COMMUNICATION

Responsive Materials

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3D Printing of Living Responsive Materials and Devices

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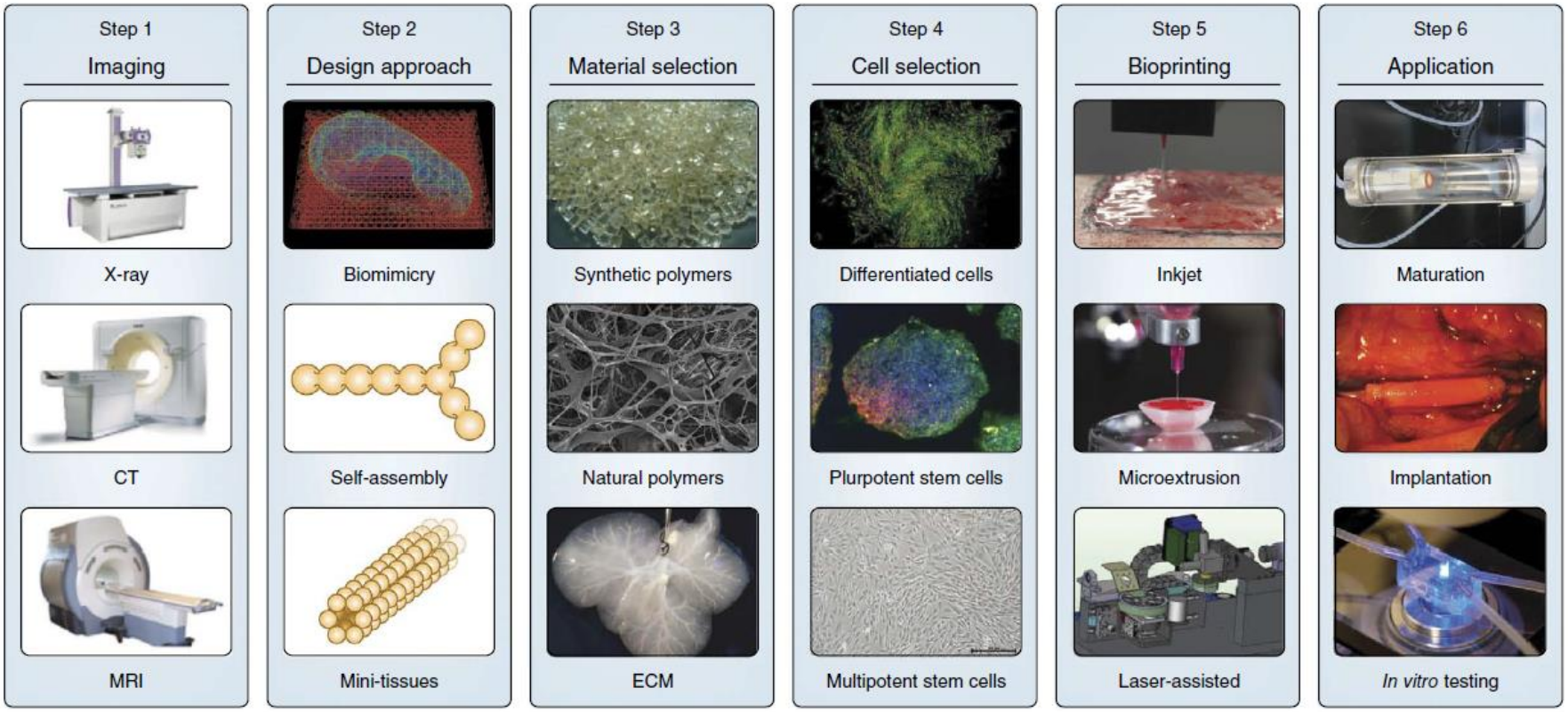
Background

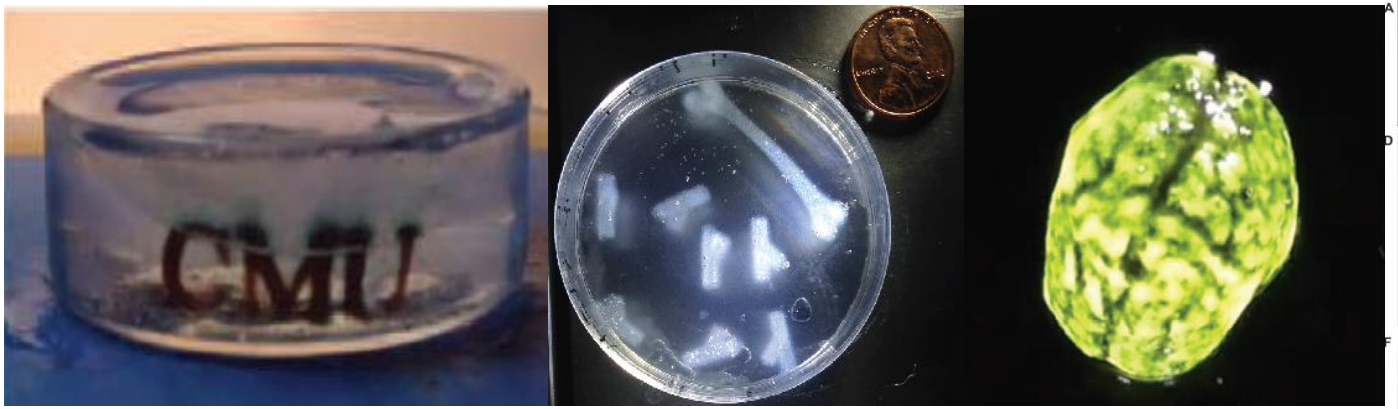


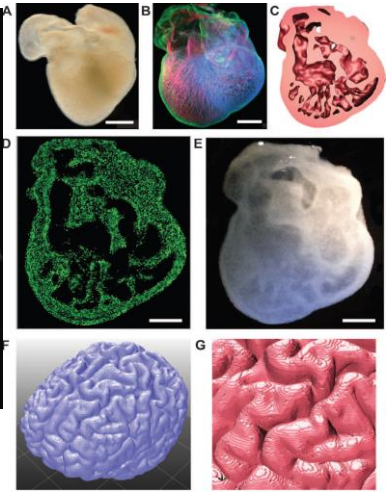
A typical process for bioprinting 3D tissues

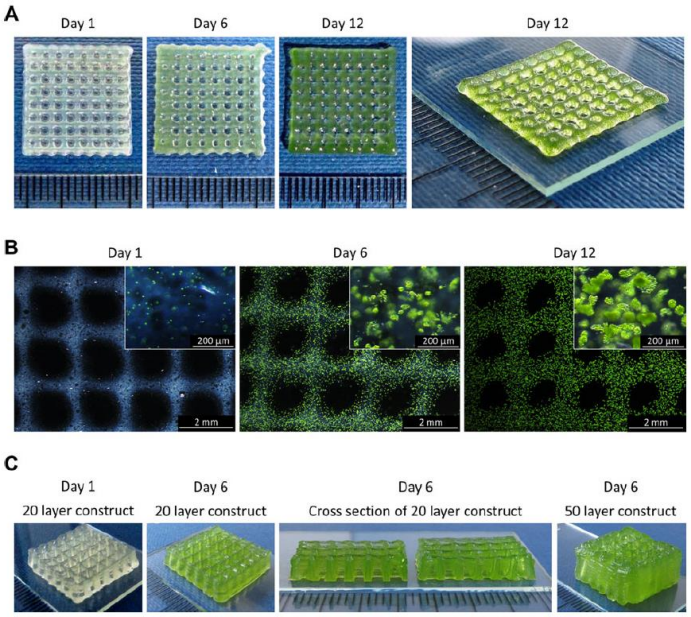
Ref: Murphy, S. V; Atala, A. *Nat. Biotechnol.* **2014**, *32* (8), 773–785.

Background

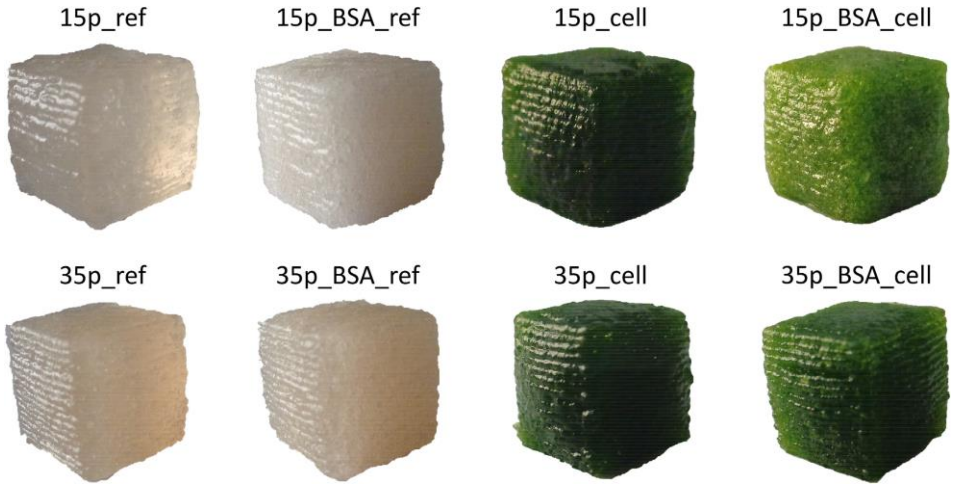
Ref: Hinton et al. Sci. Adv. 2015;1:e1500758







Ref: Lode, A. *et al. Eng. Life Sci.* **15,** 177–183 (2015).



Ref: Vancauwenberghe, V.; Baiye Mfortaw Mbong, V.; Vanstreels, E.; Verboven, P.; Lammertyn, J.; Nicolai, B. *J. Food Eng.* **2017**.

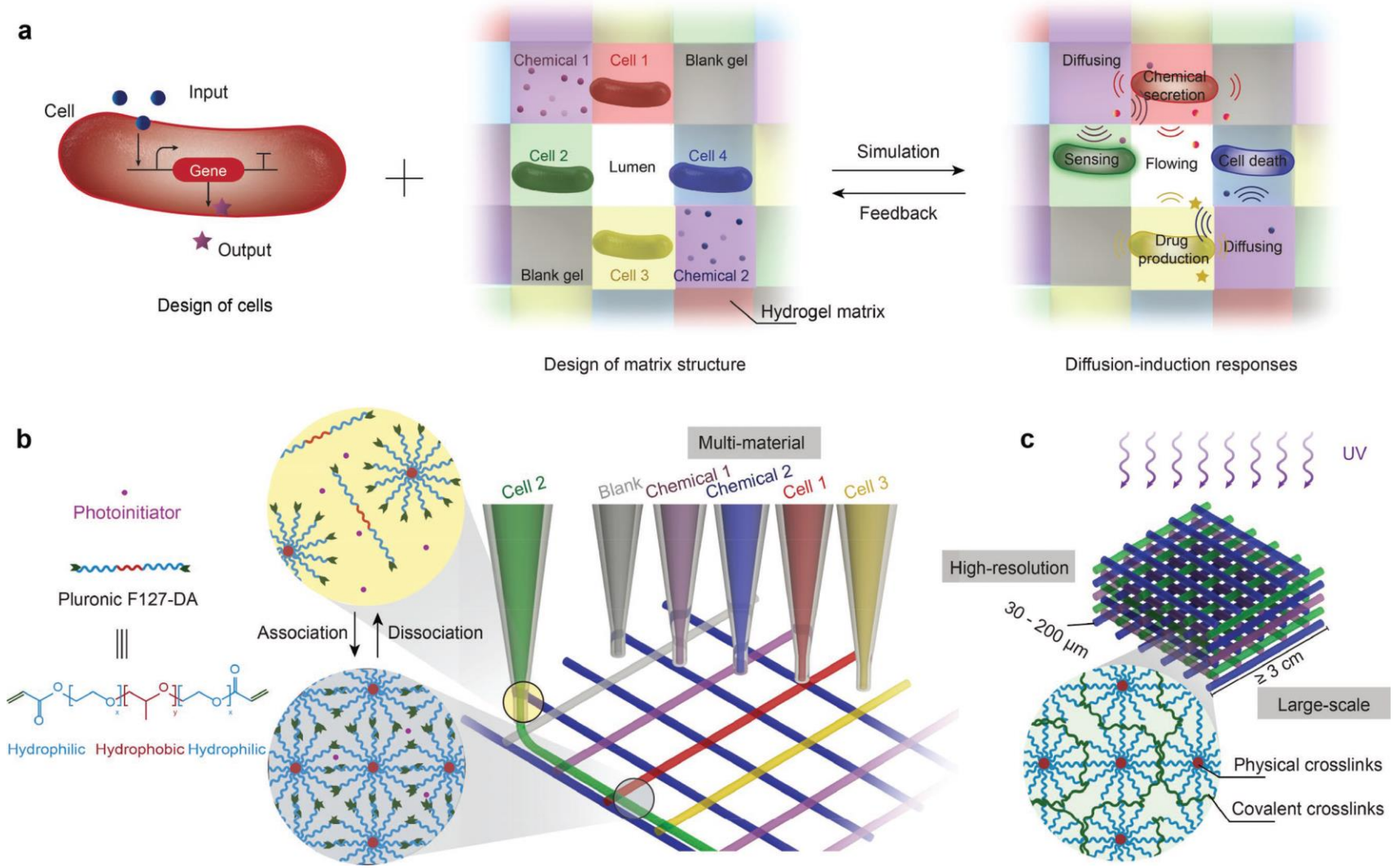
In this Paper

- 3D printing has been intensively explored to fabricate customized structures of responsive materials including hydrogels, liquid-crystal elastomers, shape memory polymers, and aqueous droplets.

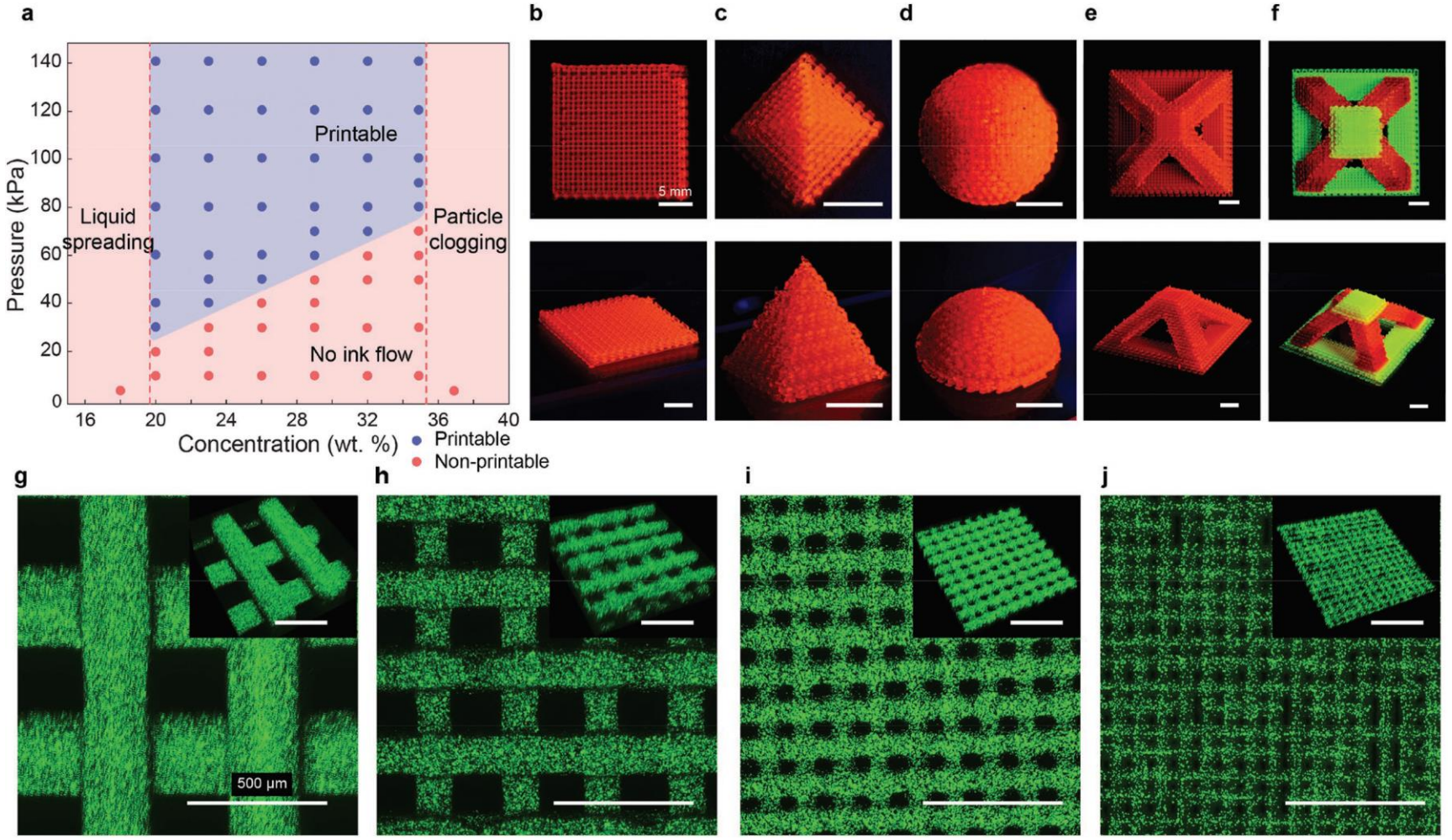
- A report on the new method and material system capable of 3D-printing hydrogel inks with programed bacterial cells as responsive components into large-scale (3 cm), high-resolution (30 μm) living materials, where the cells can communicate and process signals in a programmable manner.

- The design of 3D-printed living materials is guided by quantitative models that account for the responses of programed cells in printed microstructures of hydrogels.

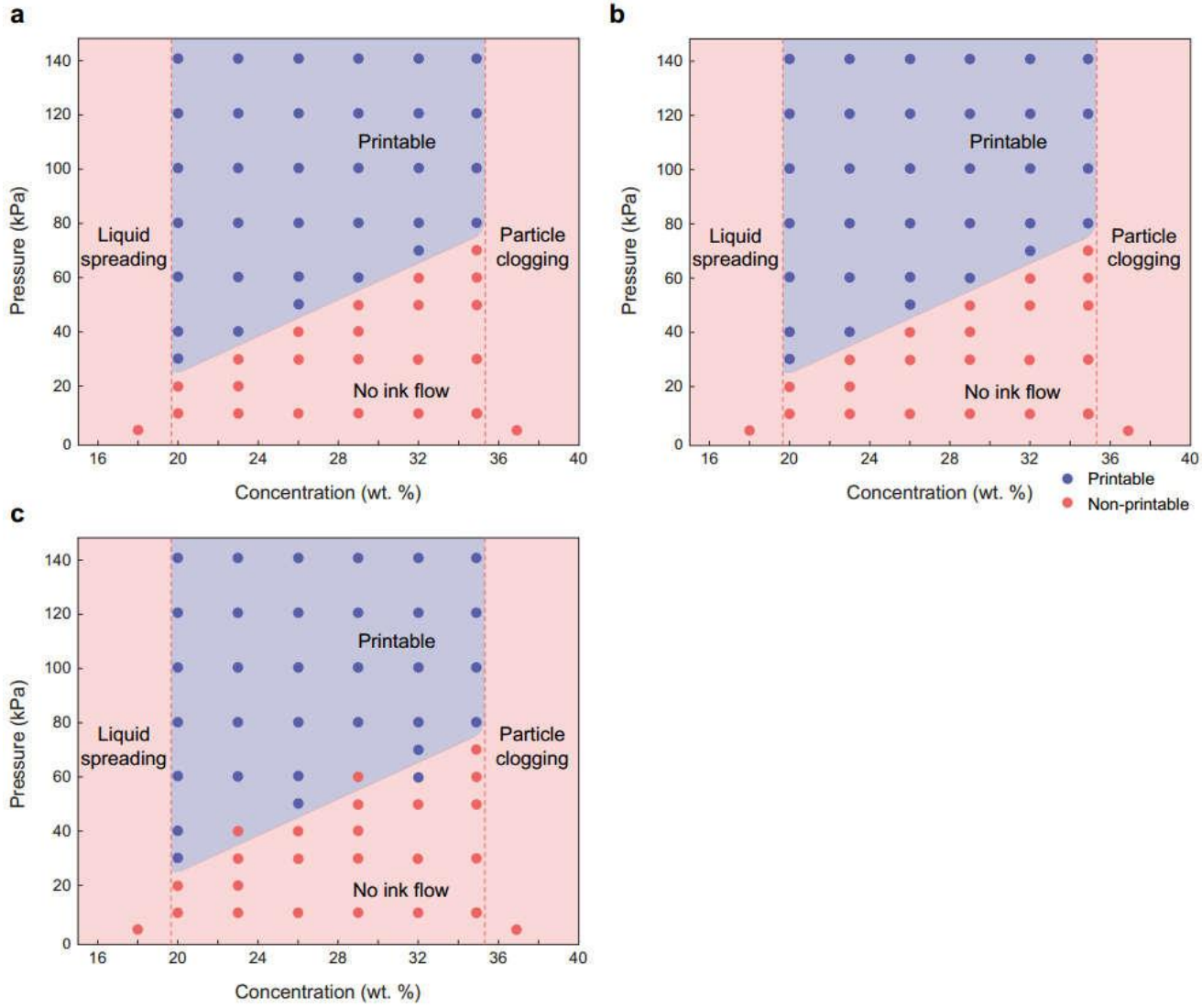
- Further demonstrate novel living devices enabled by 3D printing of programed cells, including logic gates, spatiotemporally responsive patterning, and wearable devices.



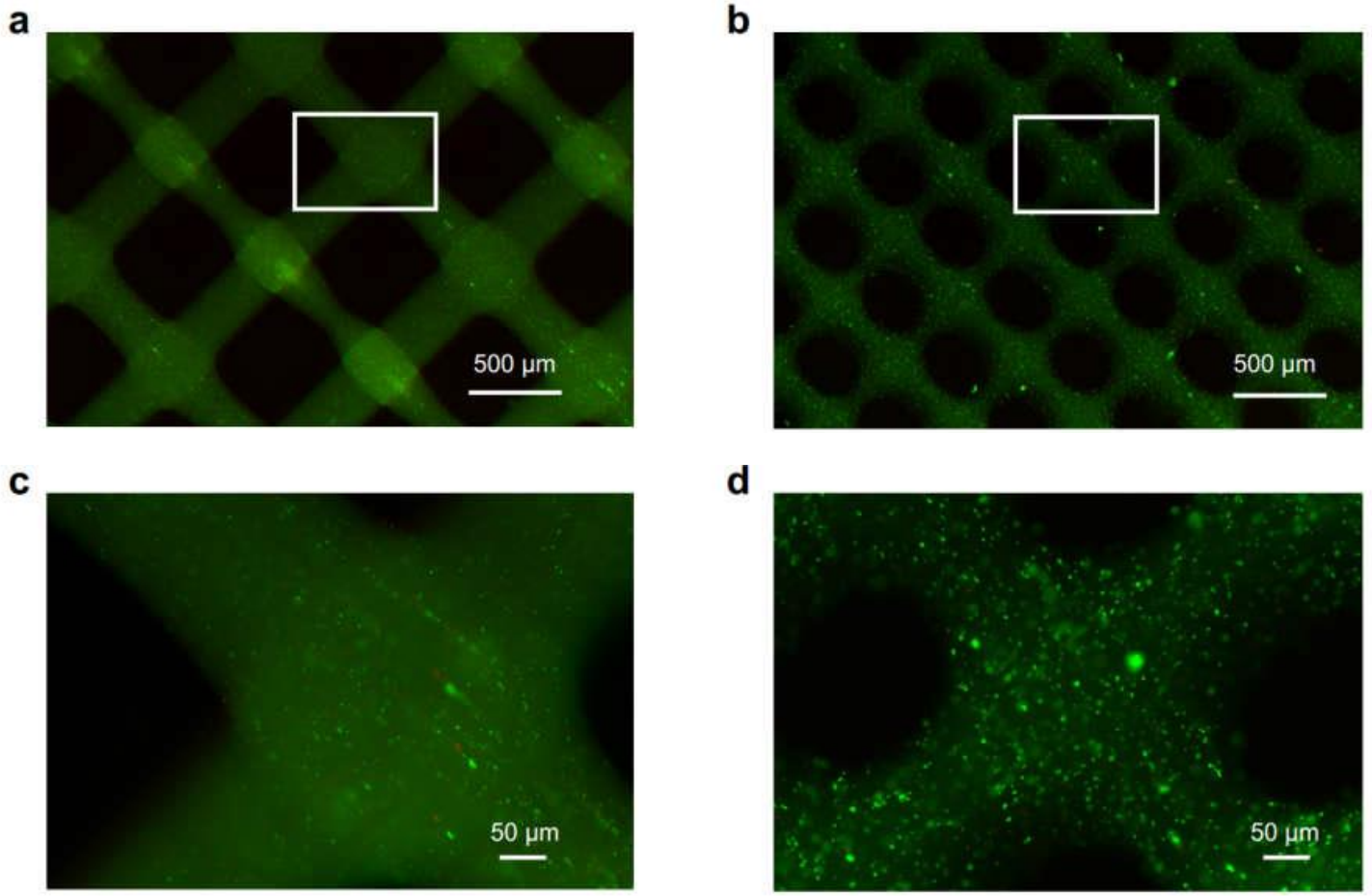
Design and 3D printing of large-scale, high-resolution living responsive materials and devices. a) Schematic workflow of living material design, b) Schematic illustration shows direct writing of hydrogel inks. c) Schematic illustration shows that covalent crosslinks form among micelles after UV crosslinking.



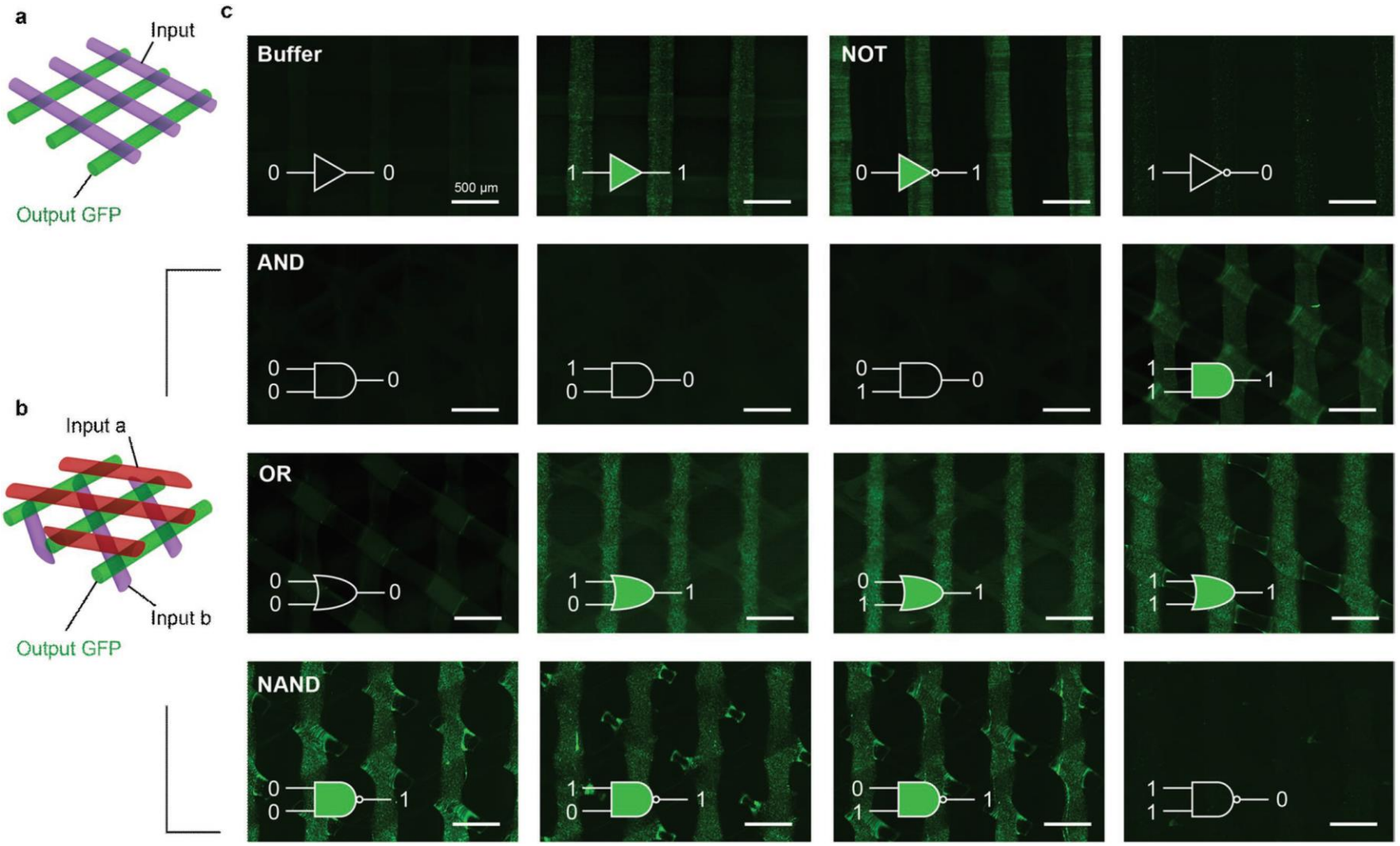
a) Phase diagram for the printability of Pluronic F127-DA ink. Optical images of various architectures generated by 3D printing, including b) a cuboid, c) a pyramid, d) a dome, and e,f) hollow pyramids. Red color denotes hydrogel ink with rhodamine B, and green color denotes hydrogel ink with fluorescein (scale bars in (b)–(f), 5 mm). g–j) Confocal top-view images and 3D reconstructed images (insets) of GFP+ bacterial cell-laden hydrogel scaffolds with a wide range of printing resolutions, including g) 200 μm, h) 100 μm, i) 50 μm, and j) 30 μm (scale bars in (g)–(j), 500 μm).



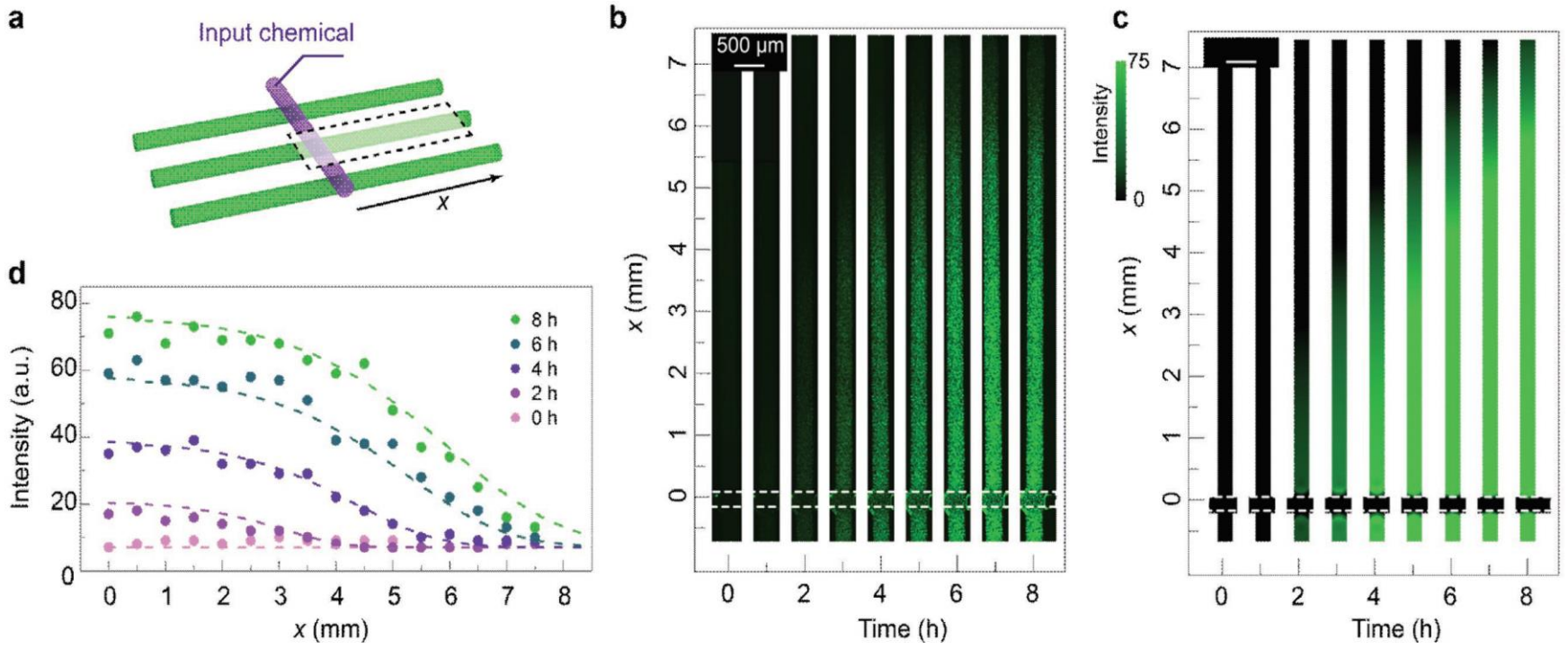
Printability diagrams with different nozzle dimensions. a-c) Phase diagrams for Pluronic F127-DA ink printability, which contains non-printable (red) and printable (blue) regions. The tests are carried out with 200 μm (a),100 μm (b), and 30 μm (c) in nozzle size.



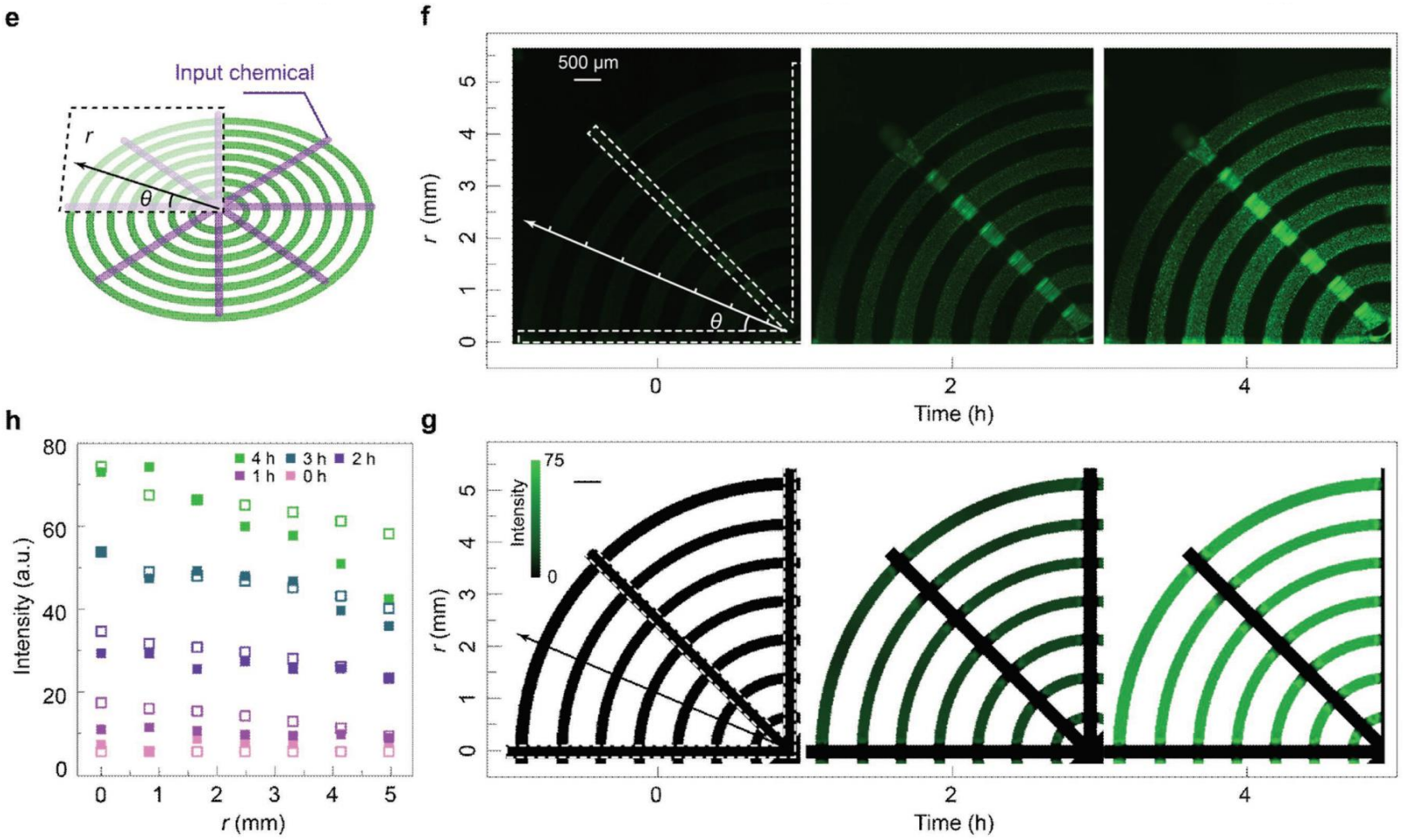
Cell viability in Pluronic F127-DA UV-crosslinked hydrogel tested by live-dead assay 24 h after printing. a,c) Fluorescent images of bacterial cells in printed living materials with 200 µm feature size. b,d) Fluorescent images of bacterial cells in printed living materials with 100 µm feature size. Red denotes dead cells (resulting from increased uptake of propidium iodide into membrane damaged/dead cells), while green denotes live cells.



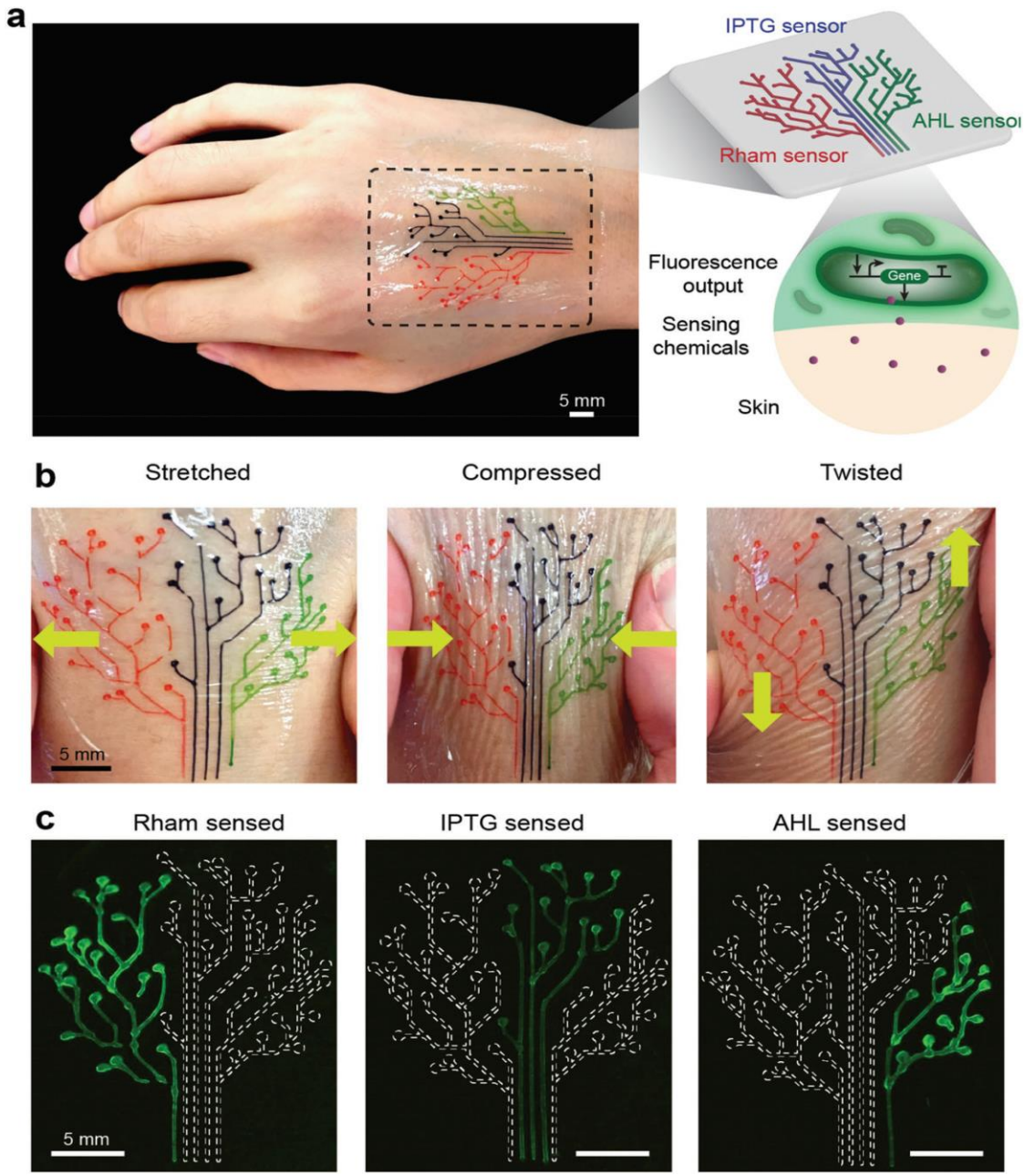
a) Schematic illustration of a 3D-printed living scaffold that can function as a single-input and single-output (SISO) Boolean logic gate. b) Schematic illustration of a 3D-printed living scaffold that can function as a double-input and single-output (DISO) Boolean logic gate. c) Experimental results of logic gates, indicated by green fluorescence in one layer of the printed hydrogel containing the output.



Spatiotemporal patterning of 3D-printed living materials. a) Schematic illustration of 1D-living structure. b) Spatiotemporal evolution of fluorescence in a straight line of the living structure (a) from experiments. c) Spatiotemporal evolution of fluorescence in a straight line of the living structure (a) from simulation. d) Quantitative comparison of fluorescence intensity over time in a straight line of the living structure (a) from experiments (solid dots) and simulations (dash lines).



e) Schematic illustration of a 2D-living structure. f) Spatiotemporal evolution of fluorescence in a segment of the living structure (e) from experiments. g) Spatiotemporal evolution of fluorescence in a segment of the living structure (e) from simulation.h) Quantitative comparison of fluorescence intensity profiles over time along *r* in different rings of the living structure (θ = 22.5° in (e)) from experiments (solid squares) and simulations (hollow squares)



3D-printed living tattoo for chemical detection on human skin. a) The design of the living tattoo. Inset: Schematic illustration of living sensors embedded in the tattoo, which can respond to different chemicals by emitting fluorescence. b) The living tattoo on skin in different states: stretched (left), compressed (middle), and twisted (right). Food dyes are added to facilitate visualization of the hydrogel pattern in (a) and (b). c) The response of the living tattoo on the skin smeared with Rham (left), IPTG (middle), or AHL (right).

Summary and Conclusions

- A new paradigm in 3D printing by using genetically programed cells as active components to create living materials and devices is reported. This can be a new 4D-printing approach to produce 3D structures with time evolving properties.

- The integrative technology of 3D living printing has the potential to be used as a general platform where a range of genetically programed cells (for example, cells with therapeutic production), matrices (for example, biodegradable hydrogels), and structures (for example, a cartilage shape) can be applied to design more customized living materials and devices with predictable dynamic functionalities.

- New ingestible devices based on our 3D printing of living materials may be able to modulate the gut microbiota and treat microbe mediated disease such as obesity and diabetes.

Thank you