Ecotoxicology and Environmental Safety 149 (2018) 241–247

Contents lists available at ScienceDirect

Ecotoxicology and Environmental Safety

journal homepage: www.elsevier.com/locate/ecoenv

Influence of direct and alternating current electric fields on efficiency promotion and leaching risk alleviation of chelator assisted phytoremediation

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ARTICLE INFO

Keywords:
Electrokinetic remediation
Phytoremediation
Chelator
Leaching risk
Heavy metal

ABSTRACT

Direct and alternating current electric fields with various voltages were used to improve the decontamination efficiency of chelator assisted phytoremediation for multi-metal polluted soil. The alleviation effect of electric field on leaching risk caused by chelator application during phytoremediation process was also evaluated. Biomass yield, pollutant uptake and metal leaching retardation under alternating current (AC) and direct current (DC) electric fields were compared. The biomass yield of *Eucalyptus globulus* under AC fields with various voltages (2, 4 and 10 V) were 3.91, 4.16 and 3.67 kg, respectively, significantly higher than the chelator treatment without electric field (2.71 kg). Besides growth stimulation, AC fields increased the metal concentrations of plant tissues especially in aerial parts manifested by the raised translocation factor of different metals. Direct current electric fields with low and moderate voltages increased the biomass production of the species to 3.45 and 3.12 kg, respectively, while high voltage on the contrary suppressed the growth of the plants (2.66 kg). Under DC fields, metal concentrations elevated obviously with increasing voltages and the metal translocation factors were similar under all voltages. Metal extraction per plant achieved the maximum value under moderate voltage due to the greatest biomass production. DC field with high voltage (10 V) decreased the volume of leachate from the chelator treatment without electric field from 1224 to 56 mL, while the leachate gathered from AC field treatments raised from 512 to 670 mL. DC field can retard the downward movement of metals caused by chelator application more effectively relative to AC field due to the constant water flow and electroosmosis direction. Alternating current field had more promotive effect on chelator assisted phytoremediation efficiency than DC field illustrated by more metal accumulation in the species. However, with the consideration of leaching risk, DC field with moderate voltage was the optimal supplementary technique for phytoremediation.

1. Introduction

With the population growth of the world, the expansion of different anthropogenic activities and the advancement of social economy, various contaminants were released into soil overwhelming its self-purification capacity, and thus led to soil pollution (Lucas et al., 2017; Romeh, 2015; Wijeyaratne, 2016). Among diverse contaminants, heavy metals, defined as metals with density greater than 5.0 g cm^{-3} (Ghosh and Singh, 2005), gained particular concern because of their non-degradation characteristic distinguishing from other pollutants (Mani et al., 2016; Prathap et al., 2016).

The main source of heavy metals includes natural processes and anthropogenic activities. The distribution and concentration of soil metals were first determined by various geological activities including bedrock weathering, volcanism and pedogenic processes (Behbahaninia et al., 2009; Misra et al., 2009). The concentrations of iron group elements containing Fe, Ni, V, Cr and Ti largely depended on ultramafic rocks distribution (Chen et al., 2014; Mandal and Ray, 2015). Elements weathered from ultramafic rocks generally contained high levels of Sn, Se, Pb and Cu (Gault et al., 2015; Luo et al., 2016). Natural processes and human activities i.e. mining, coal combustion, waste burning, traffic emission and construction processes can profoundly influence the content, distribution and especially the chemical form which more than the total amount determined the toxicity of heavy metals (Figueroa et al., 2008; Sun et al., 2011a). Among various anthropogenic activities, electronic waste (e-waste) disposing and recycling is one of

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https://doi.org/10.1016/j.ecoenv.2017.12.005
Received 26 August 2017; Received in revised form 20 November 2017; Accepted 1 December 2017
0147-6513/

the most detrimental industry because different heavy metals including Au, Ag, Pt, Cu, Cd, Cr, Pb, Zn and Sn were released into environmental media during dismantling processes particularly in the uncontrolled family-run workshops (Leung et al., 2007; Ghosh et al., 2016; Man et al., 2013).

Conventional soil treatment techniques including in situ solidification, chemical washing, thermal desorption, ex situ burning and contact oxidation filter are appropriate for heterogeneity sites and overcome a series of stress conditions i.e. temperature, compaction, contamination and salinization (Mohan et al., 2007; Witters et al., 2012). But they are not suitable for complex topography and are prohibitively expensive for large areas of polluted soil. Moreover, traditional remediation methods can devastate the physical, chemical, and biological characteristic of soil irreversibly, and the processed soil generally cannot be used for agriculture (Andreotti et al., 2015; Safari and Khalilikhah, 2010). For low to moderately polluted soil with large areas or located within special places where traditional methods cannot be used without destructing the ecosystem, phytoremediation is regarded as a promising alternative which is solar driven, inexpensive, less invasive and disruptive, terrain adaptive and aesthetically acceptable (Erakhrumen et al., 2007; Gomes et al., 2016; PazeFerreiro et al., 2014).

There are some problems limiting the extensive use of phytoremediation like the bioavailability of various metals, seasonal characteristic of the species, time consumption, disposition of the contaminated biomass and the risk of pollutant transfer (Memon and Schroder, 2009; Vargas et al., 2016). Assistant technologies, for instance, soil amendment (Pereira et al., 2010; Wu et al., 2012), microorganism inoculation (Pereira et al., 2015; Zaidi et al., 2006), gene engineering (Aken, 2008; Kotrba et al., 2009), agricultural management (Lin et al., 2016; Qu et al., 2013) and electrokinetic remediation (Reddy and Chandhuri, 2009; Kubiak et al., 2012) were used to resolve the above limitations. Unfortunately, new problems like plant growth inhibition (Pereira et al., 2010), metal leaching risk (Safari and Khalilikhah, 2010; Sun et al., 2011a) and indigenous interference (Sarwar et al., 2010) were observed. Electrokinetic remediation is a modest method which can improve the growth of some plants, ameliorate the population structure of microorganism and drive the pollutants located in deep layer into the rhizosphere (Chirakkara et al., 2015).

Chelator assisted phytoremediation with DC and AC fields was performed to dispose the multi-metal contaminated soils. The purposes of this study were to (1) evaluate the different effects of DC and AC fields on the biomass yield of the selected species; (2) observe the migration patterns of metals in plant tissues, soils and leachate under electric field with different parameters; and (3) establish the optimal combination methods to increase the remediation efficiency and retard the gravitational movement of metals.

2. Materials and methods

2.1. Collection and processing of soil sample

Soil for phytoremediation was gathered from Guiyu, a representative e-waste disposing and recycling site located in south China. The notorious town was concerned by various social communities because a huge amount of pollutants, especially heavy metals were released into the surrounding environment. Related researches reported that the average concentrations of metals like Sn, Sb, Ni, Pb and Cd of soil from the recycling place were over the regional soil background values (Guo et al., 2007). Although metals exhibited a downtrend in concentration with the increasing distance from the dismantling center, metal concentrations of agricultural soil in this town were still significantly higher than towns nearby which were not involved in dismantling and recycling industry (Zhao et al., 2015). Spatial and temporal distribution feature of metals from various functional zones including vegetable plots, paddy fields, residential quarters, waste stacking places, open burning zones and e-waste recycling areas were summarized by Li et al. (2011). They suggested that the contents of Cd, Pb and Cu of agricultural soil were slightly higher than the acceptable threshold limits established for crop cultivation, consistent well with the conclusion of the present study.

After removing the foreign material including detritus, electronic component debris and plant roots with 2 mm sieve, the top soil samples were spread on the filter paper to dry at ambient temperature. The prepared soil was equilibrated for 2 weeks, experiencing 3 cycles of saturation and drying processes to obtain relatively homogeneous substrate conducive to the success of phytoremediation, because the results were evaluated on a point to point basis instead of the mean values of the whole place (Gerhardt et al., 2009). To calculate the time consumption of phytoremediation under different experimental conditions, initial metal concentrations of the soil were analyzed.

2.2. Experimental design

All experiments were conducted under controlled conditions in a greenhouse installed with light and temperature controller. The light/dark duration was 16/8 h while the corresponding temperature was set at 26/18 °C. Eight treatments were set up through transparent PVC cylinders with 20 cm in diameter and 80 cm in height. Thirty-two kilograms of soil was filled into each cylinder up to the level of 75 cm to obtain similar density. Healthy and uniform *Eucalyptus globulus* with similar morphology characteristic cultivated on clear soil were transplanted into each container. Each treatment had five replicates with a total of 80 cylinders for the present study.

Experiment 1 (E1) was planting control without chelator or electric field (Table 1). To evaluate the remediation efficiency improvement and leaching risk increment, a single dose of 0.5 mmol L-1 Na_2-EDTA proven to be the optimal content for metal uptake during the phytoremediation process (Cui et al., 2015; Luo et al., 2016) was applied to E2 to E8 after *E. globulus* transplanting. Experiments 3–5 (2, 4 and 10 V respectively) were DC field application experiments while E6 to E8 were AC field experiments with corresponding voltages. The above 6 treatments were designed to assess the effect of different types of electric fields on the growth of plants and the alleviation of leaching risk. A stainless steel sheet pasted on the aerial part of each plant just above the ground was used as cathode and a 15 cm diameter round stainless mesh used as anode was placed at the bottom of each container. One day after chelator addition, different electric fields were applied for 6 h per day at the same time and lasted for two weeks.

Simulated precipitation experiments were performed to observe the influence of chelator, electric fields and their interaction on pollutant leaching in remediation processes. A precipitation of 25 mm was simulated with 785 mL distilled water poured on soil surface directly every day for two weeks. Precipitation experiments were conducted 1 h after the application of electric fields. The volume of the leachate gathered from the bottom of each container was measured, if any.

2.3. Sample preparation and analysis

Soil near the roots of *E. globulus* was collected just after the transplantation of this species in order to verify the homogeneity of the substrate. The harvested species was rinsed by running water to remove farraginous adhesions, washed with distilled water and then immerged

Table 1
Experimental designs.

	E1	E2	E3	E4	E5	E6	E7	E8
EDTA	–	+	+	+	+	+	+	+
DC field	–	–	2 V	4 V	10 V	–	–	–
AC field	–	–	–	–	–	2 V	4 V	10 V