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Review

Electrokinetic-enhanced bioremediation of organic contaminants: A review of processes and environmental applications

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HIGHLIGHTS

- We investigate the influence of geological matrices on EK-enhanced mixing.
- Mechanisms of EK-BIO at the field-scale including several novel applications.
- Review of the physicochemical processes that effect EK-BIO in the environment.
- Summary of design options available to enhance EK-BIO treatment at the field-scale.
- Spreadsheet model that applies EK-BIO treatment to a contaminant plume scenario.

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ABSTRACT

There is current interest in finding sustainable remediation technologies for the removal of contaminants from soil and groundwater. This review focuses on the combination of electrokinetics, the use of an electric potential to move organic and inorganic compounds, or charged particles/organisms in the subsurface independent of hydraulic conductivity; and bioremediation, the destruction of organic contaminants or attenuation of inorganic compounds by the activity of microorganisms *in situ* or *ex situ*. The objective of the review is to examine the state of knowledge on electrokinetic bioremediation and critically evaluate factors which affect the up-scaling of laboratory and bench-scale research to field-scale application. It discusses the mechanisms of electrokinetic bioremediation in the subsurface environment at different micro and macroscales, the influence of environmental processes on electrokinetic phenomena and the design options available for application to the field scale. The review also presents results from a modelling exercise to illustrate the effectiveness of electrokinetics on the supply electron acceptors to a plume scale scenario where these are limiting. Current research needs include analysis of electrokinetic bioremediation in more representative environmental settings, such as those in physically heterogeneous systems in order to gain a greater understanding of the controlling mechanisms on both electrokinetics and bioremediation in those scenarios.

Contents

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1. Introduction

Land contaminated by anthropogenic activities is of global concern and where exposure to harmful substances occurs there is potential for unacceptable risks to human and environmental health. Bioremediation is a well-established technology used to treat biodegradable contaminants, according to concepts based in general on *ex situ* treatment of excavated material (mainly used in pollutant source removal), and *in situ* treatment of sites with restricted access (where less disturbance is desirable and extended remediation timescales are acceptable) (CIRIA, 2002). Bioremediation requires environmental conditions which are favourable for the particular biochemical process and interaction between microorganisms, contaminants, nutrients and electron acceptors/donors (Sturman et al., 1995). *In situ* biodegradation can be limited by contaminant bioavailability: the immediate contact between microorganisms and substances required for contaminant biodegradation, and bioaccessibility: the fraction of these components accessible to microorganisms in the environment (Semple et al., 2004). Consequently, biodegradation processes may occur in the subsurface environment, but not at a rate to mitigate risks at a particular site.

These limitations can be overcome by coupling bioremediation with electrokinetics (EK), a remediation technology where direct current is applied within subsurface porous media to induce specific transport phenomena (Fig. 1), namely: (1) electroosmosis – the bulk movement of fluid through pores; (2) electromigration – the movement of ions in solution; and (3) electrophoresis – the movement of charged, dissolved or suspended particles in pore fluid. It is also characterised by the electrolysis of water at the electrodes (Virkutyte et al., 2002):

$$\text{Anode (oxidising)} \quad H_2O \rightarrow 2H^+ + \frac{1}{2}O_2(g) + 2e^- \tag{1}$$

$$\text{Cathode (reducing)} \quad 2H_2O + 2e^- \rightarrow 2OH^- + H_2(g) \tag{2}$$

The reaction products, hydrogen (H^+) and hydroxyl (OH^-) ions migrate towards their oppositely charged electrode, generating acid and base fronts (Acar et al., 1993). Electromigration and electroosmosis are independent of hydraulic conductivity and EK cn be used to generate mass flux in zones impervious to advective transport (Jones, C.J.F.P et al., 2011). The principles of electrokinetics have been reviewed by Acar and Alshawabkeh (1993), Virkutyte et al. (2002), Yeung and Gu (2011).

Factors which limit the performance of *in situ* bioremediation are often highly site-specific (Boopathy, 2000) and commonly include: (1) mass transfer of electron acceptors and nutrients to microorganisms responsible for biodegradation (Simoni et al., 2001), (2) limited bioaccessibility of contaminants (e.g. partitioning to aquifer material) for biodegradation (Lohner et al., 2009), and (3) adaptation of the indigenous microorganisms for biodegradation of a particular contaminant (Mrozik and Piotrowska-Seget, 2010). The aim of coupling EK to bioremediation is to overcome these limitations, increasing the effectiveness of remediation measures. This review covers a number of related topics: (1) EK-bioremediation (EK-BIO) processes at the micro and macroscale (e.g. Wick et al. (2007), Lohner et al. (2009), Wick (2009)), but with greater focus on the interactions between EK-BIO processes and the subsurface environment; (2) mechanisms supporting field application, considering the practical aspects of using EK-BIO in specific cases such as the direct influence of environmental factors on EK (e.g. Page and Page (2002)) with a critical focus on bioremediation; and (3) up-scaling EK-BIO at the field-scale. An analysis of coupled electokinetic/bioremediation processes and the potential for application of EK-BIO as a sustainable remediation technique is also presented.

2. EK-BIO processes in the subsurface environment

The processes and mechanisms that constitute EK-BIO operate at the micro and the macroscale (Sturman et al., 1995). Micro-scale (<10 mm) processes occur at pore-level and include interactions between contaminants, microorganisms and their surrounding subsurface environment. At the macro-scale (>10 mm) these processes are manipulated for application to plume-scale management and remediation.

2.1. Micro-scale

2.1.1. Substance transport by EK

EK enhances bioremediation by making bioaccessible contaminants, nutrients, electron acceptors (EAs) and electron donors