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Research article

An overview of electrokinetic soil flushing and its effect on bioremediation of hydrocarbon contaminated soil

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ABSTRACT

Combination of electrokinetic soil flushing and bioremediation (EKSF-Bio) technology has attracted many researchers attention in the last few decades. Electrokinetic is used to increase biodegradation rate of microorganisms in soil pores. Therefore, it is necessary to use solubilizing agents such as surfactants that can improve biodegradation process. This paper describes the basic understanding and recent development associated with electrokinetic soil flushing, bioremediation, and its combination as innovative hybrid solution for treating hydrocarbon contaminated soil. Surfactant has been widely used in many studies and practical applications in remediation of hydrocarbon contaminant, but specific review about those combination technology cannot be found. Surfactants and other flushing/solubilizing agents have significant effects to increase hydrocarbon remediation efficiency. Thus, this paper is expected to provide clear information about fundamental interaction between electrokinetic, flushing agents and bioremediation, principal factors, and an inspiration for ongoing and future research benefit.

1. Introduction

Electrokinetic remediation, often called electroreclamation, electrochemical soil remediation, and electrodecontamination are technologies that use weak electric field to remove and degrade organic, inorganic, and heavy metal compounds from surface of soil particles (Acar et al., 1995; Kim et al., 2010). Electrokinetic remediation has been studied for over last 2 decades (Cameselle et al., 2013). This technology has grown considerably, followed by the emergence of innovative and efficient new patents and studies (Annamalai et al., 2017; Marks et al., 1995). Some literature reviews mention the success of this technology and its integration with other technologies in both laboratory and pilot scale (Lima et al., 2017; Pham and Sillanpää, 2015). Nevertheless, the application of electrokinetic technology in the field is still rare to be found because it is more costly compared to other technologies (Kim et al., 2011) and has some limitations that still need to be concerned such as high temperature and evaporation rate, heterogeneous soil conditions, corrosion in electrode, pH control and electrical source availability in isolated areas (Environmental Protection Agency, 2007). The United States Environmental Protection Agency (2017) reports that electrokinetic technology has not been used since 1992 to recover contaminated groundwater.

Bioremediation is the most commonly technique used for remediation of contaminated soil due to its cheapness and convenience. In addition, microorganisms are very abundant to be found in natural soil, either in the form of a consortium attached to soil particles or suspended in soil pore ecosystem. This finding shows a great potential for conducting bioremediation of contaminated soil. However, bioremediation have several limitations, including environmental condition, electron acceptors and nutrients, nature of contaminants, microbial and metabolism growth (Hassan et al., 2016a; Lahel et al., 2016). Electrokinetic can solve those limitation and enhance process efficiency especially on low permeability soil

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which contain high percentage of clay or silt. Electrokinetic phenomena can transfer several contaminant, nutrient, and also microorganism through electroosmosis, electrophoresis, and electromigration process (Lear et al., 2007; Mena et al., 2016a; Wang et al., 2016). This integration is often called electro-bioremediation, electrokinetic bioremediation (EK-Bio) and bioremediation assisted by electrokinetic (Barba et al., 2017; Choi et al., 2009; Wang et al., 2016). Surfactants are able to act as solubilization agents that enhance biodegradation rate of hydrocarbon contaminants. Surfactants can reduce surface tension and increase solubility of hydrocarbon contaminants through a process called micellar solubilization (Lima et al., 2011). In electrokinetic system, surfactants may be added in the electrolyte chambers and flushed to soil pores through electrokinetic mechanism (some researchers often call it electrokinetic soil flushing/EKSF) and mixed it directly into the reactor (Reddy and Cameselle, 2010; Vieira dos Santos et al., 2016). This combined technology has been successfully remove hydrocarbon contaminant from soil (Mena et al., 2016c; Ramírez et al., 2015a,b). Table 1 describes different performance of EKSF-Bio as standalone technology in treating hydrocarbon contaminated soil.

The basic principle of EKSF-Bio as combined technology is how to make hydrophobic contaminants treated in soil without any secondary or tertiary treatment/electrolyte extraction (Gill et al., 2015a; Lima et al., 2017). In case of natural attenuation, this integrated technology is promising because it only need a short period of processing time, between 5 and 50 days (Ammami et al., 2014; Asgari et al., 2013). Meanwhile, bioremediation needs 14–90 days to exactly degrade and remove contaminant from soil (Gill et al., 2014; Wick et al., 2007). This technique is suitable to be applied both in-situ and ex-situ of hydrocarbon contaminated soil. The electrolyte solution is not only consisted of surfactant and deionized water, but also some enhancing agents such as salts, oxidant, and chelants to cover surfactant limitation (Hahladakis et al., 2014; Mena et al., 2016c; Ramírez et al., 2015a,b).

Electrokinetic and bioremediation (EK-Bio) have been reviewed by many researchers. Wick et al. (2007) has resumed the fundamental interactions between microorganism, soil, and compound in soil pore matrices; Gill et al. (2014) and Hassan et al. (2016a) has made a systematic review about electrokinetic phenomena and factors influencing EK-Bio process; Moghadam et al. (2016) have reviewed a combinations of electrokinetic application; Zhong et al. (2017) discussed about surfactant enhancing the transport of bacteria in porous media; and Ren et al. (2018) have studied about sorption, transportation and biodegradation of persistent organic pollutant in soil. However, there is no specific review and discussion about electrokinetic soil flushing and its effect on bioremediation (EKSF-Bio). The purposes of this paper are to analyze the possible combined mechanisms of EKSF-Bio, describe the latest developments and factors affecting EKSF-Bio in treating hydrocarbon contaminated soil, as well as explaining the future challenges and perspectives related to the field application of electrokinetic soil flushing and bioremediation to treat hydrocarbon contaminated soil.

2. Fundamental interaction in electrokinetic soil flushing and bioremediation (EKSF-Bio)

Electrokinetic soil flushing - bioremediation is a combination remediation technology that utilizes the interaction of weak electric field (low current/voltage), solubilizing agent and biological processes in remediating hydrocarbon contaminated soil. In principle, biodegradation processes on low permeability soils are enhanced by electrokinetic and flushing agent. Solubilizing agents, contaminants, macro - micro nutrients, oxygen, and various other compounds are transported through soil pores by using electrochemical phenomena. There are three main phenomena that occur when a weak electric field is applied to the soil: electrokinetic, chemical (release of hydrocarbon compounds and solubilization of contaminants in soil matrices), and biological phenomena. Fig. 1 shows an illustration of electrokinetic, surfactant, and biological interaction under weak electric field.

2.1. Electrokinetic phenomena

The remediation process begins with providing a weak electric field to the electrode resulting in various reactions, namely: electrolysis, electromigration, electroosmosis, and electrophoresis. Electrolysis is a changing reaction of water molecules/compounds and forms excess of hydrogen ions in anode chamber and hydroxide ions in cathode chamber (Vieira dos Santos et al., 2014).

$$\text{Anode (Oxidation): } 2H_2O \rightarrow O_2(g) + 4H^+ + 4e^- \quad (1)$$

$$\text{Cathode (Reduction): } 4H_2O + 4e^- \rightarrow 2H_2(g) + 4OH^- \quad (2)$$

As a result of electrode reactions, acid condition will be form in anode (1) and bases in cathode (2). Basically, pH at the anode will drop dramatically and reach stability at pH 2.0–3.0 while at the cathode pH will increase to 12.0. This condition has detrimental effect for microorganisms and also electrokinetic forces. By applying an electric field to electrode, ions in soil pores ecosystem move toward to the opposite charge (electromigration). Furthermore, the ions as well as the charged colloids including biocolloid

Table 1
Different performance of electrokinetic soil flushing and bioremediation as standalone technology.

Differences	Electrokinetic soil flushing	Bioremediation
Hydrocarbon removal	Removal of hydrocarbon contaminants from soil using electrochemical mechanism. Hydrocarbons are released from soil particles and flushed through soil pores into the electrode chambers for ex-situ treating (pump and treat)	Bioremediation can be performed using nutrient stimulation or engineered environmental conditions that suitable for microorganisms, bioaugmentation of hydrocarbons degrader and bioattenuation of indigenous microorganism
Contaminant transformation	Transformation of pollutants may occur on the surface of soil particles or more specifically on the diffuse double layer. In addition, contaminant transformation may occur in each of electrode	Biotransformation can occur if contaminants accessible and available for microorganism, mixing can accelerate the transformation process
Mass transfer phenomena	The existence of voltage gradient causes the emergence of some electrokinetic phenomena that can bring and drag water, ions, compounds, colloids or microorganisms through soil pores	Effective transfer of microorganisms, substrates, nutrients and contaminants can be achieved when external energy/pressure/assistance such as mixing or injection has been conducted
Main process parameter	Electrokinetic movement	Ability of microorganisms in degrading contaminants