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# Electrokinetic Amendment in Phytoremediation of Mixed Contaminated Soil

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ABSTRACT

This study examines the effects of electrokinetic amendments for phytoremediation of mixed contaminated soil where typical silty clay soil was spiked with organic contaminants (naphthalene and phenanthrene) and heavy metal (lead, cadmium and chromium). The contaminated soil was treated with compost and placed in electrokinetic cells, which were seeded with oat plant or sunflower. Thirty days after germination, 25 V alternating current was applied to selected cells using graphite electrodes for 3 h per day. The plants were harvested after a growth period of 61 days. One cell remained unplanted to evaluate the effect of the electric current on the soil, alone. The results confirm a significant reduction of heavy metals and organic contaminants in soil. However, there was no noticeable improvement of heavy metal phytoextraction or PAH degradation due to the application of electric field despite the increase in biomass production by the plants subjected to the electric current. The electric potential application time and frequency are suggested to be increased to have noticeable effects in heavy metal uptake and PAHs degradation.



## 1. Introduction

Rapid urbanization and industrialization have resulted in sites that have contaminated soil and ground water. Heavy metals and polycyclic aromatic hydrocarbons (PAHs) are major concerns at these sites and their remediation is a widely researched topic. Since these two groups of contaminants are physically and chemically different, it becomes difficult to select suitable remedial strategies when these are present together in the soil. Most of the available methods like soil washing, solidification/stabilization, vitrification, in-situ flushing, etc., are energy intensive and expensive. Compared to those methods, phytoremediation is a green and sustainable option to decontaminate mixed contaminated soils [1]. Electrokinetic remediation is another method that is proven beneficial to treat mixed contaminated soils [2,3].

In phytoremediation, suitable plants are grown in the contaminated area to uptake, degrade, immobilize, or volatilize the contaminants [4]. The term phytoremediation includes different technologies, namely: rhizofiltration, phytodegradation, phytoaccumulation (or phytoextraction), phytovolatilization, phytostabilization and rhizodegradation. Heavy metal contaminants are either accumulated in the plant tissue (phytoaccumulation) or stabilized close to root membrane (rhizofiltration) or in the rhizosphere (phytostabilization). Organic contaminants are absorbed and metabolized by the plant tissue (phytodegradation), degraded with rhizosphere microbes (rhizodegradation) or volatilized after plant uptake (phytovolatilization). In phytoaccumulation or phytoextraction, the plant biomass that contains the contaminants is harvested and disposed of properly [5]. The unavailability of heavy metal contaminants for uptake and low bioavailability of organic contaminants for microbial degradation are often limiting factors for phytoremediation of co-contaminated soil [6]. Some limitations of phytoremediation, like the unavailability of contaminants for phytoextraction or degradation or the limitation in depth of treatment to the root zone, can be overcome by combining electrokinetic remediation with phytoremediation [7]. In-field phytoremediation can be used after electrokinetic remediation to remove residual contamination and achieve cleaner soil. Phytoremediation can contribute to the recovery of soil properties and improve the soil structure through the influence of the root system. This study concentrates on combining a electrokinetic remedial strategy with phytoremediation for a soil co-contaminated with heavy metals and PAHs.

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Phytoremediation of co-contaminated sites is an area of active research [8]. Considering the influence of an electric field on plant characteristics, some research efforts have focused on a combination of electrokinetic remediation with phytoremediation. Early studies of electric field application to planted soil were conducted for agricultural purposes. Lemstrom [9] found that plants treated with an electric field were greener, with an increase in yield. In electrokinetic-assisted phytoremediation, the electric field mobilizes the contaminants into more bioavailable fractions. The electric field can efficiently drive more and more soluble heavy metals toward the plant roots to facilitate the accumulation of heavy metals by plants [10]. Studies also investigate the application of electrokinetic remediation for the removal of organic contamination from the soil [11,12]. Electric field application can stimulate and improve microbial metabolism, and consequently an improving in the degradation of organic contaminants can be observed [13]. Experimental studies were also conducted on the effectiveness of electrokinetic methods to remediate soils contaminated with a mixture of organic and heavy metal contaminants [2,3,14].

Denvir et al. [7] proposed a method of remediating soil, water and other porous media that contain organic and/or inorganic contaminants using plants in conjunction with an electric field applied through the medium. That electric field was used to control the movement of and enhance the removal of the contaminants. The hypothesis was that the electric field can be beneficially utilized to control the transport of charged and/or non-charged contaminants in soil within the rhizosphere and bring the contaminants into the root zone from a contaminated zone located deeper in the soil below the root zone. They suggested that the effectiveness of phytoremediation can also be enhanced to prevent the soil from becoming strongly acidic or basic by manipulating the electric field.

O'Connor et al. [15] combined electrokinetic remediation and phytoremediation to decontaminate two metal-polluted soils in laboratory-scale reactors. One soil sample was contaminated with copper and the other with cadmium and arsenic. The contaminated soils were filled in test reactors with two separate chambers. Rye grass seeds were sown in the reactors and a constant DC potential drop of 30 V was applied continually across the soils. The tests ran for a period of 98 days for the Cu spiked soil and 80 days for the Cd-As soil. The plant Cu uptake was enhanced near the cathode region for the Cu soil. However, the result of Cd uptake was not clear. The plant growth was affected at the anode region due to soil acidification. Also, a fungal infection seen on the rye grass in the cathode region was attributed to the alkaline pH conditions.

Lim et al. [16] examined the addition of a DC electric field around the plants as an approach to increase the uptake of lead by mustard plants. The application of electro-phytoremediation with EDTA (Ethylenediaminetetraacetic Acid) was tested in the Pb contaminated soil. The effects of parameters such as operating current/potential drop, application time of EDTA, electric potential, and daily application time of the electric potential were studied. They found that the maximum lead accumulation in the plant shoots was obtained with the application of an electric field for 1 h per day for 9 days supplemented by EDTA.

Zhou et al. [17] studied the effect of vertical direct current on metal uptake by rye grass. The anode was placed at the top, close to the surface, and the cathode was placed at bottom. EDTA or [S,S]-ethylenediaminedisuccinic acid (EDDS) was used to enhance rye grass uptake of Cu/Zn from contaminated soil. The results showed that application of EDTA/EDDS significantly increased the rye grass uptake of Cu/Zn when compared with samples without the EDTA/EDDS application. A vertical DC electric field ($1.0\,V\,cm^{-1}$) passed through the sample caused the redistribution of Cu/Zn concentrations in the soil column. In the bottom sections of the column, Cu/Zn concentrations were significantly decreased in the soil pore fluid. This study suggests that the application of a vertical electric field can control the leaching risk of heavy metal complexes. Moreover, the Cu concentration in the rye grass shoots increased with the application of the electric fields.

Aboughalma et al. [18] studied the use of AC and DC electric fields for the phytoremediation of soil contaminated with Zn, Pb, Cu, and Cd using potato tubers. In DC treated soils, the pH varied from 3 near the anode to 8 near the cathode. Biomass production of the plants was 27% lower in DC treatments compared to the control. On the other hand, plants treated with AC had 72% higher biomass than the control. In general, the soil treated with either electric fields showed higher metal accumulation by plants roots than the control. However, the shoot accumulation of metals was lower under DC treatment compared to AC treatment and control. The Zn uptake was higher in plants raised in AC treated soil. Compared to soil Cd content, the plant roots had higher Cd content in all the treatments. The Pb accumulation in either the roots or shoots was less than its content in the soil.

Cang et al. [13] investigated the effect of DC electric current on growth of Indian mustard and the speciation of soil heavy metals in multiple metal contaminated soil (Cd, Cu, Pb, and Zn). After growing the plant in contaminated soil for 45 days, four different DC potential gradients (1, 2, 3 and 4 V) were tested in different experiments of electro-phytoremediation of contaminated soil with Indian mustard. The extractable soil metals showed a significant redistribution from the anode to the cathode after the electric field treatment. This demonstrated that electric fields can enhance the plant uptake of metals. In a comparison, a potential gradient of 2 V/cm produced the highest phytoaccumulation. They commented that potential gradient was the most important factor affecting plant growth, soil properties and metal concentrations in the soil and plant.

Bi et al. [19] studied the combined application of phytoremediation and electrokinetic (AC and DC) remediation in heavy metal contaminated soil using rapeseed and tobacco. They chose three kinds of soil: un-contaminated soil from a forest area (S1), artificially contaminated soil spiked with 15 mg/kg Cd (S2) and multi-contaminated soil with Cd, Zn and Pb from an industrial area (S3). The plants, grown in soil filled experimental vessels, received one of three treatment conditions: control without electrical field, AC electric field (1 V/cm) or DC electrical field (1 V/cm). The polarity of the DC electric field was switched every 3 h to minimize the pH variation to the soil caused by the DC field. The electrical field application continued for 30 days for the rapeseed and 90 days for tobacco. The plants were harvested after a total growth of 90 days for the rapeseed and 180 days for tobacco. The plant reactions varied with the applied electric field. The AC electric field had a positive effect on biomass of the rapeseed, and no negative effects were seen for rapeseed biomass under the DC electric field. However, the tobacco plants did not show biomass enhancement under the AC electric field and the biomass was reduced under DC electric field. In the artificially contaminated soil (S2), Cd uptake was higher for both plant species that were treated with the AC electric field compared to control. The application of the AC electric field enhanced the metal uptake by rapeseed in the soil from industrial area (S3).

The impact of the electrokinetic-assisted phytoremediation of a heavy metal contaminated soil (Cd, Cu, Pb, and Zn) on its physicochemical properties, enzymatic and microbial activities was examined by Cang et al. [20]. Indian mustard plants were grown in contaminated soil for 35 days. Then, three DC potential drop (1, 2, and 4 V) were applied across the soil for 16 days for 8 h per day. Samples without the electric field application and samples without plants were treated as the controls. The concentrations of Cd and Zn increased from cathode to anode, while the extractable