Viable Solutions:

1. **ECT – copper 2D plates**
2. **EIT – Stainless steel rods (24 electrodes)**
3. **EIT -** Silver Ag/AgCl electrodes (32 electrodes)

Configuration for EIT:

[Electrode placement configurations for 3D EIT]

Best configuration: two rings of vertically aligned electrodes with electrodes placed sequentially in each ring

- Configuration replicated by Basak et al. An In Situ Electrical Impedance Tomography Sensor System for Biomass Estimation of Tap Roots

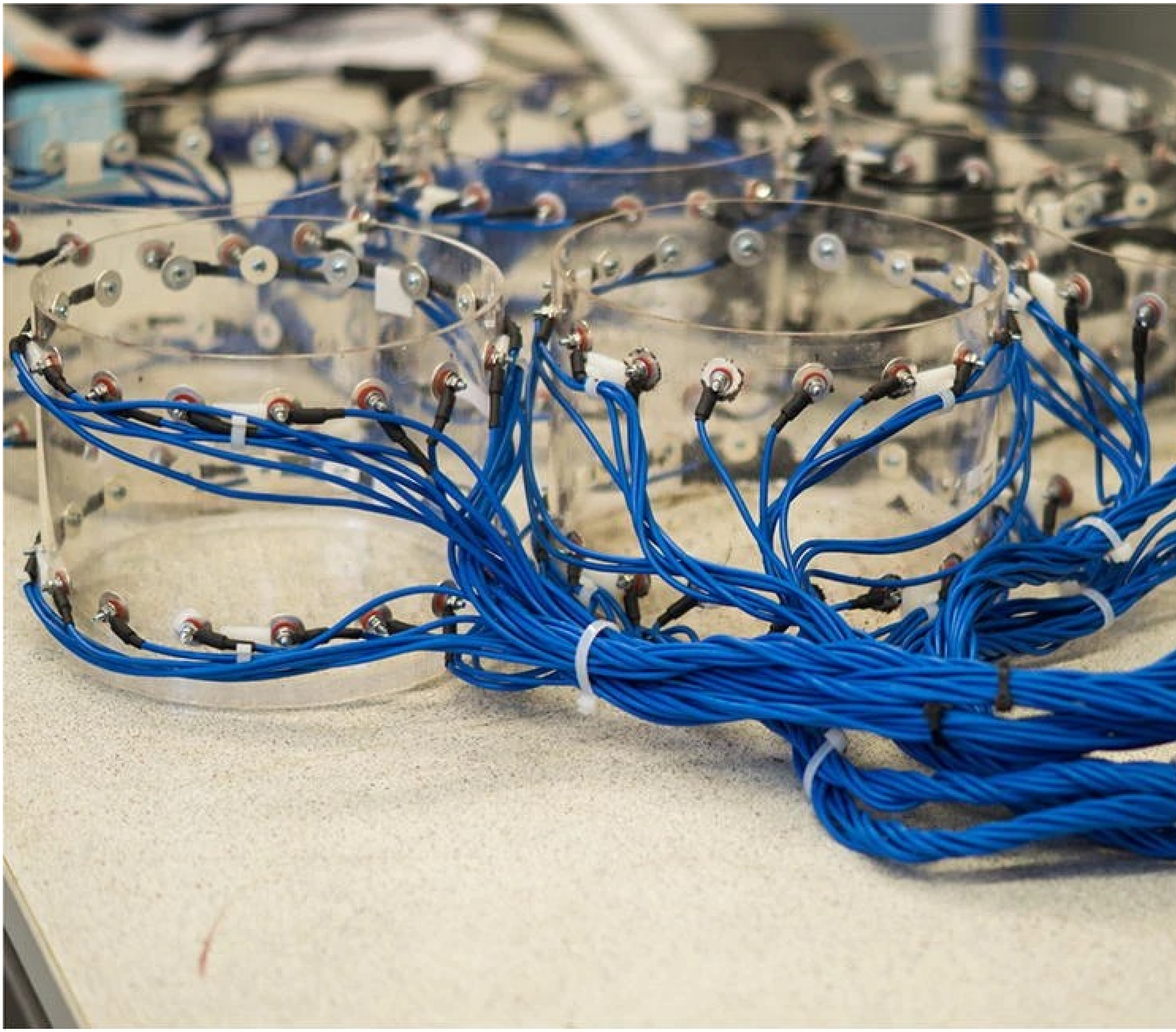
Electrode Types:

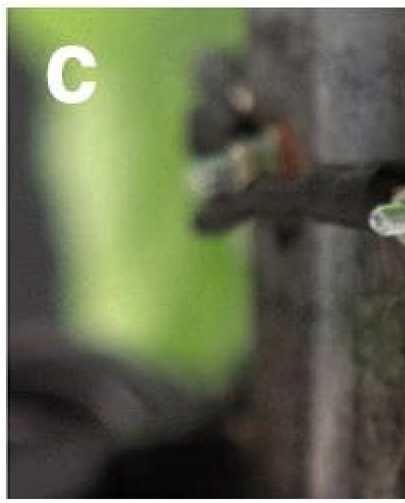
1. Stainless Steel rods

An In Situ Electrical Impedance Tomography Sensor System for Biomass Estimation of Tap Roots
“Steel electrodes were found to be suitable with good current carrying capability and a good correlation was found between the measured impedances and dimensions (length, diameter) of the electrodes. Steel material is comparatively less expensive than highly conductive materials such as silver, copper, or aluminum. In this work, a low-cost sensor was designed by using the steel electrodes in the array”

2. Silver (Ag/AgCl) electrodes

Electrical impedance tomography as a tool for phenotyping plant roots

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The EIT pots consisted of a Perspex cylinder 13 cm high with a diameter of 18 cm and two rings of 16 silver plated electrodes (radius 0.75 cm) positioned at z = 2 cm and z = 11 cm

- 32 electrodes in total

"The ill-posed nature of the soft-field inverse image reconstruction problem is such that the addition of further electrodes at the periphery has diminishing returns on increasing the spatial resolution. This limitation results in the resolution of the system being approximately 5% of the diameter of the vessel being imaged."

Data Acquisition System
Arduino Mega 2560 (microcontroller)

- Orchestrates drive pattern
- Tells breakout boards what to measure
- Collects measurements
- Sends measurements out

AD5933 evaluation board (impedance measurement)
74HC4067 breakout boards (electrode multiplexing)

- Number of these boards will depend on injection/measurement pair count

HC-05 or HM-10 Bluetooth Module

Define how exactly we're receiving the data (in what mode)
What software will we be using?

- Python

Cost:
ECT:

- Uses flat aluminum or copper 2D plates, usually aluminum to keep costs down
    - Electrodes are sheet metal: very low cost
- Real cost driver**:** The capacitance-sensing circuitry, not the electrodes
    - Needs shielding, guard electrodes, low-noise AC excitation/demodulation
    - Detecting fF-pF level capacitance changes requires precise analog front-end
- Harder to find cost benchmarks because this does nto have much proven DIY builds
- $90-165 (hard to estimate, not a lot of research on them)

EIT 16 electrodes, stainless steel polarizable:

- Material cost: Very low rod costs a couple dollars each
- 16-electrode total: Roughly $20-30 in raw material

- Downside: Polarizable → builds up charge double-layer at metal-electrolyte interface
    - Causes impedance drift
    - Higher contact impedance
    - Can distort reconstructions, especially at low frequencies
- Cheapest option, but you pay for it in signal quality
- $65-120

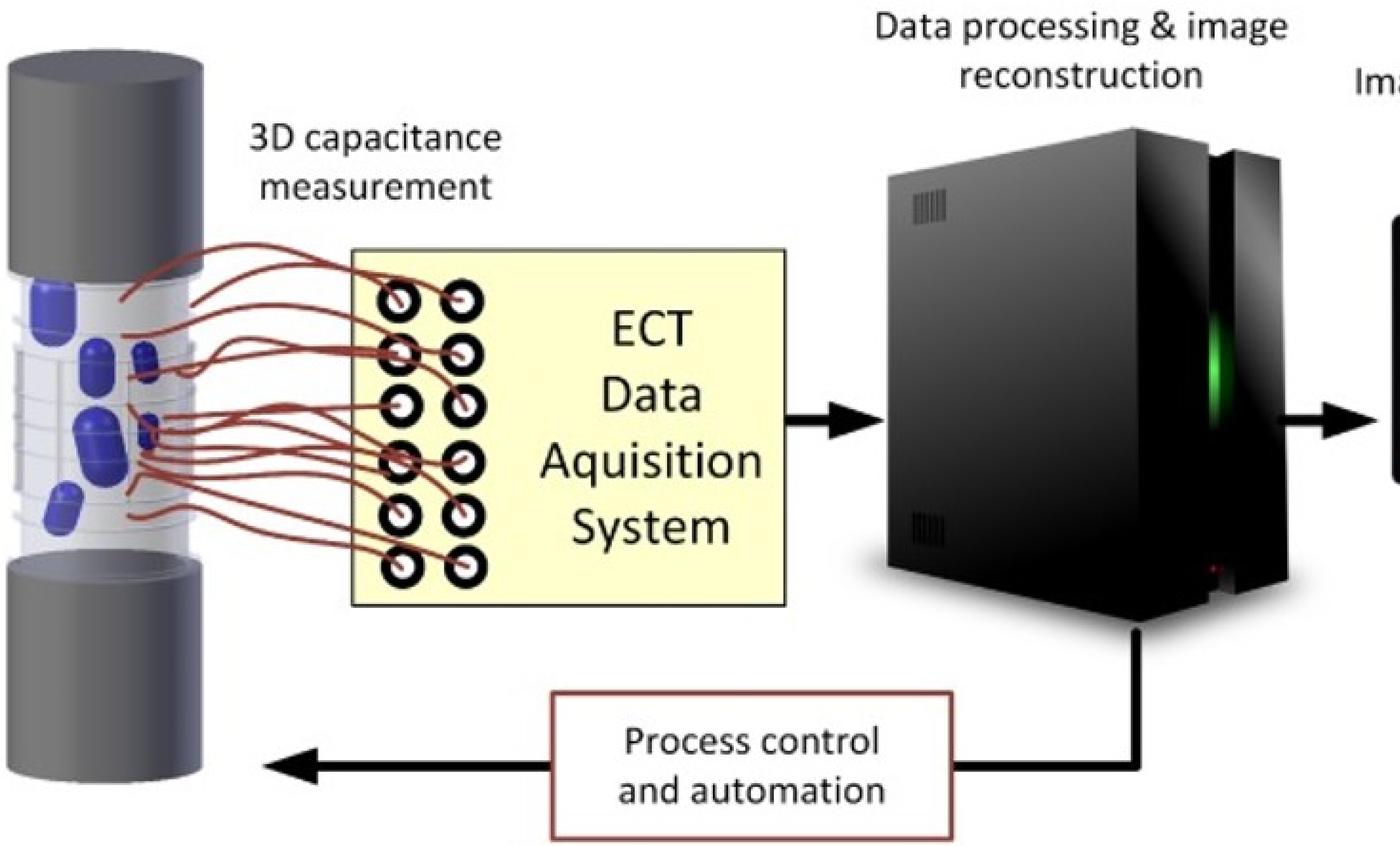
EIT 16 electrodes Ag/AgCl electrodes non-polarizable:

- Lab-grade reference electrodes: $86.90 per electrode Landt Instruments
    - 16 of these = $1390.40 just for electrodes
- DIY alternative - chloridized silver wire: Made by electro-chloridizing silver wire yourself — just a few dollars per electrode A-M Systems
- Bottom line: Can be made cheap (DIY wire) or expensive (lab-grade) — big range depending on fabrication route
- If DIY: $85-145
- If lab-grade: $3,000-12,000

EIT 32 electrodes:

- Electrode cost: double listed above
- Real cost driver: Switching/multiplexing hardware
- Citable reference design: 32-channel system using AFE4300 analog front-end, 4 rings of 8 electrodes, switched via three TI 74HC4067 multiplexers, controlled by an ESP32 ScienceDirect
    - multi-ring 3D layout
- $100-200

Durability:
EIT:
-EIT is more sensitive to contact quality, since stray capacitances, common-mode effects, and contact impedance are known as the main causes of instrumentation errors in EIT systems, an issue that scales in difficulty as electrode count and system complexity grow.
-EIT sensors, because they rely on direct electrode contact, are more exposed to mechanical wear, corrosion, and degradation of the contact interface over repeated use
https://pmc.ncbi.nlm.nih.gov/articles/PMC7571205/
https://pmc.ncbi.nlm.nih.gov/articles/PMC7118304/
ECT:
-ECT sensors tend to be more durable in industrial settings because the electrodes don't touch the process material; they sit outside a wall or embedded within it. This isolates them from abrasive, corrosive, high-pressure, or high-temperature process contents.
-For most industrial applications, a hand-made approach for an ECT sensor and its 3D extended structure fabrication is used.



https://pmc.ncbi.nlm.nih.gov/articles/PMC6696201/

Durability research pt 2 (individual scores):
Solution 1: ECT Copper/Aluminum Plates 4/5
https://ieeexplore.ieee.org/document/5962195

- Since the electrodes are mounted externally on the insulating frame, they are not in direct contact with the soil. This greatly reduces mechanical abrasion and eliminates direct exposure to moisture and soil chemistry, which are common causes of electrode degradation.
- Although copper is mechanically softer than steel, the external mounting means these electrodes avoid the mechanical stresses associated with insertion into soil.

Solution 2: EIT 8 Stainless Steel Rods (4/5)
https://pmc.ncbi.nlm.nih.gov/articles/PMC9269135/#sec4-plants-11-01713

- OK in water "During the measurements the carrot was fully immersed in water."
- The electrodes are also substantial in size (approximately 0.25-inch diameter rods), making them much less fragile than thin wires or PCB traces.
- Steel is widely used in engineering applications because it possesses high strength, hardness, and good fatigue resistance, making it mechanically robust under repeated loading when appropriately selected and used.

        - https://my.asminternational.org/asm-store?store-path=/products/06772G

Other thing to consider when researching:

- Electrical impedance measurements are very sensitive to the soil moisture content
    - https://iopscience.iop.org/article/10.1088/0957-0233/25/5/055110

Solution 3: EIT 32 Ag/AgCl Electrodes (3.5/5)
https://link.springer.com/article/10.1186/s13007-019-0438-4#Sec7

- Silver plated copper electrodes
- because silver provides excellent electrical conductivity and corrosion resistance, but plated systems can fail if the coating wears or delaminates. Studies of silver-coated electrodes show durability depends strongly on coating adhesion and the mechanical environment.
    - https://journals.sagepub.com/doi/10.1177/15280837241287561

Image Resolution:
We can quantitatively measure image resolution based on the smallest detectable object diameter the technology can resolve as a % of the imaging domain diameter.
ECT (2/5)
2 studies show that ECT provides a resolution of 10-15% of the domain diameter [1], [2]
Imaging multiphase flows and static objects

- This is in a higher contrast medium
- Since soil and roots will have a lower conductivity contrast, we would expect the resolution to be lower for our use case

EIT stainless steel rods (1/5) [3]
Multi-root and fine root architecture not studied, so we can't validate how effective it may be at this
Authors state that the reconstructed image was noisy and deteriorated when reconstructing the shape of the smallest sample. Even single-object detection is very weak, especially when the object is small
However, this system was able to measure root biomass with impressive accuracy (93%)
Didn't have a specific metric for resolution stated
EIT silver electrodes (3/5)
Literature reports that in soil, 2 ring 32 electrode configuration resolves object diameters of about 5% of the domain diameter [4]
Electrode number
16 32 electrodes doesn't provide much improvement in the image resolution

- Inverse problem of reconstruction is ill-posed. Adding more measurements won't always improve resolution

Increase in electrodes does improve the resolution of the image near the periphery of the volume (density detected near the electrodes)

Overall Safety:

- Both are noninvasive, safe and nonionizing [5]
- Both do not have ionizing radiation unlike X-ray CT
- Can receive shock if metallic electrode plates are bridged to grounded conductor, especially in wet conditions [6], [7]
- Metallic electrode plates (ECT): [8]
    - Electrodes must be bonded into single electrode system
    - Material compatibility (in reference to underground plates stabilizing voltage and protecting against shock): copper or steel, not aluminum or underground gas piping. Use only approved conductive metals
    - Wear insulated gloves when handling metallic plates
    - Installation: follow NEC or local code requirements for size, depth, spacing
    - Multiple electrodes must be at least 6 feet apart?
    - Plate electrodes require minimum surface area of 2 sq ft and burial depth 30 in?
- Metallic electrodes (EIT):
    - Prolonged skin contact, especially if rigid or poorly designed, can cause skin abrasion, pressure sores, microtrauma (particularly relevant in wearable systems so not super relevant to us) [9]
    - Moisture can corrode electrode surface – may alter impedance measurements and in extreme cases release metal ions – minimal concern with biocompatible coatings (silver-based) [10]
    - Must be properly grounded or referenced to avoid stray currents or electric shocks [10]

ECT (4): as copper and aluminum are nutrients in small amounts but can be toxic if too high a dose [11] – thinking of scalability. Aluminum may leach under acidic soil conditions [12]. No ionizing radiation. If metallic electrode plates are part of an active electrical circuit (energized/connected to power) and touched, especially with wet skin or grounded metal, current can flow through body
EIT steel rods (4.5): stainless steel highly resistant to corrosion, negligible leaching risk [12]. No ionizing radiation. If stainless steel electrode rods are part of an active electrical circuit (energized/connected to power) and touched, especially with wet skin or grounded metal, current can flow through body
EIT silver electrodes (4): moisture can corrode silver electrodes [10]. No ionizing radiation. If silver electrodes are part of an active electrical circuit (energized/connected to power) and touched, especially with wet skin or grounded metal, current can flow through body

Ease of Assembly:
Took into account:

- The imaging apparatus and sensor shall be integrated in a way that requires less than 5 assembly steps.

    - Rationale: Simplicity improves manufacturability and user adoption while minimizing interference with plant growth [33].
    - Method of Verification: Count assembly operations and verify installation dimensions.
- The very bottom component 0.15 ft x 1.25 ft is where the apparatus will go
- Send data wirelessly to app (no preference on Bluetooth or Wi-Fi)

With all 3 design solutions, you will need some baseline assembly of some pre-manufactured electrode/plate configuration at the bottom. Then some sort of controller or multiplexer board. This will be mounted with whatever wireless transmission we use to the Hydrolodge app (microcontroller, for instance). Then connecting the power and sealing the bottom layer. This is already 4-5 steps for the team but the consumer in theory should only have to insert the pre-built probe into the soil/grow bag and power on and connect Wifi-BLE.

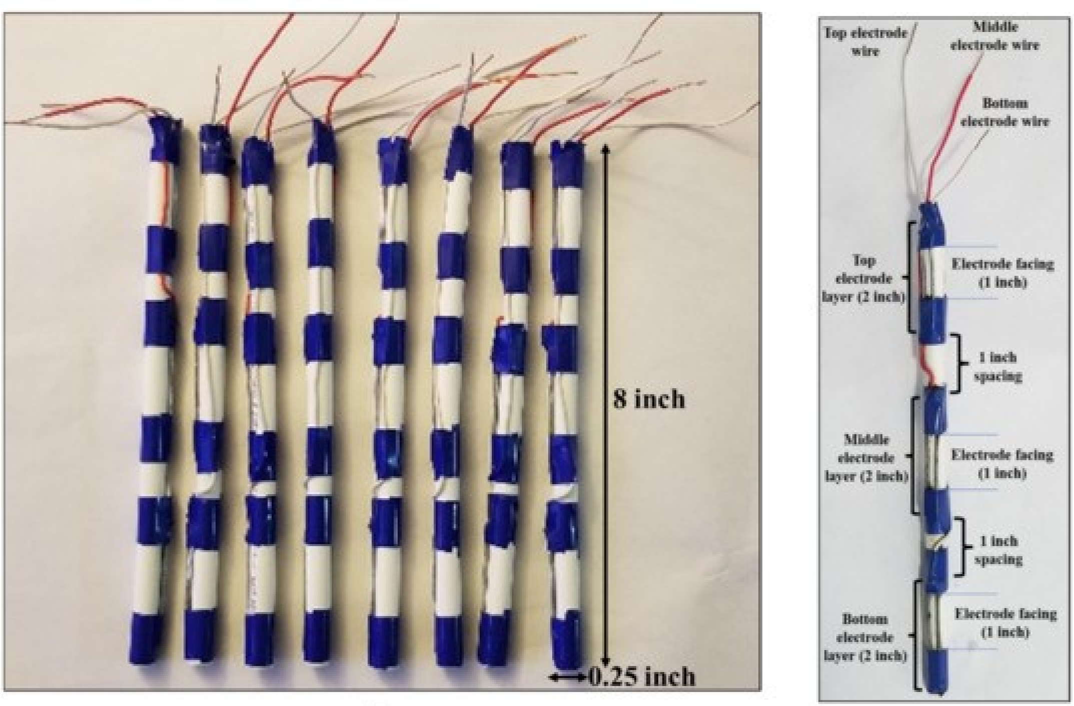
EIT (24): 5/5

https://www.mdpi.com/2223-7747/11/13/1713 Modular electrode array placement: “eight plastic sticks of 8 inches in length and 0.25 inches in diameter” --> steel electrodes for material

This paper uses 24 electrodes but same setup as 16 just with another array (no additional steps required for the consumer)

Wiring is grouped by layer, not one wire for each electrode. Consumers will have components of “two CD74HC4067 multiplexers”, an Arduino Uno, and an AD5933 impedance measurement chip --> 208 voltage measurements per scan

The two-multiplexer hardware footprint is small enough to be part of a single “mount controller board” step, and because EIT requires direct galvanic contact between electrodes and soil, the probe wall and the sensing surface are the same single boundary layer so no additional construction layer is needed. Estimated total: approximately 4 steps



(a) (b)

(**a**) Electrode array for designing an in situ 3D EIT system using 24 electrodes in eight plastic sticks of three layers each, and (**b**) distributed electrodes in three layers (top, middle, and bottom) of a plastic stick.

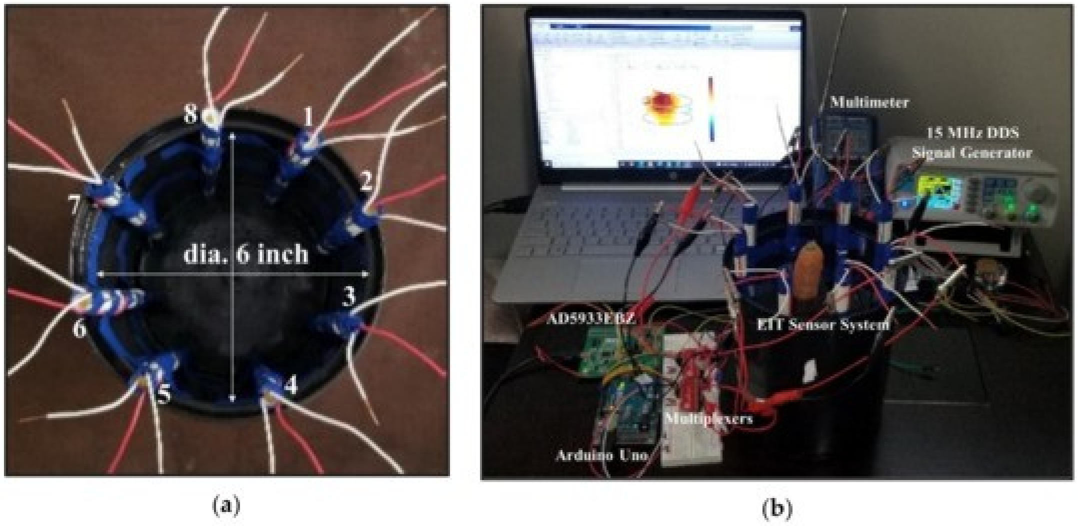


Figure 16. (**a**) EIT electrode array sensor system, and (**b**) experimental setup for EIT sensor characterization using electrodes in water media and a carrot of 6.5 inches in length. During the measurements the carrot was fully immersed in water. The visibility of the sample may vary based on the length of the sample with respect to domain height.

EIT (36): 5/5

Same baseline setup as above.

Corona-Lopez, D.D.J., Sommer, S., Rolfe, S.A., Podd, F., Grieve, B.D. Electrical impedance tomography as a tool for phenotyping plant roots. Plant Methods, 15:49, 2019.

https://plantmethods.biomedcentral.com/articles/10.1186/s13007-019-0438-4

Grudzien, K., Romanowski, A. An open-source and easily replicable hardware for Electrical Impedance Tomography. HardwareX, 2022.

https://www.sciencedirect.com/science/article/pii/S2468067222000232

What we build: - the instrumented pot/vessel where it's 32 electrodes (two rings of 16) embedded into the walls at two fixed heights

- Measurement circuitry with the controller board
- Reconstruction --> Matlab, EIDORS, Netgen pipelines

Both time difference EIT

Paper (Corona Lopez) uses a fixed 5 kHz, 1 mA signal and a specific mesh (16,055 elements) tuned for their 18 cm vessel

No multiplexers setup here vs the EIT (16)

The device needs to capture a "no root yet" reference reading before the plant's roots develop, and every subsequent 3D image is really a difference from that starting point (I don't think actual live continuous 3D imaging has been proven)

ECT: (4/5)
I have found NOTHING on root imaging, only one I have is the one Daniel used for soil moisture detection in the CDR. Assembly below is more industrial. Caveat: there is really not much we can prove that 3D reconstruction for roots specifically work in ECT
ECT

1. **Capacitor plates**
    1. external, non-contact plates arranged around the outside of the vessel wall (not stuck into soil, since ECT doesn't need galvanic contact).
2. **Insulating standoff layer**
    1. a physical gap/liner between the plates and the soil-containing wall. ECT plates must be electrically isolated from the medium to measure permittivity rather than direct conductivity.
3. **Capacitance measurement circuitry**
    1. equivalent of the LCT2-style box, but built for permittivity/capacitance readings instead of injected-current/voltage readings
4. **Reconstruction software**
    1. mesh-based inverse problem, but ECT's measurement count scales worse: $N(N-1)/2$ pairs, so 66 measurements at 12 plates --> EIT is more favorable scaling at similar electrode counts
5. **Controller/wireless mounting**
6. **Sealing the assembly**

[1]X. Gao, C. Feng, Z. Tian, Z. Ren, and X. Zhang, “Study on spatial resolution of electrical capacitance tomography for cryogenic fluid,” *Measurement*, vol. 251, p. 117333, Jun. 2025, doi: 10.1016/j.measurement.2025.117333.
[2]D. Wanta, S. Klimaszewski, W. T. Smolik, M. Ivanenko, P. Wróblewski, and M. Midura, “Spatial resolution-enhanced electrical capacitance tomography using 32-electrode sensor and neural network training based on synthetic data,” *Measurement*, vol. 258, p. 119300, Jan. 2026, doi: 10.1016/j.measurement.2025.119300.
[3]R. Basak and K. A. Wahid, “An In Situ Electrical Impedance Tomography Sensor System for Biomass Estimation of Tap Roots,” *Plants*, vol. 11, no. 13, p. 1713, Jun. 2022, doi: 10.3390/plants11131713.
[4]D. D. J. Corona-Lopez, S. Sommer, S. A. Rolfe, F. Podd, and B. D. Grieve, “Electrical impedance tomography as a tool for phenotyping plant roots,” *Plant Methods*, vol. 15, no. 1, p. 49, May 2019, doi: 10.1186/s13007-019-0438-4.
[5]Q. Marashdeh, F. L. Teixeira, and L.-S. Fan, “1 - Electrical capacitance tomography,” in *Industrial Tomography*, M. Wang, Ed., in Woodhead Publishing Series in Electronic and Optical Materials. , Woodhead Publishing, 2015, pp. 3–21. doi: 10.1016/B978-1-78242-118-4.00001-0.

[6]“Causes of Electric Shock in the Welding Industry - WeldWiki.” Accessed: Aug. 03, 2026. [Online]. Available: https://weldwiki.com/causes-of-electric-shock-in-the-welding-industry/
[7]“Welding Safety FAQs - Electric Shock.” Accessed: Aug. 03, 2026. [Online]. Available: https://www.lincolnelectric.com/en/Safety-Resources/Welding-Safety-FAQs---Electric-Shock
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[10]Z. Lin *et al.*, “The influence of reference electrode in electrical impedance tomography,” *Heliyon*, vol. 8, no. 12, p. e12454, Dec. 2022, doi: 10.1016/j.heliyon.2022.e12454.
[11]T. Olson and R. Pavlis, “Heavy Metals That are Bad for Plants – Mother Earth News.” Accessed: Aug. 04, 2026. [Online]. Available: https://www.motherearthnews.com/organic-gardening/heavy-metals-bad-plants-zm0z26amzols/
[12]Mo, “Do Metal Garden Beds Leach Into Soil? | Truths Uncovered Fast,” Gardening Beyond. Accessed: Aug. 04, 2026. [Online]. Available: https://gardeningbeyond.com/do-metal-garden-beds-leach-into-soil/