Electrokinetic Remediation of Saline Agricultural Land using Solar Energy

Aminul Islam, Sushil Kumar Kothari, Biswajit Ghosh, Krishna Kishore Satapathy, Tanuj Kumar Mandal, Shankha Koley

ABSTRACT

High salinity reduces soil productivity and crop yields, which is a significant problem in agricultural fields, particularly in arid and semi-arid areas. The technique that would seem to have been promising for stripping away salt and restoring soil health is electrokinetic soil remediation (ESR). To understand ESR, this study investigates the use of a solar-powered direct current (DC) system focuses on monitoring important soil chemical parameters like pH and electrical conductivity (EC) throughout the experiment. The ESR study has performed for in-situ agricultural field with graphite electrodes for 0-15 cm depth soil. The system's intent was ions to pass enhanced desalination by having caused through the soil medium through the application of electric field. The soil sample collected in 15-day intervals till 75 days from starting the experiment and the soil samples were analyzed in laboratory form finding changes. The results show that pH usually decreases near the anode and increases near the cathode, a pattern attributed to complex electrokinetic phenomena within the soil, including pore solution electrolysis. Also, it has been found that higher EC values near the electrodes indicate the migration of chemicals and dissolved salts towards the oppositely charged electrodes during treatment. Solar-powered electrokinetic remediation offers a sustainable and efficient way to reclaim saline soils, promoting soil health and agricultural productivity in affected areas. This ESR method can utilize renewable energy and real-time monitoring for economic and ecological benefits.

Keywords Electrokinetic remediation, Saline soils, Solar DC, pH, Electrical conductivity, Soil desalination, Sustainable agriculture.

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INTRODUCTION

Soil is one of the most important natural resources gifted by God to meet human or animal existence and expansion, which has been degrading by rapidly expanding industries, intensive agricultural practices,

landfills leachate, mine tailings, industrial waste, and mining exploitations (Kim *et al.* 2012, Lee and Kim 2010, Ma *et al.* 2018). Soil pollutant contamination has been an environmental threat worldwide and more than 3 million soil-contaminated sites were identified (Doran 2002, Gao *et al.* 2022). The study of electrokinetic phenomenon first started in 1808 by Reuss in clay soil and resulted that water movement taking place from anode to cathode through capillary during DC electric flow (Acar and Alshawabkeh 1993, Mulligan *et al.* 2001, Llorente *et al.* 2024). During the 1980s to 1990s laboratory studies investigated using DC for ions and metal extraction from contaminated soil (Runnells and Larson 1986, Acar *et al.* 1989, Dermont *et al.* 2008). Late 1930's Geotechnical researchers started using DC for investigate fine-grained soil (low hydraulic conductivity) deposits using electroosmotic consolidation and stabilization (Casagrande 1952, Alshawabkeh *et al.* 2004). Electrokinetic effect for soil remediation investigation started to treat polluted soils with organic contamination, inorganic contamination, and radioactive contamination in early 1990 (Shady *et al.* 2023). Geotechnical and environmental engineering potential researchers investigated the impacts of electrokinetic on the reduction of volume and contamination from the contaminated slurry (Acar *et al.* 1989, Chung *et al.* 2005). Several in-situ and laboratory studies were done to investigate and enhance the electrokinetic process for remediation of contaminated sites and evaluated physiochemical variables for in-situ low-disturbance soil, fine-grained soil, wet contaminated slurry, and heterogeneous soil media for remediation (Wang *et al.* 2021, Reddy 2010). Electrokinetic soil remediation process a low DC applied between cathode and anode, which changes physiochemical and hydrological characteristics of contaminated soil in the specific soil zone (Shady *et al.* 2023). The soil is a heterogeneous medium that contains solids, water and gases. Application small DC through soil mass with the help of cathode and anode initiate the movement on suspended soil particles, water, and chemical substances towards favored electrodes (Wall 2010). The basic design of elctrokinetics phenomenon studied on single vertical or horizontal direction and mixed both horizontal and vertically for contamina-

tion movement from one place to another place with 4 different process electromigration, electroosmosis, diffusion, and electrophoresis (Shady *et al.* 2023). In electrokinetic remediation process the transportation such as H+ and OH- ions towards opposite charged anode and cathode by sorption, precipitation, dissolution and aqueous phase reactions through the soil pores (Xie *et al.* 2024). Metal hydroxide precipitation often occurs in alkaline environments during migration, particularly near the cathode where hydroxide anions are electrolyzed (Drogui *et al.* 2007, Fatima *et al.* 2023). In electrokinetic remediation, these metal precipitates are sometimes left in the soil (Wen *et al.* 2021). Figure 1 shows Electroosmosis and electromigration of ions. However, they are less bioavailable and less harmful to crops due to their greater stability compared to free metallic ions. Still, the possibility of a pH drop exists (Cai *et al.* 2021). When pH is excessively high for most toxic substances, including cadmium (Cd), more soluble and negatively charged metal hydroxide complexes form, enabling them to migrate toward the anode (Rieuwerts *et al.* 2015). Limited research exists on the practicality of electrokinetic subsurface barriers to mitigate contaminant migration (Narasimhan and Ranjan 2000, Gill *et al.* 2014). These barriers leverage inverse electroosmosis, electro-migration, and localized high pH zones to impede contaminant spread. However, conventional barrier installation often faces challenges in remote areas due to the logistical constraints of transporting large equipment. Solar-powered electrokinetic barriers offer an innovative solution for such locations (Mohamedelhassan 2011). Despite this potential, few studies have explored solar cells as a power source for electrokinetic applications.Yuan *et al.* (2009) conducted a series of three laboratory experiments investigating solar-powered electrokinetic remediation of cadmium-contaminated kaolinite clay. This study investigated the effectiveness of in situ electrokinetic remediation for contaminated soil in coastal West Bengal, using a 60V voltage. It demonstrates, for the first time, the potential of electrokinetic methods to remediate salinity-contaminated agricultural soil. The study compared the removal efficiency of pH and EC in the 0–15 cm soil depth. Additionally, it showed a correlation between pH and electrical conductivity changes in the soil and the sampling locations (midfield, near anode, and near cathode).
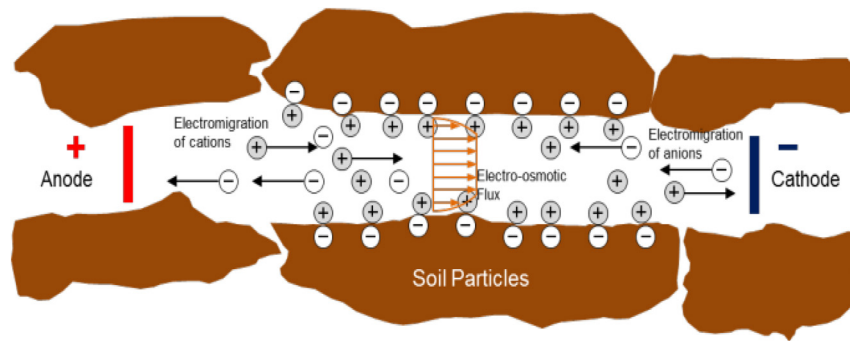
Fig 1. Electroosmosis and electromigration of ions (Source: Liu 2018).

MATERIALS AND METHODS

Research site

All field and laboratory experiments were conducted on the campus of The Neotia University in South 24 Parganas, West Bengal, India. South 24 Parganas, spanning an area of approximately 8165.05 square kilometers, is situated between latitudes 21°29'0" north and 22°33'45" north and longitudes 88°3'45" east and 89°4'50" east. The region experiences temperatures ranging from 13.6 to 36.3 degrees Celsius, with an annual rainfall of 1750 to 1770 millimeters. The predominant soil types in the area are loamy soil (covering 194,330 hectares), clay-loamy soil (covering 101,050 hectares), and clay soil (covering 93,280 hectares).

Experimental design

The study employed four photovoltaic panels (PVs), each measuring 1 meter by 2 meters. These PVs were positioned in east-west oriented strips, tilted southward at a 25-degree angle. The PVs were elevated 3 meters above ground level, with the southern side facing upwards, to facilitate mechanical cropping of the plants beneath using tractors (Fig.2, Fig. 3).

Design of electro-kinetic system

Agricultural residues, stones, and big clods from the soil was removed and the ploughing was removed. For assembly electrodes, the distance between anode and the cathode was kept at 2m and the distance between the anode to the anode was 2m and the cathode to cathode was 2m. To study electrokinetic
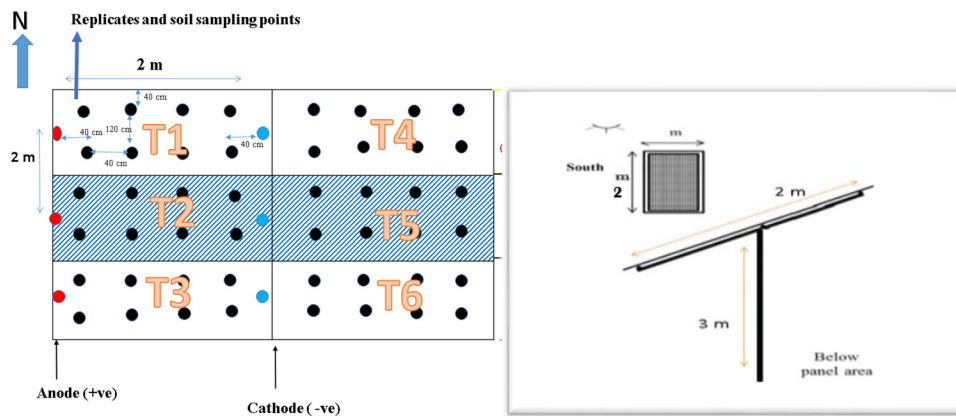

Fig. 2. Layout of agri-voltaic cultivated area. **Fig. 3.** Design of solar PV installation in agri-voltaic system.

soil remediation every 15 days' interval soil samples will collect from 40 cm intervals with 3 replicates for each of three treatments. So total 144 number of soil samples will be collected at 15 days' intervals for finding soil electrokinetic remediation. The voltage applied is 60 voltages

Soil physical properties

Soil samples were collected using a core cutter to measure soil properties. Initial measurements included texture and bulk density at a depth of 0-15 cm. To assess the impact of electrokinetics and shade, eight replicates per treatment are planned. A total of 144 soil samples will be collected every 30 days to analyze changes in soil chemical properties. Soil bulk density was determined for 18 samples using the core cutter method, measuring 0-15 cm depth with three replicates at the beginning of the in-situ experiment. The gravimetric method was used, with samples collected using a 100 cm3 core sampler. After oven-drying at 105°C for 48 hours, bulk density was calculated by dividing the dry soil weight by the sampler volume. The average bulk density for the study plot was 1.72 gm/cc. Soil texture was analyzed at 0-15 cm depth in the study plot, with 18 samples collected and processed at the beginning of the in-situ experiment. Samples were dried, crushed, and mixed with water and hydrogen peroxide. Analysis revealed a texture of 60.07% sand, 23.67% clay, and 16.26% silt, classifying the soil as sandy clay loam according to the USDA classification scheme. Monthly soil moisture at 0-15 cm depth was measured by gravimetric methods using weight balance and oven drier at 105 °C for 24 hours for the study plot.

Soil chemical properties

Soil electrical conductivity was measured in the study area using the Wheatstone bridge principle, with modifications to the current type. A 20-gram sample of air-dried, 20-micron sieved soil was placed in a 100 ml conical flask and mixed with 50 ml of distilled water (1:2.5 ratio). The mixture was shaken for 30 minutes on a mechanical shaker and allowed to settle for an additional 30 minutes. The supernatant liquid was then filtered through Whatman No. 42 filter paper into a beaker. The solution's conductance was mea-

sured directly from the digital display, and specific conductance was calculated by multiplying the electrical conductance by the cell constant value. Soil pH was measured in the study area using an electrometric pH meter. A 20-gram sample of air-dried, 20-micron sieved soil was placed in a beaker and mixed with 50 ml of distilled water. The mixture was stirred regularly for one hour. Meanwhile, the pH meter was turned on, allowed to warm up, and the glass electrode was standardized using standard buffers. The pH of the sample suspension was measured, stirring the suspension well just before introducing the electrodes and recording the reading. After each determination, the electrodes were rinsed and carefully blotted dry with filter paper. The glass electrode was standardized after every ten determinations.

RESULTS AND DISCUSSION

Soil physical properties

Soil properties were measured at the study site, revealing an average bulk density of 1.72 gm/cc. Textural analysis indicated a composition of 60.07% sand, 23.67% clay, and 16.26% silt. Using the USDA textural triangle, the soil was classified as sandy clay loam. Fig. 4 illustrates the average monthly soil moisture percentages for the top 15 cm of soil. The data revealed that the southern side of the panel had the lowest moisture content, while the under-panel plot and northern side (panel) area exhibited 24% and 27% higher moisture percentages, respectively. The soil moisture percentage ranges ranging from 23% to 29%. Interestingly, areas closer to the anode consistently show slightly higher moisture content. This trend is observed in both experiments and can be attributed to the continuous replenishment of water
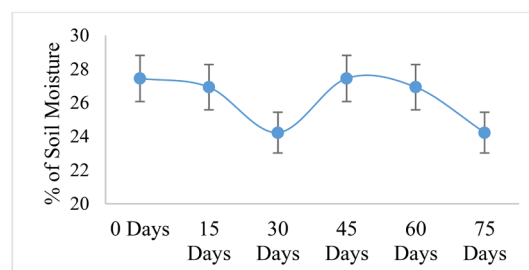

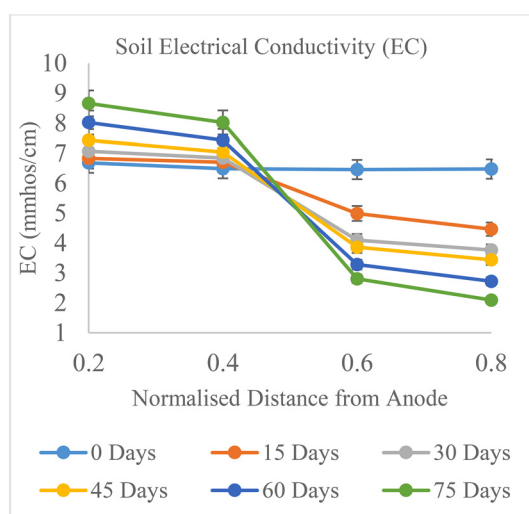**Fig. 4.** Percentage of soil moisture content.

Fig. 5. Soil EC changes after electrokinetic.

Fig. 6. Soil pH changes after electrokinetic.

in the anodic well. This replenishment compensates for water loss due to electro-osmotic flow towards the cathode well and evaporation.

Soil chemical properties

Variation of soil EC at the end of treatment

As depicted in Fig. 5, the initial electrical conductivity (EC) of the soil was 6.5 mmhos/cm. Electrokinetic treatment significantly reduced EC in the central sections of the soil samples across all three experiments. Notably, higher EC values were observed adjacent to the electrode positions. This pattern can be attributed to the migration of chemical compounds and the transport of dissolved salts towards the oppositely charged electrodes during treatment. The elevated conductivity near the anode is primarily due to the generation of mobile, conductive hydrogen ions (H^+) during electrolysis. Furthermore, the acidic environment near the anode facilitates solubilization, dissolution, and dissolution of salt precipitates, consequently increasing the EC (Bessaim *et al.* 2020). Electro-migration also plays a crucial role, transporting water-soluble ions like sulfate (SO_4^{2-}) and chloride (Cl^-) towards the anode, leading to their deposition and a rapid increase in EC in this region. Conversely, the highest EC values in the cathodic region are attributed to the formation of hydroxide ions (OH^-) during electroly-
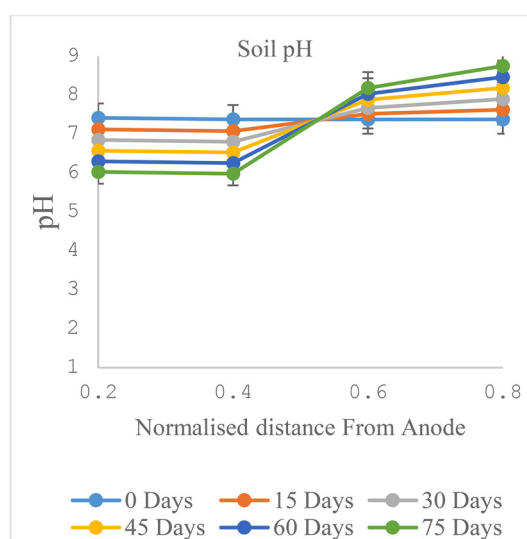
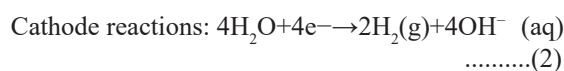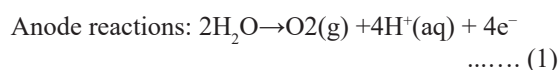sis. The highly alkaline environment in this section induces the precipitation and accumulation of cations, such as calcium (Ca^{2+}), potassium (K^+), sodium (Na^+), and magnesium (Mg^{2+}), further contributing to the increased conductivity. The lowest EC values observed in the central sections of the soil samples are a result of the rapid mobilization and migration of dissolved salts under the influence of the electrokinetic field. This phenomenon, known as electro-migration, drives these salts towards the electrodes, causing a noticeable increase in EC around the anode and cathode. Consequently, the central section's exhibit lower conductivity, particularly with an increasing electrical gradient (Singh 2022). The changes in EC during electrokinetic treatment provide valuable insights into the process. An increase in EC signifies the release of ions from the soil matrix, while a decrease suggests the successful removal of contaminants. Analyzing these EC fluctuations helps researchers evaluate the treatment's effectiveness and optimize contaminant extraction strategies.

Variation of soil pH at the end of treatment

Fluctuations in pH during electrokinetic remediation significantly impact its effectiveness. This is because pH affects both the surface charge of soil particles and the speciation of pollutants, ultimately influencing the processes of Fluctuations in pH during electrokinetic

remediation significantly impact its effectiveness. This is because pH affects both the surface charge of soil particles and the speciation of pollutants, ultimately influencing the processes of electromigration and electroosmosis. For instance, acidic pH levels can mobilize heavy metals, while alkaline conditions can immobilize them. Therefore, careful monitoring and adjustment of pH are crucial for optimal contaminant removal. Typically, pH variations during the process show a consistent trend: a decrease near the anode and an increase near the cathode (as illustrated in Fig. 6). This pattern is linked to the electrokinetic processes within the soil, which induce several complex phenomena, including the electrolysis of the pore solution. These reactions lead to oxidation and the formation of an acidic front at the anode, while reduction at the cathode results in the formation of a basic front, as depicted in Equations 1 and 2.

Anode reactions: $2H_2O \rightarrow O2(g) + 4H^+(aq) + 4e^-$
$$\text{...…… (1)}$$

Cathode reactions: $4H_2O + 4e^- \rightarrow 2H_2(g) + 4OH^- \ (aq)$
$$\text{..........(2)}$$

The generation of H+ ions reduce soil pH, while the production of OH− ions increases the medium's alkalinity. Consequently, the soil pH profile exhibits a marked decrease at the anode, reaching a value of 6 during the electrokinetic experiment. Notably, near the anode, soil pH decreased significantly, ranging from the initial value to as low as 2.7. This low pH facilitates enhanced desorption and dissolution of confined salts, thereby improving their leachability from soil surfaces and ensuring better removal. Conversely, the increased generation of OH− ions during the electrokinetic experiment causes a substantial rise in soil pH at the cathode, reaching values as high as 8 within 75 days. In areas near the cathode, the soil alkalinity increases by 1.5 units from its initial value. This increase induces salt precipitation. Moreover, the enhanced electric potential gradient, coupled with electro-migration and electro-osmosis, drives the migration of ionic complexes like NaOH, KOH, $Ca(OH)_2$, and $Mg(OH)_2$ into the catholyte, further increasing the cathodic pH. These findings demonstrate that the electrokinetic experiment enhances electrolysis in the anolyte and catholyte chambers, augmenting acidity and alkalinity in these regions, respectively (Mishra *et al.* 2024). However, the advancement of the acid front remains limited to the section immediately adjacent to the anode, despite the contribution of electro-migration, electro-osmosis, and the higher ionic mobility of hydrogen ions compared to hydroxide ions. The lowest recorded pH value remained at 6, confined to the area near the anode. Alkalinity persists in all tests due to three primary factors: the inherently alkaline nature of the soil sample (pH = 8.7), its high buffering capacity, and the abundance of hydroxide complexes, such as NaOH and KOH, which act as strong bases. These factors collectively inhibit and neutralize H+ ion migration, hindering the advancement of the acid front. Previous research supports the significant role of alkaline anions, including OH−, CO_3^{2-}, HCO_3^-, and $Al(OH)_4$, in augmenting soil buffering capacity (Xue *et al.* 2016, Zhu *et al.* 2017). Additionally, the high salinity significantly compresses the double diffuse layer (DDL), profoundly influencing the movement of the acid front (Mosavat *et al.* 2012).

CONCLUSIONS

Electrokinetic soil remediation experiments revealed significant pH and electrical conductivity (EC) fluctuations, directly influencing the remediation process. Anode proximity exhibited pH reduction due to proton (H+) generation from water electrolysis, creating an acidic environment. Conversely, the cathode area experienced increased pH from hydroxide ion (OH−) production, resulting in an alkaline region. This pH gradient significantly impacted contaminant mobility and speciation, with metals demonstrating higher mobility in acidic zones and potential precipitation in alkaline areas. Initially, EC increased as ionic species, including contaminants and electrolysis byproducts, migrated under the applied electric field. However, EC gradually decreased in areas with ion depletion or precipitation. These dynamic pH and EC changes are critical for effective contaminant removal, influencing both electroosmotic flow and contaminant solubility. Therefore, managing pH and EC during electrokinetic remediation is crucial for optimizing contaminant transport and enhancing overall treatment efficacy.

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