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Phytoremediation of mixed contaminated soil enhanced with electric current

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Abstract

Brassica rapa is a plant species that can germinate and grow in mixed contaminated soil with PAH and metals (Cr, Pb and Cd). This plant was selected among 14 plant species for electro-phytoremediation tests because its fast germination and growth in contaminated soil. The influence of type of the electric field (AC, DC) and mode of application (continuous, periodic and polarity inversion) was studied in the electro-phytoremediation tests. The application of 1 ACV/cm potential gradient around *B. rapa* resulted in the effective elimination of anthracene and phenanthrene, but only minor metal removal. The results of this work suggest that alternating current (AC) may be the most suitable electric field for large scale applications. The spatial configuration of electrodes affects the distribution of the electric field in the soil. Various spatial distribution of electrodes have been tested and it has been identified that parallel anodes and cathodes on the soil surface are the most appropriate configuration for field scale applications. Other configurations can be used to concentrate the contaminant around the growing pant or to transport the contaminants from deep soil layers to the rhizosphere.

Keywords: Phytoremediation, Electric field, Metals, PAH.

1. Introduction

Soil contamination is an environmental problem with serious implications on public health. Despite the efforts in the last 20-30 years, there is no still a reliable technology to address the problems of soil contamination [1]. Removing contaminants from a soil is costly and complicated. Most of the available technologies are expensive, they require large amount of chemicals and/or energy, other technologies uses harsh operating conditions that change the soil characteristics, sometimes irreversibly. Soil remediation technologies are also site specific. The good results obtained in a site are not transferable to other sites with different soil and contamination. In addition, if the contaminated soil contains a mixture of organic and inorganic contaminants, the remediation is even more complex, due to the different properties of the contaminants and their possible interactions [2]. In this context, phytoremediation was proposed as a sustainable and benign technology that can deal with mixed contamination [3].

Phytoremediation is the use of green plants for the degradation, accumulation or stabilization of contaminants. It is a benign technology that improves the biological quality of the soil. It is cheap and appropriate for the application to large areas [4]. Phytoremediation also shows some practical limitations. The remediation process is slow and subjected to the biological cycles. Usually, the remediation of a site requires several years. The practical application of phytoremediation is limited to those sites with medium or low contaminant concentration, with sufficient low toxicity to allow the growing of plants. The remediation depth is limited by the plant root depth [2]. The coupled technology electro-phytoremediation have been proposed to overcome the limitations of phytoremediation [5]. The electric current allows to increase the bioavailability of pollutants and nutrients of the soil, favoring the growth of the plant and the microflora associated with the roots, as well as its remedial capacity [4].

In this paper, we study the feasibility of enhanced phytoremediation with electric field as a possible technology for the remediation of soils with mixed contamination (PAHs and metals). The electric field type (AC, DC) and mode of application (continuous, periodic and polarity inversion) is analyzed to determine what are the best conditions to enhance the remedial capacity of the plants. Various plant species adapted to the soil and climate conditions were tested for their ability to grow in contaminated soil. The objective is to define the plant, the electric field type and mode of application to develop a practical electro-phytotechnology to be applied for the restoration of contaminated sites.

2. Materials and Methods

2.1. Soil sample

Soil was sampled in an agricultural field in the surroundings of Vigo (NW Spain). The soil characteristics are listed in table 1. Soil was sampled from the upper layer (between 0 and 0.2 m) in three different adjacent sites. Then, the soil was thoroughly mixed to obtain a single sample that was stored in the lab in plastic containers. Soil was extended in a thin layer of 2-5 cm to let it dry for 72 h. Then, the soil was sieved through a 2 mm mesh to remove small rocks, roots, seeds and other possible non-soil components. Soil was stored in a cool place, in the dark, at room temperature, until use.

2.2. Soil contamination

Soil was contaminated in the lab with two PAHs: Anthracene and phenanthrene; or three metals: Pb, Cr and Cd. The soil contaminated with PAHs was prepared with 1.2 g of phenanthrene and 0.6 g of anthracene dissolved in 0.5 L of acetone. This solution was mixed with 3 kg of dry soil. The acetone was allowed to evaporate at room temperature for 24 h. The soil was periodically mixed to ensure uniform distribution of the PAHs in the soil. The resulting soil has a concentration of 400 mg/kg phenanthrene and 200 mg/kg anthracene. The soil contaminated with metals was prepared with 6.79 g of potassium dichromate, 4.80 g of lead nitrate, and 0.61 g of cadmium chloride ($CdCl_2 \cdot 2.5\ H_2O$) dissolved in 0.25 L of water separately. The solutions of cadmium and lead were added to 3 kg of soil, and thoroughly mixed to assure the uniform distribution of the metals. After 24 hours, the potassium dichromate solution was added to the soil. With this procedure, the adsorption of Pb and Cd in the soil particles is favored, while the formation of precipitates between dichromate and Pb^{2+} and Cd^{2+} ions is decreased. The resulting soil has a concentration of 800 mg/kg Cr, 1000 mg/kg Pb and 100 mg/kg Cd. Soil was stored in a plastic container, in a cool place, in the dark, at room temperature, until use.

In this work, four different soil specimens were used in the phytoremediation tests as shown in table 2: Non contaminated soil (soil as sampled in the field), soil contaminated with metals, soil contaminated with PAHs, and soil with mixed contamination (PAHs and metals). The three contaminated soil specimens were prepared mixing the same amounts of the soils contaminated with PAHs or metals, or non-contaminated original soil. Thus, all the contaminated soil specimens show the same concentration of contaminants. The type and concentration of contaminants were selected to represent to contamination of brownfield sites as previously reported by Chirakkara et al. [6].

2.3. Plants

The germination and development of plants were studied in the soil specimen contaminated with PAHs and metals (Table 2) using 14 plant species. The objective of this study was to identify plant species that germinate and grow fast in the contaminated soil. The species *Brassica rapa* has been selected for further study because of its rapid growth in the contaminated soil, as well as its adaptation to local soil and climate conditions. Furthermore, species of the Brassica genus are widely used in phytoremediation applications for their remediation capacity [7].

2.4. Electro-phytoremediation

The influence of the application of an electric field on the growth of *Brassica rapa* plant and its remedial capacity has been studied using the experimental plan in Table 3. The phytoremediation tests were carried out in pots with 200 g of dry soil, with a moisture content of 41% (saturated soil). In the tests with electric current, a constant potential gradient of 1 V/cm was applied using graphite electrodes directly introduced in the soil specimen on opposite sides in the pots. The electrode gap was 10 cm. The graphite electrodes were sheets 10 cm long and 4 cm wide. The effect of the continuous application of alternate current (AC) and direct current (DC) was studied. The DC-P tests used direct current applied periodically: 4 h on, 8 h off. The DC-PI test used the same periodic application of the DC current but the polarity was exchanged in each cycle. The pots were placed under artificial light in a long-day photoperiod (12 h light: 12 h darkness). The electric field was only applied from the day 10 of the culture to let the plats to germinate and develop before the application of the electric current. The germination rate, plant growth, biomass production and the removal/degradation of contaminants (metals and PAHs) have been studied.

2.5. Analysis

The determination of pH and electric conductivity uses 1 g of soil sample suspended in 2.5 mL of DI water. After 1 h of contact with continuous agitation, the suspension was let to settle for 10 min. pH and conductivity was measured in the supernatant fluid. The moisture content was measured as dry weight using a moisture determination balance. Metal concentration in soil was determined by acid digestion following the EPA method 3050, using 5 g of dry soil and nitric and hydrochloric acids. After the digestion, the supernatant was filtered and the metal concentration was determined by ICP/OES. PAHs in soil were extracted mixing 1 g of dry soil with 3 mL of cyclohexane for 30 min in an ultrasonic bath. The extraction procedure was done twice. Then, cyclohexane was evaporated with a flow of nitrogen and the extracted PAHs were dissolved in 1 mL of ethanol. PAH concentration was then measured by HPLC with a UV–vis diode array detector [8].

3. Results

3.1. Germination of plant species in soil with mixed contamination

The development and growth of 14 plant species in soil contaminated with metals and PAHs has been studied. These species of plants have been selected based on their availability and adaptation to the soil and local climatic conditions. Results of germination and plant height are shown in tables 4 and 5. The plant species that shows better germination rate and fast growth in mixed contaminated soil are *Hordeum vulgare* (barley), *Triticum aestivum* (wheat), *Zea mays* (corn), *Lolium multiflorum* (grass), and *Brassica rapa* (turnip) (Figure 1). Among those 5 plant species, *B. rapa* was selected for the phytoremediation tests with electric field because of the well-known remediation capacity of the plants of the genus Brassica [7]. *B. rapa* is a common plant in the NW of Spain. The local varieties grows faster in the soil and climate conditions. These characteristics made *B. rapa* an excellent candidate to test the effect of the electric field in the phytoremediation of soils with metals and PAHs.

3.2. Germination of *Brassica rapa* in contaminated soil

The germination of *Brassica rapa* has been studied in soil contaminated with metals, PAHs and mixed contamination, and the results were compared with the germination in non-contaminated soil (Figure 2). The results shows that the germination ratio is very high. Even at short times (3 days) the germination ratio is above 40% for most of the tests, and it is about 80% in 6 days. The best germination was observed in the non-contaminated soil, but the soil contaminated with metals shows a similar germination ratio. The tests with PAHs showed the lower germination ratio at 3 and 6 days. This suggests that the organic contaminants may exert some negative effects on early stages of seedling development whereas the metals did not show such toxicity effects. However, at longer time (14 days) after the application of the electric field from the day 10, the germination ratio of the tests with PAHs showed similar values like the other tests. As reported by Acosta-Santoyo et al. [9], the electric field has a positive effect on the germination, and the electric field may even compensate the negative effects of the contaminants on the germination and development of the plants.

3.3. Growth of *Brassica rapa*

Figure 3 shows the average height of the plants in each pot after 26 days of growth. The plant height ranged from 9 to 12 cm depending on the electricity and contamination type of each pot. The plants cultured in non contaminated soil showed slightly higher height (11 cm) than those cultured in contaminated soil (9.9 cm). The mixed contaminated soil showed the shortest plants (9.4 cm). The use of electricity also showed some influence in the plant development. The experiment with polarity inversion showed higher heights (11cm) that the test with no electricity (10.2 cm), whereas the AC (10 cm) DC (9.5 cm) and DC-P (10.1 cm) showed slightly lower plant heights. These results may be attributed to the effect of the electric field in the physicochemical characteristics of the soil and the local concentration of contaminants and nutrients [6,10]. Anyway, the differences in plant height among the tests are small and are not considered critical for the phytoremediation capacity of the plants.

3.4. Biomass production with *Brassica rapa*

The production of biomass in electro-phytoremediation experiments with *Brassica rapa* is shown in figure 4. In general, the tests with non-contaminated soil showed the highest production of biomass. The presence of contaminants in the soil limits the development of the plant, especially in the tests with metals where an averaged reduction of 25% of biomass was observed. The organic contaminants only reduced the biomass production by 13%, compared to the test with non-contaminated soil. The relatively high concentration of metals in soil justified these results due to phytotoxicity effects [11].

The application of an electric field has also affected the production of biomass. The greatest reduction in biomass production was observed in the experiments with direct current (DC) where the production of biomass decreased by 33% with respect to the tests with no-electricity. The AC tests showed only a minor reduction of biomass of 4%. The DC-P and DC-PI showed a biomass reduction of 7% and 13% respectively. The application of a DC electric field to the soil may induce significant changes in the pH and electric conductivity (ion concentration) of the interstitial fluid [4]. Moreover, the mobilization and transportation of the contaminants by the electric field may create zones in the soil with such toxicity that the plants are irreversible damaged [10]. The physicochemical changes in the soil are the result of the DC field application for a long period of time. The periodic application of DC current and the polarity inversion ameliorate these physicochemical changes in the soil. This is why the DC-P and DC-PI showed no such biomass reduction as DC tests. The AC current does not provoke pH changes or transportation of contaminants [12]. As a result, the AC tests showed similar biomass production as the tests with no electricity. This result suggest that the AC current could be the best option for phytoremediation projects at large scale.

The analysis of the results in figure 4 also concludes that there is a crossed effect in the biomass production between the contaminants and the electricity. The tests with metal contaminated soil and electricity showed a biomass reduction of 40% compared to the tests with non-contaminated soil. In the case of PAHs the reduction of biomass was only 20%. These results proved that there is an increasing phytotoxicity due to the mobilization of contaminants, especially metals, by the electric field. The mobilization of contaminants increased their bioavailability, and hence, the toxicity to the plants [13].

3.5. Electro-phytoremediation: Removal of metals

Figure 5 shows the metal concentration at the end of the electro-phytoremediation tests (45 days). The removal of metals in the tests with or without electricity with *B. rapa* has been very limited. Only small removal (below 20%) has been observed in various tests, but there is no a general trend to draw conclusions about the influence of the electric field and its mode of operation on the metal removal. Even the tests with *B. rapa* and no electricity showed a low removal of about 20% for the three metals. This is a surprising result because the species of the genus brassica have shown their remediation capacity for various metals in contaminated soils [14,15]. This may probably due to the relatively short time of culture, 45 days. In the control experiments without electricity and without plant no elimination of metals was observed, as expected.

3.6. Electro-phytoremediation: Elimination of PAHs

The elimination results for PAHs (phenanthrene and anthracene) in figure 6 suggest that it is possible to eliminate these types of hydrophobic and recalcitrant compounds in soils by electro-phytoremediation with *Brassica rapa*. The comparison of the PAHs elimination results suggests that phenanthrene is easier to remove than anthracene. This can be explained by the higher solubility of phenanthrene in water that increases its relative bioavailability. Even the blank tests (without electricity and without plant) shows a significant anthracene removal and a good elimination of phenanthrene. These results proves that the PAHs removal mechanisms involve also in situ microbiological degradation and possible volatilization and dissipation [6,16].

The best PAH elimination results correspond to the tests where PAHs are the only contaminants. The presence of metals increases the phytotoxicity and critically affects the removal of PAHs [17]. In the tests with no plant, the residual concentrations of PAHs are even higher. Thus, we can conclude that *B. rapa* shows a major role in the degradation of PAHs, although there is a contribution of the soil microflora and possible physical dissipation. The electric field and its mode of application also affected the removal of PAHs. The best results corresponded to the tests with AC electric field. As it was commented before, the AC electric current did not induce physicochemical changes in the soil and did not transport or concentrate the contaminants [5,12]. Thus, the biological activity of plants and soil microflora is not affected [13,18] and they can metabolize organics contaminants [5].

3.7. Distribution of the electric field in a soil.

The electro-phytoremediation of contaminated soils with *B. rapa* shows interesting results to be tested at larger scale. It has been hypothesized that the application of a soft electric field improves the development and growth of the plant, as well as its remedial capacity [4]. Several authors have found a negative effect of the electric field on the plants when the electric field was too intense [13]. Unfortunately, it has not been defined where is the boundary between a soft and an intense electric field. Probably, the electric field strength (or electric potential gradient) for enhanced phytoremediation depends on the physicochemical characteristics of the soil, the type and concentration of contaminants, soil moisture and plant species [4]. Anyway, the fundamental variable is not the potential electric gradient applied to the electrodes, but the distribution of the electric field in the soil mass. We have studied the distribution of the electric field in the soil based in the configuration and spatial distribution of the electrodes. The objective is to select the most appropriate electrode distribution to achieve a uniform electric field in the soil. A rectangular cell (39 x 16.5 x 10.5 cm) was used with 4.78 kg of non-contaminated soil, with an actual density of 2.30 g/cm^3 and an apparent density of 0.98 g/cm^3. Figure 7 shows the five electrode arrangements considered in this study.

The scheme A form figure 7 results in a uniform distribution of the electric field throughout the soil mass from the anode to the cathode. This uniform profile underwent only slight modifications over time due to the redox reactions upon the electrodes, mainly the electrolysis of the water. These redox reactions modify the pH and the concentration of ions in the interstitial fluid. This provokes a modification of the electric conductivity and, hence, a non-uniform field distribution (Figure 8). These changes in the distribution of the potential gradient are more significant with time and increasing soil moisture. The scheme A seems to be appropriate for electro-phytoremediation application because of the uniform electric field distribution. The main limitation of scheme A is the implementation at field scale in large areas. This problem can be overcome with the scheme B, which only requires the installation of anodes and cathodes on the soil surface. As shown in figure 8, the scheme B tends to concentrate the electric field around the electrodes. This scheme is very interesting for a large scale applications because it allows the development of plants in the central area (with low electric field strength) and the contaminants can be transported by the electric field towards the rhizosphere.

Schemes C and D shows a circular distribution of the electric field around the central electrode. In both schemes, the greatest potential difference lies near the anode(s) and to a lesser extent around the cathode(s). This arrangement seems to be the most appropriate for the concentration of contaminants in a central point. The use of one or the other configuration will depend only on the electrical charge (anions or cations) of the contaminants to be concentrated in the center of the cell (Figure 9).

Schemes E and F shows a concentration of the electric field on both ends of the cell, and almost a flat profile in the center of the cell (Figure 8). This scheme would be useful for vertical transportation of contaminants from deep layers of soil to the rhizosphere.

The scheme A seems to be the most appropriate for lab tests because of the uniform electric field distribution throughout the soil mass. Scheme B is preferred for field applications because it is easier to implement. The C-D and E-F schemes can be selected for different applications depending on the type of contaminant, rood depth, and contamination depth.

4. Conclusions

The objective of this study was to determine the capacity of the electro-phytoremediation for the recovery of soils contaminated with organic (PAHs) and inorganic (Cd, Cr, Pb) contaminants. The plant *Brassica rapa* was selected among other 14 plant species because of its capacity to germinate and grow in mixed contaminated soil. The influence of type of electric field (AC, DC) and mode of operation (continuous, periodic, polarity inversion) was studied in four soil specimens (non-contaminated, contaminated with PAHs or metals, and mixed contamination).

The electro-phytoremediation with *B. rapa* resulted in a substantial elimination of PAHs but only minor removal of metals. The electricity showed a decisive effect on the plant growth and biomass production. The results of this work suggest that alternating current (AC) may be the most suitable for large scale treatment.

The spatial distribution of the electrodes in soil has a decisive influence in the distribution of the electric field in soil. For lab applications, the scheme A (side by side) is recommended because the uniform electric field distribution. In field applications, the scheme B (parallel anode and cathode on the soil surface) is recommended for its easy implementation.

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References

[1] M.T. Ricart, C. Cameselle, T. Lucas, J.M. Lema, Manganese removal from spiked kaolinitic soil and sludge by electromigration, Separation Science and Technology. 34 (1999) 3227–3241. doi:10.1081/SS-100100832.

[2] K.R. Reddy, C. Cameselle, Electrochemical Remediation Technologies for Polluted Soils, Sediments and Groundwater, John Wiley & Sons, 2009.

[3] USEPA. Introduction to phytoremediation. 2000. Report No.: EPA/600/R-99/107.

[4] C. Cameselle, R.A. Chirakkara, K.R. Reddy, Electrokinetic-enhanced phytoremediation of soils: Status and opportunities, Chemosphere. 93 (2013) 626–636. doi:10.1016/j.chemosphere.2013.06.029.

[5] R. Bi, M. Schlaak, E. Siefert, R. Lord, H. Connolly, Alternating current electrical field effects on lettuce (Lactuca sativa) growing in hydroponic culture with and without cadmium contamination, Journal of Applied Electrochemistry. 40 (2010) 1217–1223. doi:10.1007/s10800-010-0094-x.

[6] R.A. Chirakkara, K.R. Reddy, C. Cameselle, Electrokinetic Amendment in Phytoremediation of Mixed Contaminated Soil, Electrochimica Acta. 181 (2015) 179–191. doi:10.1016/j.electacta.2015.01.025.

[7] D. Hodko, J.V. Hyfte, A. Denvir, J.W. Magnuson, Methods for enhancing phytoextraction of contaminants from porous media using electrokinetic phenomena, US Patent nº 6145244A, 2000.

[8] M.N. Kayali-Sayadi, S. Rubio-Barroso, C.A. Díaz-Díaz, L.M. Polo-Díez, Rapid determination of PAHs in soil samples by HPLC with fluorimetric detection following sonication extraction, Fresenius' Journal of Analytical Chemistry. 368 (2000) 689–696. doi:10.1007/s002160000544.

[9] G. Acosta-Santoyo, C. Cameselle, E. Bustos, Electrokinetic – Enhanced ryegrass cultures in soils polluted with organic and inorganic compounds, Environmental Research. 158 (2017) 118–125. doi:10.1016/j.envres.2017.06.004.

[10] C.S. O'Connor, N.W. Lepp, R. Edwards, G. Sunderland, The combined use of electrokinetic remediation and phytoremediation to decontaminate metal-polluted soils: A laboratory-scale feasibility study, Environmental Monitoring and Assessment. 84 (2003) 141–158. doi:10.1023/A:1022851501118.

[11] P.C. Nagajyoti, K.D. Lee, T.V.M. Sreekanth, Heavy metals, occurrence and toxicity for plants: A review, Environmental Chemistry Letters. 8 (2010) 199–216. doi:10.1007/s10311-010-0297-8.

[12] R. Bi, M. Schlaak, E. Siefert, R. Lord, H. Connolly, Influence of electrical fields (AC and DC) on phytoremediation of metal polluted soils with rapeseed (Brassica napus) and tobacco (Nicotiana tabacum), Chemosphere. 83 (2011) 318–326. doi:10.1016/j.chemosphere.2010.12.052.

[13] L. Cang, D.-M. Zhou, Q.-Y. Wang, G.-P. Fan, Impact of electrokinetic-assisted phytoremediation of heavy metal contaminated soil on its physicochemical properties, enzymatic and microbial activities, Electrochimica Acta. 86 (2012) 41–48. doi:10.1016/j.electacta.2012.04.112.

[14] T. Vamerali, M. Bandiera, G. Mosca, Field crops for phytoremediation of metal-contaminated land. A review, Environmental Chemistry Letters. 8 (2010) 1–17. doi:10.1007/s10311-009-0268-0.

[15] H. Sarma, Metal hyperaccumulation in plants: A review focusing on phytoremediation technology, Journal of Environmental Science and Technology. 4 (2011) 118–138. doi:10.3923/jest.2011.118.138.

[16] K.A. Reilley, M.K. Banks, A.P. Schwab, Organic chemicals in the environment: dissipation of polycyclic aromatic hydrocarbons in the rhizosphere, Journal of Environmental Quality. 25 (1996) 212–219.

[17] S. Kuppusamy, P. Thavamani, K. Venkateswarlu, Y.B. Lee, R. Naidu, M. Megharaj, Remediation approaches for polycyclic aromatic hydrocarbons (PAHs) contaminated soils: Technological constraints, emerging trends and future directions, Chemosphere. 168 (2017) 944–968. doi:10.1016/j.chemosphere.2016.10.115.

[18] L. Cang, Q.-Y. Wang, D.-M. Zhou, H. Xu, Effects of electrokinetic-assisted phytoremediation of a multiple-metal contaminated soil on soil metal bioavailability and uptake by Indian mustard, Separation and Purification Technology. 79 (2011) 246–253. doi:10.1016/j.seppur.2011.02.016.

Figure Captions

Figure 1. Germination and development of various plants species in PAH and metal contaminated soil.

Figure 2. Germination of *Brassica rapa* in non-contaminated soil (NC) and soil contaminated with metals (HM), PAHs and mixed contaminants (HM+PAH) as per table 2.

Figure 3. Development of *Brassica rapa* plants in in electro-phytoremediation tests as per table 2.

Figure 4. Biomass production of *Brassica rapa* in electro-phytoremediation tests after 45 days

Figure 5. Metal (Pb, Cr y Cd) removal from soil in electro-phytoremediation tests with *Brassica rapa*.

Figure 6. Removal of PAHs in electro-phytoremediation tests with *Brassica rapa*.

Figure 7. Electrode disposition in a rectangular cell.

Figure 8. Distribution of the electric field in a phytoremediation cell as per figure 7.

Figure 9. Distribution of the electric field in a phytoremediation cell as per figure 7 (Schemes C and D).

Table

Table 1. Characteristics of soil sampled in the field

Properties	**Value**	**Method**
Gravel + sand (%)	23	ASTM D422
Silt (%)	36	
Clay (%)	41	
Organic matter (%)	12	ASTM D2974
Moisture content (%)	28	ASTM D2216
Specific gravity (g/cm^3)	2.3	ASTM D854
pH	5.7	ASTM D4972
Electric conductivity (mS/cm)	0.23	

Table 2. PAHs and metal concentration in the soil specimens

Contaminants	**Metals (mg/kg)**			**PAHs (mg/kg)**	
	Cr	Pb	Cd	Phenanthrene	Anthracene
Non contaminated	-	-	-	-	-
Metals	400	500	50	-	-
PAHs				200	100
Metals + PAHs	400	500	50	200	100

Table 3. Experimental plan for the influence of the electric field in phytoremediation.

Tests	Test Code	Electric Current				No Electricity	Blank
		AC	DC	DC-P	DC-PI		
Non-contaminated soil	NC	p	p	p	p	p	b
Soil contaminated with metals	HM	p	p	p	p	p	b
Soil contaminated with PAHs	PAH	p	p	p	p	p	b
Soil contaminated with metals and PAHs	HM+PAH	p	p	p	p	p	b
Soil contaminated with metals and PAHs, without plant	HM+PAH/nP	np	np	np	np	np	

p: tests with plant. np:tests with no plant. b: tests with no plant and no electricity

AC: alternate current, DC: direct current, DC-P: periodic application of direct current, DC-PI: direct current with polarity inversion

Table 4. Germination of various plant species in PAHs and metals contaminated soil.

	day 1	day 2	day 6	day 9
Hordeum vulgare (Barley)	X	X	X	X
Triticum aestivum (Wheat)	X	X	X	X
Zea mays (Corn)			X	X
Lolium multiflorum (grass)			X	X
Helianthus annuus (Sunflower)			X	X
Helianthus annuus (Ornamental Sunflower)			X	X
Lactuca sativa, var. Capitata (Iceberg lettuce)				
Lactuca sativa (Golden lettuce)	X	X	X	X
Lactiva longifolia (Little Gem lettuce)	X	X	X	X
Spinacia oleracea (Spinach)			X	X
Beta vulgaris, var. cicla (Chard)			X	X
Cuminum cyminum (Cumin)				
Origanum majorana (Marjoram)			X	X
Brassica rapa (Turnip)	X	X	X	X

Table 5. Development of various plant species in PAH and metal contaminated soil.

	Plant height (cm)		
	Day 6	Day 13	Day 20
Hordeum vulgare (Barley)	10±0.5	15±1.0	22±1.5
Triticum aestivum (Wheat)	7±0.5	15.5±1.0	20±1.0
Zea mays (Corn)	1±0.5	10±0.5	18±1.0
Lolium multiflorum (grass)	9±0.5	13±1.0	15±1.0
Helianthus annuus (Sunflower)	1±0.5	4.5±0.5	8±0.5
Helianthus annuus (Ornamental Sunflower)	1.5±0.5	3.5±0.5	8.5±0.5
Lactuca sativa, var. Capitata (Iceberg lettuce)	-	-	-
Lactuca sativa (Golden lettuce)	2±0.5	2.8±0.5	3±0.5
Lactiva longifolia (Little Gem lettuce)	2.5±0.5	3±0.5	3.5±0.5
Spinacia oleracea (Spinach)	2±0.5	6±0.5	6.5±0.5
Beta vulgaris var. cicla (Chard)	2±0.5	5.5±0.5	6±0.5
Cuminum cyminum (Cumin)	-	-	-
Origanum majorana (Marjoram)	-	1±0.5	1.5±0.5
Brassica rapa (Turnip)	6.5±0.5	8±0.5	8.5±0.5


Barley
Corn
Sunflower
Wheat
Grass
Ornamental Sunflower
Iceberg
Spinach
Cumin
Golden L.
Marjoram
Little Gem
Chard
Turnip

Figure 1

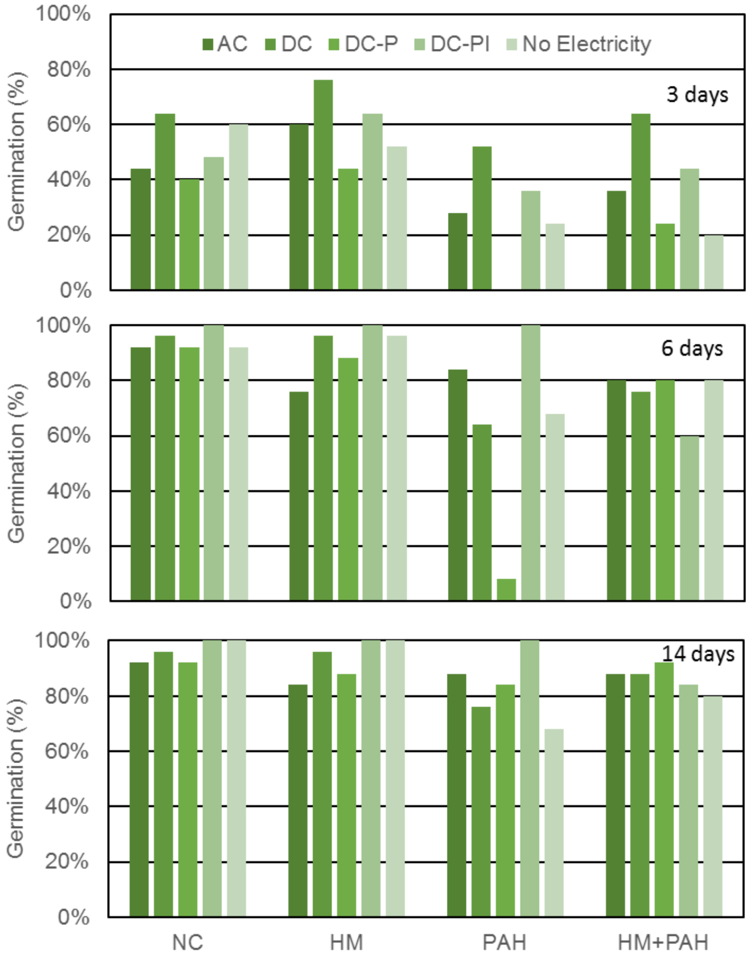
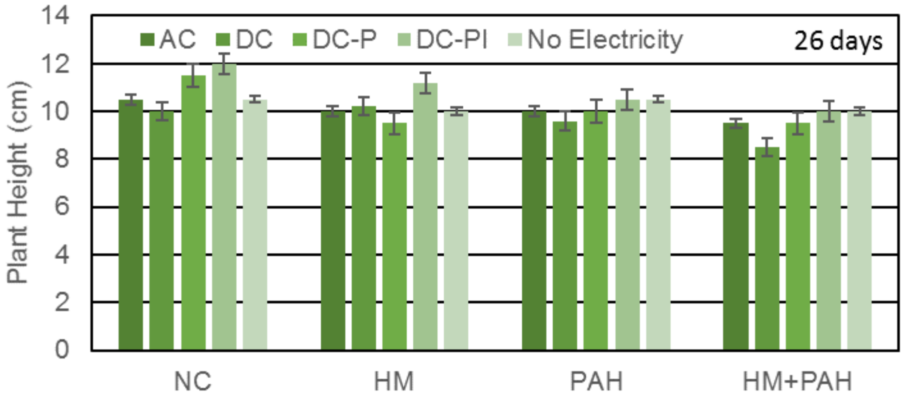

AC
DC
DC-P
DC-PI
No Electricity
3 days
6 days
14 days
Germination (%)
100%
80%
60%
40%
20%
0%
NC
HM
PAH
HM+PAH

Figure 2.



AC
DC
DC-P
DC-PI
No Electricity
26 days
Plant Height (cm)
0
2
4
6
8
10
12
14
NC
HM
PAH
HM+PAH

Figure 3.

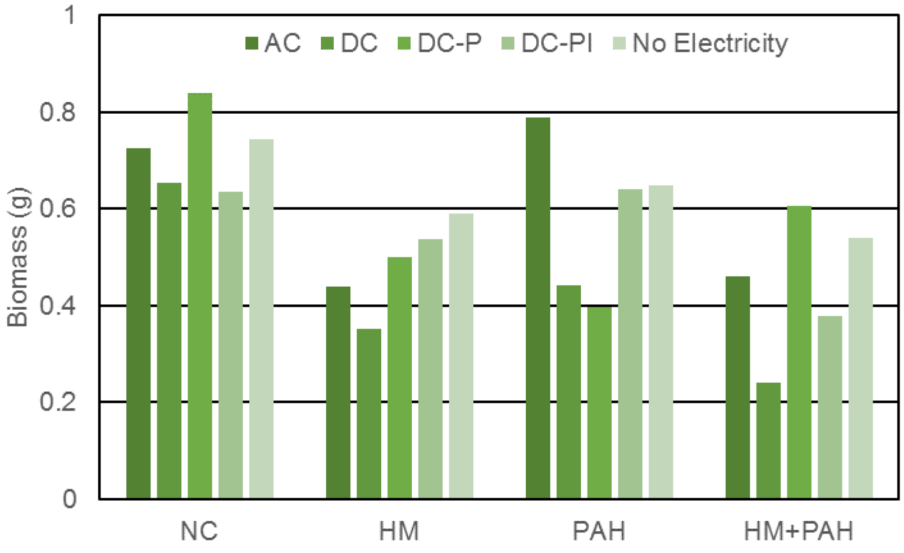

AC
DC
DC-P
DC-PI
No Electricity
Biomass (g)
1
0.8
0.6
0.4
0.2
0
NC
HM
PAH
HM+PAH

Figure 4.

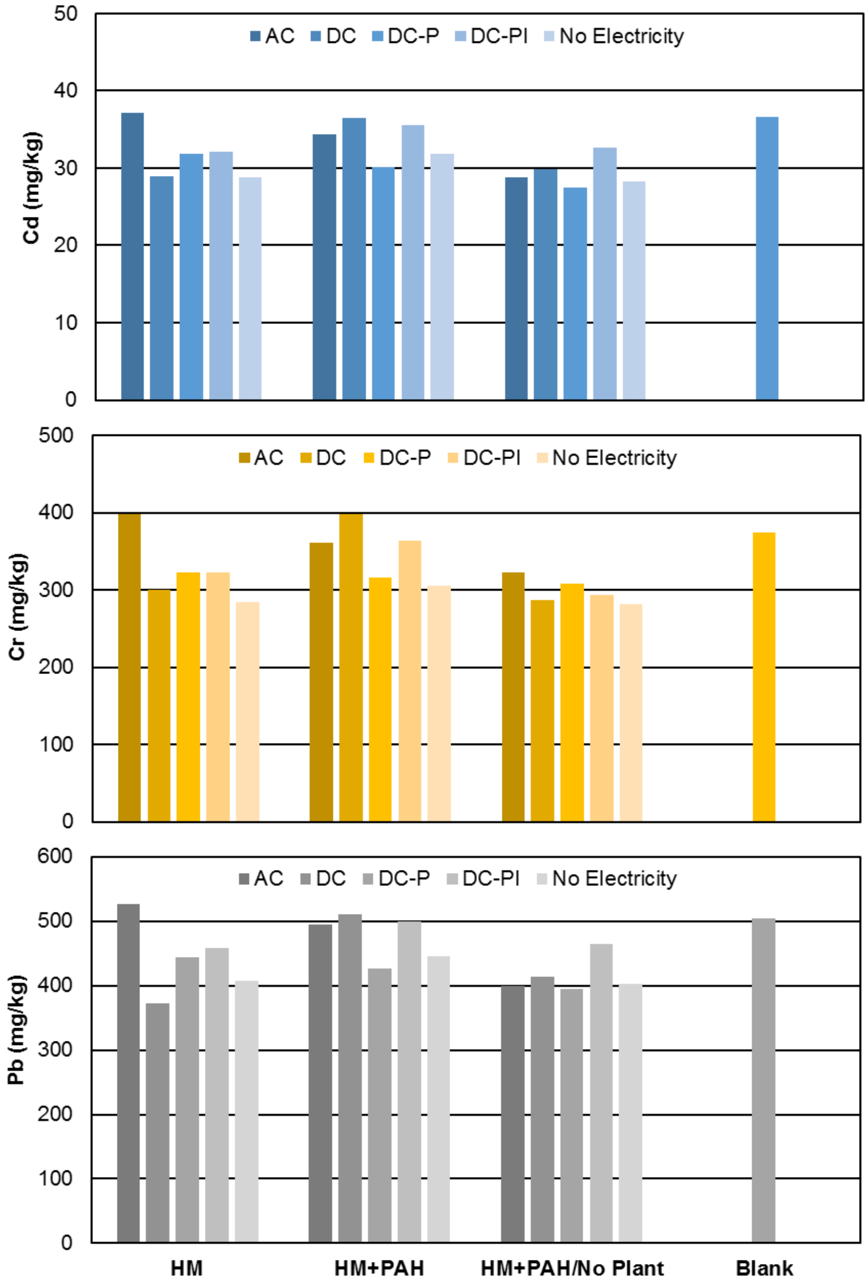

50
40
30
20
10
0
Cd (mg/kg)
AC
DC
DC-P
DC-PI
No Electricity
500
400
300
200
100
0
Cr (mg/kg)
AC
DC
DC-P
DC-PI
No Electricity
600
500
400
300
200
100
0
Pb (mg/kg)
AC
DC
DC-P
DC-PI
No Electricity
HM
HM+PAH
HM+PAH/No Plant
Blank

Figure 5.

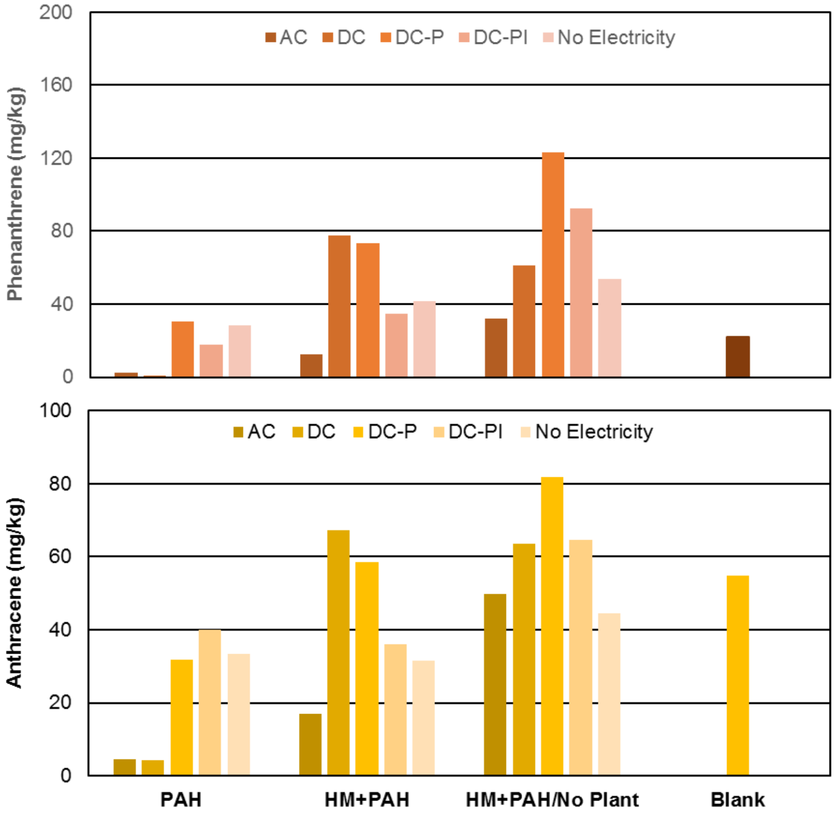

Phenanthrene (mg/kg)
200
160
120
80
40
0
AC
DC
DC-P
DC-PI
No Electricity
Anthracene (mg/kg)
100
80
60
40
20
0
AC
DC
DC-P
DC-PI
No Electricity
PAH
HM+PAH
HM+PAH/No Plant
Blank

Figure 6.

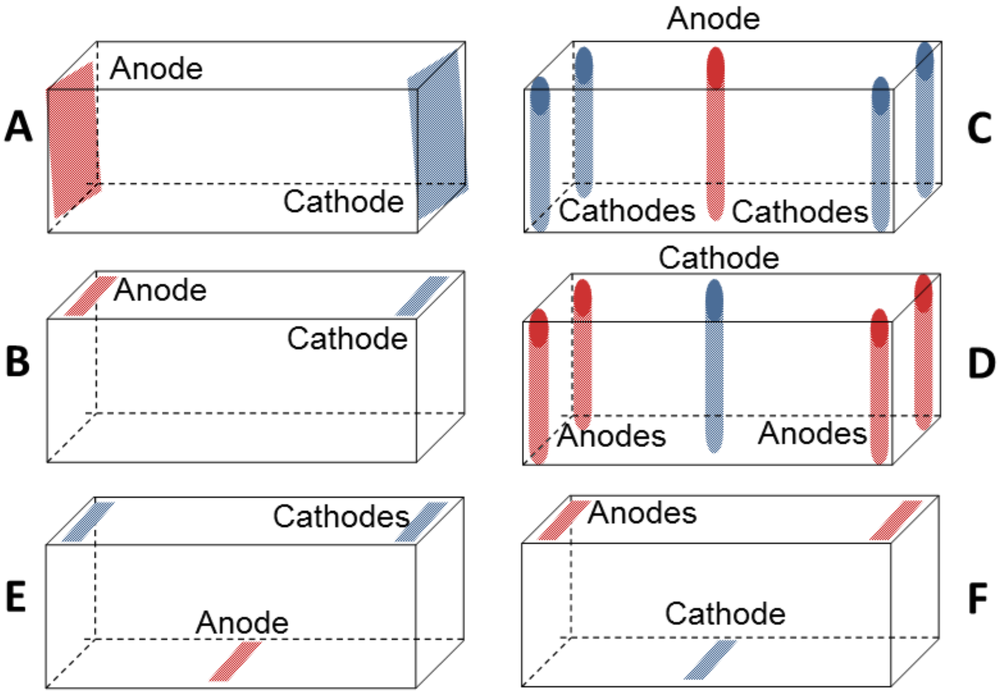

A
Anode
Cathode
Anode
C
Cathodes
Cathodes
B
Anode
Cathode
Cathode
D
Anodes
Anodes
E
Cathodes
Anode
Anodes
Cathode
F

Figure 7.

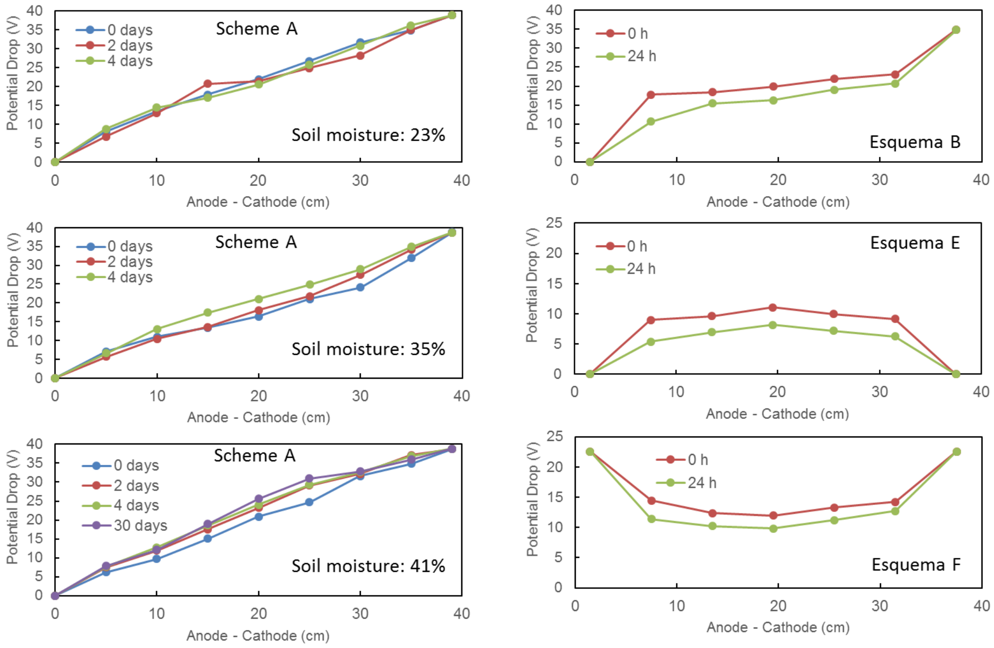

Scheme A
0 days
2 days
4 days
Soil moisture: 23%
Scheme A
0 days
2 days
4 days
Soil moisture: 35%
Scheme A
0 days
2 days
4 days
30 days
Soil moisture: 41%
0 h
24 h
Esquema B
0 h
24 h
Esquema E
0 h
24 h
Esquema F
Potential Drop (V)
Anode - Cathode (cm)
0
5
10
15
20
25
30
35
40

Figure 8.

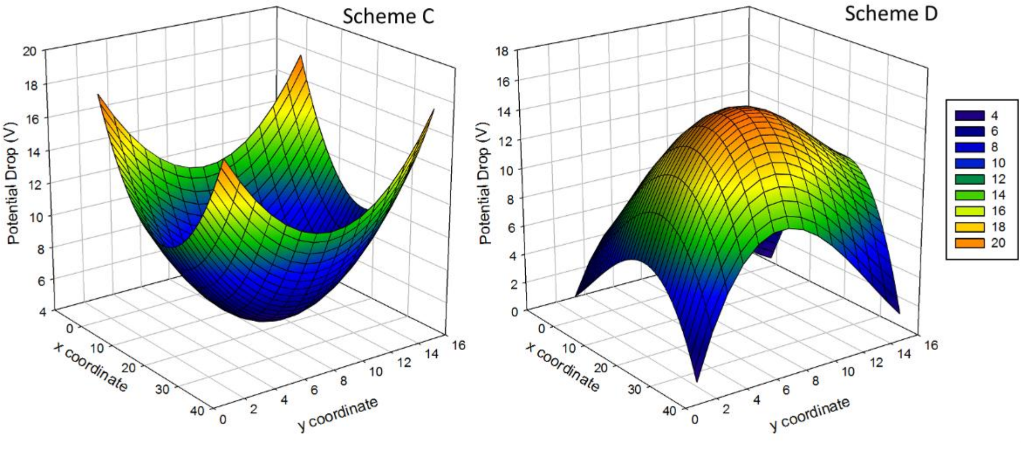

Scheme C
Scheme D
Potential Drop (V)
x coordinate
y coordinate
4
6
8
10
12
14
16
18
20

Figure 9.