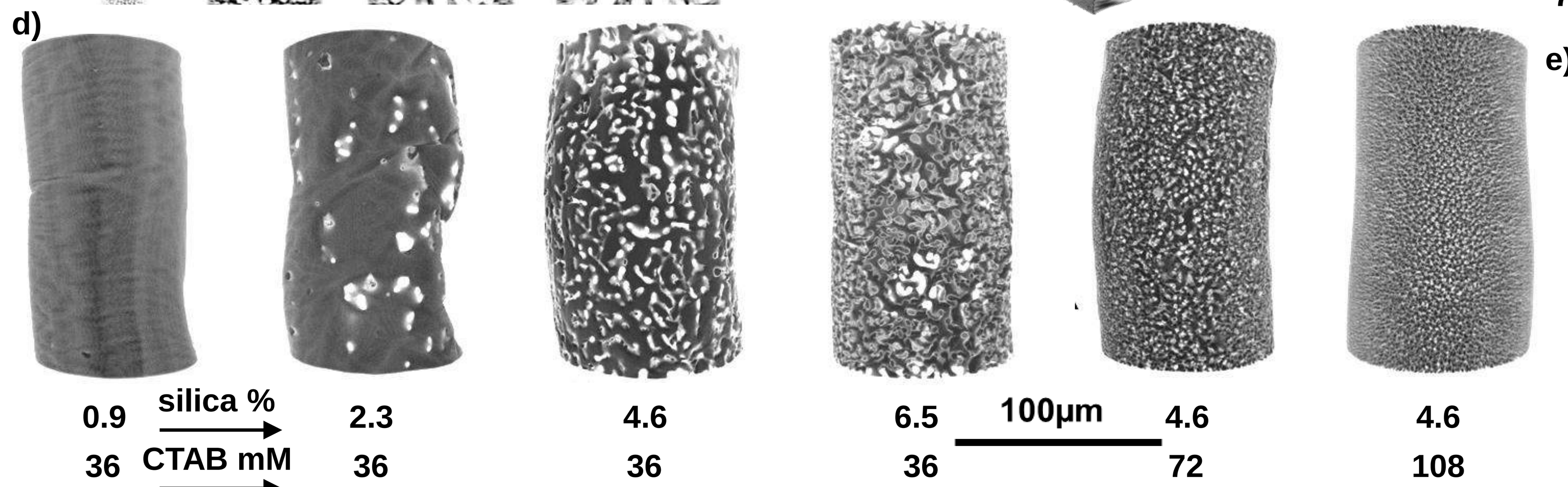
3. Fiber or Membrane formation

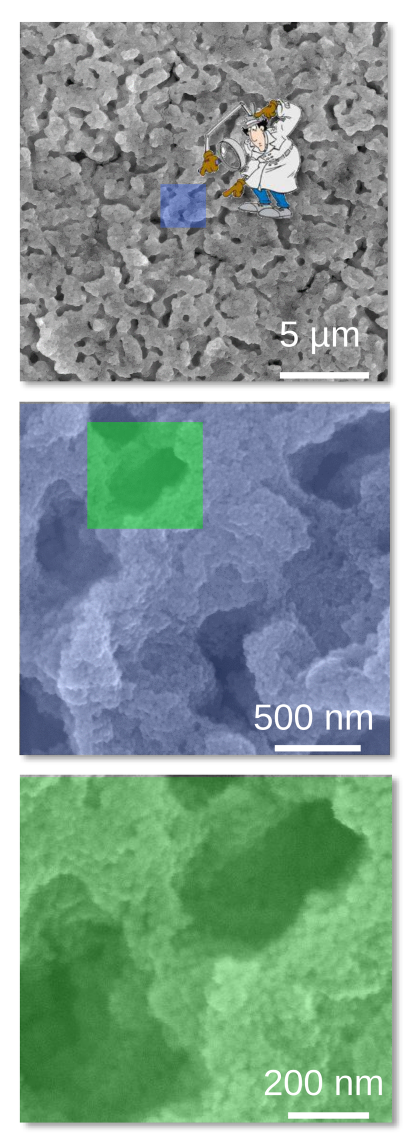


Instead of irregularly shaped droplets a uniform fiber can be extruded **(a)**. You can see the coarsening of the oil/water structures within the fiber over its trajectory under the microscope. At the end a liquid fiber stabilized by nanoparticles is formed. Alternatively, a thin film of the ternary mixture coated onto a plate can be immersed into a water bath and the same process takes place in a planar geometry **(b)**.

4. 3D-analysis of STRIPS-Bijel Fibers, Membranes and Particles

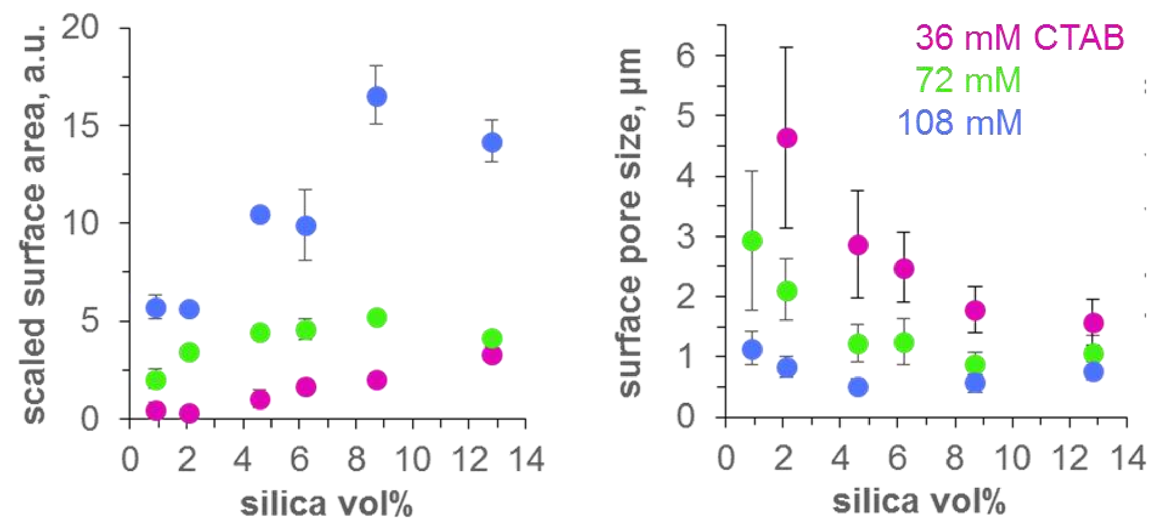






The structure of the oil/water channels within these fibers can be analyzed by confocal laser scanning microscopy. In **(a)** tomographic visualization (slice-by-slice) of two different fibers fabricated at different surfactant concentrations is shown. Using this technique we can obtain 3D-reconstructions of STRIPS-bijel fibers, membranes and particles **(b, c, d)**. As you can see in **(c)**, the fibers can have remarkably different internal structures. Moreover, **(d)** shows that the surface pore size strongly depends on the concentration of the surfactants and the nano-particles. These different structures suggest different applications for the STRIPS-bijels, for instance hollow fiber membranes are very useful as separation membranes.
Scanning electron microscopy allows us to magnify the surface of the fibers further **(e)**. At magnifications as high as 150,000x we can see the interfacially jammed nanoparticle film. The nanoparticles can be quite useful in applications of the STRIPS-bijels, for instance they can act as catalysts to promote reactions for the synthesis of manifold chemical products.

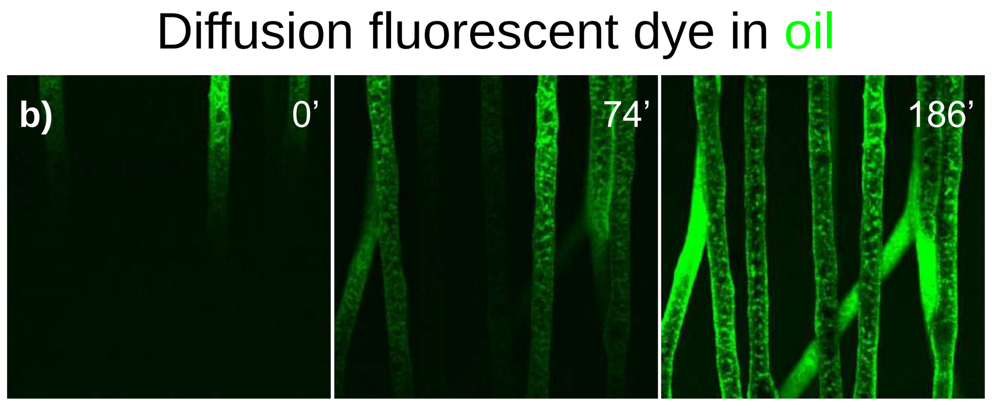
5. Surface area and pore size



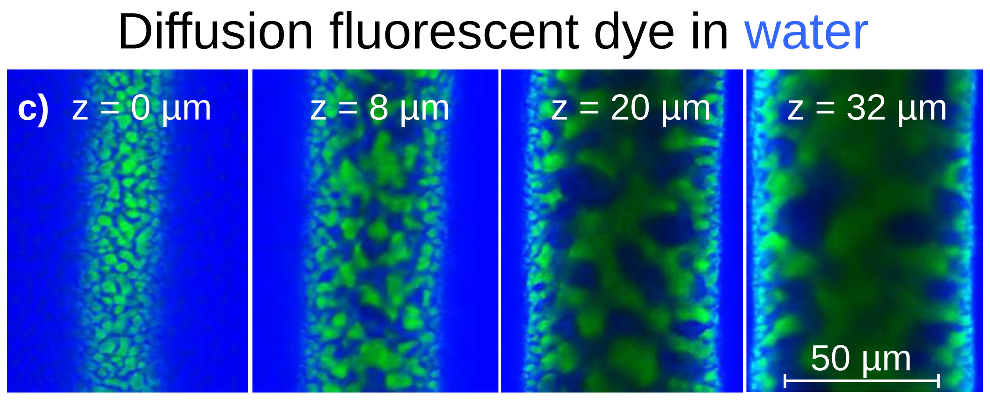
With the 3D structure data we can analyze the surface area and pore size in dependence of the surfactant and nanoparticle concentration. The general trends are increasing both concentrations leads to smaller pores and higher surface areas.

6. Mass-transfer in bicontinuous channel system

Diffusion fluorescent dye in oil



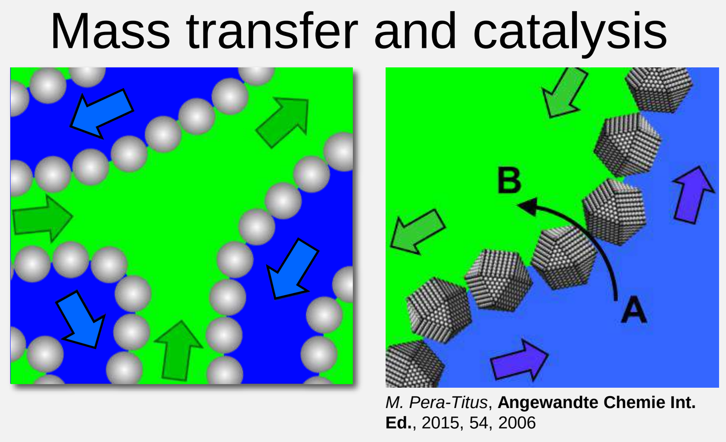
Diffusion fluorescent dye in water



Aligning the fibers as parallel bundles and connecting those to oil reservoirs allows us to study their application as porous transport pipes **(a)**. In **(b)** you see the transport of a green dye over time through diffusion in the oil channels of the fiber. Moreover, when we inject a blue dye into the surrounding water we can see that the blue color penetrates into the water pores of the STRIPS-bijel fiber. This openness and channel interconnectivity of the fibers shows great potentials for applications as outlined in **7**.

7. Outlook and Future applications

Mass transfer and catalysis



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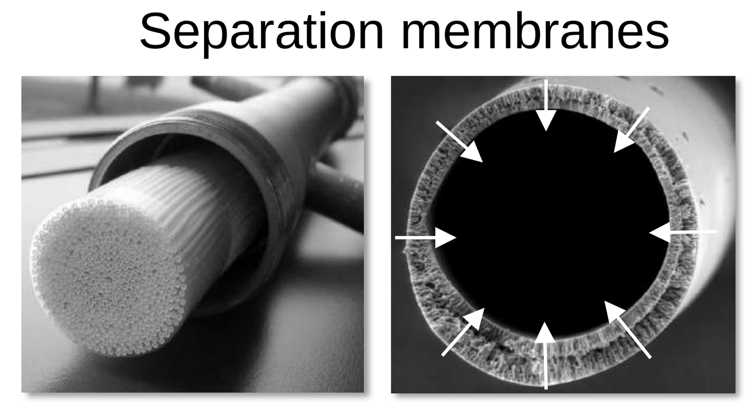
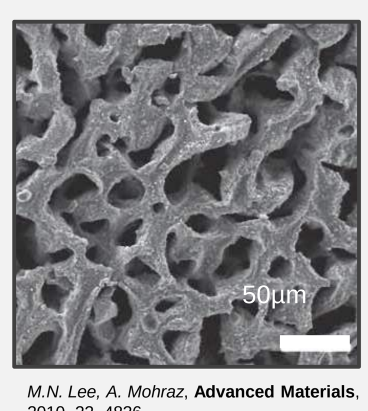
Separation membranes



Edible Bijels

Cosmetics

Sensors



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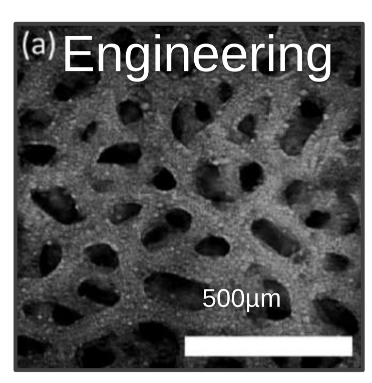

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