3D-PRINTED CELLULOSE AEROGELS FOR CARBON CAPTURE & ENERGY STORAGE

Self-directed nanomaterials research connecting composite formulation, hydrogel 3D printing, freeze-drying, and early electrochemical testing at Kamkar Labs, University of Waterloo.

Hydrogel Formulation	3D Printing	Freeze-Drying	Graphene / CNTs	Cyclic Voltammetry	CO2 Capture

3D	**4+**	**CV**	**8 mo**
Printed hydrogel scaffolds	Material additives tested	Electrochemical screening	Duration at Kamkar Labs

CONTEXT

How this project started

Prof. Milad Kamkar taught my 1A engineering course at the University of Waterloo. After the term I reached out directly to ask whether there were any opportunities to contribute to research in his lab. He gave me access to Kamkar Labs and I used that access over eight months to run an independent materials research project with minimal institutional oversight.

The project was self-directed from the start. I wanted to work with nanomaterials and sustainable energy systems and used the lab resources to prototype something that connected both: porous cellulose-based structures that could function as either CO2 sorbents or electrochemical electrode materials depending on their formulation. The work spanned materials chemistry, additive manufacturing, and early device testing.

Fig. 1 — Finished cellulose aerogel scaffold held for scale, showing the open-cell grid geometry and ultralow density of the freeze-dried structure. The mechanical integrity after lyophilization confirmed successful pore preservation through the flash-freeze and sublimation process.

COMPOSITE FORMULATION

Building the hydrogel ink

The starting point for each sample was a cellulose-based hydrogel matrix, selected for its biocompatibility, biodegradability, and natural porosity at the nanoscale. To tune the electrical and structural properties of the final aerogel, I incorporated conductive and functional additives into the base formulation.

Graphene

Added to increase electrical conductivity and surface area. Graphene sheets distributed through the cellulose matrix create continuous conductive pathways that are critical for electrochemical applications and improve charge transport in supercapacitor configurations.

Carbon nanotubes (CNTs)

Incorporated alongside graphene to reinforce the mechanical structure of the hydrogel during extrusion and post-processing. CNTs also contribute to the conductive network and add mesoporosity that benefits both ion transport and gas diffusion.

Polyaniline (PANI)

Selected for its pseudocapacitive behavior and tunable redox activity. PANI doping was explored as a route to increase specific capacitance in supercapacitor testing without relying solely on the double-layer capacitance of the carbon additives.

Each formulation was measured by weight percent, hydrated, and mixed using high-shear dispersion to achieve nanoscale homogeneity before printing. This step was critical for preventing additive agglomeration, which would have created inconsistent pore distribution and unreliable electrochemical performance.

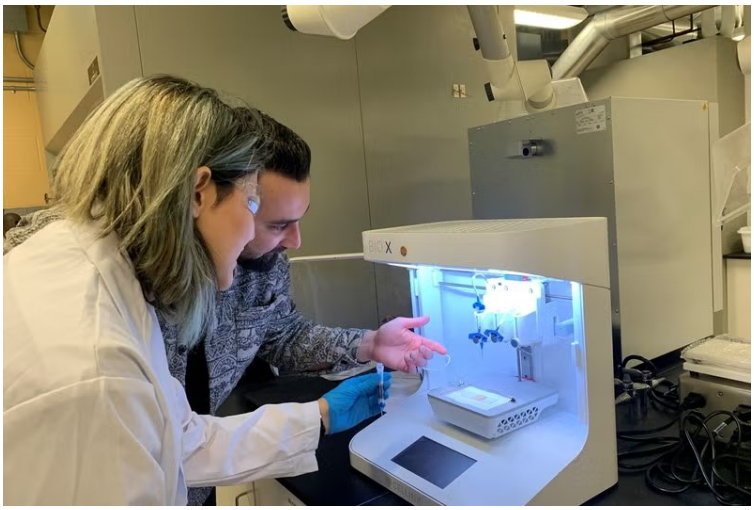

Fig. 4 — Prof. Milad Kamkar (left) and Alonso Portillo (right) operating the BioX hydrogel 3D printer at Kamkar Labs, University of Waterloo. This printer was used alongside the Complex-3 for scaffold fabrication during the project.

ADDITIVE MANUFACTURING

3D printing and porosity engineering

Formulated hydrogel inks were loaded into a Complex-3 hydrogel 3D printer and extruded into custom scaffold geometries designed for freeze-drying compatibility. Three primary architectures were fabricated: hexagonal lattices for isotropic gas diffusion, gradient porosity blocks for directional flow control, and hierarchical honeycombs for high surface-area-to-volume ratios.

Each geometry was modeled to optimize the tradeoff between structural integrity during printing and open-cell porosity after drying. Denser geometries held their shape better during extrusion but risked collapsing internal channels during freeze-drying. More open geometries maximized surface area but were prone to warping. Finding the printable range for each formulation was iterative.

After printing, structures were flash-frozen using dry ice to lock the internal pore architecture in place before any water could redistribute. The frozen gels were then freeze-dried (lyophilized) to remove water via sublimation, leaving a lightweight, sponge-like aerogel with visible open-cell networks and ultralow density.

Lab process videos — 3D printing and formulation:
Printing sequence (Short): https://www.youtube.com/shorts/WSL09jyLUPA

Extrusion detail (Short): https://www.youtube.com/shorts/3u0QUvQdvD8

Mixer and homogenizer: https://www.youtube.com/watch?v=yE0KSUVgCMI

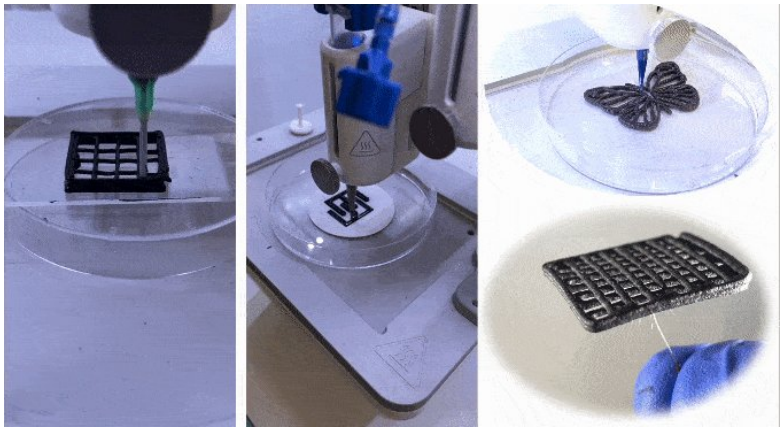

Fig. 3 — 3D printing process at Kamkar Labs. Left: Complex-3 printer extruding cellulose hydrogel ink into a grid scaffold geometry. Center: precision deposition of a custom pattern on print substrate. Right: butterfly geometry print (top) and finished freeze-dried aerogel grid held for scale (bottom), showing the range of printable architectures achieved.

FUNCTIONAL APPLICATIONS

Carbon capture and supercapacitor testing

CO2 uptake — qualitative carbon capture

Aerogels were evaluated for passive CO2 absorption by exposing samples to CO2-rich vapor in ambient air and measuring mass gain over time. The hydrophilic-hydrophobic balance of the cellulose matrix was tuned through formulation adjustments to maximize microporous content and gas-solid interaction. Results were qualitative — mass gain was tracked visually and gravimetrically — forming the basis for a conceptual low-energy sequestration material rather than a quantified sorption isotherm.

Cyclic voltammetry — supercapacitor screening

Graphene-doped aerogels were integrated into a basic electrode framework and tested using cyclic voltammetry (CV). I ran a small number of CV samples independently on the lab equipment; the remainder of the testing was carried out alongside graduate researchers in the lab. Results showed measurable capacitance, suggesting the conductive aerogel network can function as a pseudocapacitive medium. The data was preliminary and not publication-ready, but it confirmed that the formulation-to-fabrication pipeline was producing electrochemically active structures.

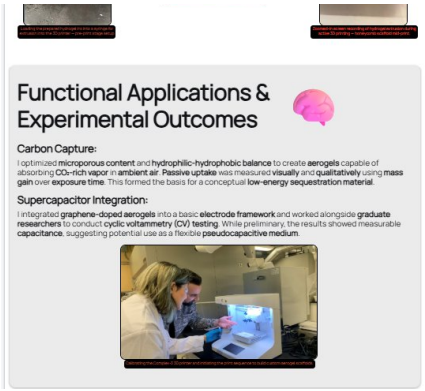

Fig. 4b — Functional applications section from project documentation showing CV testing setup and carbon capture evaluation methodology.

ENGINEERING CONTEXT

What this project developed

This was the first project where I designed experiments from scratch without a defined protocol to follow. Every decision — which additives to use, what geometry to print, how long to freeze-dry, how to set up the CV test — came from reading literature, talking to researchers in the lab, and iterating on failures.

The practical skills it built were nanomaterials processing, porosity modulation through freeze-drying, additive manufacturing of soft materials, and a working understanding of structure-property relationships in electrochemical devices. More broadly it taught me how to move a project forward with ambiguity — which is the same mindset needed for clean energy R&D;, electrode design, and cell architecture work.

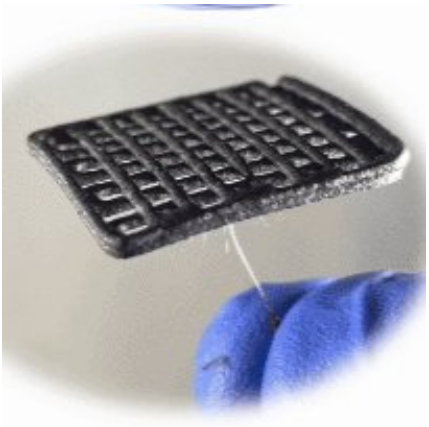

Fig. 5 — Final aerogel product: cellulose-based scaffold showing open-cell pore geometry and structural integrity after freeze-drying. The lightweight, porous structure is the end product of the full formulation-print-lyophilization pipeline.

RETROSPECTIVE

What I'd do differently

01 **Quantify porosity before testing applications**

Most of the characterization was qualitative. Running BET surface area analysis and mercury porosimetry on the aerogel samples before moving to CO2 uptake or CV testing would have given a concrete structural baseline, made the electrochemical results interpretable, and let me compare formulations objectively rather than by visual inspection alone.

02 **Standardize the extrusion parameters before varying formulation**

I was changing both the ink composition and the print parameters at the same time in early iterations, which made it hard to isolate which variable was causing scaffold failures. Fixing the print speed, nozzle pressure, and layer height first and then varying formulation would have produced cleaner results faster.

03 **Run more CV cycles and include EIS alongside cyclic voltammetry**

The CV testing gave a first indication of capacitance but was limited in scope. Adding electrochemical impedance spectroscopy (EIS) would have separated the resistive and capacitive contributions and given a much more complete picture of how the aerogel network was actually performing as an electrode material.

REFERENCE

Technical specifications

Lab	Kamkar Labs, University of Waterloo
Supervisor	Prof. Milad Kamkar (Chemical Engineering, UWaterloo)
Engagement type	Self-initiated independent R&D; — access arranged directly with Prof. Kamkar after 1A
Duration	8 months (2025)
Base material	Cellulose hydrogel matrix
Additives	Graphene, carbon nanotubes (CNTs), polyaniline (PANI)
Mixing method	High-shear dispersion for nanoscale homogeneity
Printer	Complex-3 hydrogel 3D printer
Geometries	Hexagonal lattices, gradient porosity blocks, hierarchical honeycombs
Drying method	Flash-freeze (dry ice) then lyophilization (freeze-drying)
CO2 testing	Qualitative passive uptake — mass gain over exposure time in CO2-rich vapor
Electrochemical test	Cyclic voltammetry (CV) — ran select samples independently, remainder with grad researchers
CV result	Measurable capacitance confirmed in graphene-doped aerogels — preliminary, not publication-ready

Lab videos	youtube.com/watch?v=yE0KSUVgCMI (mixing) | youtube.com/watch?v=8wkZXespwvM (printing)