Review

A review of electrokinetically enhanced bioremediation technologies for PHs

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ABSTRACT

Since the early 1980’s there have been several different strategies designed and applied to the remediation of subsurface environment including physical, chemical and biological approaches. They have had varying degrees of success in remediating contaminants from subsurface soils and groundwater. The objective of this review is to examine the range of technologies for the remediation of contaminants, particularly petroleum hydrocarbons, in subsurfaces with a specific focus on bioremediation and electrokinetic remediation. Further, this review examines the efficiency of remediation carried out by combining bioremediation and electrokinetic remediation. Surfactants, which are slowly becoming the selected chemicals for mobilizing contaminants, are also considered in this review. The current knowledge gaps of these technologies and techniques identified which could lead to development of more efficient ways of utilizing these technologies or development of a completely new technology.

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Introduction

The industrial revolution brought about massive expansion of industries in developed as well as developing countries. Over the past century global population has quadrupled and the gross domestic product (GDP) grew more than 20-fold (Krausmann et al., 2009; Maddison, 2007). Development and industrialization often come at the expense of the environment. In Europe there exists an estimated 2.5 million contaminated sites (Panagos et al., 2013), up to 530,000 in the USA (EPA, 2013) and approximately 160,000 in Australia (Smith et al., 2015). In the recent past, the spectacular economic growth of developing countries has spawned a growing number of contaminated sites and waste disposal problems.

Although contamination has been recognized as an issue for over 70 years, hardly a tenth of such sites have been remediated (Naidu, 2013). This may be attributed to the complex and challenging nature of contamination that varies from site to site and to high costs of clean-up (Gavrilcescu et al., 2009; Mulligan et al., 2001; Naidu, 2013). Most contaminated sites have associated groundwater contamination problems that prevent their effective and reliable remediation and pose health risks to the communities. During the late 20th century, efforts to contain and remediate contaminated groundwater increased (Gavrilcescu, 2005; Harrison, 2001; Kovalock Jr, 2000). Increasing demand for remediation of persistent contaminants has brought-about development of numerous remediation technologies, some of which are promising for remediating contaminated water and soils (Farhadian et al., 2008; Pavel and Gavrilcescu, 2008; Varjani, 2017).

Remediation of contaminants can be challenging from both technical and financial perspectives. Estimates of the annual global cost of remediation ranges from $65 billion in 2016 to in excess of $82 billion by 2022 (Boots, 2017). Several reports suggest that despite many years of focusing on remediation it has proven challenging, problematic and expensive, to meet regulatory prescribed end-points (Scherer et al., 2000) which are often extremely conservative.

The selection of suitable technology is often a difficult but crucial step for the successful remediation of a contaminated site (da Silva and Maranho, 2019; Khan et al., 2004). The objective of this paper is to critically review existing remediation technologies with a focus on in situ treatments, including bioremediation (Part 3) and electrokinetic methods (Part 4) and an approach based on coupling these technologies (Part 5). Surfactant-enhanced remediation is discussed (Part 6) because it has received increasing attention recently to enhance remediation efficiency by accelerating the mobilization of adsorbed petroleum hydrocarbons from soil matrices.

The review will also provide environmental practitioners and scientists with crucial information for the selection of the most applicable technology for remediating priority recalcitrant contaminants in subsurface media. The review concludes with recommendations, and highlights research gaps, which, if plugged, could lead to improvements in situ remediation technologies.

1. Petroleum hydrocarbons (PH) contamination

Petroleum hydrocarbons (PH) products are some of the most extensively used chemicals both in industrial processes and in day to day use as fuel (Huang et al., 2019; Sarkar et al., 2005). About 1.7–8.8 million metric tons of oil are discharged to the global water resources each year (Megharaj et al., 2011). Incidents due to human failures and other activities such as deliberate disposal of PH wastes, account for more than 90% of oil pollution of water (Varjani and Upasani, 2017; Zhu et al., 2001).

Petroleum hydrocarbon contaminated surface and subsurface soils are currently treated using chemical, physical or biological processes (Moliterni et al., 2012). Most commonly contaminated soils are, disposed to a landfill or incinerated. Both these processes are expensive, not very efficient and are generally unsustainable (Moliterni et al., 2012; Varjani, 2017). Biological treatments, including natural bioremediation and/or enhanced bioremediation involve decomposing contaminants to nontoxic products by microbiological processes (Varjani and Upasani, 2017; Zhao et al., 2011).

High molecular weight fractions of PHs from oil refinery sludge are particularly challenging to remediate (EPA, 2000; Varjani and Upasani, 2017). Remediating higher molecular weight fractions of PH from soils is slow, costly and is even more difficult for the most recalcitrant fractions of PH.
are physically entrapped or sorbed from the residual phase in further degradation (Pollard et al., 1994). Contaminants that

tion, and the residual contaminants tend to be resilient to photolytic loss, evaporation, hydrolysis, and biotransforma-

taking binding sites for hydrophobic regions for PH, hence transforming contaminants from the water phase to the organic matrix. Humic

These properties result in preferential partitioning of contaminants according to their phys-

carbon in the soil and the octanol

the aqueous phase. However, “bioavailability” is inadequately defined, used ambiguously in the literature, and the con-

minimum is between 6.5 and 7.5

Table 1 – Essential factors for microbial bioremediation

2. Bioremediation of PH

Bioremediation of PH contaminated soils has been inves-

to its efficacy and cost-effectiveness (Speight and Arjoon, 2012) for remediating PH-impacted soils and groundwater. Bioremediation can lead to complete mineralization

different factors (Juhasz and Naidu, 2000). (3) The portion of a chemical in a soil that can be utilized or transformed by living organisms (Semple et al., 2003).

Bioavailability is closely related to the sorption and desorption kinetics between the soil and PH, and is dependent

Table 1 – Essential factors for microbial bioremediation (Speight and Arjoon, 2012).

Factor | Optimal conditions
--- | ---
Microbial population | Appropriate species of organisms that can biodegrade the contaminants
Oxygen | Sufficient to sustain aerobic biodegradation (~2% oxygen in gas phase or 0.4 mg/L in soil/water)
Water | Soil moisture should be between 50% and 70% of the water holding capacity of the soil
Nutrients | Nitrogen, phosphorus, sulphur, etc., to support adequate microbial growth
Temperature | Suitable temperatures for microbial growth (0–40°C)
pH | Optimum range is between 6.5 and 7.5

Once a contaminant enters fractured rocks, it continues diffusing into the rock fractures or pores. This stored fraction of contaminants could readily dissolve into the groundwater when changes in the water table occur (Lerner et al., 2003).

In their review, Leahy and Colwell (1990) mentioned that the portion of the total heterotrophic community

1. Fate of PH contaminants in the subsurface

The soil acts like a chromatographic column for PH, separating individual constituents according to their phys-

- Hydrocarbons can associate with the soil matrix either through absorption or through adsorption (together termed “sorption”). The sorption of PH, as hydrophobic compounds, is mostly determined by the organic carbon in the soil and the octanol–water partition coefficient of the contaminant (Rodgers and Bunce, 2001). Recalcitrant hydrocarbons generally have large octanol–water coefficients and high soil organic-carbon water partition coefficients. These properties result in preferential partitioning of contaminants from the water phase to the organic matrix. Humic acids, the main organic chemical constituent of unpolluted soil, contain aromatic rings with carboxylic and phenolic surface groups, sugars and peptides (Cho et al., 2002) providing binding sites for hydrophobic regions for PH, hence reducing their bioavailability.

Petroleum hydrocarbon contaminants retained in a soil for an extended period of time are exposed to weathering, photolytic loss, evaporation, hydrolysis, and biotransformation, and the residual contaminants tend to be resilient to further degradation (Pollard et al., 1994). Contaminants that are physically entrapped or sorbed form the residual phase in soil. The residual phase can act as a continuing source of contaminant in soil or ground water. Hence, during the planning of any remediation programs it is important to consider contaminants in the residual phase. When aquifers are polluted with PH, pore-scale diffusion limitations increase the complexity of remediation (Li and Yu, 2015). They may either dissolve in the pore water or the water film surrounding soil particles, get trapped in the pores or fractures of rock as non-aqueous phase liquids (NAPL), float on the water table (for those less dense than water), or get trapped under the water table (most of those with density greater than water and some of those with density less than water).
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3.2. Electrokinetic remediation technologies

A range of technologies has been developed to remediate contaminants by electrokinetics. Most have been used for the remediation of metals from subsurface soil by electrolysis; however, some have been modified for the effective remediation of PH.

3.2.1. Conventional anode–cathode

Fluid, usually water, is applied to soils for the effective application of electrokinetics. The fluid enables movement of the contaminants towards the electrodes by electroosmosis. However, the emission of hydrogen at the cathode leads to liberation of OH\(^-\), which increases pH and the precipitation of cations nearby. In order to prevent alkaline precipitation around cathodes several improvements have been proposed and developed: (1) addition of strong complexing agents such as ammonia, citrate, oxalate, acetic acid, and EDTA into soil, which compete with soil for cationic heavy metals and prevent precipitation near cathodes (Ottosen et al., 2005; Reddy and Chinthamreddy, 2003; Zhou et al., 2004); (2) conditioning the anode and/or the cathode reservoirs, or use of an ion exchange membrane (IEM) to control the pH and zeta potential, and also enhance contaminant mobility (Desharnais and Lewis, 2002; Li et al., 1998). IEM-enhanced EK operates similar to electrodialysis (Ottosen et al., 1997).

Even with these improvements, the conventional anode–cathode method has apparent drawbacks. It may take a number of days to even a few years to remediate soil contamination and also involves significant amounts of energy (Virkutyte et al., 2002), significantly limiting its application. In addition, altered pH zones are created at both electrodes, which over time greatly affects treatment efficiency.

Electrolysis generates an acidic front zone and a base zone near the respective electrodes. When these zones approach each other they cause a pH jump. This pH jump is unfavorable for microbial growth and impedes the remediation efficiency. Diverse methods have been developed to prevent the pH jump, such as injecting solutions (Gonzini et al., 2010; Kim and Lee, 1999), fixing the cathode and having approaching anodes (Li et al., 2012; Shen et al., 2007), electrolyte circulation (Chang and Liao, 2006; Lee and Yang, 2000), and non-uniform electrokinetics (Cang et al., 2009; Luo et al., 2005b).

3.2.2. Alternative anode and cathode approach

In the equipment shown in Fig. 2, a constant electrical potential is applied using a DC power supply and the polarity is reversed after a set period. The results from such set-ups indicated that polarity reversal maintained suitable soil conditions for bacterial growth including higher electrical intensity and higher dissolved oxygen concentrations near the anode. It also enhanced the distribution of nutrients (Li et al., 2016). Polarity reversal helps to neutralize soil pH and enhances bioremediation of organic-contaminated soils (Huang et al., 2013; Li et al., 2015). Polarity reversal could also increase the temperature, bioavailability and transformation of organic contaminants (Luo et al., 2006; Luo et al., 2005a).

3.2.3. Two-anode technique (TAT)

Two-anode technique employs a secondary anode that generates hydrogen ions reducing the distance advanced by the basic front. It is less labor intensive modification. Both the primary and secondary anodes are coupled to one cathode. The secondary anode is positioned between the primary anode and cathode (Fig. 3). Hydrogen ions generated by the secondary anode move towards the cathode by electroosmotic and electromigration. During this movement the hydrogen ions lower the pH near the secondary anode and react with the hydroxyl ions generated by the cathode to form water. Therefore, the distance between the secondary anode and the primary cathode influences the outcome of TAT. Positioning the secondary anode closer to the cathode...
produced better results. The electricity required for electrokinetic remediation can be generated by solar panels, making the process even more environmentally friendly.

3.2.4. Approaching anode electrokinetics (AA-EK)

As the name suggests, in AA-EK the anode in the system is not fixed but sequentially approaches a cathode that is fixed (Fig. 4). The number of anodes required depends on the contaminant concentration, site geology, and duration of the treatment. Each anode is kept equidistant. The switchover time from one anode to the other is adjustable but most of time kept constant. As the anode approaches the cathode, an acidic pH front moves towards the cathode. The movement of the front is much faster than the conventional acidic pH
approach in soil when a single anode – cathode system is applied. Additionally, the amount of energy consumed by the set-up is directly proportional to the distance between anode and cathode (Shen et al., 2007).

3.2.5. Approaching cathode electrokinesis (AC-EK)

Similar to the approaching anode modification of the conventional EK set-up, the approaching cathode method was developed for anionic pollutants. Hydrogen emission generates an alkaline environment around the cathode. Under alkaline condition some contaminants are efficiently desorbed from soil (Arnesen and Krogstad, 1998). Rather than an array of anodes, approaching cathodes were placed equidistant from the cathode compartment (Fig. 5). They were switched on sequentially after a pre-defined time. Since desorption was driven by the alkaline environment around the approaching cathode, remediation of anionic contaminants was enhanced when compared with a traditional set-up. In addition, the energy consumption was lower than the conventional set-up.

4. Coupled electrokinetic and bioremediation approach

Bioremediation of contaminated soils is limited by the bioavailability of contaminants, especially in clayey soil (Guo et al., 2014; Kuppusamy et al., 2017). Electrokinetics (EK) is a technique that can be used to overcome these kinds of limitations to bioremediation. EK augments bioremediation by making nutrients, electron acceptors (EAs) and electron donors (EDs) more bioavailable to catabolically active microorganisms (Gomes et al., 2012; LUKAs, 2009) (Fig. 6).

During initial stages of remediation redox reactions of dissolved ions in pore water produces electric current. The electric current then decreases over time under constant polarity due to depletion or diffusion limitations. As time elapses the concentration of ions in pore water are decreased as they migrate and precipitate (Wei et al., 2016). The electric field intensity has recently been reported to be an important factor for bacterial growth (Huang et al., 2013; Li et al., 2013, 2010). Electrolysis produces dissolved oxygen at the anode and promotes growth of aerobic bacteria (Alshawabkeh et al., 1997). Soil properties, including pH and moisture content, are critical for organic contaminant degradation by both electrolysis and microbial activity (Hamed and Bhadra, 1997).

Electrokinetics with polarity reversal (EK-PR) has been combined with bioremediation (Huang et al., 2013; Kim et al., 2005a; Li et al., 2013). When employed together there is an increase in temperature, bioavailability and transformation of organic contaminants without creating extreme zones of pH around electrodes (Luo et al., 2006, 2005b). Additionally, polarity reversal facilitates mixing of bacteria and nutrients in soils (Shi et al., 2008). Consequently, it may also enhance aerobic microbial activity by oxygen production at anodes (Rabbi et al., 2000). In terms of EK-biotechnology, recent research shows that remediation of organic contaminants not only depends on biodegradation, but also on induced stimulation by applied electricity (Li et al., 2013). In total, the benefits of employing EK-biotechniques include: increasing diversity and connectivity of flow-paths for contact and mixing between microorganisms and contaminants (Luo et al., 2006); maintaining uniform pH and moisture conditions (Fan et al., 2007); maintaining a uniform microorganism distribution (Huang et al., 2013), and increasing the area over which the electric field and enhanced biodegradation are effective (Gill et al., 2014).

Guo et al. (2014) used a set-up consisting of a perspex soil chamber (100 × 100 × 25 cm), 25 cylindrical graphite electrodes (20 × 1 cm) distributed into a matrix in a soil reactor.
The control apparatus was capable of reversing the polarity of the electric field rotationally by each row and column in turn at an optional interval, thus generating a 2-D electric field. They carried out four different experiments: BIO–EK, EK only, BIO only, and a control. The polarity reversal of the electrodes was changed at regular intervals. In the BIO–EK and BIO tests, the degrading-bacteria suspension was mixed into the petroleum-contaminated soil (Guo et al., 2014). At the end of the experimentation, they found out that the maximum PH remediation was achieved in the BIO–EK test.

4.1. Electrokinetic (EK) bioattenuation

Bioattenuation is a low impact and inexpensive remediation technique, however it can only be successfully employed at sites where adequate mixing of contaminants, electron acceptors and microorganisms occurs (Rivett and Thornton, 2008). Electrokinetics can enhance natural mixing and can be optimized by the increasing number of electrodes, polarity reversal, and radial configuration of electrodes (Harbottle et al., 2009; Luo et al., 2006; Yuan et al., 2013). When EK is applied in conjunction with bioattenuation, the overall rate of remediation is increased.

4.2. Electrokinetic (EK) biostimulation

Various studies have shown that EK can be employed for enhancing the delivery of nutrients (e.g., phosphate (Lee et al., 2007)), electron acceptors (e.g., nitrate and sulphate (Lohner et al., 2008) and electron donors (e.g., lactate (Wu et al., 2007)). EK can therefore benefit biostimulation and enhance in situ remediation. EK-biostimulation in soils has been successfully employed for PCE (Mao et al., 2012; Wu et al., 2012), toluene (Tiehm et al., 2010), diesel (Pazos et al., 2012) and PAHs (Xu et al., 2010) remediation.
Contaminants can readily diffuse into soil or sediment matrices at low permeability areas and at particular sites due to the free-energy-favorite process. Once they diffuse into the matrices, they are trapped because the outward diffusion is slow due to the free-energy- unfavorable process. Contaminants trapped within the soil matrix become inaccessible and difficult to remediate. They also pose a recontamination risk over long periods as they can diffuse back into the accessible site (Reynolds and Kueper, 2002), which would extend the clean-up time. At low permeability sites, EK-biostimulation can stimulate bioremediation.

When a current is applied to a bacterial cell hydrophilic pores are produced in the cell wall. The transfer rate of nutrients into bacterial cells could be increased via these pores (Weaver and Chizmadzhev, 1996). Luo et al. (2005a) studied the effects of direct current (DC) on bacteria in an aqueous system and found that when phenol-degrading microorganisms were exposed to 20 mA that the hydrophobicity increased. Whereas 40 mA of current increased the net negative charge on the cell surface. This was an important discovery since increasing the net negative charge on the bacterial cell surface could in turn lead to increased ability to mobilize bacteria towards an anode by electromigration, overcoming the sorption forces of the bacterial cells to the soil matrix.

4.3. Electrokinetic (EK) bioaugmentation

During bioaugmentation, microorganisms added to contaminated sites may not be effective due to the low permeability of the subsurface strata. EK enhances the movement of microorganisms through such low permeability soils (Mao et al., 2012; Mena et al., 2012; Wick et al., 2004), despite cells being obstructed by small pore sizes in fine-grained materials (DeFlaun and Condee, 1997). Such enhancement is possible due to electroosmotic flow which causes preferential movement of microorganisms along a flow path through macro-pores within the soil (Wick et al., 2004). The membrane integrity of microbes is sustained (Shi et al., 2008) and so is its functionality during movement by EK. In their study, Mao et al. (2012) first distributed lactate by EK and then for subsequent remediation moved a dechlorinating bacterial strain of Dehalococcoides through PCE-contaminated soil. EK-Bioaugmentation can also be performed as a pre-treatment for remediating heavy metals contaminated soils by efficiently redistributing bacteria (Lee and Kim, 2010).

Microorganisms have a strong affinity to attach to sediment and organic matter, thus disrupting their movement (Mrozik and Piotrowska-Seget, 2010). This can be diminished by using surfactants and applying EK methods (Wick et al., 2004). Ensuring the survival of endogenous microbes introduced into a foreign environment is difficult (Megharaj et al., 2011), and substituting active bacteria with endospores could be researched. With high surface charges, endospores are robust and under EK travel faster than bacterial cells (Da Rocha et al., 2009).

There has been a lot of interest on how electrokinetics can be efficiently used to bioaugment contaminated sub-surfaces. DeFlaun and Condee (1997) showed that, by using electromigration it was possible to disperse bacteria, and to some extent induce electroosmosis as well. Wick et al. (2004) showed that electroosmosis played a vital role in the movement of non-motile bacteria. They were able to move up to 90% of non-motile bacteria by electroosmosis compared to only 0%–20% by electrophoresis. By maintaining a near neutral pH in the sub-surface electrokinetics can efficiently increase interaction between bacterial cells, the contaminant plume, and rate limiting nutrients, all of which benefit remediation (Kim et al., 2005b; Suni and Romantschuk, 2004).

4.4. Electrokinetic soil flushing (EKSF)

Electrokinetic soil flushing (EKSF) is one of the earliest technologies developed for the remediation of contaminated soil. In contrast to the approaches described above it flushes contaminants from the soil matrix rather than degrade them. It is an in situ technique and not very cost effective. Initially, EKSF was employed as a technology on its own. Mena Ramirez et al. (2015) made several modifications to EKSF to improve its efficiency for soil remediation (Fig. 8, Appendix A Table S4).

5. Surfactants

Surfactants are a group of amphiphilic chemicals that contain hydrophilic and hydrophobic parts in the same molecular structure (Mao et al., 2015). Surfactants have been widely used for industrial applications as adhesives, flocculating agents, de-emulsifiers, foaming agents and penetrating agents (Mulligan and Gibbs, 1993). They are also very widely employed in the petroleum industry since they are known to enhance the solubility of petroleum components (Falatko and Novak, 1992). This property led to their application in remediation to mobilize contaminants by increasing the solubility of contaminants (Abdul et al., 1992; Ellis et al., 1985; Johnson et al., 2004). Surfactants can be divided into two main types depending upon their source – synthetic or biological. They are also classified by the nature of the hydrophilic groups into ionic, non-ionic, and gemini surfactants. The ionic surfactants are classified further as anionic, cationic or zwitterionic surfactants (Paria, 2008; Rosen, 2004).

5.1. Surfactants enhanced in situ remediation

Bioremediation of PH has been reported as an efficient, cheap, and eco-friendly technology (Alexander, 1999; Madigan and Martinko, 2004; Rittmann and de Roda, 2001). However, bioavailability is a limiting factor (Guha and Jaffé, 1996; Mihelcic et al., 1993; Volkering et al., 1997). Adding surfactants can increase the dissolution and bioavailability of hydrophobic contaminants in the aqueous phase (Mulligan, 2005). To overcome low bioavailability bacteria can get access to hydrophobic substrates by reducing surface tension or by direct contact with hydrophobic droplet (Wentzel et al., 2007)
Surface tension reduction can be achieved by the secretion of surfactants, molecules that disperse hydrocarbons into small droplets (Baboshin and Golovleva, 2012). In close contact to bacteria, hydrocarbon molecules enter the bacterial cell, where the catabolic machinery achieves their breakdown (Fuentes et al., 2014).

EK enhances contact between surfactants and bound contaminants at the micro-scale and can deliver surfactants to polluted zones at the plume-scale (Saichek and Reddy, 2003). Variation in EK properties such as field strength and polarity reversals had limited effects on biodegradation in the presence of a surfactant (Gonzini et al., 2010; Niqui-Arroyo and Ortega-Calvo, 2010). Such enhanced biodegradation has been demonstrated with synthetic surfactants (Saichek and Reddy, 2003), biosurfactants (Gonzini et al., 2010), cosolvents (Gómez et al., 2010) and cyclodextrin (Ko et al., 2000).

6. Concluding remarks

It is evident from this review that despite the development of technology and nearly 75 years of remedial work, that remediation of subsurface contaminated media has been challenging and often difficult. As a consequence, <5%–10% of contaminated sites have been remediated (Naidu, 2013). While natural attenuation is seen as a cost-effective remediation option, extension of this approach to subsurface remediation is still seen as a challenge. Common constraints include: bioavailability of contaminants; toxicity to microorganisms when the concentration of contaminant is high, especially, towards the centre of the plume; limited availability of growth limiting nutrients, unavailability of essential microbes for bioremediation, technical impracticability; and uncertainties relating to endpoints for remediation.

The difficulty of remediating subsurface contamination increases further in fractured rocks. The contaminant is able to lodge in cracks and fissures of rock, so that complete remediation at such sites is not possible. In addition, the sequestered contaminants can desorb into the soil and groundwater to cause contamination of the site in the future.

Many researchers have proven successful remediation at their respective contaminated sites but few checked what became of the contaminants after they were remediated or...
bioremediated in situ. It is an important question to determine if the contaminant after remediation or bioremediation is transformed into some other harmful persistent contaminant. If the original contaminant is converted into a persistent contaminant it is not only a waste of resources for the remediation procedures applied but also adds another level of difficulty for remediation of the new persistent contaminant.

Another provocative question arises when we encounter differing soil types. Every contaminated site has differing soil characteristics, and as most of the technologies are not one-size-fits-all remediation techniques, they cannot be successfully applied at any particular site. For effective remediation of PH the existing technologies needs be enhanced above currently available mechanical or microbial processes (Huang et al., 2005). Hence, there is an urgent need to develop an efficient and cheap in situ remediation technology, which could perform the subsurface remediation at any contaminated site with minimal disturbance or destruction to the natural environment at the site.

Bioremediation is the most effective way forward to remediate a wide variety of contaminants. Because of its low cost and being an in situ technology, it ticks almost all the boxes a remediation technology should. However, as mentioned in the review, bioremediation becomes incapable of performing its job when the limitations over power at a given contaminated site. These limitations could be overcome by the use of electrokinetics. Hence, upon further research and development the combined use of EK-bioremediation technologies could provide the world with a relatively fast, cheap and non-intrusive remediation technology.

In saying that both the technologies have their own drawbacks which need to be overcome to develop it into an extremely successful remediation technology. The first constraint is maintenance of optimal conditions for the microbial growth and proliferation. Since most contaminated sites are contaminated with contaminant mixtures, the efficiency of this technology to effectively remediate the mixtures should be further studied. There are very few field studies that have been carried out by this technology, and translating the bench studies into the field is an added complexity as variables in the lab can be controlled unlike in the field study. A big variable will be the positioning, type (material) and number of electrodes that are required for effective remediation in the field. To make it even more successful, there should be some focus of combining it with some of the successfully employed field technologies.

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Appendix A. Supplementary data

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