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Enhanced Soil Decontamination via Electrokinetic Removal of Organic Pollutants

Hui Yee Ngieng[1], Muhammad Noor Hazwan Jusoh[1]*, Noraziah Ahmad[2]*, Md Abdullah Al Masud[3], Hasara Samaraweera[4], Mohamed Mostafa Mohamed[5,6]

[1]Department of Civil and Construction Engineering, Faculty of Engineering and Science, Curtin University Malaysia
[2]Fakulti Teknologi Kejuruteraan Awam, Universiti Malaysia Pahang Al Sultan Abdullah Kampus Gambang, 26300 Kuantan, Pahang, Malaysia
[3]School of Architecture, Civil, Environmental and Energy Engineering, Kyungpook National University, Daegu, 41566, Republic of Korea
[4]Department of Civil and Environmental Engineering, Western University, London, N6H0B6, Ontario, Canada
[5]Department of Civil and Environmental Engineering, United Arab Emirates University, Al Ain P.O. Box 15551, United Arab Emirates
[6]National Water and Energy Center, United Arab Emirates University, Al Ain P.O. Box 15551, United Arab Emirates

*Correspondence: mn.hazwan@curtin.edu.my; aziahahmad@umpsa.edu.my

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ABSTRACT: Soil pollution is one of the concern issues in the Asia region. Soil acts as a shelter for underground microorganisms and provides nutrients for plants. Most of the organic contaminants are sourced from agriculture and industrial areas. Organic contaminants which are volatilized and immiscible lead to air and water pollution. Electrokinetic remediation is a technology that has been developed for soil remediation since a few decades ago. It is not fully developed and is still under investigation. Electrokinetic remediation is being applied to improve the removal efficiency of organic contaminants which exist in low hydraulic conductivity of soil or fine-grained soil. Generally, a low direct current, 1DCV/cm is applied. Facilitating agents including surfactant and co-solvent combined with electrokinetic remediation eliminated more organic contaminants compared with electrokinetic remediation alone. Electrokinetic remediation with the addition of bioremediation or phytoremediation process manipulates the transportation of organic contaminants in soil to increase the efficiency of remediation technologies. Electrokinetic remediation is recommended due to its flexibility, cost-effectiveness, and safety. One of the drawbacks is low effectiveness in removing non-polar organic pollutants due to weak desorption capacity and poor solubility in water. Co-solvents and surfactants can be introduced as alternatives to enhancing the solubility of non-polar pollutants and reducing surface tension, which improves their mobility within the soil matrix. These facilitating agents help improve the overall effectiveness of electrokinetic remediation, particularly for challenging contaminants.

KEYWORDS: Soil pollution; electrokinetic; organic contaminants; remediation technique; surfactants; bioremediation

1. Introduction

In the past few decades, industrialization and urbanisation in Asia have grown rapidly. This swift progress has transformed rural areas into bustling urban hubs, driving economic prosperity and a significant rise in population density. The development of industrial and economic growth raises the population. However, this rapid population escalated the demand for natural resources, often leading to overuse and environmental harm. Our environment is contaminated with different types of pollutants at the same time. Soil covers roughly 25% of the Earth's surface, and is a critical part of our terrestrial ecosystem [1]. Despite this, only 7.5% of this area can be used for agriculture, which requires preserving this crucial resource. As in the ecosystem, soil provides a habitat for a wide range of organisms, including bacteria, fungi, insects, and small mammals. These organisms are important for soil health and plant growth, where they contribute to nutrient cycling, organic matter breakdown, and maintaining soil structure and fertility. Soil offers nutrients and water for plant growth, which is an essential medium on land. This support is not only crucial for food crop production but also vital for human survival. Besides, the penetration of surface water into the soil will be naturally filtered by the soil layers. This natural filtration system safeguards groundwater from contamination by capturing and degrading pollutants. Despite its significance, soil is increasingly under threat from pollution. Soil pollution in Asia countries is a growing concern due to the region's fast-paced industrial and agricultural expansion. In agricultural activities, the extensive use of pesticides and fertilizers further contributes to soil degradation and contamination.

Heavy metals such as lead, cadmium, and mercury, are the common pollutants discharged from industrial processes that end up in the soil. This contaminated soil can pose serious risks to human health and the environment. Besides, these contaminants can be absorbed by crops, which then enter the food chain, and lead to pose health risks to humans [2]. Under certain conditions, these contaminants can seep into groundwater and cause negative impacts on drinking water supplies. While pesticides and fertilizers are used to improve agricultural productivity, inside them contain harmful chemicals that can linger in the soil and water. These chemicals can change soil composition and decrease its fertility over time, which lowers agricultural productivity. The persistence of such pollutants in the environment endangers biodiversity. Toxic substances are known to cause harm to soil organisms and disrupt ecosystem functions. The implications of soil pollution go beyond environmental effects to socio-economic aspects. Soil degradation can jeopardize food security by lowering the quality and quantity of agricultural produce, which is particularly crucial in densely populated and economically vulnerable regions. Moreover, the cleanup of contaminated soils is expensive and resource-intensive, imposing a financial strain on governments and communities. Due to that, researchers and scientists across Asia are concentrating on this issue. They are investigating sustainable practices and innovative technologies to alleviate soil contamination and rejuvenate soil health. Tackling soil pollution is not only vital for environmental protection but also for ensuring the long-term sustainability of agricultural systems and the well-being of populations in Asia. By preserving soil health, we can safeguard ecosystems, ensure food security, and foster a healthier, more sustainable future.

2. Source and Type of Organic Pollutants in Asia

In Asia, the pollutants in soil are from anthropogenic activities and are mostly sourced from agriculture and industry. Table 1 shows the general organic pollutants that are always found in agricultural and industry fields. Due to the population growth, the demand for food supply increases. The agriculture field is gradually developing. To ensure the supply amount and quality of crops, pesticides, insecticides, and herbicides are widely used. The machinery used for cultivation or harvesting might have petroleum leakage problems [3]. Besides that, the accidental spill and petroleum products leakage from industries are one of the pollutant sources as well [4]. The organic contaminants like petroleum, oil and grease are hydrophobic so they adsorb on the surface of soil particles. Other sources such as electronic appliances, household, furnishing, and others [5]. Table 2 shows different organic pollutants can be found in different countries.

Table 1. Organic pollutants in agricultural and industrial fields stemming from pesticides [6, 7].

Agricultural		Industry
• Aldrin • Chlordane • DDT • Dieldrin • Endrin • Heptachlor • Hexachlorobenzene • Mirex	• Toxaphene • Alpha hexachlorocyclohexane • Beta hexachlorocyclohexane • Chlordecone • Lindane • Pentachlorobenzene	• Polychlorinated biphenyls (PCBs) • Polybrominated diphenyl ethers (PBDEs) • Polyaromatic or polycyclic aromatic hydrocarbons (PAHs)

Table 2. Organic pollutants in different Asian countries.

Asia countries	Organic pollutants	Source	Reference
China	PAHs, Organochlorine pesticides (OCPs), Phthalic acid esters (PAEs), Polychlorinated biphenyls (PCBs)	Fossil fuel combustion, Agriculture, Industrial, Improper electronic waste processing	[8]
Northern Indo-Gangetic alluvial plains	OCPs	Agriculture	[9]
Hong Kong	PAHs	Incomplete combustion and petroleum	[10]
Vietnam	Persistent toxic substances (PTSs), Toxaphene, PAHs	Agriculture, petrogenic and pyrogenic sources	[11]

2. Effect of Organic Contaminants in Soil

Soil pollution creates a chain reaction between living things and the environment. The organic contaminants in soil may cause air pollution and water pollution. Organic contaminants such as gasoline and chlorinated solvents undergo volatilization and vaporization into air leading to air pollution [12]. Immiscible organic contaminants in liquid form like trichloroethene or dissolved organic contaminants flow into groundwater, aquifers, rivers, lakes, or other water bodies through surface runoff or rainfall [12, 13]. Furthermore, soil pollution causes underground living organisms to loss of habitat. The organisms might not survive in a polluted environment or migrate to a new environment. This might decrease the organic matter of soil and lower the natural nutrients in the soil indirectly. In other words, the fertility of the soil is affected. The organic contaminants in the soil create abiotic stress on plants and influence the photosynthesis process and growth of plants leading to the rise of stress volatile emission and carotenoid pigments [14]. The contaminants enter the food web through the crops eaten by humans. The plants or crops with contaminants ingested by primary consumers accumulate in the bodies of secondary consumers and tertiary consumers and end up in the human body through biomagnification. Biomagnification indicates that the density of contaminants increases with trophic levels within the same food web [15]. The highest density of contaminants in the human body and the density of contaminants increases with time through bioaccumulation affects human health adversely. Organic pollutants are carcinogenic, disrupt the immune system, bring chronic diseases, depression of the nervous system, and other health issues [16]. Various technologies using remediation approaches have been developed to address soil pollution. For instance, the use of electrokinetic techniques combined with facilitating agents and other remediation technologies. Table 3 provides a summary of combined technologies with electrokinetic methods [17].

Table 3. Technologies which combine with electrokinetic [17].

Facilitating agent	Remediation technology
Surfactants	Phytoremediation
Co-solvents	Bioremediation

Electrokinetic remediation is innovative technology that uses electric fields to mobilize contaminants in the soil. The addition of facilitating agents such as surfactants and co-solvents, enhanced the process by increasing the solubility and mobility of contaminants [18]. Surfactants are used to reduce the surface tension between pollutants and water, aiding in the desorption of contaminants from soil particles [19]. While co-solvents enable to modification of chemical compounds to further enhance the mobility of contaminants [20]. These facilitating agents are often used in combination with other remediation technologies like phytoremediation and bioremediation.

Phytoremediation is the process that uses plants to absorb, accumulate, and detoxify contaminants from the soil [21], meanwhile, bioremediation involves microorganisms to degrade and detoxify pollutants [22]. In combination with electrokinetic methods, these technologies are able to improve the efficiency of soil remediation processes, offering more sustainable and effective solutions to soil pollution. This integrated approach not only addresses the contamination but also helps restore the ecological balance and fertility of the soil, ensuring long-term environmental and agricultural sustainability.

3. Electrokinetic

Electrokinetic remediation is applicable for both organic and inorganic contaminants. At first, electrokinetic remediation is developed to remediate inorganic contaminants such as heavy metals [17]. The pH value of soil affects the removal efficiency of contaminants because the amount of H^+ and OH^- ions present in soil react with heavy metals [23]. After that, the electrokinetic remediation used to remove the organic contaminants in soil is developed and grows rapidly. Some experiments and studies are done. Organic contaminants discovered in the soil such as benzene, toluene, phenol, and trichloroethylene can be removed by using electrokinetic remediation [24]. For example, direct current is applied to remove phenol and hydrocarbon from saturated kaolinite and clay respectively [25, 26].

Electrokinetic remediation is considered one of the environmental remediation techniques that take advantage of the properties of contaminants and do not produce any secondary pollution to the environment. Electrokinetic remediation is used to treat contaminants in soil, sediments, sludge, and any solid porous material frequently [27]. This remediation technology is suitable and efficient for low permeability of porous matrix and fine-grained soil [28, 29]. The application of electrokinetic remediation is to utilize the voltage for the formation of an electric field gradient [30]. It utilises the low direct current, generally 1DCV/cm, and a pair of electrodes (anode and cathode) which is embedded in contaminated soil. During operation, the mobilized anions and cations of contaminants will move toward the anodes and cathodes through electroosmotic, electromigration, or electrophoresis [29, 30]. The charge transfer for area between the electrodes is no difference due to the constant current but only resistivity in soil is different because high current in low resistivity soil zone [31]. Figure 1 briefs the electrokinetic transport in soil. Anode and cathode are inserted into chambers full of water or fluid to gather, collect, bring out, and treat the contaminants that exist in soil [27].

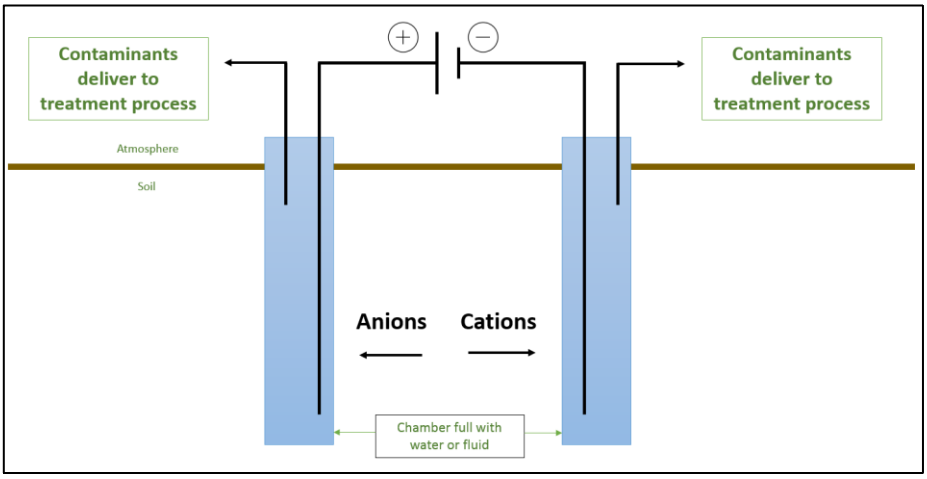

Figure 1. Electrokinetic transport in soil.

4. Electrokinetic Transport Process

Three main mechanisms drive electrokinetic processes including electroosmosis, electromigration, and electrophoresis. Owing to the influences of the electric field, electroosmosis denotes the process when pore water (water in the soil) moves from anode to cathode, electromigration denotes the process when the ions in the soil move to the electrode with opposite charge and electrophoresis denotes the process when the charged bacteria and macroparticles with the move to electrode with opposite charge [27]. The common point of these three mechanisms is that charged particles or molecules are necessary. However, the electroosmosis process is likely to happen in the removal of hydrophobic organic contaminants in low hydraulic conductivity soil whereas the electroosmosis process is likely to happen in soluble organic contaminants in soil. The electroosmosis will be more efficient in removing pollutants in water in terms of soil saturated, low hydraulic conductivity, and fine particles. To allow the water molecules to move towards the cathode in low hydraulic conductivity soil the electricity consumption is high and professional as well as advanced equipment are required [32]. Azo dye such as Reactive Black 5 (RB5) which is a soluble organic contaminant in kaolinite clay can be removed through the electromigration towards the anode and will undergo an oxidation process resulting in colour degradation and elimination [33]. Capillary electrophoresis is a new technique to separate the components of a mixture by utilizing electric field and it is used to analyse the organic contaminants in food [34, 35].

5. Surfactant and Co-Solvents

Electrokinetic and surfactant are mainly focused on the remediation of hydrophobic contaminants in low hydraulic conductivity soil. The mechanism of this combination is electroosmosis. The addition of surfactant in electrokinetic remediation enhances the solubility of hydrophobic organic contaminants and slows their movement [36]. This is because the characteristics of surfactants which contain hydrophilic and hydrophobic functional groups enhance the critical micelle concentration [37]. There are some experiments carried out to compare the presence of surfactants with removal efficiency or to compare the efficiency of ionic and non-ionic surfactants shown in Table 4. Obviously, the removal efficiency of surfactants with electrokinetic remediation is higher than electrokinetic remediation itself only. From Table 4, the removal efficiency increased from 40% to 45% (with non-ionic surfactants) and 50% (with ionic surfactants). Furthermore, the removal rate of organic contaminants is high with the usage of ionic surfactant compared to non-ionic surfactant. SDS has a higher removal rate of kerosene compared to the Tween 80. In the removal of the DDT experiment, DDT is more soluble in water with the presence of SDBS compared to Tween 80. Therefore, the surfactant carries charge has higher reaction with organic contaminants by solubilizing contaminants into micelles [38]. Even though the ionic surfactant has high removal efficiency, there are some disadvantages. Anionic surfactants which have negative charges will form a repulsion force with soil particles as most of the soil is negatively charged. It does lower the adsorption of surfactant onto soil particles but the electroosmotic flow might be affected [38]. The toxicity of ionic surfactants is more significant in comparison with non-ionic surfactants. Cation surfactant is more harmful to microorganisms compared to anionic surfactant [39]. However, anionic surfactant is still used for remediation as the toxicity is not significant and removal efficiency is higher. Non-ionic surfactants are neutral and most of them are biodegradable [38]. In terms of environmental-friendly, non-ionic surfactant is recommended for electrokinetic remediation even if it has lower removal efficiency.

Table 4. Ionic surfactant vs non-ionic surfactant.

Organic contaminant	Surfactants		Result / Observation	Reference
	Non-ionic	Ionic		
Kerosene	Tween 80	Sodium dodecyl sulfate (SDS)	Removal efficiency • Electrokinetic = 40% • Electrokinetic + SDS = 50% • Electrokinetic + Tween 80 = 45%	[40]
DDT	Tween 80	Sodium dodecylbenzene sulfonate (SDBS)	• Mass of DDT in aqueous with SDBS is higher compare with the aqueous with Tween 80. • DDT did not have significant movement with Tween 80.	[36]

The introduction of cosolvent with electrokinetic remediation is to improve the removal efficiency of hydrophobic organic contaminants as well. The presence of cosolvent upgraded the solubility of immiscible solution leading to the hydrophobic organic contaminants being more soluble in aqueous solution. Same as surfactant, organic co-solvent which is more environmentally friendly will affect the electroosmosis flow as well. The organic co-solvent which is low in conductivity will lower the interaction of interstitial fluid and soil particles [41]. The addition of cosolvent into surfactant with electrokinetic remediation is more efficient compared with using either cosolvent or surfactant only.

6. Electrokinetic and Bioremediation

Bioremediation is considered as a green process that has been widely used to treat the organic contaminants in soil and groundwater. Bioremediation is a process that makes use of microbes in soil to treat or degrade the organic contaminants into low toxic or unharmful through biostimulation and bioaugmentation. Biostimulation is a method that stimulates the native microorganisms or microbes in soil by adding or introducing oxygen (bioventing), water, nutrients, or electron acceptors [42]. Other than that, bioaugmentation is a method that increases the existing microbes in soil by adding the existing microbes or non-indigenous to improve the remediation in contaminated areas [42]. In short, biostimulation is to add external factors to stimulate the microbes whereas bioaugmentation is to increase the concentration of microbes through the addition of native or non-native microbes. The bioremediation process in soil is affected by some environmental conditions which are pH, temperature, humidity of soil and soil properties as these may affect the distribution or concentration of microorganisms [43].

The integration of electrokinetic and biostimulation improves the transportation of nutrients to native microbes in soil for enhancement of the interaction of microbes with contaminants and the motion of ions in soil [44]. The contribution of electrokinetic in bioaugmentation is to lead transport or bring the microbes population to a particular zone [45]. Table 5 summarizes the integration of electrokinetic and bioremediation does remove organic contaminants more efficiently.

Table 5. Electrokinetic and bioremediation technology.

Remediation technology	Result / observation	Reference
Electrokinetic + biostimulation	Removal of total petroleum hydrocarbon (TPH) • Electrokinetic = 11.5% to 28.6% • Electrokinetic + biostimulation = 51.6% • Electrokinetic + biostimulation + Tween 80 (surfactant) = 72.8% to 88.3%	[46]
Electrokinetic + biostimulation	Removal rate of organic contaminants with 1.0 Vcm^{-1} • Electrokinetic = 28% • Electrokinetic + biostimulation = 64%	[47]
Electrokinetic + biostimulation	Voltage gradient with DO • 0.5 Vcm^{-1} = 5 mgL^{-1} of DO • 1.0 Vcm^{-1} = 8 mgL^{-1} of DO	[48]
Electrokinetic + bioaugmentation	• The chlorinated ethene in contaminated soil undergoes dechlorination because electrokinetic improves the interaction of Dhc bacterial strain and lactate ions with contaminants. • Dhc bacterial strain used to treat perchloroethylene (PCE) in soil.	[45, 49]
Electrokinetic + biological permeable reactive barriers	Removal of diesel hydrocarbon • With 1.5 Vcm^{-1}, the removal efficiency of hydrocarbon reached 36% which is equal to 50% of diesel biodegradable fraction	[50]

With a constant voltage of 1.0 V/cm, electrokinetic showed its contribution in removal efficiency. Based on Table 5, electrokinetic remediation does contribute to the removal efficiency of TPH but the addition of surfactant increases the efficiency to the next level. This is because the Tween 80 increases the solubility of TPH. The voltage applied is one of the factors which affect the removal rate as well. Another experiment was carried out to prove that the oxygen dissolved in the soil will be affected by the voltage applied. The higher the voltage applied in soil, the higher the level of dissolved oxygen (DO) but this happens until the optimum level only. Lastly, electrokinetic does improve the interaction of added dehalococcoides (Dhc) bacteria with contaminants. For electrokinetic and bioaugmentation remediation technology, an appropriate number of additional agents is needed as electrokinetic remediation aids in the interaction to remove organic contaminants. The excess addition of microbes into the soil might lower the efficiency as the porous soil is full of microbes and the transportation of microbes might be limited.

7. Electrokinetic and Phytoremediation

Phytoremediation is also considered as a green remediation technology that eliminates or degrades the organic or inorganic contaminants in soil by using plants. The mechanisms used for phytoremediation are phytoaccumulation, phytodegradation, phytostabilization, rhizofiltration, and rhizodegradation [51]. Phytoaccumulation involves the uptake and concentration of contaminants within plant tissues, particularly useful for heavy metals and certain organic pollutants. Phytodegradation refers to the breakdown of contaminants through metabolic processes within the plant. This mechanism is effective for organic pollutants like PAHs, PCBs, and halogenated hydrocarbons, which can be metabolized by different plant species [52]. Phytostabilization is applied to immobilize contaminants in the soil, reducing their bioavailability and preventing their migration, which is beneficial for areas with extensive soil contamination. Rhizofiltration and rhizodegradation leverage the plant root system to absorb and degrade contaminants present in water or soil, further enhancing the efficiency of phytoremediation in managing both organic and inorganic pollutants.

Incorporating electrokinetic with phytoremediation involves the application of a low intensity electric field on contaminated areas with plants to improve the bioavailability of pollutants by desorption and transportation of contaminants [53, 54]. This can assume that the application of electrokinetic can move organic contaminants towards the plant roots, which increases their uptake and degradation. The limitation of traditional phytoremediation is that it is less effective in shallow areas and has a low intensity of contaminants. The primary focus of the electrokinetic phytoremediation combination technique has been on heavy metals rather than organic contaminants. This is due to the easier mobilization of ionic species under electric fields compared to non-ionic organic pollutants, which require further research and development to optimize electrokinetic systems for organic contaminant removal.

8. Advantage, Disadvantage, Limitation, Challenge, and Solution

Electrokinetic remediation offers a range of advantages that make the technique a promising technology for soil contamination treatment. One of its benefits is the increased removal efficiency. This technology effectively mobilizes and extracts various contaminants from the soil using electrical fields. These electric fields have enhanced the overall efficiency of contaminant removal compared to traditional methods. Flexible installation is another significant advantage. Electrokinetic systems can be easily adapted to different site conditions, whether in-situ or ex-situ [55]. This adaptability makes the remediation process suitable for a wide range of contamination conditions. In addition, the operation cost is relatively low. Compared to energy-intensive methods like thermal remediation, electrokinetic remediation requires less electricity and this option provides lower operational expenses. In large-scale or long-term remediation projects, cost-effectiveness is crucial making electrokinetic remediation a financially viable option for addressing extensive soil contamination. Other than that, electrokinetic remediation also provides safe operation where it requires minimal direct exposure of operators to contaminants. During the operation, it reduces health risks for workers and minimizes the need for extensive protective measures, particularly in hazardous environments. The employ of electrokinetic remediation is not limited to treating small contaminated areas [56]. The system can be scaled up to address large amounts of contaminants that are applicable for both localized pollution and widespread contamination. This scalability ensures that the technology can be used effectively from small industrial sites to large agricultural lands. Despite its numerous advantages, electrokinetic remediation also has prominent disadvantages. One major drawback is its low effectiveness in removing non-polar organic pollutants [55]. These contaminants, including certain pesticides and industrial chemicals, have weak desorption capacity and poor solubility in water. These characteristics are difficult to mobilize using electrical fields alone, and therefore, reduce the overall effectiveness of electrokinetic remediation for a wide range of common soil contaminants.

The limitations of electrokinetic remediation are closely linked to the nature of the contaminants that it can effectively address. Most organic contaminants found in soil are neutral in charge and have low solubility in water. The mechanisms that drive electrokinetic remediation (electroosmosis and electromigration) rely on the presence of molecules with charges and adequate solubility in fluids [57]. Therefore, the remediation of neutral and poorly soluble organic contaminants is limited. This poses a significant challenge for contaminated sites with complex mixtures of pollutants. One of the operational challenges of electrokinetic remediation is the impact on soil pH conditions. During the process, water within the soil undergoes oxidation and reduction reactions at the electrodes [58]. The cathode, undergoing oxidation, releases hydroxide ions (OH^-), which create an alkaline environment, while the anode, undergoing reduction, releases hydrogen ions (H^+), resulting in an acidic environment [31]. These varying pH conditions can affect the chemical reactions of pollutants, potentially complicating the remediation process and affecting the stability of certain contaminants. Moreover, the effectiveness of single electrokinetic remediation is limited by time and pollutant removal efficiency [55]. It often requires prolonged treatment periods to achieve desired levels of contaminant removal, which can be impractical for sites needing quick remediation. This time-consuming process can also increase overall project costs and delay the return of the site to productive use.

To overcome these challenges, several solutions have been proposed and implemented. One effective approach is the introduction of co-solvents and surfactants [17]. Co-solvents, such as alcohols or organic solvents, can enhance the solubility of non-polar pollutants, making them more amenable to mobilization and removal. Surfactants, which are compounds that reduce surface tension, can facilitate the desorption of contaminants from soil particles and increase their mobility within the soil matrix. These facilitating agents help improve the overall effectiveness of electrokinetic remediation, particularly for challenging contaminants. Combining electrokinetic remediation with other technologies is another recommended solution [59]. Integrating electrokinetic methods with technologies like bioremediation and phytoremediation enhances contaminant removal by leveraging the strengths of each approach. For example, bioremediation uses microorganisms to degrade pollutants, while phytoremediation employs plants to absorb and accumulate contaminants [60]. When used in conjunction with electrokinetic techniques, these methods provide a more comprehensive and effective remediation strategy, addressing a broader range of contaminants and improving overall site cleanup. Additionally, addressing the variable pH conditions requires careful management. Techniques such as buffering the soil to stabilize pH levels or using pHneutralizing agents can help mitigate the impact of pH fluctuations on the remediation process [61, 62]. This ensures that the chemical environment remains conducive to effective contaminant removal and prevents potential adverse effects on soil health and contaminant behavior.

9. Conclusions

In conclusion, the function of electrokinetic remediation is to improve the removal of organic contaminants in low hydraulic conductivity of soil. This is because the majority of the organic contaminants are hydrophobic (repel from water) and non-polar. When direct current is applied, the organic contaminants are charged and the transportation of contaminants can be controlled. Thus, the electrokinetic combined with bioremediation or phytoremediation is able to raise the removal efficiency of organic contaminants. The addition of surfactants and cosolvent is to overcome the hydrophobic characteristics by increasing the solubility of contaminants. Electrokinetic remediation can be recommended as it is eco-friendly as stated in most of the review articles. The application of electrokinetic has been widely accepted as it is flexible, cost-effective, and safe. However, the removal efficiency of non-polar organic contaminants in soil is low, and professional knowledge is required for operation. In summary, electrokinetic remediation can be recommended as it is eco-friendly as stated in most of the literature and some remediation technology does produce secondary contamination on the environment. The best solution is to reduce the usage of pesticides, insecticides, and herbicides that contain high organic contamination and replace them with those that are biodegradable. Machinery should be sent for servicing regularly to avoid oil and grease leakage.

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Competing Interest

The authors declare no conflict of interest.

References

[1] Moore, D.; Robson, G.D.; Trinci, A.P.J. (2020). 21st Century Guidebook to Fungi, 2nd ed.; Cambridge University Press: Cambridge, United Kingdom.

[2] Rai, P.K.; Lee, S.S.; Zhang, M.; Tsang, Y.F.; Kim, K.-H. (2019). Heavy metals in food crops: Health risks, fate, mechanisms, and management. *Environment international*, *125*, 365–385. https://doi.org/10.1016/j.envint.2019.01.067.

[3] Chernysh, Y.; Chubur, V.; Ablieieva, I.; Skvortsova, P.; Yakhnenko, O.; Skydanenko, M.; Plyatsuk, L.; Roubík, H. (2024). Soil Contamination by Heavy Metals and Radionuclides and Related Bioremediation Techniques: A Review. *Soil System*, *8*, 36. https://doi.org/10.3390/soilsystems8020036.

[4] Snousy, M.; Khalil, M.; Abdel-moghny, T.; Ali, E.-s. (2016). An Overview on the Organic Contaminants. *SDRP Journal Of Earth Sciences & Environmental Studies*, *1*, 9. http://doi/org/10.25177/JESES.1.2.1.

[5] Zhang, L.; Li, J.; Zhao, Y.; Li, X.; Yang, X.; Wen, S.; Cai, Z.; Wu, Y. (2011). A national survey of polybrominated diphenyl ethers (PBDEs) and indicator polychlorinated biphenyls (PCBs) in Chinese mothers' milk. *Chemosphere*, *84*, 625–633. http://doi/org/https://doi.org/10.1016/j.chemosphere.2011.03.041.
[6] Paz-Ferreiro, J.; Gascó, G.; Méndez, A.; Reichman, S.M. (2018). Soil Pollution and Remediation. *I nternational Journal of Environmental Research and Public Health*, *15*, 1657. https://doi.org/10.3390/ijerph15081657.
[7] Tsiantas, P.; Karasali, H.; Pavlidis, G.; Kavasilis, S.; Doula, M. (2023). The status of organochlorine pesticide contamination in Greek agricultural soils: the ghost of traditional agricultural history. *Environmental Science and Pollution Research*, *30*, 117654–117675. http://doi/org/10.1007/s11356-023-30447-2.
[8] Sun, J.; Pan, L.; Tsang, D.C.W.; Zhan, Y.; Zhu, L.; Li, X. (2018). Organic contamination and remediation in the agricultural soils of China: A critical review. *Science of the Total Environment*, *615*, 724–740. http://doi/org/https://doi.org/10.1016/j.scitotenv.2017.09.271.
[9] Singh, K.P.; Malik, A.; Sinha, S. (2007). Persistent Organochlorine Pesticide Residues in Soil and Surface Water of Northern Indo-Gangetic Alluvial Plains. *Environmental Monitoring and Assessment*, *125*, 147–155. http://doi/org/10.1007/s10661-006-9247-0.
[10] Zhang, H.B.; Luo, Y.M.; Wong, M.H.; Zhao, Q.G.; Zhang, G.L. (2006). Distributions and Concentrations of PAHs in Hong Kong Soils. *Environmental Pollution*, *141*, 107–114. http://doi/org/https://doi.org/10.1016/j.envpol.2005.08.031.
[11] Nguyen, N.V. (2009). Occurrence of persistent toxic substances in soils, sediments, fishes and human breast milk in southern Vietnam; Lausanne, EPFL: Lausanne, Switzerland. http://doi/org/10.5075/epfl-thesis-4520.
[12] Brusseau, M.L. (1991). Cooperative sorption of organic chemicals in systems composed of low organic carbon aquifer materials. *Environmental Science & Technology*, *25*, 1747–1752. http://doi/org/10.1021/es00022a011.
[13] Mackay, D.M.; Roberts, P.V.; Cherry, J.A. (1985). Transport of organic contaminants in groundwater. *Environmental Science & Technology*, *19*, 384–392. http://doi/org/10.1021/es00135a001.
[14] Copaciu, F.; Opriş, O.; Niinemets, Ü.; Copolovici, L. (2016). Toxic Influence of Key Organic Soil Pollutants on the Total Flavonoid Content in Wheat Leaves. *Water, Air, & Soil Pollution*, *227*, 196. http://doi/org/10.1007/s11270-016-2888-x.
[15] Zhang, Y.; Li, S.; Zhang, Y.; Chen, Y.; Wang, X.; Sun, Y. (2022). Bioaccumulation and Biomagnification of Hexabromocyclododecane in Marine Biota from China: A Review. *Toxics*, *10*, 620. https://doi.org/10.3390/toxics10100620.
[16] Carpenter, D.O. (2011). Health effects of persistent organic pollutants: the challenge for the Pacific Basin and for the world. *Reviews on Environmental Health*, *26*, 61–69. http://doi/org/doi:10.1515/reveh.2011.009.
[17] Cameselle, C.; Gouveia, S. (2018). Electrokinetic remediation for the removal of organic contaminants in soils. *Current Opinion in Electrochemistry*, *11*, 41–47. http://doi/org/https://doi.org/10.1016/j.coelec.2018.07.005.
[18] Tiwari, M.; Tripathy, D.B. (2023). Soil contaminants and their removal through surfactant-enhanced soil remediation: a comprehensive review. *Sustainability*, *15*, 13161. https://doi.org/10.3390/su151713161.
[19] Liu, J.-W.; Wei, K.-H.; Xu, S.-W.; Cui, J.; Ma, J.; Xiao, X.-L.; Xi, B.-D.; He, X.-S. (2021). Surfactant-enhanced remediation of oil-contaminated soil and groundwater: A review. *Science of the Total Environment*, *756*, 144142. https://doi.org/10.1016/j.scitotenv.2020.144142.

[20] Zahn, D.; Neuwald, I.J.; Knepper, T.P. (2020). Analysis of mobile chemicals in the aquatic environment—current capabilities, limitations and future perspectives. *Analytical and Bioanalytical Chemistry*, *412*, 4763-4784. https://doi.org/10.1007/s00216-020-02520-z.
[21] Yaashikaa, P.; Kumar, P.S.; Jeevanantham, S.; Saravanan, R. (2022). A review on bioremediation approach for heavy metal detoxification and accumulation in plants. *Environmental Pollution*, *301*, 119035. https://doi.org/10.1016/j.envpol.2022.119035.
[22] Mousavi, S.M.; Hashemi, S.A.; Iman Moezzi, S.M.; Ravan, N.; Gholami, A.; Lai, C.W.; Chiang, W.-H.; Omidifar, N.; Yousefi, K.; Behbudi, G. (2021). Recent advances in enzymes for the bioremediation of pollutants. *Biochemistry Research International*, *2021*, 5599204. https://doi.org/10.1155/2021/5599204.
[23] Cameselle, C.; Pena, A. (2016). Enhanced electromigration and electro-osmosis for the remediation of an agricultural soil contaminated with multiple heavy metals. *Process Safety and Environmental Protection*, *104*, 209–217. http://doi/org/https://doi.org/10.1016/j.psep.2016.09.002.
[24] Wang, J.-Y.; Huang, X.-J.; Kao, J.C.M.; Stabnikova, O. (2007). Simultaneous removal of organic contaminants and heavy metals from kaolin using an upward electrokinetic soil remediation process. *Journal of Hazardous Materials*, *144*, 292–299. http://doi/org/https://doi.org/10.1016/j.jhazmat.2006.10.026.
[25] Bruell, C.J.; Segall, B.A.; Walsh, M.T. (1992). Electroosomotic Removal of Gasoline Hydrocarbons and TCE From Clay. *Journal of Environmental Engineering*, *118*, 68–83. http://doi/org/doi:10.1061/(ASCE)0733-9372(1992)118:1(68).
[26] Acar, Y.B.; Li, H.; Gale, R.J. (1992). Phenol Removal from Kaolinite by Electrokinetics. *Journal of Geotechnical Engineering*, *118*, 1837–1852. http://doi/org/doi:10.1061/(ASCE)0733-9410(1992)118:11(1837).
[27] Vocciante, M.; Dovì, V.G.; Ferro, S. (2021). Sustainability in ElectroKinetic Remediation Processes: A Critical Analysis. *Sustainability*, *13*, 770. https://doi.org/10.3390/su13020770.
[28] Shin, S.-Y.; Park, S.-M.; Baek, K. (2017). Soil moisture could enhance electrokinetic remediation of arsenic-contaminated soil. *Environmental Science and Pollution Research*, *24*, 9820–9825. http://doi/org/10.1007/s11356-017-8720-3.
[29] Hassan, I.; Mohamedelhassan, E.; Yanful, E.K. (2015). Solar powered electrokinetic remediation of Cu polluted soil using a novel anode configuration. *Electrochimica Acta*, *181*, 58–67. https://doi.org/10.1016/j.electacta.2015.02.216.
[30] Yao, Z.; Li, J.; Xie, H.; Yu, C. (2012). Review on Remediation Technologies of Soil Contaminated by Heavy Metals. *Procedia Environmental Sciences*, *16*, 722–729. https://doi.org/10.1016/j.proenv.2012.10.099.
[31] Ottosen, L.M.; Larsen, T.H.; Jensen, P.E.; Kirkelund, G.M.; Kerrn-Jespersen, H.; Tuxen, N.; Hyldegaard, B.H. (2019). Electrokinetics applied in remediation of subsurface soil contaminated with chlorinated ethenes – A review. *Chemosphere*, *235*, 113–125. https://doi.org/10.1016/j.chemosphere.2019.06.075.
[32] Song, X.; Carlsson, C.; Kiilsgaard, R.; Bendz, D.; Kennedy, H. (2020). Life Cycle Assessment of Geotechnical Works in Building Construction: A Review and Recommendations. *Sustainability*, *12*, 8442.https://doi.org/10.3390/su12208442.
[33] Ricart, M.T.; Pazos, M.; Gouveia, S.; Cameselle, C.; Sanromán, M.A. (2008). Removal of organic pollutants and heavy metals in soils by electrokinetic remediation. *Journal of Environmental Science and Health, Part A*, *43*, 871–875. http://doi/org/10.1080/10934520801974376.
[34] Juan-García, A.; Font, G.; Picó, Y. (2005). Determination of organic contaminants in food by capillary electrophoresis. *Journal of Separation Science*, *28*, 793–812. http://doi/org/10.1002/jssc.200500041.

[35] Whatley, H. Balbaied, T.; Moore, E. (2023). Overview of Capillary Electrophoresis Analysis of Alkaline Phosphatase (ALP) with Emphasis on Post-Translational Modifications (PTMs). *Kinases Phosphatases*, *1*, 206–219. https://doi.org/10.3390/kinasesphosphatases1030013.

[36] Karagunduz, A.; Gezer, A.; Karasuloglu, G. (2007). Surfactant enhanced electrokinetic remediation of DDT from soils. *Science of the Total Environment*, *385*, 1–11. http://doi/org/https://doi.org/10.1016/j.scitotenv.2007.07.010.

[37] Jeon, C.-S.; Yang, J.-S.; Kim, K.-J.; Baek, K. (2010). Electrokinetic Removal of Petroleum Hydrocarbon from Residual Clayey Soil Following a Washing Process. *CLEAN – Soil, Air, Water*, *38*, 189–193. http://doi/org/https://doi.org/10.1002/clen.200900190.

[38] Han, H.; Lee, Y.-J.; Kim, S.-H.; Yang, J.-W. (2009). Electrokinetic Remediation of Soil Contaminated with Diesel Oil Using EDTA–Cosolvent Solutions. *Separation Science and Technology*, *44*, 2437–2454. http://doi/org/10.1080/01496390902983794.

[39] Wang, B.; Wang, X.; Hu, F.; Wang, X.; Yang, Z.; Zhu, X.; Li, G.; Wang, K. (2024). Study on the Properties of Compound Surfactants with PO Groups. *Energies*, *17*, 513. https://doi.org/10.3390/en17020513.

[40] Fardin, A.B.; Jamshidi-Zanjani, A.; Darban, A.K. (2021). Application of enhanced electrokinetic remediation by coupling surfactants for kerosene-contaminated soils: Effect of ionic and nonionic surfactants. *Journal of Environmental Management*, *277*, 111422. ttps://doi.org/10.1016/j.jenvman.2020.111422.

[41] Calenciuc, C.; Fdez-Sanromán, A.; Lama, G.; Annamalai, S.; Sanromán, A.; Pazos, M. (2022). Recent Developments in Advanced Oxidation Processes for Organics-Polluted Soil Reclamation. *Catalysts*, *12*, 64. https://doi.org/10.3390/catal12010064.

[42] Liu, X.; Wang, Y. (2022). Identification and Assessment of Groundwater and Soil Contamination from an Informal Landfill Site. *Sustainability*, *14*, 16948. https://doi.org/10.3390/su142416948.

[43] Kang, J.W. (2014). Removing environmental organic pollutants with bioremediation and phytoremediation. *Biotechnology Letter*, *36*, 1129–1139. http://doi/org/10.1007/s10529-014-1466-9.

[44] Hassan, I.; Mohamedelhassan, E.; Yanful, E.; Yuan, Z. (2016). A Review Article: Electrokinetic Bioremediation Current Knowledge and New Prospects. *Advances in Microbiology*, *6*, 57–72. http://doi/org/10.4236/aim.2016.61006.

[45] Gill, R.T.; Harbottle, M.J.; Smith, J.W.N.; Thornton, S.F. (2014). Electrokinetic-enhanced bioremediation of organic contaminants: A review of processes and environmental applications. *Chemosphere*, *107*, 31–42. https://doi.org/10.1016/j.chemosphere.2014.03.019.

[46] Dong, Z.-Y.; Huang, W.-H.; Xing, D.-F.; Zhang, H.-F. (2013). Remediation of soil co-contaminated with petroleum and heavy metals by the integration of electrokinetics and biostimulation. *Journal of Hazardous Materials*, *260*, 399–408. ttps://doi.org/10.1016/j.jhazmat.2013.05.003.

[47] Pazos, M.; Plaza, A.; Martín, M.; Lobo, M.C. (2012). The impact of electrokinetic treatment on a loamy-sand soil properties. *Chemical Engineering Journal*, *183*, 231–237. https://doi.org/10.1016/j.cej.2011.12.067.

[48] Mena Ramírez, E.; Villaseñor Camacho, J.; Rodrigo Rodrigo, M.A.; Cañizares Cañizares, P. (2014). Feasibility of electrokinetic oxygen supply for soil bioremediation purposes. *Chemosphere*, *117*, 382–387. https://doi.org/10.1016/j.chemosphere.2014.07.075.

[49] Mao, X.; Wang, J.; Ciblak, A.; Cox, E.E.; Riis, C.; Terkelsen, M.; Gent, D.B.; Alshawabkeh, A.N. (2012). Electrokinetic-enhanced bioaugmentation for remediation of chlorinated solvents contaminated clay. *Journal of Hazardous Materials*, *213–214*, 311–317. http://doi/org/10.1016/j.jhazmat.2012.02.001.

[50] Mena, E.; Villaseñor, J.; Rodrigo, M.A.; Cañizares, P. (2016). Electrokinetic remediation of soil polluted with insoluble organics using biological permeable reactive barriers: Effect of periodic

polarity reversal and voltage gradient. *Chemical Engineering Journal*, *299*, 30–36. https://doi.org/10.1016/j.cej.2016.04.049.

[51] Cameselle, C.; Chirakkara, R.A.; Reddy, K.R. (2013). Electrokinetic-enhanced phytoremediation of soils: Status and opportunities. *Chemosphere*, *93*, 626–636. https://doi.org/10.1016/j.chemosphere.2013.06.029.

[52] Park, J.K.; Oh, K. (2023). Advancements in Phytoremediation Research for Soil and Water Resources: Harnessing Plant Power for Environmental Cleanup. *Sustainability*, *15*, 13901. https://doi.org/10.3390/su151813901.

[53] Cameselle, C.; Gouveia, S.; Cabo, A. (2021). Enhanced Electrokinetic Remediation for the Removal of Heavy Metals from Contaminated Soils. *Applied Sciences*, *11*, 1799. https://doi.org/10.3390/app11041799.

[54] Mulati, H.; Mamat, A.; Ailijiang, N.; Jiang, L.; Li, N.; Hu, Y.; Su, Y. (2023). Electrokinetic-Assisted Phytoremediation of Pb-Contaminated Soil: Influences of Periodic Polarity Reversal Direct Current Field. *Sustainability*, *15*, 8439. https://doi.org/10.3390/su15118439.

[55] Moghadam, M.J.; Moayedi, H.; Sadeghi, M.M.; Hajiannia, A. (2016). A review of combinations of electrokinetic applications. *Environmental Geochemistry and Health*, *38*, 1217–1227. http://doi/org/10.1007/s10653-016-9795-3.

[56] Tripathi, M.; Singh, S.; Pathak, S.; Kasaudhan, J.; Mishra, A.; Bala, S.; Garg, D.; Singh, R.; Singh, P.; Singh, P.K.; et al. (2023). Recent Strategies for the Remediation of Textile Dyes from Wastewater: A Systematic Review. *Toxics*, *11*, 940. https://doi.org/10.3390/toxics11110940.

[57] Han, D.; Wu, X.; Li, R.; Tang, X.; Xiao, S.; Scholz, M. (2021). Critical review of electro-kinetic remediation of contaminated soils and sediments: mechanisms, performances and technologies. *Water, Air, & Soil Pollution*, *232*, 335. https://doi.org/10.1007/s11270-021-05182-4.

[58] Lageman, R.; Clarke, R.L.; Pool, W. (2005). Electro-reclamation, a versatile soil remediation solution. *Engineering Geology*, *77*, 191–201. https://doi.org/10.1016/j.enggeo.2004.07.010.

[59] Huang, D.; Xu, Q.; Cheng, J.; Lu, X.; Zhang, H. (2012). Electrokinetic Remediation and Its Combined Technologies for Removal of Organic Pollutants from Contaminated Soils. *International Journal of Electrochemical Science*, *7*, 4528–4544. https://doi.org/10.1016/S1452-3981(23)19558-7.

[60] Demarco, C.F.; Quadro, M.S.; Selau Carlos, F.; Pieniz, S.; Morselli, L.B.G.A.; Andreazza, R. (2023). Bioremediation of Aquatic Environments Contaminated with Heavy Metals: A Review of Mechanisms, Solutions and Perspectives. *Sustainability*, *15*, 1411. https://doi.org/10.3390/su15021411.

[61] Wang, F.; Wang, H.; Dong, W.; Yu, X.; Zuo, Z.; Lu, X.; Zhao, Z.; Jiang, J.; Zhang, X. (2024). Enhanced multi-metals stabilization: Synergistic insights from hydroxyapatite and peroxide dosing strategies. *Science of the Total Environment*, *927*, 172159. https://doi.org/10.1016/j.scitotenv.2024.172159.

[62] Gonçalves, N.P.; da Silva, E.F.; Tarelho, L.A.; Labrincha, J.A.; Novais, R.M. (2024). Simultaneous removal of multiple metal (loid) s and neutralization of acid mine drainage using 3D-printed bauxite-containing geopolymers. *Journal of Hazardous Materials*, *462*, 132718. https://doi.org/10.1016/j.jhazmat.2023.132718.