

Application of a Vertical “Electric Sieve” to Mitigate and Prevent Salinization in Coastal Soil

Yuehua Li¹, Lin Zhao¹, Menglu Huang¹, and Liang Chen¹

¹Tianjin University

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Abstract

This study explored the application of a Vertical Electrokinetic system (V-EK) with multilayer electrodes in shallow soil to form an “Electric Sieve” to mitigate and prevent the soil salinization caused by salts rising from shallow groundwater in the coastal areas. In the model V-EK system, the electric resistances of soil column, reversely corresponding to salinity, at the applied voltages 4, 10 and 20 V were 266, 487 and 1272 Ω , respectively. Meanwhile, lower electrical conductivity (EC, between 67-230 $\mu\text{S}/\text{cm}$) were observed in the soil within 50 cm below the surface at the voltages of 10 V and 20 V, which was much lower than the minimum value (581 $\mu\text{S}/\text{cm}$) of the control with no current applied. For the control column without EK treatment (0 V), soil in the surface layer had the highest EC value at 1721 $\mu\text{S}/\text{cm}$ due to the salts rising from the bottom, and the EC values of soil beneath the surface were in the range of 581-1127 $\mu\text{S}/\text{cm}$. Compared to control column, the level of ions in the surface soil significantly declined after V-EK treatment, especially for the column with voltage at 10 V and 20V. When voltage was at 20 V, Na^+ was detected at a range of 0.06-0.08mg/g in the surface soil, a >99% reduction when compared to the controls. Similar efficacy was observed for chloride (Cl^-), in the V-EK column with the voltages at 10 V and 20V.



School of Environmental Science and Engineering

135#, Yaguan Rd.,

Haihe Education Park, Tianjin 300350 PRC

Tel. +86-15802213082

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Dear Editor of *Land Degradation & Development* :

Please consider our manuscript “*Application of a Vertical “Electric Sieve” to Mitigate and Prevent Salinization in Coastal Soil*” for publication in the *Land Degradation & Development*.

Soil salinization is a key soil degradation factor in the worldwide, especially in the coastal areas. In coastal areas, landscaping is enormously restricted due to its higher soil salinity, and this low vegetation cover in coastal areas could lead to a fragile ecosystem for coastal saline land. Therefore, to find an effective and economic salt controlling technology for this kind soil with low permeability porous media is a challenge, where re-salinization is easily happened because of the continuous supplement of salts from the shallow saline phreatic water and sea.

In this study, a Vertical Electrokinetic system (V-EK) with multilayer electrodes was considered as an “Electric Sieve” were proposed to mitigate and prevent the surface soil salinization caused by salts rising from shallow groundwater in coastal area were explored. Different to the traditional perspective of saline soil restoration that used the horizontal electrical field configurations to transfer contaminants to both side of electrodes in combination with the saturated water conditions or irrigation, we focus on the mitigation and inhibition of the salt rising from shallow groundwater by the vertical EK system with multilayer electrodes, which could be considered as an “Electric Sieve”. The results showed that different salts rising from shallow

groundwater were effectively inhibited under the V-EK system. Moreover, it will be energy saved if the power was produced by solar.

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Prof. Zhiyong Jason Ren, Princeton University, Email: zjren@princeton.edu

Prof. Patricia J.S. Colberg, University of Idaho, colberg@uidaho.edu

Prof. Qiang Xue, China University of Geosciences (Beijing), xueqiang@cugb.edu.cn

Dr. Hongwen Yu, Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, yuhw@iga.ac.cn

Dr. Ahmed Abou-Shady, Water Resources and Desert Soils Division, Desert Research Center, shady-desert@yahoo.com

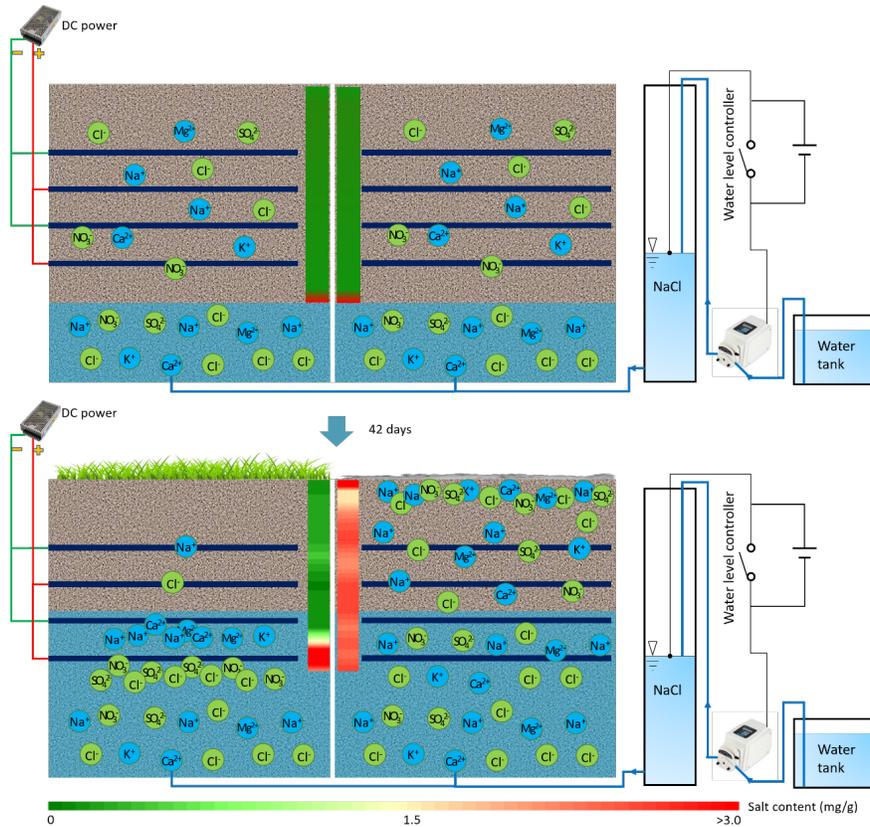
We believe this work meets the requirements for publication in *Land Degradation & Development*. Your careful consideration of this manuscript is greatly appreciated. Please feel free to contact me if there are any questions.

Yours sincerely,

Liang Chen, Ph.D.

Associate Professor

Graphic abstract?



Highlights:

- A novel vertical electrokinetics (V-EK) system with multilayer electrodes was used to mitigate and prevent soil salinization
- The V-EK system in salty soil serves as an “electric sieve” to block salts
- The salinity of soil can be well mitigated and prevented by the V-EK system
- The highest Na^+ and Cl^- inhibition rates reached >99% and >97%, respectively, at a voltage of 10-20 V
- The V-EK design could offer a cost-effective and sustainable tool for preventing upward migration of salt

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YueHua Li^{a, b}, Lin Zhao^{a, b, c}, MengLu Huang^{a, b}, Liang Chen*^{c, d}

^a School of Environmental Science and Engineering, Tianjin University, Tianjin 300072, China

^b Tianjin Engineering Center for technology of Protection and Function Construction of Ecological Critical Zone

^c State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin 300072, China

^d School of Civil Engineering, Tianjin University, Tianjin 300072, China

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Corresponding author: Liang Chen

Liang Chen

School of Civil Engineering, Tianjin University, Tianjin 300072, China

E-mail: liangchen@tju.edu.cn

Abstract: This study explored the application of a Vertical Electrokinetic system (V-EK) with multilayer electrodes in shallow soil to form an “Electric Sieve” to mitigate and prevent the soil salinization caused by salts rising from shallow groundwater in the coastal areas. In the model V-EK system, the electric resistances of soil column, reversely corresponding to salinity, at the applied voltages 4, 10 and 20 V were 266, 487 and 1272 Ω , respectively. Meanwhile, lower electrical conductivity (EC, between 67-230 $\mu\text{S}/\text{cm}$) were observed in the soil within 50 cm below the surface at the voltages of 10 V and 20 V, which was much lower than the minimum value (581 $\mu\text{S}/\text{cm}$) of the control with no current applied. For the control column without EK treatment (0 V), soil in the surface layer had the highest EC value at 1721 $\mu\text{S}/\text{cm}$ due to the salts rising from the bottom, and the EC values of soil beneath the surface were in the range of 581-1127 $\mu\text{S}/\text{cm}$. Compared to control column, the level of ions in the surface soil significantly declined after V-EK treatment, especially for the column with voltage at 10 V and 20V. When voltage was at 20 V, Na^+ was detected at a range of 0.06-0.08mg/g in the surface soil, a >99% reduction when compared to the controls. Similar efficacy was observed for chloride (Cl^-), in the V-EK column with the voltages at 10 V and 20V.

Keywords: Chloride, Electrodes; Electrokinetics; Salinity, Coastal area

Introduction

Soil salinity is one of the main reasons for soil degradation that has drawn wide attention under the background of global change, brings about an environmental issue of worldwide significance (Bessaim et al., 2019; Mao et al., 2016; Li 2018; Wang et al., 2018; Hamdan et al., 2014). At the world level, saline soil extends over all the continents including Africa, Asia, Australasia, and America (Yan et al., 2013; Litalien & Zeeb, 2020). General statistics estimates that 7% of the earth’s continental surface area (Rengasamy, 2006; Cho et al. 2010), and at least 20% of arable soil and half of the uncultivated soil in the world are affected by

varying levels of salts (Klouche et al., 2020; Nouri et al., 2017; Long et al., 2016; Scudiero et al., 2016; Cho et al. 2010). Coastal area is one of the main areas affected by soil salinity under the comprehensive action of human and natural factors, which is formed by the marine and terrestrial sedimentation and directly associated with seawater intrusion (He et al. 2015; Li et al., 2014). Besides, 70% of the world population concentrated in coastal areas (Fan et al., 2018; Hamdan et al., 2014), and this make a huge and continuously increasing demand for landscape re-construction in urban and peri-urban. However, landscaping is enormously restricted in coastal soils, due to the high salinity, and low vegetation cover lead to a fragile ecosystem for coastal saline land.

In coastal characterize by low elevation and flat terrain, global warming makes evaporation more intense as well as sustained sea level rise, which aggravates salinization (Xie et al., 2019; Yu et al., 2014; Xu et al., 2020). Meanwhile, evaporation causes the continue rise of capillary water from saline phreatic, which is one of the main reasons for increasing salinity in coastal area (Lou et al. 2018; Chi et al., 2019). To mitigate and prevent the soil salinization, many conventional remediation methods had been investigated and applied, including soil substitution, soil drainage, irrigation, chemical amendments and salt-accumulating plant (Yang et al., 2018; Kim et al. 2010; Choi et al. 2012; Jo et al. 2015; Li et al. 2016). However, most have failed mainly due to freshwater shortage (Fei et al. 2018; Liu et al. 2018), higher cost (Chen et al. 2015), longer reclamation time (Sun et al. 2017; Jo et al. 2012) and not environmentally sustainable (Chen et al., 2019). Additionally, fine-grained soil in coastal areas render remediation work more difficult. To find the effective and economic salt remediation for this kind soil with low permeability porous media is a challenge, especially in coastal area where re-salinization is easily happened because of the continuous supplement of salts from the shallow saline phreatic water and sea (Qadir et al. 2000; Chi et al., 2019; Fan et al., 2018; Yu et al., 2014; Walter et al., 2018).

As an innovative, sustainable and inexpensive technology, Electrokinetic (EK) has considerable potential for the remediation of saline soils with low permeability. Cho et al. (2010) utilized EK to achieve a removal efficiency of 99 and 95% for nitrate and chloride ions, respectively; and Kim et al. (2010) reached a removal efficiency of 100% for sodium and 58% for chloride ions from tidelands. Similar result obtained by Lee et al. (2012) that Na⁺ and Cl⁻ were easily removed from the soil (>97%) by electromigration During 1 or 2 weeks and the ions such as chloride, sodium, and nitrate were reduced to over 90% after in situ EK process applied to two ridges in a greenhouse for growing chrysanthemum (Choi et al., 2012). By using EK, Kim et al. (2013) observed that the removed cations from saline soils (EC = 13.7 dS/m) including Ca²⁺, Mg²⁺, K⁺, and Na⁺ were 19.5%, 34.4%, 58.9%, and 89.6%, respectively; and the removed anions including Cl⁻, NO₃⁻, and SO₄²⁻ were 47.9%, 91.5%, and 67.6%, respectively. Klouche et al. (2020) achieved removal rates of 83% and 58% for sodium and calcium ions, respectively after 15 days of EK treatment. Generally, the EK removal of including Na⁺, NO₃⁻, and Cl⁻ removal were quite high compared to the EK removal of Ca²⁺, Mg²⁺, and SO₄²⁻ (Abou Shady, 2016; Choi et al., 2012; Kim et al., 2012; Kim et al., 2013). Besides, the percentage reduction of EC was found to be 87% (64 days), 73-83% (60 days), and 64-90% (1 or 2 weeks), as noticed by various EK cases (Lee et al., 2011; Choi et al., 2012; Lee et al., 2012).

For EK remediation, two key factors including the electrode materials and the distance between electrodes are always significantly considered due to the corrosion resistance of electrode materials and the removal efficiency and limitations of EK. Copper, iron, titanium, stainless steel, graphite, platinum and some inert metal coating materials are commonly used electrode materials that accepted by the cost effective or the corrosion resistance (Table S1). Generally, corrosion reactions occur at the anode together with electrolysis reaction. Materials such as Cu and Fe could be oxidized and dissolved that results in the introduction of corrosive products into the soil. Thus, these materials may not be suitable for long-term applications (Jia et al., 2005). Meanwhile, the spacing between electrodes correlated with the process efficiency and the cost, the voltage gradient of 1 V/cm is usually used if both removal rate and energy are considered (Cho et al., 2012).

However, the electrode configurations should be seriously considered during the application of EK. Hamdan et al (2014) discussed electrode configurations influence the active area of the electric field, suggested that 2D

electrode configuration has a smaller inactive electric field area than a 1D electrode configuration. Zhang et al (2010) applied both horizontal and vertical electric fields and found it significantly effective when prevent Cr (VI) from migrating downward. In coastal areas, shallow groundwater makes salt rise to surface by capillary water continually, render most remediation methods unsustainable. Moreover, the low permeability of soil makes salt difficult move downwards when using irrigation related techniques.

Therefore, Vertical Electrokinetic system (V-EK) with multilayer electrodes was considered as an “Electric Sieve” were proposed in this work to mitigate and prevent the surface soil salinization caused by salts rising from shallow groundwater in coastal area, and the influences of electric action on salt transport in aquifer - vadose zone system were explored. Different to the traditional perspective of saline soil restoration that used the horizontal electrical field configurations to transfer contaminants to both side of electrodes in combination with the saturated water conditions or irrigation, we focus on the mitigation and inhibition and of the salt rising from shallow groundwater by the vertical EK system with multilayer electrodes, which could be considered as an “Electric Sieve”.

Materials and Methods

2.1 Soil and NaCl solution

The soil used in this study was collected near a coastal area in Tianjin, China. After the air drying of the soils, the blocks were crushed and then screened by 1-mm sieve and mixed uniformly afterwards before the experiment. And 10 g/L NaCl (99.5%, Tianjin Yuanli chemical co. LTD, China) solution was prepared with deionized water to simulate groundwater.

Table 1 Physico - chemical properties of the soil

Physico-chemical properties	Physico-chemical properties	value
Soil constitution	clay content (%)	32
	Quartz (%)	30
	Potassium feldspar (%)	5
	Plagioclase (%)	18
	Calcite (%)	5
	Dolomite (%)	5
	Hornblende (%)	5
Cation (1:5) (mg/L)	Na ⁺	14.06
	K ⁺	0.97
	Ca ²⁺	5.70
	Mg ²⁺	1.59
Anion (1:5) (mg/L)	Cl ⁻	2.14
	NO ₃ ⁻	4.79
	SO ₄ ²⁻	10.03
electrical conductivity (1:5, μ S/m)	electrical conductivity (1:5, μ S/m)	106
pH	pH	9.24

2.2 Experimental Design

A schematic diagram of experimental setup was shown in Fig. 1, composed by a PVC pipe column with the inner dimension of 75 mm, and a direct current power source. At the bottom of the soil column, 8~10 mm grain diameter of gravel was loaded with a thickness of 15 cm to simulate a groundwater aquifer while ensuring uniform water retention at the bottom of the column. Above gravel, a volume-weight of 1.4 g/cm³ of soil were filled, and a piece of non-woven fabrics was set between gravel and soil to prevent the entering of soil into gravel layer. Multilayer electrodes in each column consist of four electrodes that were electrode A (E_A), electrode B (E_B) electrode C (E_C) and electrode D (E_D) as shown in Fig. 1 with the electrode

spacing is 20 cm. E_A and E_C are connected to the positive pole of the power supply, while E_B and E_D are connected to the negative pole of the power supply. The multilayer electrodes were made by the titanium belt within two pieces carbon fiber. A water inlet was installed at the bottom of the column connected to saline water with rubber hose. The stable water level (fluctuated in ± 1 cm) was maintained by a water level controller (HHY7G, JYB-714G, XinLing Electric Co., Ltd, China), which connected with a peristaltic pump and a water tank.

In each test, four columns were set, and each water inlet of soil column were connected to saline water with T-junction to ensure at the same water level. Voltages of 0, 4, 10, 20 V were provided to the four columns respectively. The initial water level was controlled at -90 ± 1 cm, and then raised at a rate of 1-2 cm per day to -50 cm. The current of the soil during the water level rises was monitored continually. When the experiment finished, the soil was sampled in different layers (L1-L15) to measure the water content, electrical conductivity, pH and the concentration of anion and cation in soil.

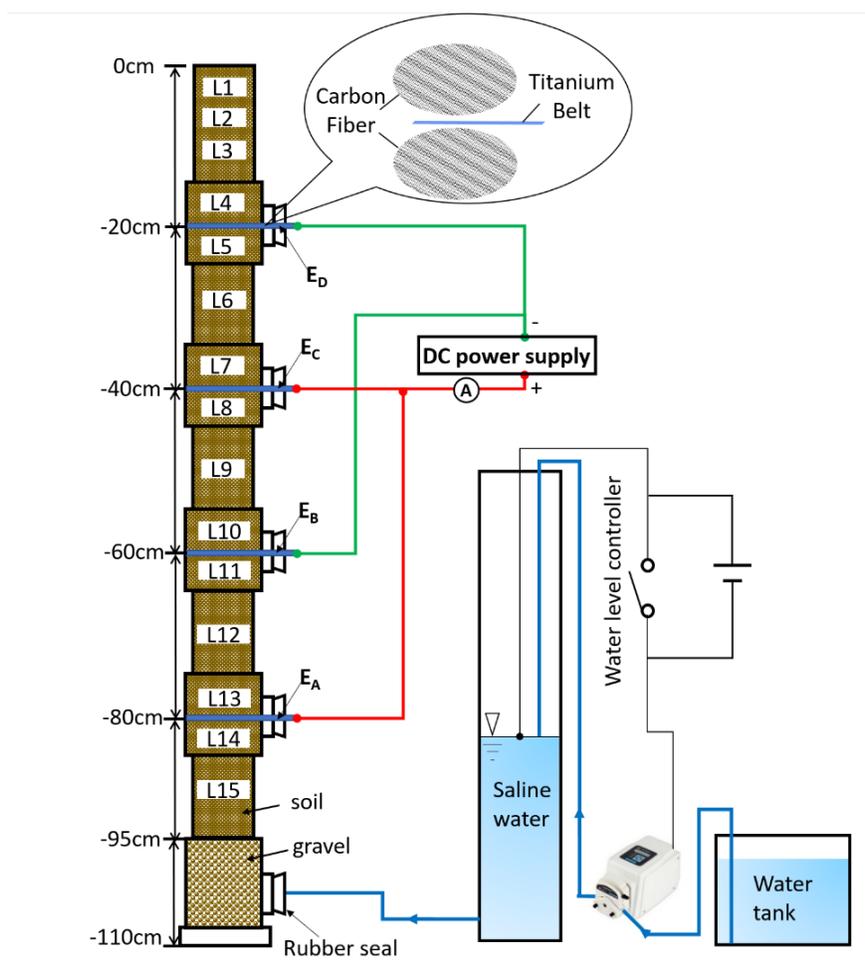


Fig.1 Schematic diagram of experimental setup

2.3 Analysis Method

The current through soil was read by the connected ammeter (Pro'sKit, Shanghai, China) each day.

Soil moisture was determined by weighing the wet soil and dry soil. When the test stopped, about 50 g of soil were collected from the soil column at different locations, weight the mass recorded as m_1 . Afterwards,

drying them in the oven (105 , 101-2AB, Tianjin Tester Instrument Co. Ltd, China), continuously weight the dry soil weight and records it as m_2 when the weight values stabilized. And the soil moisture calculated by:

$$\vartheta = (m_1 - m_2) / m_2 \times 100\%$$

where ϑ is the soil moisture (%), m_1 is the mass of wet soil (g), m_2 is the mass of dry soil (g).

Sampled dry soil 5.00 g in 50 ml bottles with 25 ml deionized water before shaken 30 min at 20 ± 1 (200 r/min, QE-1, Tianjin Aunuo Instrument & Meter Co. Ltd, China). Supernatant solution was collected after centrifuged for 30 min (3000 r/min, TGL-16M, HuNan XiangYi Centrifuge Instrument Co. Ltd, China). EC were detected using supernatant solution by Conductivity meter (LAQUA EC-33, Horiba Corporation of Japan). Remaining supernatant solution filtered through 0.45 μm membrane before cations (Na^+ , K^+ , Ca^{2+} , Mg^{2+}) and anions (Cl^- , NO_3^- , SO_4^{2-}) detections using ion chromatography (YC3000, Qingdao Ailun General Technology Co., Ltd, China). The volume of injection was 10 μl , and the method detection limit were as follows: Na^+ : 0.011 mg/L, K^+ : 0.011 mg/L, Ca^{2+} : 0.022 mg/L, Mg^{2+} : 0.011 mg/L; Cl^- : 0.007 mg/L, NO_3^- : 0.0167 mg/L, SO_4^{2-} : 0.0187 mg/L. Similar as the above preparation of supernatant except the ratio of soil and water was 1:2.5. Then the value of pH was detected by pH meter (LAQUA pH-22, Horiba Corporation of Japan).

Results and discussions

3.1 The Variation of Current and Calculated Resistance

The EK process involves the construction of an electrical field within the salty soil and leads to the generation of electrical potential, which caused the movement and the migration of ionic species and induces the changing of electrical current (Kim et al., 2011). Meanwhile, soil resistivity is a comprehensive characterization of soil physical properties, which is correlated with soil salinity, moisture, porosity, saturation, permeability coefficient, etc. (Beck et al., 2011; Chang & Cheng, 2007). Therefore, the resistance of soil columns (R) were calculated in this study by Ohm 's Law ($R=U/I$) to reflect the changing of soil salinity.

The calculated resistances across the salty soil column as a function of the duration of the treatment under different applied voltages as the water level raised gradually are shown in Fig. 2. The variations of the electrical current across the column are shown in Fig. S1. Results indicated that the electrical current in all columns were increased to the maximum value of 27 mA, 68 mA and 114 mA in the first few days with the voltage at 4 V, 10 V and 20 V, respectively. Then declined sharply and kept at the range of 8-26 mA, 20-34 mA, 13-38 mA, respectively. The final electrical current in the soil with the voltage at 4V, 10V and 20V were 14 mA, 20 mA and 16 mA, respectively, and showed in the order of 10 V > 20 V > 4 V. Similarly, the calculated resistances of soil were reduced to the minimum value at 137 Ω , 135 Ω and 164 Ω after few days under the application of voltage at 4 V, 10 V and 20 V, respectively, then showed a slow increasing trend. The final calculated resistances of soil with the voltage at 4 V, 10 V and 20 V were 266 Ω , 487 Ω and 1272 Ω , respectively, and showed in the order of 20V > 10V > 4V.

The similar trends have been observed in previous studies (Klouche et al., 2020; Bessaim et al., 2019). As capillary water gradually raised, the electric gradient was established. Simultaneously, desorption and mobilization of ions from soil generate the liberation of free charged ionic species, result reduction of the salty soil column resistance and therefore raising the current intensity (Cameselle and Reddy 2012; Wu et al. 2015). Moreover, the generations of hydrogen and hydroxide ions during the pore fluid water by electrolysis may also another reason for the above phenomenon in the first few days (Bahemmat et al. 2015). The specific process included the charged ions in the soil media moved towards the electrode of opposite charge by electromigration and the pore water moved towards the cathode by electro-osmosis (Bahemmat et al., 2015; Li et al., 2014). Since water is the necessary medium for the movement of ions, soil moisture plays a very important role in V-EK process, a low degree of soil moisture increases the electrical resistance of the soil. The final soil moisture at different conditions were shown in Fig. S2. High resistance of soil reduces the efficiency of the process drastically, thus reduces the EK effects and most of the charged energy will be

lost as heat (Fahadani et al., 2018). The resistance of soil with voltage at 20 V is about three times than that of soil with voltage at 10 V. It proves that why maximum electrical current was observed in soil with voltage at 10 V.

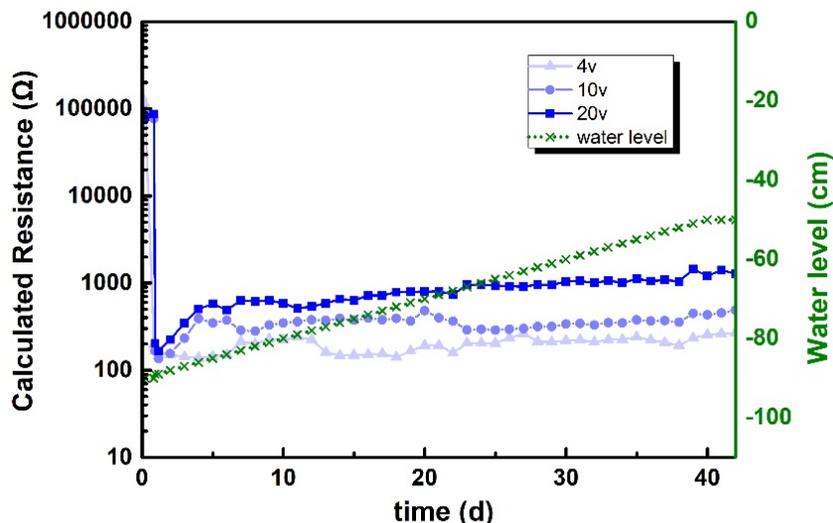


Fig.2 The variation of Resistance with time as the water level raised

3.2 The Distribution of Electrical Conductivity

Electrical Conductivity (EC) is a relevant parameter concerned about the salt accumulation in soil specimen (Bessaim et al., 2019). The distribution of EC across the soil column after the V-EK treatment is illustrated in Fig.3. For the control column that without EK treatment (voltage = 0 V), the soil in surface layer (> -15cm) has the highest EC value at 1721 $\mu\text{S}/\text{cm}$ due to the salt rises from the bottom, and the EC values of salty soil under the surface were in the range of 581-1127 $\mu\text{S}/\text{cm}$. With V-EK treatment, the lower values of EC were observed in the soil within 50 cm below the surface with the voltage at 10 V and 20 V, reached to a value of 67-230 $\mu\text{S}/\text{cm}$, which was much lower than the minimum value (581 $\mu\text{S}/\text{cm}$) in control column. Besides, the other lower values of EC were found between E_A and E_B (electrodes located at the -80cm and -60cm respectively) with range of 93-134 $\mu\text{S}/\text{cm}$, and this is attributed to the transport and movement of ionic compounds toward the electrode of opposite charges by EK processes under the applied electrical field (Jayasekera & Hall, 2007; Cho et al. 2010; Zhu et al. 2016). Thus, the higher EC values were appeared near E_A and E_B . And another reason for this was the generation of ions by electrolytic around E_A and E_B . It can see from the pH changes of around E_A and E_B (Fig. S3). Additionally, EC value around E_A is higher than E_B due to the production of H^+ at anode, which is very conductive and migrate 1.8 times faster than OH^- (Bessaim et al., 2019b). The conclusion is that ions were mitigated effectively under V-EK treatment, especially at the voltage of 10V and 20V.

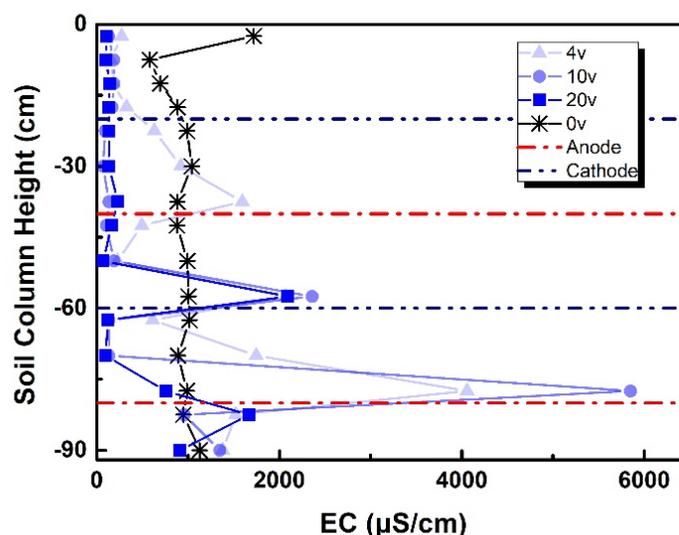


Fig.3 Distributions of EC after V-EK treatment

3.3 The Distributions of Different Ions

3.3.1 Cations

During the application of EK process, electromigration and electroosmosis were two main mechanisms (Klouche et al., 2020). Electromigration results in the migration and movement of ionic compounds, while the electroosmosis mechanism is drive the flow of water along with solutes from anode to the cathode. Fahadani et al (2018) noticed that at low contamination, the dominant phenomenon in migrating the contaminations is electromigration process, and in case of high contamination, the electroosmosis process is dominant.

Fig.4 and Fig. S4 shows the concentration distributions of cations include Na^+ (exogenous added ion), K^+ , Mg^{2+} and Ca^{2+} in different soil layers after V-EK treatment. For control column (applied voltage = 0 V), the Na^+ concentration decreases from the bottom up but accumulates in the surface layer. It is because the ion exchange reaction that displacement of Ca^{2+} and Mg^{2+} from a soil adsorption complex by Na^+ resulting in the loss of Na (Sun et al., 2012; Kim et al., 2010), and this can be seen from the increase tendency of Ca^{2+} and Mg^{2+} .

Even so, the maximum increasement percentage of Na^+ , K^+ , Ca^{2+} and Mg^{2+} were 1528%, 318%, 2182% and 2451% respectively compared with the initial value of soil.

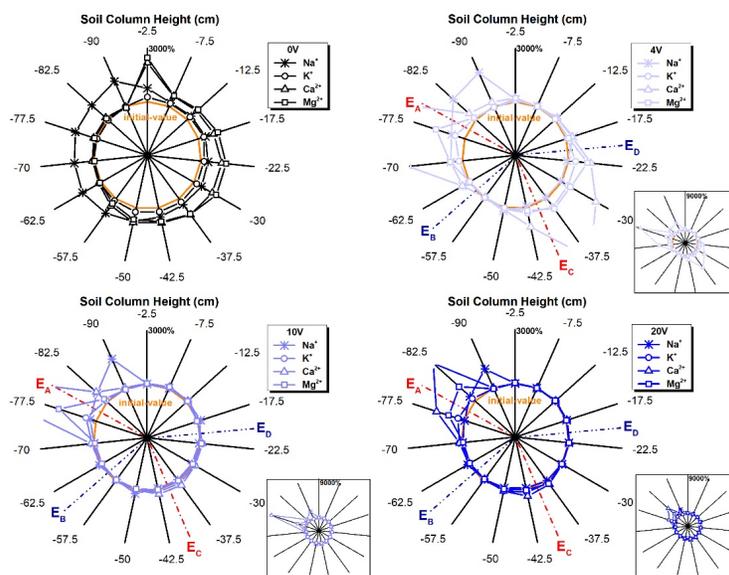


Fig. 4 Variations of cations at different voltage compared to the initial value

Na^+ control for planting soils is critical because Na^+ has a dispersive effect on soil particles and prevents root penetration (Amini et al., 2016). The highest Na^+ decrements ($>99\%$) in soil column were found between E_B (electrode located at -60 cm) and E_C (electrode located at -40 cm) after V-EK treatment, which reduce the source ions that would rise to the surface. Moreover, the concentration of Na^+ ions after V-EK treatment were significantly lower than the control column. For the soil with voltage at 20 V, the lower concentration of Na^+ was detected with a range of 0.06 - 0.08 mg/g at the surface soil compared to the control column (0.21 - 0.60 mg/g). This is due to the combined process of the high ionic mobility of Na^+ under the electrical field and soil ion exchange (Klouche et al., 2020; Lee et al., 2012).

Variations of K^+ , Ca^{2+} and Mg^{2+} were calculated compared with the control column under different voltage system (4 , 10 , 20 V). There was no obvious change of K^+ in Fig.4 and Fig.S4, which may be due to its low level. And the other two ions in the surface soil (>-15 cm) reached the decreased percentage of 70 - 96% and sustained at low concentration. Moreover, between E_B and E_D (-20 - -60 cm), it observed that ions were also significantly declined, except Ca^{2+} under the condition of 4 V. Further, Ca^{2+} and Mg^{2+} had significant increase tendency below -60 cm, reached max percentages of 3163% and 1018% . The OH^- produced by the cathode (E_B) migrated to E_A and formed alkaline environment, leads to the precipitation of ionic compounds, thus reducing their ionic mobility and accumulated around E_A (anode at -80 cm, Klouche et al., 2020).

From the figure, Ca^{2+} shows the most obvious variation compared with the other three ions after V-EK treatment, the maximum increment of Ca^{2+} were reached 8035% , 8568% and 3154% at applied voltage of 4 V, 10 V and 20 V respectively. Since Ca^{2+} was an endogenous ion, which conclusively that the increase come from the soil alone. And the result proved that V-EK treatment increases the content of Ca^{2+} , which was believed from solubilization of minerals that inside the soil due to the acid environment produced by the anode. Because the increasement of Ca^{2+} at different voltage was positive correlation to the change in pH (Fig. S3), which also related to the intensity of the current.

3.3.2 Anions

Fig.5 and Fig.S5 illustrates the distributions of Cl^- (exogenous added ion), SO_4^{2-} , NO_3^- concentrations in different soil layers after V-EK treatment. For control column (applied voltage = 0 V), the Cl^- , SO_4^{2-} and NO_3^- concentrations increases from the bottom up and accumulates in the surface layer owing to the

evaporation especially for Cl^- and NO_3^- . However, there was no accumulation of SO_4^{2-} observed at the top surface. The reason for this was considered that sulfate tends to form insoluble CaSO_4 , which may decrease its migration (Kim et al., 2012).

For V-EK tests, Cl^- decreased >97% compared with control column at the voltage of 10 V and 20 V, and mainly accumulated around E_A (electrode located at -80 cm). The maximum concentration values of Cl^- around E_A were reached 8.4mg/g, 5.8mg/g and 2.7mg/g at the voltages of 4V, 10V and 20V, respectively. The concentrations of Cl^- were detected with a range of 0.01-0.02 mg/g and 0.02-0.06 mg/g at the surface soil with the voltage at 20V and 10V respectively, while the concentrations of Cl^- were 0.84-2.70 mg/g in control test. Results indicated that Cl^- upward migration from shallow groundwater were effectively mitigated and prevented at the applied voltage of 10V and 20V. Moreover, Cl^- displayed the most obvious difference between control and V-EK treatment. The increments of Cl^- were range from 1095% to 3901% at control column. While the maximum increment of Cl^- were 11887%, 8233%, 3724% occurred around anode at the applied voltage of 4V, 10V and 20V respectively. The result showed that Cl^- could be better mitigated by V-EK treatment test as applied voltage increase.

For NO_3^- , ions migrated to anode and settled around it (Choi et al., 2009), which was mostly influenced by the developed pH gradient due to electrolysis (Edi et al., 2000). The concentration at the surface after V-EK process were much lower (0.02 mg/g at 20V and 0.04 mg/g at 10V) than the control column (0.54 mg/g). Additionally, SO_4^{2-} were also well mitigated and prevented above -40 at the applied voltage of 10 and 20V. With voltage at 20 V, the decrement rate of SO_4^{2-} were at the range of 57%-75%. As can be seen from the above, the salts upward migration from shallow groundwater were effectively mitigated and prevented at the applied voltage of 10 V and 20 V, but less effective at 4 V.

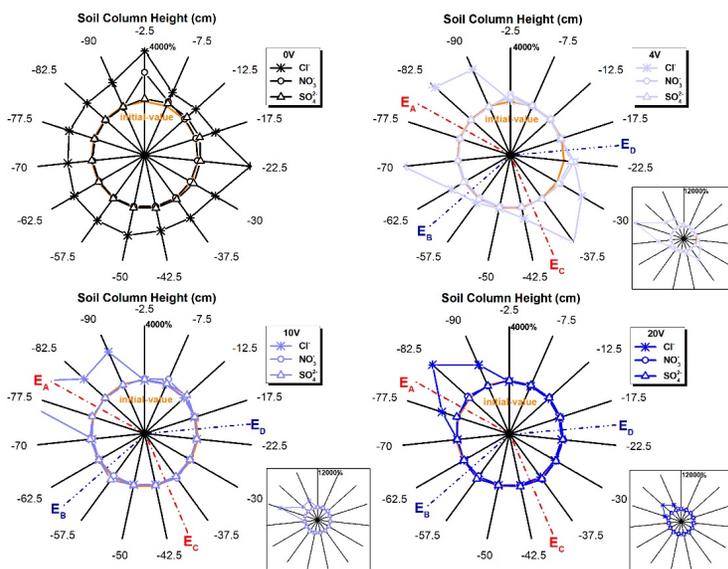


Fig. 5 Variations of anions at different voltage compared to the initial value

Conclusions

Soil salinization is becoming a seriously global ecological and environmental problem and has drawn wide attention. In this study, the Vertical Electrokinetic system (V-EK) with multilayer electrodes considered as an “Electric Sieve” was used to mitigate and prevent the soil salinization caused by salts rising from shallow groundwater in coastal area. After the addition of direct current, the final calculated resistances of the soil column under the voltage at 4V, 10V and 20 V were 266, 487 and 1272 Ω , respectively, and showed

in the order of $20\text{ V} > 10\text{ V} > 4\text{ V}$. The low values of EC ($67\text{-}230\ \mu\text{s}/\text{cm}$) were observed in the soil within 50 cm below the surface with the voltage at 10 V and 20 V, which was much lower than the minimum EC value ($581\ \mu\text{s}/\text{cm}$) in control column. The results revealed that all the cations and anions in the surface soil with different voltage added were significantly declined compared to control column without current addition. The highest Na^+ decrements ($>99\%$) in soil column were found between -60 cm and -40 cm after V-EK treatment, which reduce the source ions that would rise to the surface. With voltage at 20 V, the lower concentration of Na^+ was detected with a range of $0.06\text{-}0.08\ \text{mg}/\text{g}$ at the surface soil compared to the control column ($0.21\text{-}0.60\ \text{mg}/\text{g}$). Further, Ca^{2+} and Mg^{2+} in the surface soil ($>15\ \text{cm}$) reached the decreased percentage of $70\text{-}96\%$ and sustained at low concentration. For V-EK tests, Cl^- decreased $>97\%$ compared with control column at the voltage of 10 V and 20 V, and mainly accumulated around anode (electrode located at -80 cm). The concentrations of Cl^- were detected with a range of $0.01\text{-}0.02\ \text{mg}/\text{g}$ and $0.02\text{-}0.06\ \text{mg}/\text{g}$ at the surface soil with the voltage at 20V and 10V respectively, while the concentrations of Cl^- were $0.84\text{-}2.70\ \text{mg}/\text{g}$ in control test. Results indicated that Cl^- could better mitigated and prevented by V-EK treatment test as applied voltage increase. Finally, different salts rising from shallow groundwater were effectively inhibited under the application of different voltage at 10 V and 20 V, but slightly effective was observed with voltage at 4 V. Therefore, it is believed that V-EK with multilayer electrodes considered as an “Electric Sieve” could significantly inhibit and mitigate the salts rising from shallow groundwater to surface soil and reducing the soil salinity at the same time. Positive influences of this “Electric Sieve” could be obtained on the saline soil management in agriculture and in landscape works, and even in civil engineering sectors.

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