Salt removal of greenhouse soils using electrokinetic technology

Kyunghwa Han1 · Sangjae Han2 · Eunjin Kim3 · Heerae Cho1 · Youngho Seo4 · Hyubsung Lee1 · Junghun Ok1 · Mijin Seo1 · Kangho Jung1 · Yongseon Zhang1

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Abstract Excess nutrients are easily accumulated in greenhouse soils due to the interception of rainfall by plastic film and repeated over-application of compost and fertilizers. This study was conducted to evaluate the application of electrokinetic (E/K) technology for salt removal from soils with high electrical conductivity (EC) in greenhouses. Three types of soil in plastic film greenhouses were used: artificial soil (Site A), poorly drained soil (Site B), and well-drained soil (Site C). The salt-enriched surface soils were used to fill 37-cm-long-box-type E/K cells, and a constant voltage gradient was applied at a rate of 1 V cm⁻¹ for 30 days. The decrease in soil EC was achieved with water content of greater than 30% for silt loam (Sites A and B) and 20% for sandy loam (Site C). The E/K technology decreased soil EC by more than 80%, with a greater reduction ratio for sandy loam than for silt loam. After 30 days of the E/K treatment, 98–99% of NO₃-N and 95–99% of sodium were removed in all three sites under saturated condition, implying that nitrate and sodium ions had higher mobility than the other ions during the E/K process. The results obtained from the study suggested, therefore, that the E/K technology is highly efficient for wet and nitrate-enriched sandy loam soils, and the technology can be a feasible and environmentally sound practice for the removal of excessive nutrients in greenhouse soils without water pollution by nutrients such as nitrate as can be caused by flooding and repeated washing with water.

Keywords Electrical conductivity · Electrokinetic technology · Greenhouse · Salt removal · Soil

Introduction

Farmers can increase crop productivity and economic profit using plastic film greenhouses and through multiple cropping in a year, as well as by regulation of growing conditions such as soil moisture, temperature, and air humidity [1, 2]. In terms of soil environment, the interception of rainfall and over-application of compost and fertilizers result in excess nutrients remaining in the greenhouse soil after crop harvest, consequently causing salt accumulation and high electrical conductivity (EC). The average content of available phosphate (P₂O₅) and exchangeable potassium (K) of 1334 greenhouse soils in Korea in 2012 were 1049 mg kg⁻¹ and 1.58 cmol⁺ kg⁻¹, respectively, higher than the optimum levels of 300–550 mg kg⁻¹ and 0.5–0.8 cmol⁺ kg⁻¹ [1]. As a result, soil EC was 3.1 dS m⁻¹, higher than the optimum level of less than 2 dS m⁻¹. The excess nutrients in soil eventually cause reductions in crop productivity, as well as quality deterioration through water uptake depression due to osmosis, imbalanced nutrition [2, 3], and accumulation of NO₃-N in crops [4, 5].

To reduce excess nutrient levels in greenhouse soils, numerous agricultural practices have been developed and disseminated to farmers, such as the cultivation of crops with a high nutrient absorption ability, the addition of low-
fertility soil, rotation cropping, flooding, and high-ridge establishment [2, 6–11]. However, adoption of a rotation cropping system or the cultivation of crops with a high nutrient absorption ability, such as maize, may reduce profitability, compared with cash crops such as vegetables. Application of low-fertility soil, or the removal of surface soil with high EC, may be a temporary solution and may also require labor and transportation. In addition, flooding and repeated washing with water can involve the consumption of large volumes of water and can cause contamination of water resources with nutrients such as nitrate and phosphorus. Therefore, an environment-friendly technology needs to be developed to reduce salt concentration and soil EC in greenhouse soil, without causing environment pollution.

Electrokinetic (E/K) technology has been widely applied to remediation of contaminated soils since Puri and Anand [12] used it to remove exchangeable bases from alkaline soils. It has been used on soils contaminated with heavy metals, nutrients, or organic pollutants, and also to purify water of contaminants such as radioactive materials, oils, organic pollutants, and heavy metals [13–25]. When a low-intensity direct current is applied to soil between anode and cathode, charged species produced by electrolysis [14, 26] move toward cathode or anode through E/K processes such as electroosmosis (water transport from anode to cathode [27–29]), electromigration (ion transport to the opposite electrode [14, 30–33]), and electrophoresis [34, 35]. The E/K technology can be used to effectively remove pollutants even in soils with low hydraulic conductivity [36, 37]. Thevenayagam and Wang [38] showed that cations including heavy metals around the cathode can be removed through deposition, with OH⁻ produced at cathode. The objective of this study was to evaluate the application of E/K technology in the removal of salts (excess nutrients) from greenhouse soils in Korea.

Materials and methods

Characteristics of greenhouse soils

Three types of plastic film greenhouses were selected for the study: artificial soil (Site A), poorly drained soil (Site B), and well-drained soil (Site C). Site A was located in Jinjeop-up, Namyangju-si, Gyeonggi-do, Korea; Site B in Daejeo2-dong, Gangseo-gu, Busan-si, Korea; and Site C in Gangdung-dong, Gangseo-gu, Busan-si, Korea. The soil series of Site B was Gimhae, and Site C was Nagdong. The soil series for indigenous soil of Site A was Deogcheon. The soil textures of Sites A and B were silt loam, and that at Site C was sandy loam. Soil EC and soluble ions in soil from surface to 100 cm depth were measured for soil samples taking from the three sites. The distribution of soil EC, soluble cations, and soluble anions with depth is shown in Fig. 1 for Site A, Fig. 2 for Site B, and Fig. 3 for Site C. Soil EC was high at 0–10 cm depth for the three sites, and decreased with soil depth except at Site A where another EC peak at occurred at 70 cm, the boundary of artificial and indigenous soils. Site C, which had sandy textured soil and no compacted zone, had the thinnest upper salt accumulated zone and lowest EC values below 10 cm depth of soil. The main soluble ions were Ca²⁺ and SO₄²⁻ for Site A, Na⁺ and Cl⁻ for Site B, and Ca²⁺ and NO₃⁻ for Site C.

Soil chemical properties were determined using the soil analysis method devised by the National Institute of Agricultural Science and Technology [39]. Briefly, soil pH and EC were measured after mixing soil with H₂O (1:5). After EC was measured, soluble ions were analyzed with inductively coupled plasma spectrophotometer (CINTRA6, GBC Scientific Equipment, Braeside, Victoria, Australia) and ion chromatography (DX-600, Dionex, Themo Fisher Scientific, Waltham, MA, USA) using the water extracts. Soil bulk density was determined using a core sampler.

Electrokinetic (E/K) experiments

The salt-enriched soils from upper part of each site were used for establishing the methodology of E/K technology for salt removal. The 37-cm-long-box-type cells were filled with surface soil (5 cm depth for Site A, and 10 cm for Sites B and C) from the three sites (Fig. 4). The soil water content in each cell of the E/K apparatus was set to be different, ranging from the initial state to a saturated state. A constant voltage gradient was applied at a rate of 1 V cm⁻¹ for 30 days. Soil EC and the concentration of soluble ions were determined for soils taken from five spots of each cell.

Column experiments Column experiments were performed under saturated conditions, using soils from Sites B and C. Columns with a radius of 3.63 cm and height of 3.63 cm were filled with 360 g of dried soil. The bulk density of the soil was 1.20 Mg m⁻³, and the saturated hydraulic conductivity was 0.06 cm h⁻¹ for Site B and 1.49 cm h⁻¹ for Site C. The concentrations of soluble ions and EC were measured for each effluent fraction of total five pore volume. The mobile ion ratio was obtained by comparing the total amount of each ion in effluents with the initial total amount of the soluble ion.

Results and discussion

The physical and chemical characteristics of the soils used in E/K experiments are shown in Tables 1 and 2, respectively. The initial soil moisture content was 17.3% for Site
A, 21.1% for Site B, and 6.3% for Site C. After applying an electrokinetic current, the soil pH decreased in the anode compartments to almost pH 3, whereas it increased in cathode compartments up to almost pH 12, especially under high water content conditions, when compared with the initial pH (Fig. 5). H⁺ is produced through water...
oxidation at the anode, whereas OH⁻ is produced through water reduction at the cathode [16, 18, 19, 21, 23, 24, 40, 41].

The soil EC for Site A decreased, especially for water contents greater than 30%, compared with an initial EC of 3.6 dS m⁻¹ (Fig. 6). For Site B, the soil EC decreased, except for a water content of 21%, compared with the initial EC of 15.0 dS m⁻¹ (Fig. 7). For Site C, the soil EC decreased, especially for water contents of 30 and 49%, compared with the initial EC of 11.2 dS m⁻¹ (Fig. 8). The concentrations of soluble ions for the three sites are listed in Tables 3, 4, and 5. The concentrations after 30 days of E/K treatment decreased, probably through electromigration, diffusion, and electroosmosis.

The reduction of soluble ions ranged from 74 to 99% in high soil water content, based on the contents of soluble ions at spots 2–4 except around the anode and cathode (Table 6). The highest reduction was observed for NO₃-N, followed by Na > S > Mg > K > Ca. After 30 days of the E/K treatment, 98–99% of the initial NO₃-N was eliminated for the three sites under saturated water condition. Cho et al. [40] reported that 86% of NO₃-N was removed after only 8 days of E/K treatment of a sulfate-accumulated saline greenhouse soil, whereas it took 16 days to remove...
70% of sulfates, due to their high affinity for soil organic matter, and their tendency to precipitate with Ca\(^{2+}\). Lee et al. [24] also reported that nitrate removal efficiency was greater than 90% from a greenhouse soil with a dimension of 5 by 6 m through in situ E/K process. Manokararajah and Ranjan [25] suggested that the main mechanisms for nitrate removal are electromigration toward the anode and denitrification to nitrogen gas. Choi et al. [16] conducted in situ E/K process for a greenhouse soil with a 3 m by 2 m plot and reported that removal efficiency of nitrate and chloride was greater than 80% after 30 days of the treatment, due to the easier desorption from soil particles and the higher solubility in the pore water than for sulfate. In addition, sodium showed the highest removal efficiency among the cations because of its low adsorption strength, although sodium has the lowest value of diffusion and ionic valence. Calcium and magnesium are relatively easy to adsorb to soil particles, because of their high adsorption strength and their ability to precipitate with anions such as sulfate and hydroxide [16]. Cho et al. [40] reported potassium removal of 46–68%, and magnesium removal of up to 70%, after 16 days of E/K treatment. Lee et al. [24] reported that an in situ E/K process removed 93% of

| Water content (%) | Ca  | K  | Mg  | Na  | NO\(_3\)-N | S  |
|-------------------|-----|----|-----|-----|-----------|----|
| 17                | 2   |    |     |     |           |    |
| 2                 | 246 | 53 | 66  | 4   |           |    |
| 3                 | 264 | 58 | 76  | 9   |           |    |
| 4                 | 157 | 35 | 45  | 8   |           |    |
| 5                 | 49  | 12 | 27  | 7   |           |    |
| 30                | 1   | 47 | 12  | 6   |           |    |
| 2                 | 66  | 9  | 12  | 8   |           |    |
| 3                 | 51  | 8  | 8   | 9   |           |    |
| 4                 | 75  | 16 | 12  | 31  |           |    |
| 5                 | 146 | 33 | 16  | 8   |           |    |
| 40                | 1   | 110| 5   | 33  | 2         | 52 |
| 2                 | 175 | 36 | 9   | 8   |           | 175|
| 3                 | 99  | 11 | 14  | 9   |           | 16 |
| 4                 | 101 | 10 | 13  | 3   |           | 10 |
| 5                 | 120 | 2  | 16  | 2   |           | 4  |
| 58                | 1   | 142| 4   | 14  | 2         | 5  |
| 2                 | 32  | 0  | 5   | 0   | 1         | 27 |
| 3                 | 48  | 1  | 7   | 3   | 1         | 8  |
| 4                 | 108 | 1  | 10  | 1   |           | 3  |
| 5                 | 79  | 1 | 5   | 10  | 1         | 3  |

\(^a\) Position from anode side (1) to cathode side (5) in Fig. 4
### Table 4
Concentrations (mg kg\(^{-1}\)) of soluble ions for Site B after 30 days of E/K treatment

| Water content (%) | Position\(^a\) | Ca  | K   | Mg  | Na  | NO\(_3\)-N | S  |
|-------------------|----------------|-----|-----|-----|-----|------------|----|
| 21                | 1              | 2497| 522 | 1164| 1650| 334        | 759|
|                   | 2              | 1339| 422 | 801 | 1958| 266        | 879|
|                   | 3              | 1322| 445 | 832 | 2016| 244        | 935|
|                   | 4              | 1289| 451 | 831 | 2023| 245        | 894|
|                   | 5              | 969 | 436 | 624 | 2065| 217        | 927|
| 30                | 1              | 921 | 475 | 761 | 39  | 485        | 429|
|                   | 2              | 1608| 317 | 410 | 33  | 312        | 912|
|                   | 3              | 1263| 206 | 266 | 37  | 16         | 1347|
|                   | 4              | 1495| 190 | 395 | 58  | 14         | 1672|
|                   | 5              | 132 | 424 | 14  | 2178| 4          | 232|
| 40                | 1              | 425 | 160 | 476 | 13  | 134        | 1453|
|                   | 2              | 399 | 72  | 82  | 9   | 13         | 349|
|                   | 3              | 172 | 52  | 42  | 7   | 10         | 79|
|                   | 4              | 134 | 60  | 94  | 24  | 2          | 16|
|                   | 5              | 130 | 589 | 12  | 1662| 0          | 47|
| 62                | 1              | 378 | 80  | 269 | 10  | 70         | 928|
|                   | 2              | 164 | 20  | 35  | 5   | 2          | 87|
|                   | 3              | 110 | 35  | 36  | 6   | 0          | 21|
|                   | 4              | 119 | 34  | 51  | 6   | 1          | 14|
|                   | 5              | 76  | 401 | 3   | 475 | 0          | 22|

\(^a\) Position from anode side (1) to cathode side (5) in Fig. 4

### Table 5
Concentrations (mg kg\(^{-1}\)) of soluble ions for Site C after 30 days of E/K treatment

| Water content (%) | Position\(^a\) | Ca  | K   | Mg  | Na  | NO\(_3\)-N | S  |
|-------------------|----------------|-----|-----|-----|-----|------------|----|
| 6                 | 1              | 818 | 134 | 302 | 231 | 488        | 390|
|                   | 2              | 777 | 126 | 291 | 224 | 448        | 394|
|                   | 3              | 803 | 127 | 295 | 224 | 463        | 413|
|                   | 4              | 787 | 128 | 288 | 218 | 449        | 401|
|                   | 5              | 685 | 101 | 178 | 87  | 165        | 566|
| 30                | 1              | 473 | 161 | 330 | 12  | 1314       | 529|
|                   | 2              | 643 | 85  | 131 | 21  | 22         | 669|
|                   | 3              | 702 | 114 | 219 | 148 | 302        | 441|
|                   | 4              | 319 | 53  | 112 | 36  | 2          | 355|
|                   | 5              | 72  | 65  | 35  | 239 | 2          | 12|
| 40                | 1              | 345 | 162 | 388 | 17  | 1690       | 709|
|                   | 2              | 20  | 9   | 7   | 2   | 15         | 9|
|                   | 3              | 51  | 22  | 18  | 2   | 3          | 9|
|                   | 4              | 62  | 30  | 15  | 2   | 2          | 7|
|                   | 5              | 127 | 75  | 7   | 54  | 1          | 7|
| 49                | 1              | 192 | 143 | 417 | 21  | 1181       | 816|
|                   | 2              | 28  | 7   | 11  | 3   | 21         | 26|
|                   | 3              | 40  | 13  | 14  | 2   | 2          | 9|
|                   | 4              | 76  | 27  | 20  | 4   | 1          | 9|
|                   | 5              | 155 | 61  | 4   | 11  | 1          | 10|

\(^a\) Position from anode side (1) to cathode side (5) in Fig. 4
potassium after 26 days. Site C, which had sandy loam soil, showed higher reductions than the sites with silt loam, especially for calcium and magnesium, which are more resilient to the E/K treatment. Among the silt loam soils, a higher salt reduction was shown at saturated water content than for unsaturated conditions.

For the column experiment, Fig. 9 shows changes in EC and ions in effluents as a function of pore volume. Concentrations of ions in effluents decreased to almost 0 with a pore volume of 3 for Site B with silt loam, and 1.5 for Site C with sandy loam. Nitrate and chloride showed relatively fast movement before one pore volume.

Mobile ion ratios, calculated by the total amount of each ion in effluents divided by the initial total amount of the soluble ion for column experiment, were compared with reduction percentages for the E/K experiment (Table 7). Mobile ion ratios for Site B (silt loam) ranged from 106 to 167%, greater than the reduction ratios of 85–99%. For Site C (sandy loam), E/K reduction ratios ranged from 96 to 98%, greater than the mobile ion ratios of 62–91%. Mobile ion ratios for Site B were greater than those for Site C, possibly because of the site's low hydraulic conductivity and long reaction time. Please note that saturated hydraulic conductivity for Site C was about 25 times greater than that for Site B. The results of this study indicated that the efficiency of the E/K technology is greater than that of flooding and repeated washing method for sandy loam soil.

However, electrical energy consumption can be one of the main barriers for the application of E/K process in agriculture, because it accounts for 25% of the operating cost of the technology [37]. Jo et al. [21] reported that a pulsed E/K process reduced the electrical energy consumption by 42% compared with conventional processes for the restoration of greenhouse soil. Moreover, the technology can be integrated with other remediation processes such as bioremediation, permeable reactive barriers, phosphate amendment, and phytoremediation [15, 17, 42, 43].

This study demonstrated the applicability of E/K technology to reduce excess nutrients in greenhouse soils in an environmentally friendly manner. The E/K technology decreased soil EC by more than 80% for silt loam with a water content of greater than 30% (Sites A and B), and 20% for sandy loam (Site C). After 30 days of the E/K treatment, 98–99% of NO₃-N and 95–99% of sodium were

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**Table 6**  Reduction percentage of soluble ions after 30 days of E/K treatment

| Site | Water content (%) | Ca | K | Mg | Na | NO₃-N | S |
|------|------------------|----|---|----|----|-------|---|
| A    | 40               | 74 | 77| 82 | 86 | 90    | 76|
|      | 58               | 87 | 97| 94 | 95 | 98    | 95|
| B    | 40               | 74 | 82| 82 | 98 | 93    | 83|
|      | 62               | 85 | 91| 90 | 99 | 99    | 95|
| C    | 30               | 96 | 83| 96 | 99 | 98    | 98|
|      | 49               | 96 | 86| 96 | 98 | 98    | 97|

**Table 7**  Mobile ion ratios calculated from column experiment and reduction percentage from E/K experiment

| Site | Experiment | Ca    | Mg    | Na    | S    |
|------|------------|-------|-------|-------|------|
| B    | Column     | 110   | 144   | 106   | 167  |
|      | Electrokinetic | 85  | 90   | 99   | 95  |
| C    | Column     | 91    | 79    | 62    | 65  |
|      | Electrokinetic | 96  | 96   | 98   | 97  |
removed. Therefore, E/K technology can provide a feasible and environmentally sound practice for the removal of excess nutrients from greenhouse soils. This is achieved without causing water pollution by nutrients such as nitrates, as occurs when flooding and repeated washing with water is used, especially for wet and nitrate-enriched sandy loam soils. It should be noticed that the E/K technology may enhance emissions of nitrous oxide, one of the greenhouse gases, during denitrification under wet soil conditions. Further studies are required to investigate ways to increase the salt removal efficiency and to decrease the cost and the treatment period. Nonetheless, E/K technology is currently already feasible as a method for the reduction of EC in greenhouse soils.

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References

1. Kang SS, Roh AS, Choi SC, Kim YS, Kim HJ, Choi MT, Ahn BG, Kim HK, Park SJ, Lee YH, Yang SH, Ryu JS, Sohn YG, Kim MS, Kong MS, Lee CH, Lee DB, Kim YH (2013) Status and change in chemical properties of polytunnel soil in Korea from 2000 to 2012. Korean J Soil Sci Fertil 46:6410–6646
2. Jung YS, Yoo SH (1975) Effect of watering on eluviation of soluble salts in the vinyl house soils. Korean J Soil Sci Fertil 8:53–60
3. Kang BG, Jeong IM, Min KB, Kim JJ (1996) Effect of salt accumulation on the germination and growth of lettuce (*Lactuca sativa* L.). Korean J Soil Sci Fertil 29:360–364
4. Jin SJ, Jo HJ, Jeong JB (2004) Effect of soil salinity on nitrate accumulation of lettuce. Korean J Soil Sci Fertil 37:91–96
5. Sohn SM, Oh KS (1993) Influence of nitrogen level on the accumulation of NO₃⁻ on edible parts of Chinese cabbage, red-dish, and cucumber. Korean J Soil Sci Fertil 26:10–19
6. Khoshgoftarmanesh AH, Shariatmadari H, Vakil R (2003) Reclamation of saline soils by leaching and barley production. Commun Soil Sci Plant Anal 34:2875–2883
7. Jun HS, Park WC, Jung JS (2002) Effects of soil addition and subsoil plowing on the changes of soil chemical properties and the reduction of root-knot nematode in continuous cropping field of oriental melon (*Cucumis melo* L.). Korean J Environ Agric 20:127–132
8. Kim LY, Cho HJ, Hyun BK, Park WP (2001) Effects of physical improvement practices at plastic film house soil. Korean J Soil Sci Fertil 34:92–97
9. Kim LY, Cho HJ, Han KH (2003) Effects of tile drain on physicochemical properties and crop productivity of soils under newly constructed plastic film house. Korean J Soil Sci Fertil 36:154–162
10. Kim DS, Yang JE, Ok YS, Yoo KY (2006) Effect of perforated PVC underdrainage pipe on desalting of plastic film house soils. Korean J Soil Sci Fertil 39:65–72
11. Kwak HK, Seong KS, Lee NJ, Lee SB, Han MS, Roh KA (2003) Changes in chemical properties and fauna of plastic film house soil by application of chemical fertilizer and composted pig manure. Korean J Soil Sci Fertil 36:304–310
12. Puri AN, Anand B (1936) Reclamation of alkali soils by electrodialysis. Soil Sci 42:23–28
13. Acar YB, Alshawabkeh AN, Gale R (1993) Fundamentals of extracting species from soils by electrokinetics. Waste Manag 12:141–151
14. Acar YB, Alshawabkeh AN (1993) Principles of electokinetic remediation. Environ Sci Technol 27:2638–2647
15. Choi JH, Maruthamuthu S, Lee HG, Ha TH, Bae JH (2009) Nitrate removal by electro-bioremediation technology in Korean soil. J Hazard Mater 168:1208–1216
16. Choi JH, Lee YJ, Lee HG, Ha TH, Bae JH (2012) Removal characteristics of salts of greenhouse in field test by in situ electroschismic remediation. Electrochim Acta 86:63–71
17. Couto N, Guedes P, Zhou DM, Ribeiro AB (2015) Integrated perspectives of a greenhouse study to upgrade an antimony and arsenic mine soil–potential of enhanced phytotechnologies. Chem Eng J 262:563–570
18. dos Santos EV, Souza F, Saez C, Canizares P, Lanza MRV, Martinez-Huitle CA, Rodrigo MA (2016) Application of electroschismic soil flushing to four herbicides: a comparison. Chemosphere 153:205–211
19. Eid N, Elshorbagy W, Larson D, Slack D (2000) Electro-migration of nitrate in sandy soil. J Hazard Mater B79:133–149
20. Hamed J, Acar YB, Gale RJ (1991) Pb(II) removal from kaolinite by electrokinetics. J Geotech Eng 117:241–271
21. Jo SU, Kim DH, Yang JS, Baek K (2012) Pulse-enhanced electroschismic restoration of sulfate-containing saline greenhouse soil. Electrochim Acta 86:57–62
22. Kim WS, Park GY, Kim DH, Jung HB, Ko SH, Baek K (2012) In situ field scale electroschismic remediation of multi-metals contaminated paddy soil: influence of electrode configuration. Electrochim Acta 86:89–95
23. Lee HH, Yang JW (2000) A new method to control electrolytes pH by circulation system in electroschismic soil remediation. J Hazard Mater B77:227–240
24. Lee YJ, Choi HJ, Lee HG, Ha TH, Bae JH (2011) Pilot-scale study on in situ electroschismic removal of nitrate from greenhouse soil. Sep Purif Technol 79:254–263
25. Manokararajah K, Ranjan RS (2005) Electrokinetic retention, migration and remediation of nitrates in silty loam soil under hydraulic gradients. Eng Geol 77:263–272
26. Acar YB, Gale RJ, Hamed J, Putnam G (1990) Electrochemical processing of soils: theory of pH gradient development by diffusion and linear convection. J Environ Sci Health Part A Environ Sci Eng 25:687–714
27. Casagrande IL (1949) Electro-osmosis in soils. Geotechnique 1:159–177
28. Eykholt GR, Daniel DE (1994) Impact of system chemistry on electroosmosis in contaminated soil. J Geotech Eng 120:797–815
29. Yeung AT, Datla S (1995) Fundamental formulation of electroschismic extraction of contaminants from soil. Can Geotech J 32:569–583
30. Holmes PJ (1962) The electrochemistry of semiconductors. Academic press, London
31. Mattson ED, Bowman RS, Lindgren ER (2002) Electrokinetic ion transport through unsaturated soil: I. Theory, model development, and testing. J Contam Hydro 54:99–120
32. Shackelford CD, Daniel DE (1991) Diffusion in saturated soil(I): background. J Geotech Eng 117:467–484
33. Shackelford CD, Daniel DE (1991) Diffusion in saturated soil(II): results for compacted clay. J Geotech Eng 117:485–506
34. Mitchell JK (1991) Conduction phenomena: from theory to geotechnical practice. Geotechnique 41:299–340
35. US EPA (1999) Sandia national laboratories-in situ electrokinetic extraction technology: innovative technology evaluation report. EPA/540/R-97/509

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36. Li Z, Yu JW, Neretnieks I (1996) A new approach to electrokinetic remediation of soils polluted by heavy metals. J Contam Hydrol 22:241–253
37. Alshawabkeh AN, Yeung AT, Brika MR (1999) Practical aspects of in situ electrokinetic extraction. J Environ Eng 125:27–35
38. Thevanayagam S, Wang J (1994) Flow behavior during electrokinetic soil decontamination. In: 1st international congress on environmental geotechnics, Edmonton, Alberta, Canada, pp 379–385
39. National Institute of Agricultural Science and Technology (NIAST) (2010) Methods of soil and plant analysis. NIAST, Rural Development Administration, Suwon
40. Cho JM, Kim DH, Yang JS, Baek K (2011) Electrokinetic restoration of sulfate-accumulated saline greenhouse soil. CLEAN Soil Air Water 39:1036–1040
41. Risco C, Lopez-Vizcaino R, Saez C, Yustres A, Canizares P, Navarro V, Rodrigo MA (2016) Remediation of soils polluted with 2,4-D by electrokinetic soil flushing with facing rows of electrodes: a case study in a pilot plant. Chem Eng J 285:128–136
42. Gomes HI, Dias-Ferreira C, Ribeiro AB (2012) Electrokinetic remediation of organochlorines in soil: enhancement techniques and integration with other remediation technologies. Chemosphere 87:1077–1090
43. Rodrigo M, Oturan N, Oturan M (2014) Electrochemically assisted remediation of pesticides in soils and water: a review. Chem Rev 114:8720–8745