



Combination of bioremediation and electrokinetics for the in-situ treatment of diesel polluted soil: A comparison of strategies



Esperanza Mena Ramírez^{a,*}, José Villaseñor Camacho^a, Manuel A. Rodrigo^b, Pablo Cañizares^b

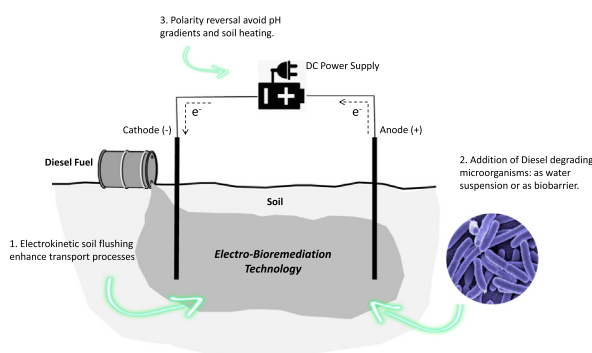
^a Chemical Engineering Department, Research Institute for Chemical and Environmental Technology (ITQUIMA), University of Castilla La Mancha, 13071 Ciudad Real, Spain

^b Chemical Engineering Department, Faculty of Chemical Sciences and Technology, University of Castilla La Mancha, 13071 Ciudad Real, Spain

HIGHLIGHTS

- Good strategy required to reach an efficient combination of EKSF and bioremediation
- Direct combination of EKSF and bioremediation lead to infeasible biological cultures
- Reversal polarity is a good control strategy in EKSF-bioremediation processes
- Combination of EKSF and a biological PRB is the best strategy for removal of diesel

GRAPHICAL ABSTRACT



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ABSTRACT

The aim of this work is to compare different strategies based on electrokinetic soil flushing and bioremediation for the remediation of diesel-polluted soil. Four options were tested at the laboratory scale: single bioremediation (Bio), performed as a control test; a direct combination of electrokinetic soil flushing and biological technologies (EKSF-Bio); EKSF-Bio with daily polarity reversal of the electric field (PR-EKSF-Bio); and a combination of electrokinetic soil flushing and a permeable reactive biological barrier (EKSF-BioPRB). Four batch experiments of 14 days duration were carried out for comparing technologies at room temperature with an electric field of 1.0 V cm^{-1} (in EKSF). A diesel degrading microbial consortium was used. The experimental procedure and some specific details, such as the flushing fluids used, varied depending on the strategy. When using the EKSF-Bio option, a high buffer concentration was required to control the pH, causing soil heating, which negatively affected the biological growth and thus the diesel removal. The PR-EKSF-Bio and the EKSF-BioPRB options attained suitable operating conditions and improved the transport processes for biological growth. Polarity reversal was an efficient option for pH, moisture and temperature control. Homogeneous microbial growth was observed, and approximately 20% of the diesel was removed. The BioPRB option was not as efficient as PR-EKSF-Bio in controlling the operating conditions, but the central biobarrier protected the biological activity. Microbial growth was observed not only in the biobarrier but also in a large portion of the soil, and 29% of the diesel was removed in the short remediation test.

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* Corresponding author.

E-mail address: Esperanza.Mena@uclm.es (E.M. Ramírez).

1. Introduction

Soil pollution is a major environmental problem. Depending on the type of soil and pollutant, there are many possible scenarios whose effective treatment requires the specific research and development of the correct technologies. One common case is the accidental discharge of fuels, which may significantly damage the environment due to the hazardousness of the organic species, affecting not only the ecosystem but also preventing the use of water reservoirs for human supply because of the resultant serious health concerns (Fingas, 2013). Soil remediation is a solution to these fuel discharges, but despite the large range of possibilities (Juwarkar et al., 2010), there is not a single technology that can be currently proposed for highly efficient treatment in terms of depollution efficiency and cost.

Biological remediation technologies (bioremediation) use microorganisms to degrade pollution, and they can efficiently remove fuels from soil (Alexander, 1994). Because of the heterogeneity of soil, these biological processes are not as simple as those occurring in the liquid phase, and finding the conditions in which pollutants, microorganisms and nutrients meet in the same treatment region becomes a major concern. Various technological approaches exist to optimize this coexistence using different methodologies (Mohan et al., 2006; Tomei and Daugulis, 2013).

To enhance bioremediation efficiency, this technique could be combined with additional technologies (Soleimani et al., 2013). Promising alternatives are electrokinetic processes. The electrokinetic treatment of polluted soils is the application of a low intensity direct electric current through the soil between appropriately distributed electrodes (Korolev et al., 2008; Reddy and Cameselle, 2009). When an electric field is applied between electrodes inserted directly into soil (or inside electrolyte wells), many transport processes may occur (such as electro-osmosis, electromigration and electrophoresis) that could help (or disturb, if not correctly applied) biological processes by collocating pollution, nutrients and microorganisms. Electrical heating, as a consequence of the huge ohmic drops associated with the typically low ionic conductivity of soil, can lead to an increase in the temperature, which may also affect the performance of the microorganisms (Chilingar et al., 1997).

There are many possibilities to combining the two technologies, resulting in very different technological approaches that are globally referred to as “soil electro-bioremediation” (Wick et al., 2007). One is a combination of electrokinetic soil flushing (EKSF) with bioremediation. EKSF consists of the use of a flushing solution to drag pollutants contained in the soil by the above-mentioned mechanisms. This flushing fluid may contain surfactants, pH regulators, or other species that aid in the efficient removal of pollution (López-Vizcaino et al., 2011). This fluid may also transport other species such as microorganisms, nutrients and electron acceptors (Schmidt et al., 2007; Mena et al., 2011), thereby addressing the key challenge of biological degradation of combining in the same place all of the species involved in the process. Gill et al. (2014) reviewed the different possibilities, processes and applications of the electrokinetic and biological combined technology for the remediation of organic contaminants.

The present work aims to compare different strategies in a combined technology using electrokinetic soil flushing and bioremediation for a hydrocarbon-polluted soil remediation process. We studied four options in this work: (1) bioremediation alone (Bio) performed as a control test to evaluate the biodegradation process without the application of electric current; (2) a combination of direct electrokinetic soil flushing and the biological technology (EKSF-Bio test) to assess the enhancement of the biological pollutant removal under the influence of electrokinetic phenomena; (3) a combination of direct electrokinetic soil flushing and the biological technology that also includes a daily polarity reversal of the electric

field (PR-EKSF-Bio test) to analyse the mixing process that results in the soil when periodic changes are made to the polarity of electric current; and (4) a combination of electrokinetics and a permeable reactive biological barrier (EKSF-BioPRB) located in the soil with microbial consortia attached on the surface of gravel particles. Because diesel fuel is a complex mixture of different hydrocarbons, it was used as a model to study the treatment of this type of pollution in soils. The efficiency and the advantages or disadvantages of the different alternatives have been discussed. Experiments of 14 days duration were carried out to compare the technologies. This period is short enough to allow the complete removal of the pollutant, and hence, it allows us to compare the comparative remediation rates of the technologies. At the same time, it is high enough to be representative of the main processes involved in the remediation of the diesel pollutant.

2. Material and methods

2.1. Bench scale set-up

The lab scale set-up is shown in Fig. 1, and it was made of transparent methacrylate and divided into five compartments. The central compartment contained compacted polluted soil. Two graphite electrodes were placed on either side of the polluted soil in compartments separated from the soil by a 0.5 mm nylon mesh. The electrodes were connected to the power supplier device (HQ Power, Gavere, Belgium), constituting the anodic and cathodic compartments. Both electrode compartments were connected to an additional collector compartment at either side to collect the liquid overflowing from the electrode wells. The dimensions of the graphite electrodes, provided by Carbosystem (Madrid, Spain), were $10.0 \times 10.0 \times 1.0 \text{ cm}^3$.

To obtain a homogeneous distribution of current lines throughout the soil, the electrodes were positioned to cover the same cross section as the fraction of the soil to be studied. The flushing fluids (or electrolytes) were loaded into the anodic and cathodic compartments at the beginning of the tests. The liquid level decrease in the anodic compartment (caused by the electro-osmotic flow) was regulated by a level control loop, and a peristaltic pump was connected to the cathodic compartment to extract the electro-osmotic flow transported towards the cathode.

2.2. Materials

2.2.1. Soil

Electrochemical techniques are especially recommended for treating low permeability soils, such as clays. Therefore, in this study, kaolinite (provided by Manuel Riesgo Chemical Products, Madrid, Spain) was used as a model for clay soil. The properties of this synthetic clay soil are detailed in Table 1. This soil is characterized by its inertness, low hydraulic conductivity, lack of organic content and low cation exchange capacity.

2.2.2. Hydrocarbons

Diesel oil, a conventional petroleum-derived fuel, was selected as a model of a hydrocarbon pollutant. Diesel was purchased from a petrol station in Ciudad Real, Spain, and characterized as previously reported (Molteni et al., 2012). To artificially pollute the soil, the diesel was diluted tenfold in acetone before evenly distributing the solution drop by drop in a corresponding amount of kaolinite. Simultaneously, the soil was continuously mixed in order to ensure the correct homogenization of the acetone-diesel solution. The solvent (acetone) and the higher volatile diesel fractions (approximately 6% of the initial amount of diesel) were allowed to evaporate at room temperature for at least two days. The concentration of diesel present in the soil at the beginning of the experiment was approximately 10 g kg^{-1} .

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