Research article

Enhancing Plant Growth using a 6 V Solar Cell–Powered Electrokinetic Treatment

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Abstract Application of electrokinetic treatment powered by a 6 V solar cell (ET-6V) has been found to release essential nutrients (N, P, and K) from saturated organic soil. Additionally, this treatment accelerates the growth of Japanese mustard spinach near the anode due to oxidation reactions. However, growth inhibition occurs near the cathode due to reduction reactions. These effects may vary in unsaturated soils managed with irrigation water. Therefore, the aim of this study was to determine the effects of ET-6V on plant growth in unsaturated soils through laboratory experiments. Specifically, we examined changes in electrode potential and the growth rate of Japanese mustard spinach after applying ET-6V to andosol mixed with cow manure compost. Although reduction reactions occurred at the cathode, facilitating the flow of irrigation water through the soil layer maintained a stable cathode potential exceeding 0 V. Growth rate measurements revealed a 1.2–1.8-fold increase in the wet weight of Japanese mustard spinach near both the anode and cathode. Notably, the growth rate of spinach was higher in the soil located 5–20 cm from both electrodes. Surprisingly, reduction reactions did not negatively affect growth rate but instead contributed to increased Japanese mustard spinach growth in unsaturated soil. The enhancement of soil potential through irrigation water is a key driver underlying this growth. Therefore, ET-6V should be applied to upper-land soils to boost crop productivity.

Keywords 6 V solar cell, electrokinetic treatment, unsaturated soil, growth rate, Japanese mustard spinach

INTRODUCTION

In organic farming, the decomposition of organic matter plays a pivotal role in nutrient supply. This decomposition is heavily reliant on the soil chemical environment (SCE). As highlighted by Yan and Hou (2018), understanding the SCE is essential for maintaining healthy soil to support crop production.

Electrokinetic treatment (ET) is a technology that establishes a low-intensity electrical field between two electrodes buried in the soil by applying direct current or constant voltage via an external power supply. For decades, ET has been effectively used to eliminate contaminants, such as dyes and heavy metals (Hanay et al., 2009; Almomani and Baranova, 2013). Kim et al. (2010) reported changes in the SCE, including pH and electrical conductivity, resulting from the application of ET in soil. However, the common practice of applying a large potential gradient, e.g., 3–5 V/cm, in soils introduces substantial fluctuations in the SCE, thereby influencing soil biology and hindering organic matter decomposition.

Addressing this concern, Touch et al. (2022a) used a 1.5 V solar cell (with a potential gradient of 0.03 V/cm) in ET and applied it to the soil. This application led to the release of ammonium ions and the proliferation of microorganisms in the soil. However, no phosphate release was observed, indicating that a 1.5 V solar cell is insufficient for releasing phosphate in soils. Touch et al. (2022b) conducted further investigations into the solar cell voltage required to induce phosphate release, concluding that at a minimum of 3 V was required to enhance phosphate concentration in soils. By increasing the voltage of the solar cell, a higher electrical current and a lower cathode potential (or lower SCE) can be achieved. This, in turn, results in the release of more nutrients in the soil, thereby boosting crop productivity.

Extending on their previous findings (Touch et al., 2022b), Touch et al. (2023a) explored nutrient distribution in soils when employing ET powered by 3 or 6 V solar cell. They proposed that a 6 V solar cell was well-suited for ET to facilitate the release nutrients (N, P, and K) from organic soils. Subsequently, Touch et al. (2023b) applied ET powered by a SC-6V (ET-6V) to saturated organic soil, where no water flow was present in the soil layer. They investigated the effects of the ET-6V on the growth rate of Japanese mustard spinach. Their observations revealed that reduction reactions at the cathode inhibited the growth of Japanese mustard spinach, whereas oxidation reactions at the anode promoted such growth.

Touch et al. (2023b) revealed the effects of ET-6V on plant growth in saturated soils. However, the impact of ET-6V treatment on unsaturated soils remains uncertain, given that, in these soils, the absence of flow from the soil layer maintains the soil in a reduced state. Conversely, in unsaturated soil with water outflow, the reduced state of the soil may be ameliorated by the flow of water. This, in turn, could affect plant growth in the soil.

OBJECTIVE

Given the lack of data regarding ET-6V in unsaturated soil therefore, this study aimed to determine the effects of ET-6V on plant growth in unsaturated soil.

METHODOLOGY

Experimental Procedures and Operations

Commercially available dried cow manure compost (fully matured, with N, P, and K at 1.09%, 2.29%, and 2.28%, respectively) was initially mixed with andosol (volcanic-derived soils rich in organic matter and aluminum compounds) at a volume ratio of 47% (typical range: 40%–60%). This mixture was used in the experiments, which were conducted under two conditions: without treatment (Control; Fig. 1a) and with ET-6V (Fig. 1b). Both cases were conducted under unsaturated conditions, with water able to flow freely from the soil layer. A consistent daily water was supplied from the top of the soil layer using an automatic pump (Fig. 1c).

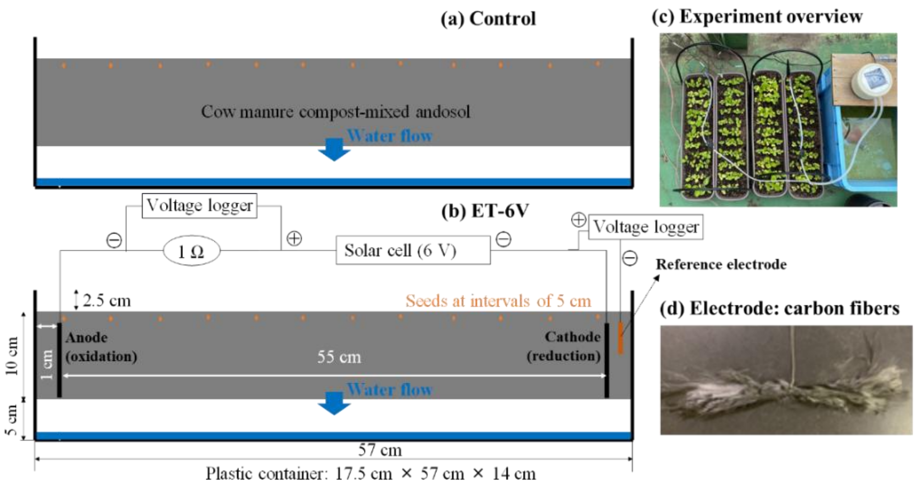


Fig. 1 Experimental devices and operations

For the ET-6V treatment, two electrodes were embedded in the soil layer (Fig. 1b). To generate an electrical current, one electrode (the anode) was connected to the positive terminal, and the other (the cathode) was connected to the negative terminal of a 6 V solar cell (Tamiya, 1.5 V-500 mA connected in series) using the circuit shown in Fig. 1b. An external resistance of 1 Ω was introduced between the anode and the solar cell. The electrode material used was carbon cloth (News Company, PL200-E), which was preheated to 500°C for 1 h before usage, in accordance with the recommendations of Nagatsu et al. (2014). The heated carbon cloth, measuring 10 cm in width and 10 cm in height, was separated into fibers to form a brush-type electrode (Fig. 1d).

The voltage at both terminals of the external resistance was measured every 15 min using a voltage logger (T&D Corp., MCR-4V) to calculate the circuit current, following Ohm's law. Current density was determined by dividing the current by the electrode surface area, which was 0.01 m^2. The electrode, along with a reference electrode (Toyo Corp., W-RE-7A), were placed in the soil layer, and connected to the voltage logger (using the circuit shown in Fig. 1b) to measure the cathode potential.

After Day 36 of the experiment, Japanese mustard spinach was collected for analysis. Images of the spinach were captured and processed in ImageJ to determine the area of each spinach strain. Subsequently, the weight, maximum leaf length, and maximum leaf width of each spinach strain were measured using a vernier caliper.

RESULTS AND DISCUSSION

Variations in Electrode Potential and Current Density

Figure 2 depicts the temporal changes in cathode potential (indicative of reduction reactions) and current density throughout the experiments. Under the saturated condition (Touch et al., 2023a), a stable cathode potential registered below −0.5 V, indicating a strong reduction state near the cathode. Conversely, under the unsaturated condition, the stable cathode potential exceeded 0 V, indicating an oxidation state near the cathode (Fig. 2a). The current density was approximately 0.06–1.30 A/m^2 under the saturated condition (Touch et al., 2023a) and remained below 0.05 A/m^2 under the unsaturated condition (Fig. 2b).

These findings suggest that, under unsaturated conditions characterized by water flowing from the top to the bottom of the soil layer, oxygen from the irrigated water can induce an oxidation state in the soil, leading to a high cathode potential. Consequently, this results in a lower electrical current due to a diminished potential difference between the anode and the cathode.

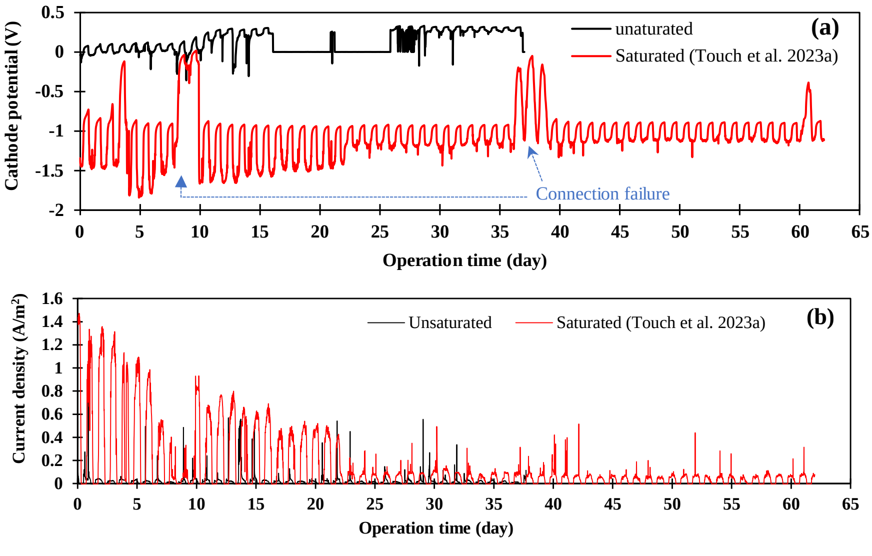


Fig. 2 Comparison of cathode potentials and current densities in saturated/unsaturated soils

Enhancement of Japanese Mustard Spinach Productivity

Figure 3 shows distributions of the average wet weight of spinach between the electrodes, with the average wet weight of 3–5 strains at each distance from the anode (0 cm in Fig. 3) shown. Compared with the Control, a 1.2–1.8-fold increase in weight was observed at a distance of 5–20 cm from the cathode (55 cm in Fig. 3). Similarly, an increase of 1.2–1.6-fold in weight was observed within 15 cm from the anode.

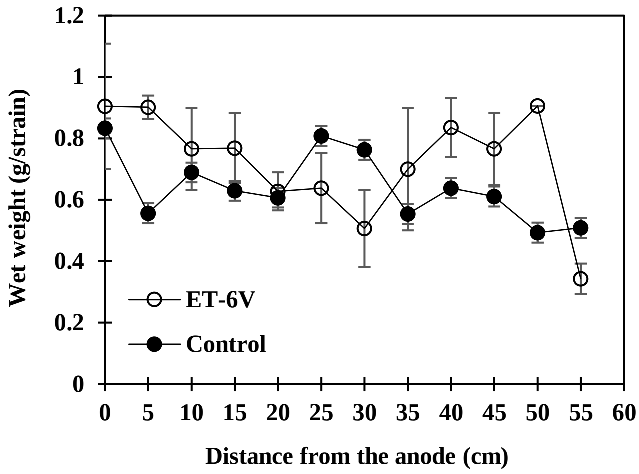
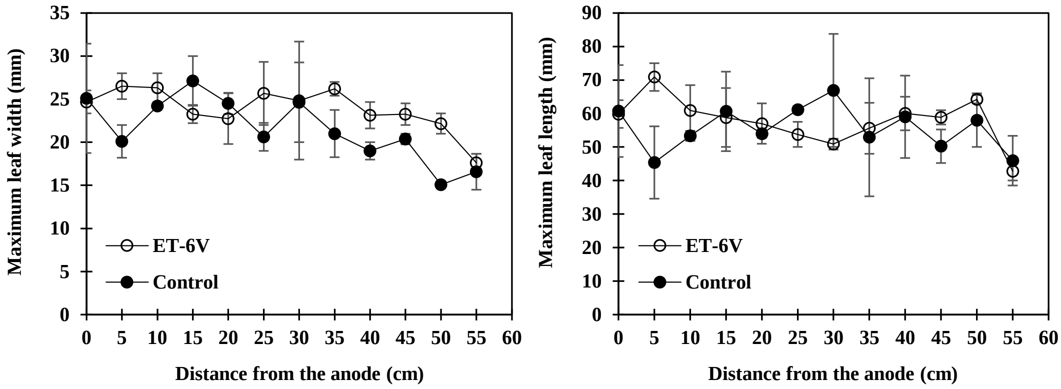


Fig. 3 Distributions of wet weight between the anode and the cathode

A similar trend was evident in the distributions of maximum leaf length (Fig. 4a) and width (Fig. 4b). At a distance of 5–15 cm from the anode, increases in length of 1.1–1.6-fold were found, and a 1.1–1.2-fold increase in length was observed at a distance of 5–20 cm from the cathode (Fig. 4a). As shown in Fig. 4b, width increased 1.1–1.3-fold near the anode, and a 1.1–1.5-fold increase in width was observed near the cathode. Interestingly, no differences in either length or width were observed at the anode and the cathode.



(a) maximum leaf length (b) maximum leaf width

Fig. 4 Distributions of maximum leaf length and width between the anode and the cathode

As a single strain of spinach typically bears multiple leaves, the maximum leaf length and width may not accurately reflect the overall growth rate. To validate our claims, spinach area was determined using ImageJ. The relationship between the determined area and the spinach weight (Fig. 5) indicated that the area can serve as an index for assessing the growth rate of spinach, given its strong correlation (r = 0.88) with weight.

According to the distribution of spinach area (Fig. 6), an increased spinach growth rate was observed at a distance of 5–15 cm from each electrode. Increases in area were 1.1–2.0-fold near the anode and 1.1–1.5-fold near the cathode.

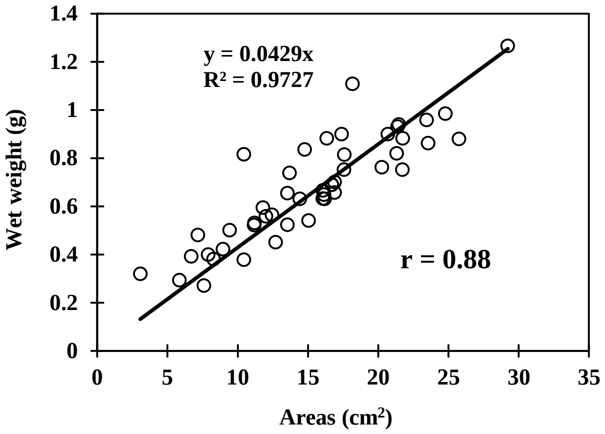


Fig. 5 Relationship between spinach area (determined in ImageJ) and wet weight

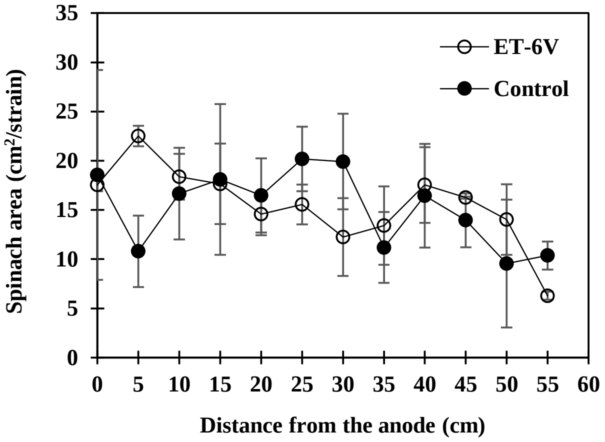


Fig. 6 Distribution of spinach area between the anode and the cathode

Taken together, these results affirm the efficacy of ET-6V treatment in enhancing the growth rate of spinach within 20 cm from each electrode, although no growth rate increase was noted at either the anode or the cathode. Touch at al. (2023a) previously reported that applying an ET-6V in saturated soils released ammonium ions, calcium ions, and potassium ions within 20 cm of the anode, whereas phosphate ion levels in the soil increased at a distance of 15–45 cm from the anode. These increased nutrient ions, contributed to the enhanced growth rate of spinach. Moreover, these findings align with those of Touch et al. (2023b), who demonstrated an increased growth rate of spinach near the anode following the implementation of ET-6V treatment in saturated soils.

Touch et al. (2023b) also noted that the spinach growth rate was inhibited within 20 cm from the cathode, which our results corroborate, indicating an increased growth rate of spinach near the cathode in unsaturated soils. Under saturated conditions (Touch et al., 2023b), reduction reactions occurred at the cathode, resulting in a prolonged robust reduction state in soils, which, in turn, affected the spinach growth rate. Conversely, under unsaturated conditions, reduction reactions occurred at the cathode; however, the reduced state could be ameliorated by water flow through the soil layer (Fig. 2a). This mitigated the effects of reduction reactions on spinach growth rate. Given that phosphate was also released near the cathode (Touch et al., 2023b), it is evident that reduction reactions are more conducive than oxidation reactions for increasing the growth rate of spinach in unsaturated soils.

CONCLUSIONS

Laboratory experiments were conducted to examine the effects of ET-6V on plant growth in unsaturated soils. Specifically, we investigated changes in electrode potential and the growth rate of Japanese mustard spinach after the application of ET-6V to andosol mixed with cow manure compost. Under unsaturated conditions, with water flowing through the soil layer, the influence of water flow contributed to maintaining a stable cathode potential exceeding 0 V, indicating an enhanced reduction state due to water flow. Analysis of spinach weight, leaf length, leaf width, and area distributions revealed a notable increase in spinach growth rate in soils located 5–20 cm from both the anode and the cathode. In particular, a 1.2–1.8-fold increase in wet weight was observed. It was previously reported that reduction reactions had a limiting effect on spinach growth in saturated soils. However, our study showed an increase in growth rate attributed to reduction reactions. The improvement in soil potential facilitated by irrigation water played a pivotal role in this growth increment. Overall, our data suggest that reduction reactions may provide greater benefits in enhancing plant growth rates. The outcomes of this research may contribute to further development of organic farming methodologies. In particular, the application of our proposed technology facilitates nutrient release in the soil, thereby potentially reducing the amount of fertilizer required.

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