

EIT pot sensor for potato tuber visualization

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Abstract

Assessing the maturity and size of crops with below-ground edible parts, such as potatoes (*Solanum tuberosum*), traditionally requires labour-intensive digging and excavation. This study evaluates the use of Electrical Impedance Tomography (EIT) as a non-destructive tool for monitoring potato growth under varying soil moisture levels and tuber sizes in pot conditions. Our results show that both tuber size and soil moisture content significantly impact the quality of potato reconstructions using EIT. At low soil moisture levels (around 10 %), tubers are not detectable due to high impedance, but their visibility improves as moisture increases to 28–35 %. Larger tubers yield more accurate reconstructions across all frequencies, while smaller tubers perform better at lower frequencies (below 5 kHz).

[Keywords] EIT, non-destructive imaging, tuber development, tomography

1. Introduction

Potatoes (*Solanum tuberosum* L.) are recognized as the fourth most crucial crops worldwide, contributing significantly to food security (Thiele et al., 2010). Potato productivity is hampered by abiotic stresses, such as drought and high temperature (Aksoy et al., 2015), but despite this, potato cultivation spans diverse geographic regions, including those prone to heatwaves and droughts. The prospect of adverse effects on potato yields due to these stressors, whether individually or in tandem, is quite likely. Therefore, it is paramount to develop high yielding varieties that not only adapt to the recent climate changes, but also ensure stable production. This presents the opportunity to move towards eliminating hunger by stabilizing potato production.

Traditionally, monitoring of the growth of potatoes has relied on canopy measurements from remote sensing techniques where properties such as crop height and volume (Njane et al., 2023), combined with machine learning algorithms (Li et al., 2021), have shown potential in tuber yield estimation. In recent times, there has been a surge in state-of-the-art technologies for the potato industry, including advancements such as monitoring above-ground biomass (Ashourloo et al., 2020), measuring sugar content (Rady et al., 2021), detecting black heart disease (Zhou et al., 2015) and even predicting the onset of early blight-disease (Jindo et al., 2021). De la Morena et al. (1994) reported that yield in potatoes consists of the number of stems, tubers and average tuber weight. However, all these techniques are limited since they rely on above-ground information to correlate with the below-ground tuber properties. Hence, it becomes imperative to monitor the below-ground biomass of potato crops.

Due to the subterranean development of tubers, the monitoring of below-ground biomass has relied on the manual excavation of

tubers. This monitoring not only aids in refining cultivation practices and evaluating new varieties, but also assists in predicting tuber yields. It is common for farmers to determine the timing of potato harvests by gauging tuber size through soil excavation to inspect the potatoes. Yet, relying solely on this method and providing a single snapshot is not an ideal approach for monitoring tuber size and pinpointing the optimal harvest time. Instead, farmers often adopt a combination of strategies, including sampling a portion of the crop, measuring tuber size, and observing various maturity indicators such as plant senescence, skin thickness, and skin set. This multifaceted approach offers a more comprehensive assessment of the potatoes' readiness for harvest. However, these field practices are labour-intensive.

Consequently, there is an urgent need to develop innovative, non-destructive technologies for tuber measurement. To monitor the growth of roots without disturbing the soil, minirhizotrons have been extensively used in monitoring the growth of roots (Cai et al., 2016) and could monitor canola roots (Rahman et al., 2020) and monitor root growth uptake (Cai et al., 2018). A combination of electrical capacitance measured on wheat plants using an Agilent U1733C portable LCR instrument and minirhizotron showed potential in monitoring the growth of wheat (Cseresnyés et al., 2021). However, electrical capacitance is limited in that the sensor must be attached to the plant stem and soil, which requires very special techniques not to injure the crops. For minirhizotrons, the tube has to be inserted into the soil, after which the minirhizotron is inserted to take images, a process which is not only laborious but also requires the roots to be closer to the tubes where images are captured and can be monitored.

Acoustic sound signals in the 3.2–20 kHz range propagated through sandy soil containing tuberous roots could non-

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destructively detect different sizes of sweet potatoes (Iwase et al., 2015). However, the sound signal could only be enhanced when the soil was wet, limiting application in dry soils. The use of X-ray computer tomography (CT) has been extensively studied and applied in the three-dimensional monitoring of plant roots since it is less affected by soil parameters (Mooney et al., 2012). By using X-ray CT, roots of size 0.35 mm could be detected (Heeraman et al., 1997). Recently, automatic segmentation of X-ray CT data to automatically detect roots, detect threshold and estimate root diameter has been developed (Phalempin et al., 2021). Furthermore, high-throughput processes using non-medical X-ray CT have been developed for both 3D and 4D visualization of rice (Teramoto et al., 2020, 2022) and have even shown potential in monitoring the growth of potato tubers (Van Harsselaar et al., 2021). However, these techniques are not only expensive but high-energy X-rays may affect the physiological growth of the crops and long-time exposure to X-rays may pose detrimental health risks to the users. The use of ground penetrating radar has been successfully applied in the study of larger underground structures like tree roots (Butnor et al., 2001; Hruska et al., 1999) and could even be utilized to estimate root bulking of cassava (Delgado et al., 2017). However, in most cases, only high-water content roots could be detected (Hirano et al., 2009), and the measurements are also easily affected by soil anomalies, thus causing inaccuracies during measurement.

The objective of this study was to investigate a methodology to detect and visualize potato tubers in the soil. The study focused on the electric impedance tomography (EIT) technique (Metherall et al., 1996), which uses the differences in electrical conductivity of the soil and plant to map it underground (Li et al., 2023). This technique has been investigated for many years in the medical field as it is a non-invasive way to take images of the lungs and chest cavity (Shi et al., 2021).

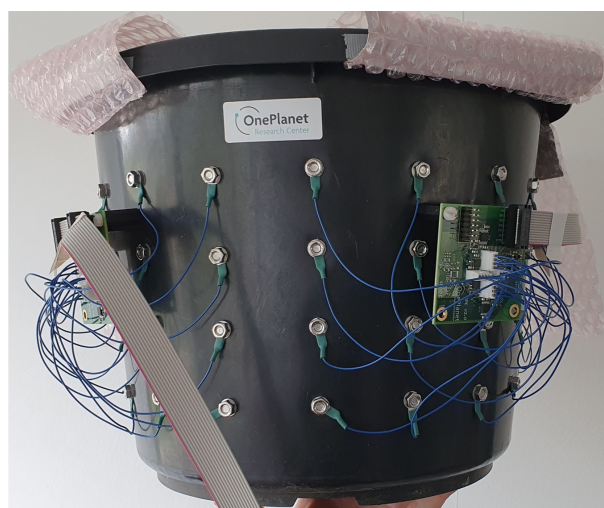
Nowadays, EIT is considered as a well-known technique to monitor the plant and soil status. EIT has been used to assess various plant and soil properties, including the evaluation of plant roots, stem water content (Zhu et al., 2022), in internal decay in woods (Brazee et al., 2011), and hydraulic conductivity of soil (Gutiérrez Gneccchi et al., 2012). However, there are several common challenges such as the low resolution of the technique (Li et al., 2023), and soil heterogeneity around the roots (Weigand et al., 2019). These limitations have made root phenotyping difficult, but large tap roots and total root mass are able to be imaged (Basak et al., 2022; Corona-Lopez et al., 2019).

This study provides a technical basis for a system that could be used to detect potato tubers while still growing in the ridges. The system will need to address the multiple challenges of EIT for open field and this first experiment investigates the specific conditions required for proper EIT reconstructions in a simulated Dutch and Japanese climate.

2. Materials and methods

2.1. EIT Potato monitoring pots

Two EIT pots were constructed for this experiment, a larger pot with a diameter of 24 cm and a smaller pot with a diameter of 16 cm. Each pot was constructed from a black plastic shell, 64 holes were drilled into the side of the pot in an evenly spaced (16×4) grid as shown in Fig. 1. Into these holes stainless steel bolts and washers were threaded through to create the electrodes for the impedance tomography. Each washer was connected through a series of custom-made multiplexer and amplifier circuits to a Digilent analogue discovery 2 (Digilent Inc., USA). The Digilent analogue discovery 2 was controlled by a laptop for data acquisition, signal generation and control of the multiplexers. This distance between electrodes is determined by the number of electrodes and the size of the pot. The chosen 64 electrodes are a trade-off between electrode size and resolution. More electrodes would enhance resolution near the circumference of the pot, but not in the middle as it would lead to smaller electrodes, resulting in more contact problems.

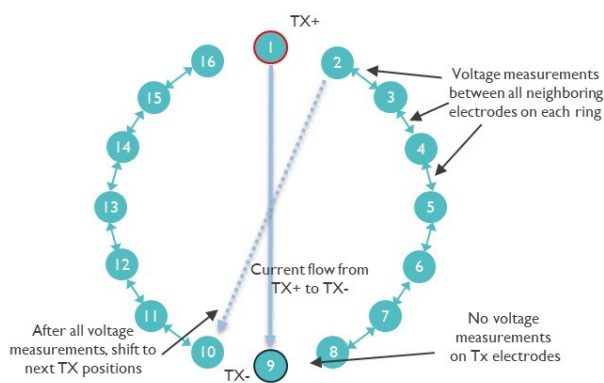


The grid of electrodes connected to the multiplexers can be seen on the outside. The grey ribbon cable goes from the pot to a Digilent analogue discovery 2. Also, visible from the outside are four small swatches of bubble wrap that were used to keep excess soil or moisture off of the multiplexers during measurement.

Fig. 1 A photo of the impedance monitoring pot

A program written in Digilent Waveforms software was used for acquisition and data storage. For a complete measurement cycle, 960 different selections of the electrodes are made, resulting in 960 complex impedance spectrograms. Each spectrogram consists of 7 frequencies ranging from 1 kHz to 100 kHz.

EIT Reconstruction algorithms needed 4 wire impedance measurements as input data. Each measurement involved a known current flowing between two driving electrodes (Tx_+ , Tx_-) and measuring the voltage difference between the receiving electrodes (Rx_+ , Rx_-). The differential voltage measurement was done by means of buffers amplifiers on the multiplexer PCBs connected to the differential input of the analogue discovery as shown in Fig. 2.



Current flows between the two opposite Tx electrodes 1 and 9. The voltage was then measured between neighbouring pairs of Rx electrodes starting from 2 and 3 and moving around the ring except for the transmitting electrodes, 1 and 9, which are skipped. After this was completed, two new electrodes 2 and 10 become the Tx electrodes, and the process is repeated. In the end, this yields 216 measurements.

Fig. 2 An example of the measurement of a one ring system of electrodes inside the pot

Most EIT setups use an AC current source to acquire the impedance by dividing the measured differential voltage by the applied current. An AC voltage generated by the analogue discovery was applied in this setup instead. The current was then measured by means of a TIA circuit integrated into the multiplexer PCBs and fed to the second input channel of the analogue discovery 2 (Fig. 3). Using a driving voltage and measuring the current instead of a current source, made the setup suitable for a wider range of high impedance of dry soil while not being limited by the maximum voltage swing of the practical current source. The ratio between voltage and current, representing a measured complex impedance, was used as input for the reconstruction algorithm.

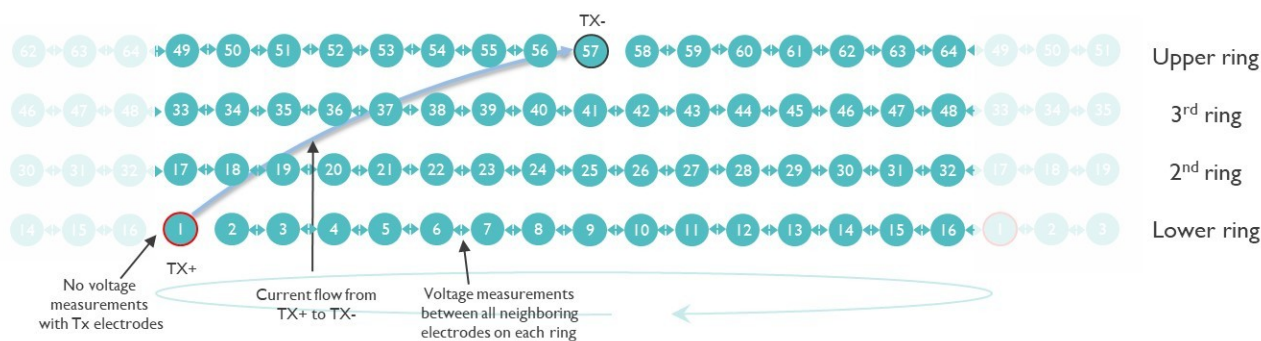
The multiplexers were designed for a low input capacitance to ensure a consistent response across the 1 kHz to 100 kHz frequency range, even under conditions of high soil impedance that occur at lower moisture levels. This was achieved by careful selection of the multiplexer chip and by avoiding a full (64 × 4)

multiplexer configuration. Instead, 16 individual (8 × 1) multiplexers were used, each connected to local buffer amplifiers on the multiplexer PCBs. This setup effectively created a single multiplexer with some limitations in electrode selection. For voltage measurements, only half of the electrodes could be selected for the positive input, and the other half for the negative input, arranged in a checkerboard pattern to allow differential voltage measurements between neighbouring electrodes. For the driving electrodes, the upper and third rings from the top were used to supply voltage, while the second and lowest rings served as the return electrodes for current measurement through the TIA circuit. Control of the multiplexers PCBs was done in a daisy-chain manner so multiples PCBs could be connected in one series. This allowed for flexibility in the number of electrodes per pot or including multiple pots in one setup.

2.2. Impedance measurements of potato and soil

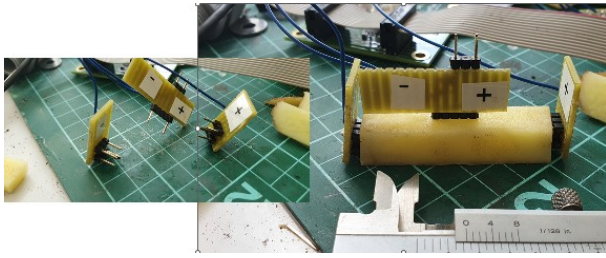
The electrical properties of both the soil and the potato needed to be characterized first before measurement could commence. A trial was conducted at Wageningen University in the Netherlands where store bought potatoes were cut into 10 mm square, 50 mm long potato chips, and positive and negative electrodes were attached to either end. AC voltage was then applied, and the current through the chip and the voltage drop over a 10.16 mm distance were measured to establish the complex specific impedance at 13 frequencies from 1 kHz to 10 MHz as shown in Fig. 4.

In addition, three soil types were analysed corresponding to the major soil types in the Netherlands: Pure cleaned sand, potting soil, and sandy soil. Small samples of soil were lightly packed into a clear Plexiglas box measuring 32 mm by 11 mm cross section and measuring the voltage drop over a distance 20 mm. From this the specific impedance of the soil was calculated. Soil samples were dried prior to the trial in an oven at 95 °C for two days to remove as much soil moisture as possible. Measurements on each sample began at its driest state, and then a small amount of water was added and allowed to fully diffuse over the sample for 30 min. The sample was then remeasured, and the same amount of water was added again until the soil reached its holding capacity in steps of 10 % water content by weight from 10 % to 50 %.



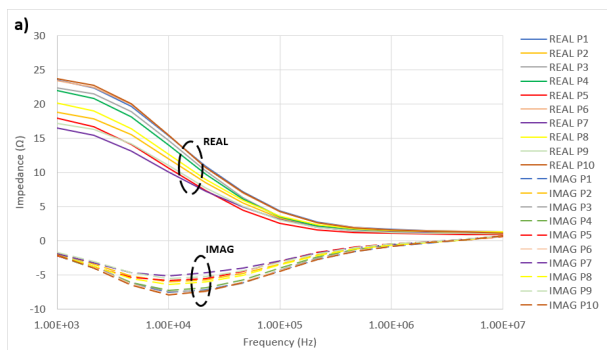
Current flows between the two opposite Tx electrodes 1 and 57. The voltage was then measured in neighbouring pairs on each ring except the transmitting electrodes which are skipped. After this was completed, two new electrodes from the lower and upper ring become the Tx electrodes, and the process is repeated. In the end, this yields 960 measurements per tuber.

Fig. 3 An example of the measurement of multiple rings of electrodes inside the pot

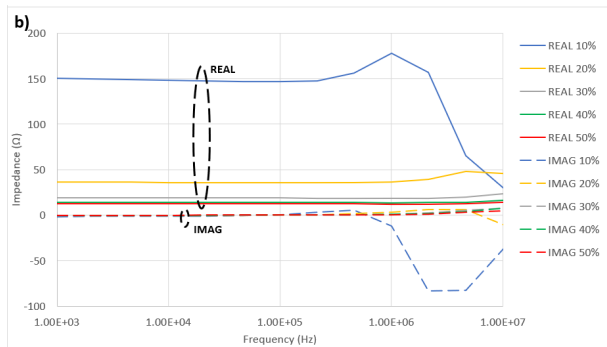


The same set was used for measuring soil properties, but the samples were packed into a small plexiglass box. This allowed us to determine impedance response of soil and potato separately over the frequencies.

Fig. 4 Image of the Measurement setup attached to a small chip of potato



(a) The frequency response of 10 potato slices



(b) The frequency response of one sample of sandy soil at different moisture levels

In both cases, the real components of the impedance are positive before 100 kHz and the imaginary components are negative before 100 kHz. (a) The frequency response of 10 potato slices. All tubers show a similar response curve with amplitude of the real component of the impedance dropping at higher frequencies. (b) The frequency response of one sample of sandy soil at different moisture levels. While the amplitude of the impedance varies greatly, it remains mostly constant over the measured range until 100 kHz.

Fig. 5 Impedance per frequency response for both potato and sandy soil

Our results showed that all of the measured potatoes had very similar responses across the frequency range from 1 kHz to 10 MHz, with the real component decreasing as the frequency increased as shown in Fig. 5. The measured soils were however

found to be much more varied, with the amount of moisture and compression having great effects magnitude of the specific impedance. Notably, in all cases the impedance did not show the same decreasing of amplitude in relation to frequency. It was then possible to separate the soil from the tuber by using the change in amplitude between a baseline frequency of 1 kHz and a second higher frequency around 100 kHz.

From this information a measurement protocol was defined. The tuber would first be measured at 1 kHz and then in progressive steps up to 100 kHz (2, 5, 10, 22, 46, 100 kHz). Each tomographic reconstruction would then be constructed from the difference of the progressive step and the baseline frequency, enhancing contrast between the potato and soil.

2.3. Effects of soil moisture on measurements of potato

The minimum resolution of each pot was determined by its diameter, as shown in Section 2.1. Two pots were used in this study, each with a different diameter. It was determined that for the larger pot, with a diameter of 24 cm, the resolution of the reconstruction was 2.4 cm, and for the smaller pot, with a diameter of 16 cm, the resolution of the reconstruction was 1.8 cm. From the measurements conducted in Section 2.1., it was expected that the difference in impedance response between the soil and the potato over frequency was necessary to create a detectable contrast in the signal. To test this, a trial was conducted at the NARO Hokkaido Agricultural Research Center. Three Konahime potatoes of different sizes were selected for this trial, with average diameters of 3.05, 5.5, and 7.5 cm, respectively, as shown in Table 1.

Table 1 Dimensions of each potato size

Size	Width (cm)	Length (cm)	Height (cm)	Volume (cm ³)
Small	3.5	2.6	2.3	11
Medium	6.0	5.0	4.2	71
Large	9.0	4.2	4.8	147

Air-dried soil at 10 % soil moisture content was used as a baseline before modifying each pot's water content as shown in Fig. 6. To each pot, various amounts of water were added: 400, 900, 1,200, 1,500, and 1,800 mL to 4 kg of air-dried soil, mixed well, and allowed to homogenize over 24 h. A single potato was then placed in the centre of the small pot. After the water had been allowed to diffuse evenly throughout the pot, the potato was measured with the EIT pot system. This process was repeated three times for the same size potato and the same water content of the soil. The pot was then cleaned and dried, and the next size of potato was added.

3. Results and discussion

3.1. Results

3.1.1. Reconstruction of the potato 3D model

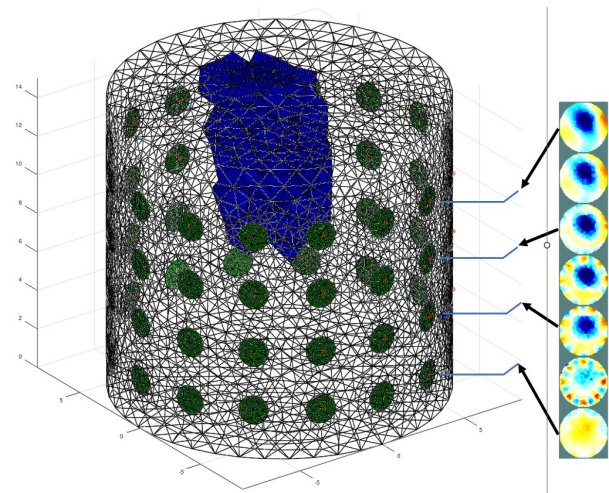
After data collection, a 3D reconstruction model was made in EIDORS, an open-source toolbox for EIT reconstructions.

Frequency-difference electrical impedance tomography (fdEIT) was used for potato detection. As mentioned in section 2.2., this works because the impedance of a potato decreases with frequency whilst the impedance of the soil remains rather constant over this frequency range. By using fdEIT the chance of soil impedance being equal to the potato impedance was avoided. Furthermore, a differential EIT method was less vulnerable to model errors, parasitic impedances and electrode contact variance. The reconstructions were not based on point clouds as is normal in stereo vision re-constructions but based on intersecting impedance planes. By combining these intersecting planes, a 3D polygon could be reconstructed as shown in Fig. 7. These planes could only be reconstructed at heights equal to the electrodes or halfway between subsequent electrodes. Because multiple frequencies were used in the reconstruction slices 196, at these heights it was easier to analysis them than the full 3D shape.

3.1.2. Effect of soil moisture content on visualization

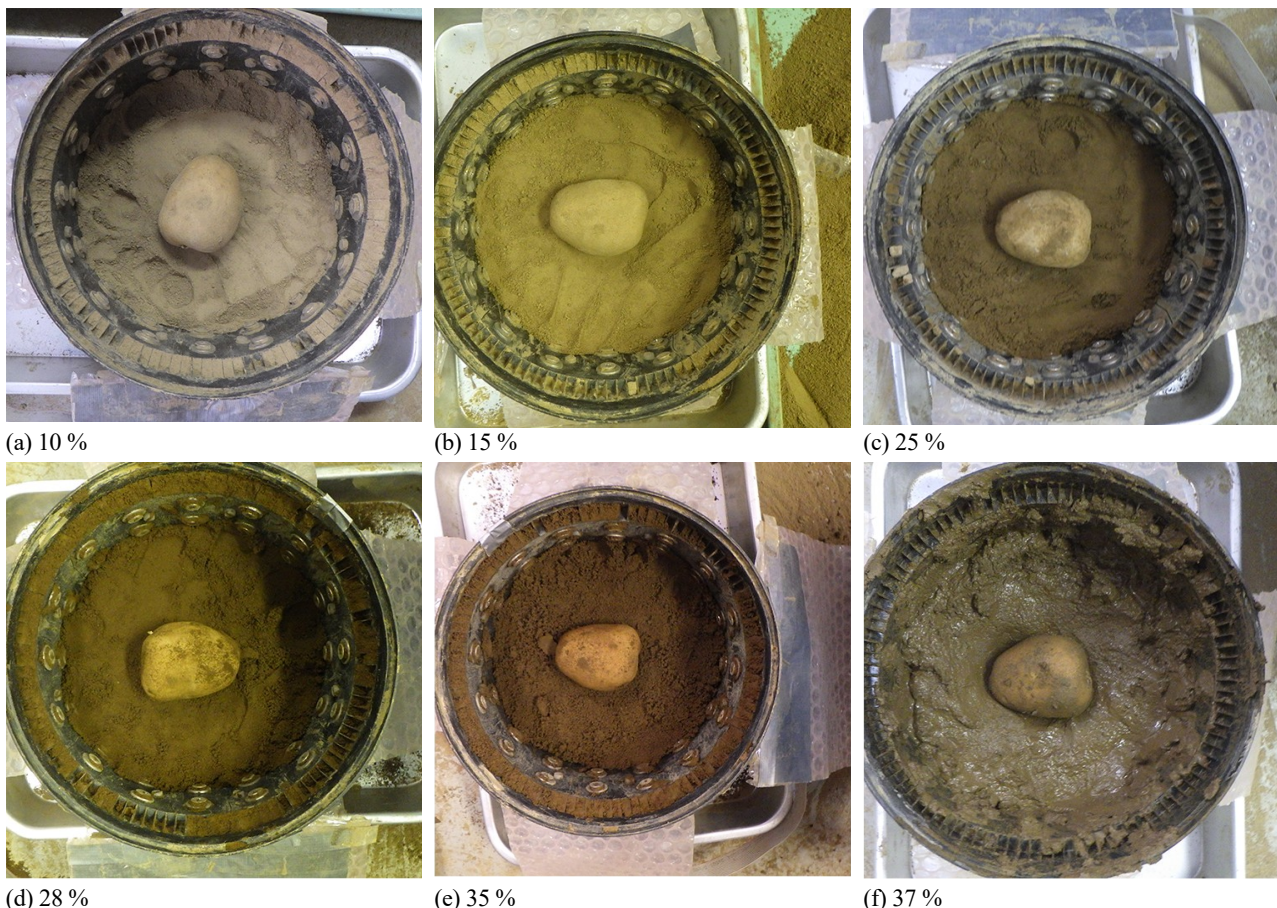
As can be seen in Fig. 8, all size of potato tubers sometimes failed to be visualized if the soil water content was less than 10 %. Medium and large tubers were successfully visualized if the soil water content was more than 28 % (Fig. 9). The tubers were clearly visualized when the soil water content was 37 % (Fig. 10). However, small tubers could not be visualized even at 37 % soil water content. When medium tubers were successfully visualized, the distribution of impedance was clearly seen when compared

with 2–5 kHz. On the other hand, the effect of frequency was small in case of large tubers.



The blue in this case corresponds to a region of higher difference between the two frequencies. The tuber can be seen in both 3D and in the slices corresponding to different cross sections of the pot. Cross sections can only occur at the height of electrodes (represented in green in the reconstruction) or halfway between them.

Fig. 7 An example of the 3D Reconstruction of a potato using fdEIT from 1 kHz to 10 kHz



Notice that at the highest water contents, the soil became saturated as it hit its carrying capacity.

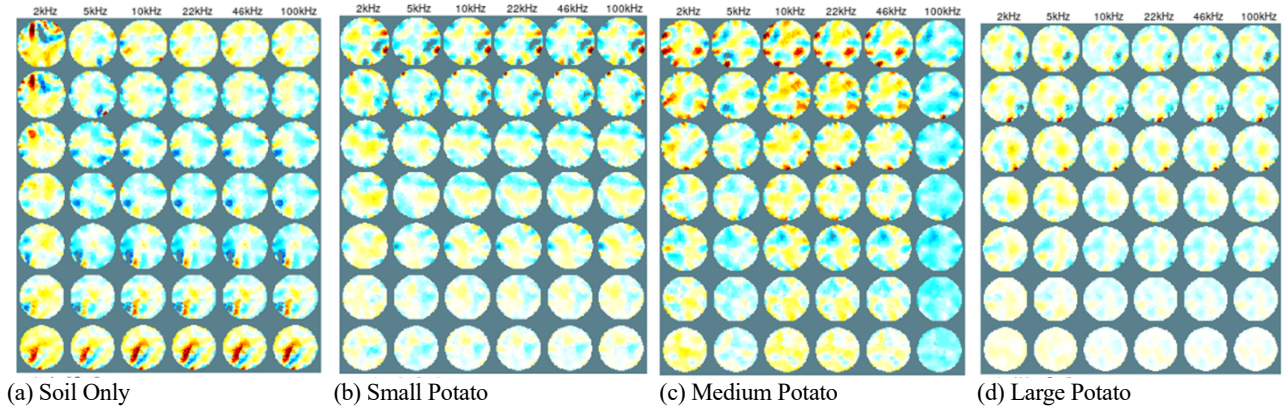
Fig. 6 Photo of an example potato in various moisture contents

3.2. Discussion

Electrical Impedance Tomography (EIT) and Electrical Resistivity Tomography (ERT) have been used to detect crop presence, estimate belowground biomass, and monitor physiological or environmental changes in the root zone (Basak et al., 2022). While most studies using these methods focus on maize (Michels et al., 2025; Rao et al., 2018; Weigand et al., 2019),

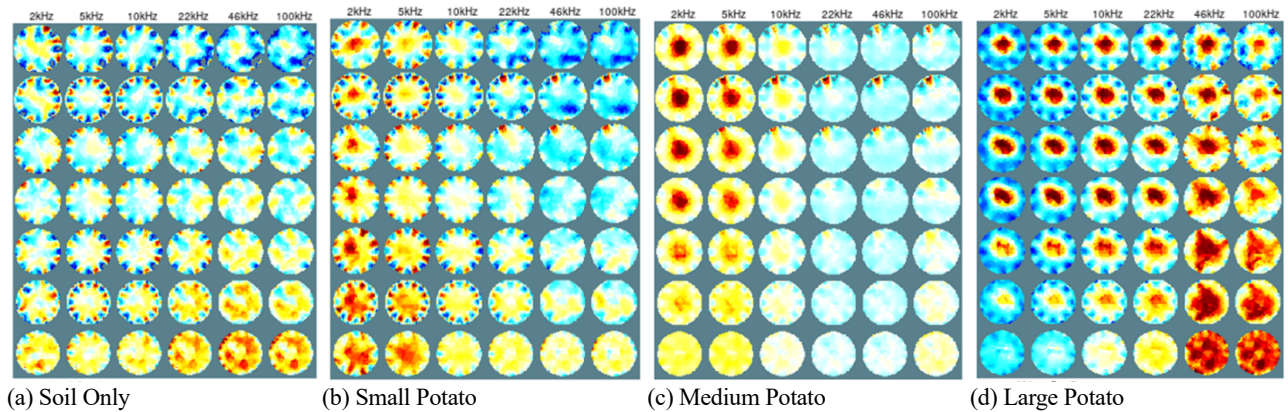
little is known about their application to potato research.

The analysis in our study indicates that both the size of the potato tuber and the soil moisture content have a significant impact on the quality of potato reconstruction using EIT. Our reconstructions demonstrate that at low soil moisture contents, around 10 %, the potato was not visible, likely due to the high impedance across the pot. However, as we increase the soil



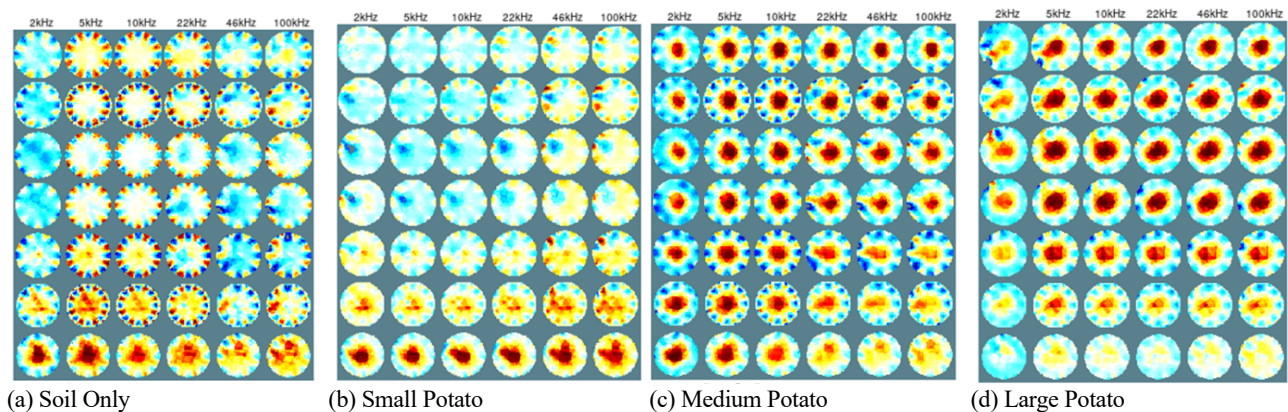
Each column represents a reconstruction at different frequencies of 2, 5, 10, 22, 46 and 100 kHz. Each row was an additional 4 cm deep in the pot from the first row of electrodes to the bottom of the pot.

Fig. 8 Visualization of tubers with soil moisture of 10 %



Each column represents a reconstruction at different frequencies of 2, 5, 10, 22, 46 and 100 kHz. Each row was an additional 4 cm deep in the pot from the first row of electrodes to the bottom of the pot.

Fig. 9 Visualization of tubers with soil moisture of 28 %



Each column represents a reconstruction at different frequencies of 2, 5, 10, 22, 46 and 100 kHz. Each row was an additional 4 cm deep in the pot from the first row of electrodes to the bottom of the pot.

Fig. 10 Visualization of tubers with soil moisture of 37 %

moisture content to the range of 28 % to 35 %, the potato becomes more apparent. Moreover, we observe that larger tubers yield more accurate reconstructions across all frequencies. In contrast, smaller tubers show better signal-to-noise ratios at lower frequencies, less than 5 kHz, compared to higher frequencies. This difference could further be exploited for tuber size estimation. Also, the size of the detected region relates to the size of the potato.

This study uncovered some hardware limitations that must be addressed before this technique could be adapted further. Three soil types were investigated in the study: Clay-based soil, sand-based soil, and andosol-based soil. While the soil was very wet, the impedance difference between the soil and potato decreased making reconstructions harder. It was found that the clay soil had a very similar impedance to the potatoes, which would limit the applicability of this technique in the world. In addition, the resolution of the sensor had a hard limit at one-tenth of the pot's radius. This limitation restricts its application for measuring fine root structures, except in cases where only the total root mass is required. But that does not mean that such a technique holds no value, for other tuber and taproot breeders, such as carrots (Basak et al., 2022), EIT could provide a way to monitor the growth of tubers non-destructively. It may also be possible to improve resolution by changing the ring-shaped geometry of the electrodes to new geometries that may lower this limit but will require additional modelling before it is deployed. These hardware steps must be addressed before EIT techniques are ready for field trials.

Finally, the most pronounced challenge we encountered while using the EIT pot was maintaining consistent contact with the soil. The electrodes need to make contact with the soil or else the air gap creates higher resistance and the reconstruction deteriorates. This problem was particularly evident at higher soil moisture contents, where the soil tended to clump together, resulting in air gaps. We investigated several electrode designs in this study including pins, plates, and rings, and settled on our bolt design, but the issue persisted. For the technique to be adaptable to open field applications, it is imperative to develop better methods for ensuring consistent soil contact. For example, by using spring loaded on deformable contacts like printed electronics.

As mentioned previously, there is a pressing need for non-destructive technologies to measure root traits. We have shown that there is an electronic response but the dragging of electrodes through the potato ridges disturbs the soil and if potatoes are right below the soil, this could damage the crop. It may be that another methodology of measuring the difference in electrical properties of soil and tuber is needed. Work has been done recently with Radio Frequency (RF) tomography which utilizes an array of antennas to reconstruct the interior of an object (Ghavami et al., 2019). If this could be adapted to a field condition, the antennas would not need to contact the soil at all and may offer a potential solution. Ongoing research is being conducted to explore the feasibility of such an approach. Where EIT performs best in moist soil, RF will be best for rather dry soil. Moisture in the soil attenuates the RF signals, especially at frequencies beyond a GHz,

needed for higher resolution imaging.

In controlled setups such as hydroponics and rhizotrons, multifrequency EIT has demonstrated strong quantitative relationships with root traits (e.g., R^2 up to 0.82, correlations > 97 %) (Basak et al., 2022). However, field and soil-based applications face several key limitations including low spatial resolution due to sparse or simple electrode layouts, overlapping soil-plant signals (Weigand et al., 2019), sensitivity to soil conditions (e.g., moisture, compaction, temperature) (Newill et al., 2014), slow data acquisition (Weigand et al., 2019), and difficulty detecting fine or low-biomass roots (Michels et al., 2024). Reported solutions include denser or 3D electrode arrays, improved inversion and spectral analysis (e.g., Electrical Root Index), streamlined calibration protocols, and integration with complementary imaging techniques like RF.

4. Conclusion

Our research has demonstrated the potential of Electrical Impedance Tomography (EIT) as a non-destructive method for measuring potatoes. EIT offers the ability to accurately measure potatoes as small as 3 cm in size, across a range of soil moisture conditions, from sandy to highly organic soils, and with soil moisture contents ranging between 10 % to 35 %. It was found that the sensor had a resolution limit at 1/10 the radius of the pot. By setting the sensors in the open-field, the possibility of utilization of this sensor in the open-field was explored. This technology holds promise for further development towards measuring tubers in other crops, such as sweet potato, taro, or carrots. However, while dragging the sensor on top of the ridges was not preferable for tuber crops, a new technique involving RF tomography is proposed as an improvement of the current studies. Future studies may focus on advancing hardware—such as increasing electrode density, adopting layered or three-dimensional arrays, and expanding measurement volumes—alongside refining inversion algorithms. Efforts to streamline measurement protocols through improved calibration and automation, as well as integrating EIT/ERT with complementary imaging techniques, could also enhance applicability in complex field conditions. Adapting these methods for uneven or ridge-based planting systems, and exploring alternative sensing modalities like RF tomography, may offer more robust solutions for detecting and quantifying tuber development across diverse cropping systems.

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Declaration of conflicting interests

The authors declare no conflicts of interest.

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