

Background

Dye-Sensitized Solar Cells (DSSCs) are low-cost, flexible solar devices that mimic *artificial photosynthesis* to generate electricity. While promising, DSSCs face challenges such as low efficiency and costly materials. A key component, the **counter electrode (CE)**, enables charge transfer and catalyzes redox reactions, but traditional flat planar designs limit surface area and performance.

A 2018 study showed that 3D-printed, nature-inspired fractal CEs can enhance catalytic activity by increasing active surface area and conductivity. Building on this, our research investigates six novel 3D-printed CE designs, using conductive PLA and copper-graphite co-deposition, to evaluate how geometry influences conductivity and potential DSSC performance. Using **additive manufacturing** and affordable materials, we aim to improve DSSC performance and scalability.

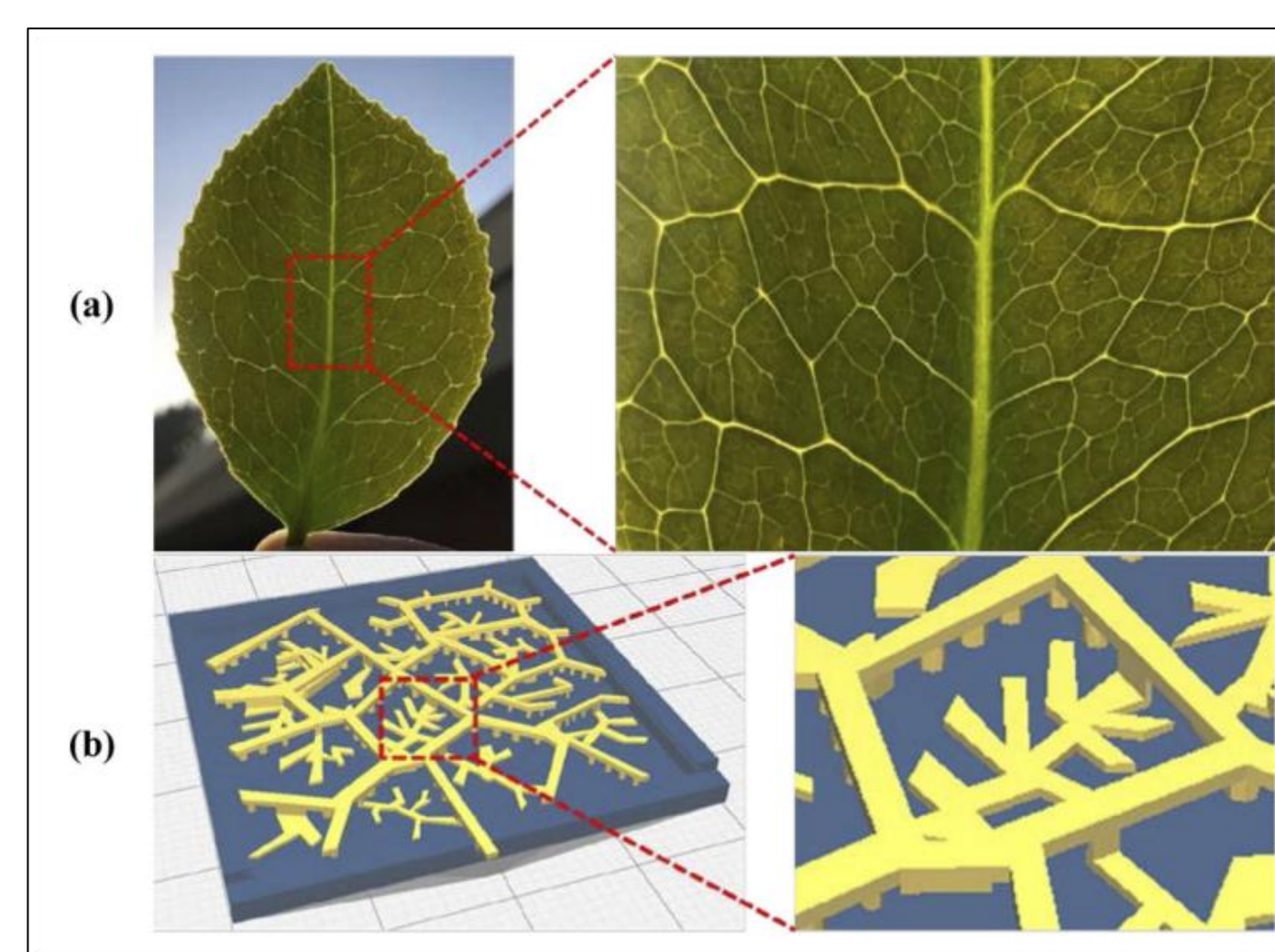


Figure 1. (a) Photo of a *Camellia japonica* leaf showing its vein pattern. The inset shows a close-up of the smaller veins. (b) CAD model of a 3D fractal design for a DSSC counter electrode inspired by the leaf. The inset shows a close-up of the smaller branches in the design. Taken from the 2018 article.

Methods

- Design and Printing of Counter Electrodes (CEs):** Six CEs were created using SolidWorks. They are then 3D-printed with conductive PLA, using the Bambu X1 Carbon 3D printer.
- Initial Measurements:** Initial resistance and weight of CEs were measured using a two-probe digital multimeter and an electronic balance.
- Electroplating: Copper Deposition**
 - The CE and copper foil were then suspended (2-3 cm apart) in a 500 mL beaker filled with 250 mL of copper(II) sulfate (CuSO_4) aqueous solution, placed on a magnetic stirrer. The CE was connected to the negative terminal (cathode) and copper foil to the positive terminal (anode) of an 8V DC power supply.



Figure 2.
Copper
Deposition



Figure 3.
Bambu X1
Carbon 3D
Printer

- Co-deposition:** After a proper layer of copper was visible, 2 g of graphite powder (40–50 μm) was added to the CuSO_4 bath. Electroplating continued for an additional time, allowing co-deposition of copper and graphite particles on the CE surface.
- Post-Deposition Measurements:**
 - CE samples were carefully removed and cleaned. The final resistance and weight of the CEs were measured. CEs were viewed under a microscope at 10X zoom for observation of the uniformity of the copper/graphite deposition and identification of any structural defects or inconsistencies in the coating.

Results

All six CE designs—Flat, Hash, Longitudinal, Reticulate, Cross-Venation, and Hilbert—were 3D-printed using conductive PLA and evaluated for initial resistance and mass. The **Flat** design had the lowest initial resistance at **0.616 k Ω** , while the **Hilbert Curve** showed the highest at **11.84 k Ω** . Initial masses ranged from **0.321 g** (Reticulate) to **2.639 g** (Flat), reflecting differences in material density across geometries.

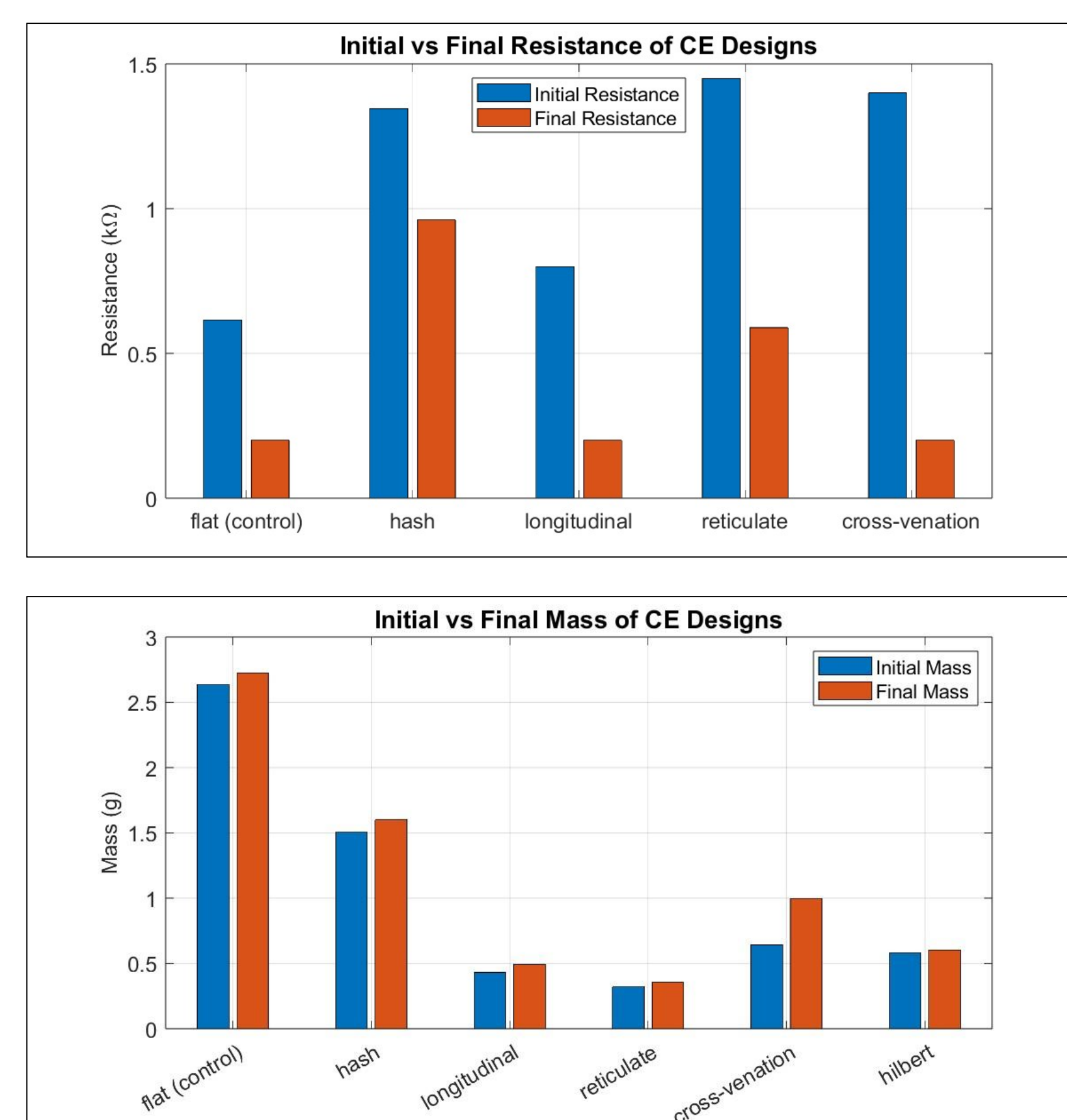


Figure 4. Initial and Final Resistance and Mass of CEs

During electrochemical co-deposition, all CEs were plated in a copper(II) sulfate solution. After 3-4 hours, **2 g of graphite powder** was introduced to enable the co-deposition of copper and graphite. Post-processing results varied notably by design:

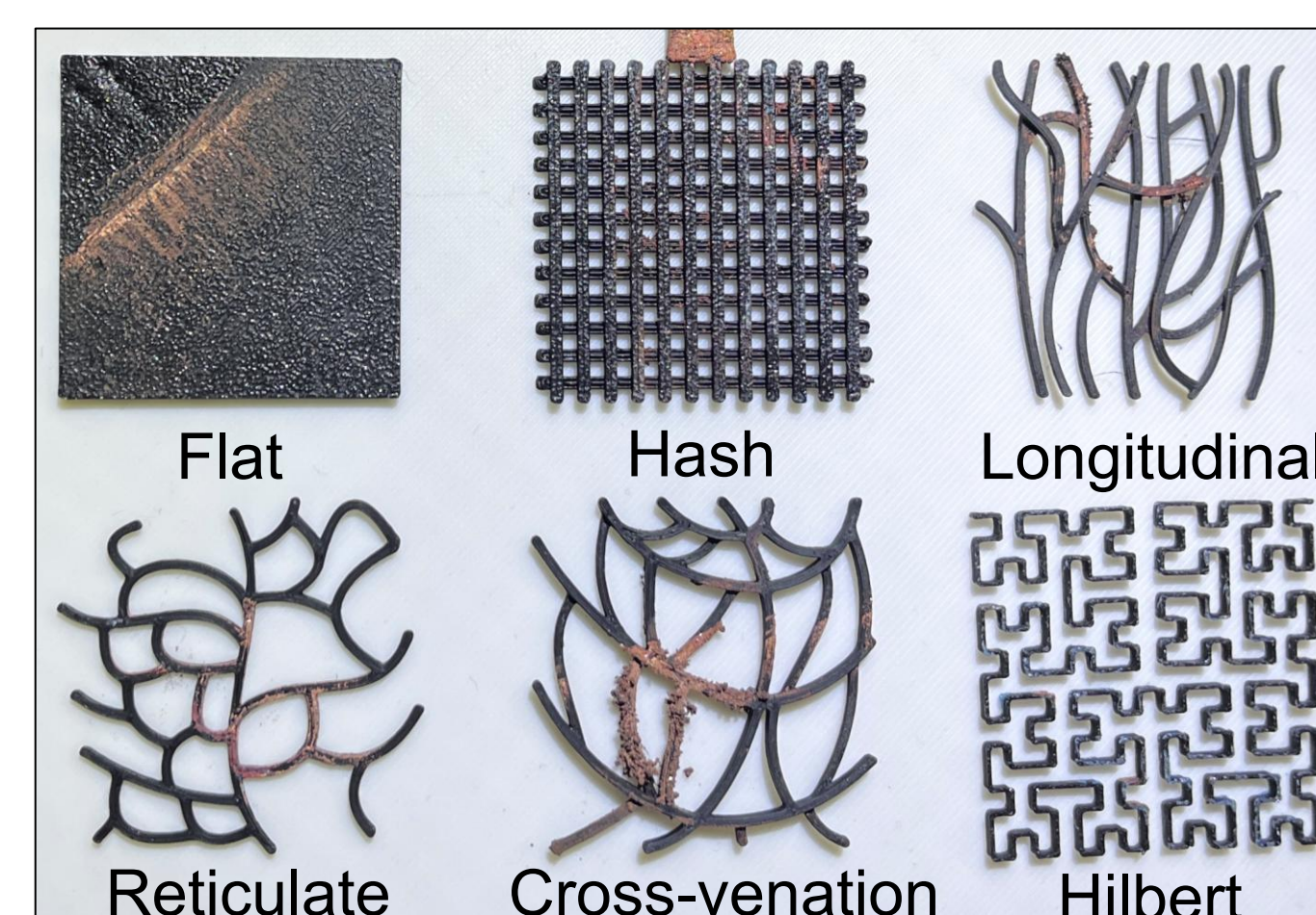


Figure 5. CEs
post-experiment

- Flat CE** showed the most uniform copper coating, confirmed visually and under 10X magnification, but had minimal graphite integration and no notable active site formation.
- Hash** failed to plate effectively despite 4 hours of deposition. High resistance (1.346 k Ω), narrow gaps, and thin walls likely prevented copper deposition. Surface inspection confirmed sparse coverage, and the design was excluded from final analysis.
- Longitudinal CE** showed successful co-deposition of copper and graphite. Microscopy revealed surface nodules typical of active sites. Resistance decreased, and mass gain indicated effective plating.
- Reticulate CE** had partial copper coverage with limited graphite integration. Although mass increased slightly, plating was inconsistent and active site formation was minimal.
- Cross-Venation CE** was the most effective, with uniform copper coating, extensive graphite deposition, and widespread active sites. Resistance dropped from 1.4 k Ω to 0.2 k Ω , and microscopy showed dense catalytic surface features.
- Hilbert CE** gained some mass but showed no measurable conductivity post-deposition. Optical inspection suggested poor copper coverage and failed graphite integration, likely due to current bottlenecks in the design.

Conclusion

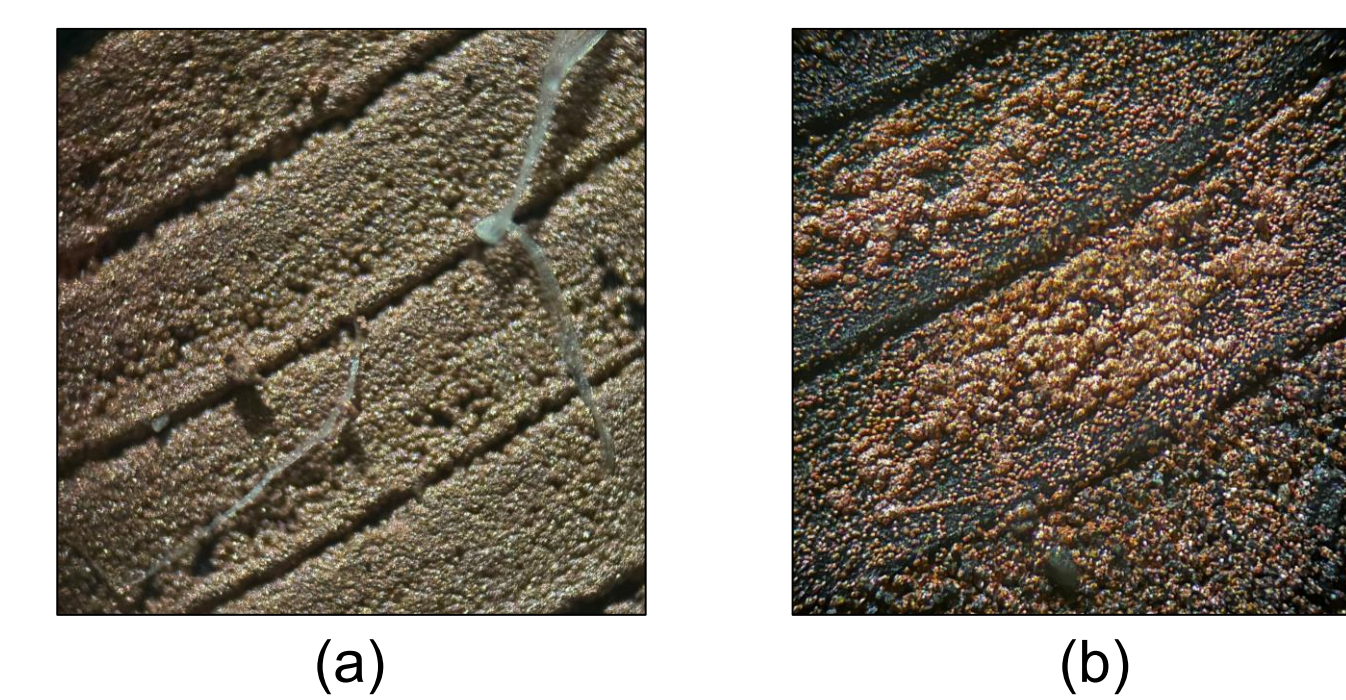


Figure 6. (a) Smooth copper layer after plating. (b) Rough surface with active sites after copper-graphite co-deposition.

- Cross-Venation and Longitudinal designs improved copper-graphite co-deposition, active site formation, and conductivity.
- Geometry with **complex branching** enhances DSSC performance
- Cross-Venation showed the **greatest resistance drop** (1.4 k Ω to 0.2 k Ω) and best surface coverage.

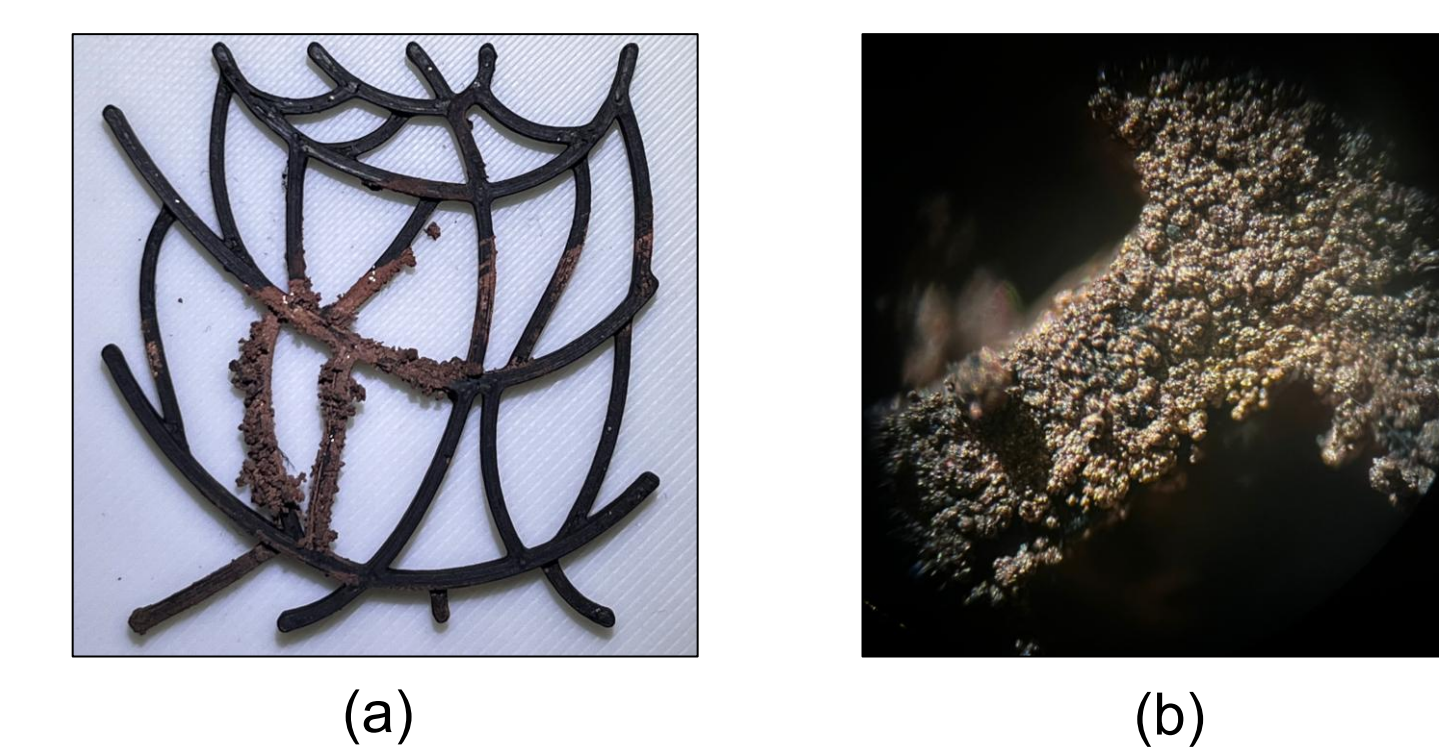


Figure 7. (a) Cross-Venation CE after electrochemical co-deposition. (b) Close-up microscope image showing active sites on the surface.

- Flat had uniform copper but few active sites; Hash and Hilbert failed due to high resistance and poor plating.
- Limitations include high base resistance of conductive PLA and uneven graphite dispersion.

Future Work

To build on the promising results of this study, future work will focus on the full assembly of Dye-Sensitized Solar Cells (DSSCs) incorporating the most successful counter electrode designs, particularly the Cross-Venation and Longitudinal geometries. This will allow direct evaluation of how improvements in counter electrode structure translate into overall device performance, including power conversion efficiency and stability. Additionally, multiple repeats of these top-performing designs will be conducted to verify the consistency and reproducibility of the electroplating process and catalytic activity. Further optimization of the co-deposition parameters, such as graphite dispersion and plating time, will also be explored to enhance the uniformity and density of active sites. Finally, modifications to the electrode geometry to improve current distribution and reduce base resistance will be investigated, aiming to maximize the electrochemical efficiency and scalability of these 3D-printed electrodes for practical DSSC applications.

References

James, S., Contractor, R. Study on Nature-inspired Fractal Design-based Flexible Counter Electrodes for Dye-Sensitized Solar Cells Fabricated using Additive Manufacturing. *Sci Rep* 8, 17032 (2018). <https://doi.org/10.1038/s41598-018-35388-2>

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