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Review

Enhanced electrokinetic technologies with oxidization–reduction for organically-contaminated soil remediation

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HIGHLIGHTS

- Physical enhancement approaches for EK technologies were analyzed.
- Various additives-aided Redox-EK technologies were reviewed and compared.
- Advanced Redox-EK systems were presented.
- Comprehensive comparison among enhanced EK technologies was made.
- Future directions were provided for the related researchers.

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ABSTRACT

EK remediation has been extensively studied over the last two decades and widely recognized as a promising method to treat different types of organically-contaminated soil (especially low-permeability soil). After EK remediation, however, the pollutants mainly concentrate in a small area or change to liquid phase in its original form and still need more efforts for complete removal. Through combining EK with other remediation technologies, not only can the reaction time be saved effectively, but also organic pollutants are decomposed within the soil and thus do not need extra treatment. This review focuses on the enhanced EK technologies with oxidization–reduction, aiming to interpret useful information to the researchers and practitioners in this field and provide promising research directions for future studies. Firstly, implications of many common oxidizing–reducing agents on the performance of EK technologies for soil remediation are analyzed, which include Fenton reagent, permanganate and persulfate. Various applications of oxidization–reduction technologies in configurations (i.e. zero-valent iron and Lasagna™) integrated with EK are then discussed, with respect to the treatment efficiency and limitation. The potentials and challenges of developing new enhanced/integrated EK technologies are finally discussed, providing many demanding areas for the future research, such as photoelectro-Fenton, EK-Fenton with ultrasound, EK-nano-ZVI, bimetallic systems with EK, EK-hypochlorite, EK-percarbonate and EK-ozone, and EK-redox-thermal desorption.

Contents

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1. Introduction

Because of accidental spills or improper management, a large number of organic contaminants have been discharged into the environment, particularly in the surrounding soil. The process is often dynamic, hidden, cumulative and not reversible. Generally, the common volatile and/or soluble organic contaminants include aromatic compounds, polychlorinated organic compounds, herbicides, and pesticides. Most of these contaminants are low-soluble, toxic, mutagenic and even carcinogenic, and may be of great risk to human health and ecosystems [1]. To remediate the contaminated soil, a variety of technologies have been developed in recent decades [2].

Since the late 1980s, a comprehensive electrokinetic (EK) remediation process has been proved to be capable of remediating various types of soils contaminated with heavy metal (e.g. Pb, Cr, Cd, Zn, Hg, Cu) and organic contaminants (e.g. chlorinated solvents, hydrocarbons, herbicides, creosote, polycyclic aromatic hydrocarbons, nitrate and phenol), comparing with other conventional technologies (e.g. landfilling, incineration, heat-adsorption, phyto-remediation and biodegradation). Reddy and Cameselle [3] provided a detailed introduction of the EK remediation technologies used in the soil contaminated by inorganic and organic pollutants; various related principles and mathematic models, bench-scale investigations, and field projects were demonstrated. However, the remediation efficiency is always low when solely using EK technologies to remove soil pollutants, particularly when permeable and heterogeneous subsurface of the to-be-treated sites is not particularly desirable.

To improve the remediation efficiency, various types of enhanced and/or integrated EK technologies have been studied for soil remediation. Although a variety of literatures already exist in this area, the study focuses on enhanced EK technologies particularly for organically contaminated soil remediation. It will be structured as follows: (1) physically enhanced EK remediation, (2) additives-aided Redox-EK remediation technologies, (3) advanced Redox-EK remediation systems, (4) potential directions for future research, and (5) discussion and conclusions.

2. Physically enhanced EK remediation

In situ EK remediation technologies are based on the application of direct current across unsaturated soil by installing electrodes through drilling wells. Compared with conventional remediation methods, EK processes seem to be simple, safe, flexible, and are capable of treating a wide range of contaminated media and contaminants. During EK remediation, removal of contaminants from the soil is accomplished by physic-chemical processes and transport mechanisms of electrolysis, electro-osmosis, electrophoresis, electromigration and diffusion [4,5]. Generally, an EK process involves the application of an electrical field across a porous medium, which could induce the migration of a low-intensity electrolyte solution and drive the transport of contaminants toward the negative cathode electrode [6]. In specific, it includes (1) the advection of electroosmotic (EO) flow driven under an active electrical system, (2) the movement of H^+ ions generated from water electrolysis (i.e. oxidation reaction) at the anode advancing through soil toward the cathode, and (3) the electromigration of hydroxyl ions decomposed by water (i.e. reduction reaction) at the cathode toward the opposite electrodes. Previously, the researchers explored many advanced approaches to enhance the remediation efficiency based on the mechanisms of electric remediation for different pollutants. The main goal is to improve desorption and/or solubilization of organic matters in soil. Two physical methods (i.e. soil pH control and facilitating agents addition) are often considered to enhance conventional EK processes.

2.1. Soil pH control

The flow velocity of electroosmotic could be influenced by zeta potential that may be affected by solution pH, so a preferable soil pH is very important for organic removal during EK processes. It should be highlighted that when the solution pH is lower than the point of surface charge, the movement direction of ions will be changed from the cathode toward the anode, hence impede the removal efficiency. Therefore, adjusting the soil pH is beneficial for coordinating the high velocity of electroosmotic flow [7], which was also proved by Baraud et al. [8].

Various attempts related to working solutions, circulation systems, and electrode materials were conducted to enhance the effectiveness of EK remediation. In order to make electricity consumption being at a stable status, Chang and Cheng [9] served 0.01 M sodium carbonate as working solution to maintain the pH value at neutral range; after 10 d treatment, the removal efficiency of perchloroethylene (PCE) reached 99%. Saichek and Reddy [10] conducted six bench-scale EK experiments to treat