Electrokinetic-Assisted Bioremediation and Phytoremediation for the Treatment of Polluted Soil

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24 Electrokinetic-Assisted Bioremediation and Phytoremediation for the Treatment of Polluted Soil

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Abstract

The contamination of soil from heavy metals (HMs), petroleum hydrocarbons (PHCs), and pesticides have become a serious environmental problem in the current world. The pollution has resulted from anthropogenic activities, rapid industrialization, and urbanization. Pesticides are used extensively in farming activities to meet the increasing demand for food and feed. The pollutants change the physicochemical and microbiological characteristics of soil and have mutagenic, carcinogenic, immunotoxic, and teratogenic effects on human health. There is an urgent necessity for sustainable and eco-friendly remediation technologies for the elimination of contaminants from soil. Electrokinetic-assisted remediation (EKR) is an opportune technology for complete remediation of polluted soil including fine-grained soils, which are typically difficult to clean-up using traditional bioremediation and phytoremediation approaches because of several drawbacks. Electrokinetic-Assisted Bioremediation (EKBR) and Electrokinetic-Assisted Phytoremediation (EKPR) are novel and effective technologies for soil remediation which decontaminate heavy metal, remove PHCs and pesticides from polluted soils. This chapter emphasizes electrokinetic-assisted remediation, current development, process, field applications, advantages, disadvantages, and further prospects.

Keywords

Bioremediation · Electrokinetic-assisted remediation · Phytoremediation · Pollutants · Sustainable

24.1 Introduction

Soil and sediment pollution is a geo-environmental problem that negatively affects the environment (Amundson et al. 2015; Gomiero 2016; Xu et al. 2019). Anthropogenic activities are causatives of these problems that negatively affect the geo-environment (Gill et al. 2014). Numerous anthropogenic roots of pollutants from farming, mining, smelting,

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electroplating, and other industrial movements are in continuation all over the world that are producing unusual depositions of unwanted quantities of pollutants including petroleum hydrocarbons, polynuclear aromatic, solvents, pesticides, and toxic heavy metals in soil (Moosavi and Seghatoleslami 2013; Jamari et al. 2014; Kanianska 2016; Tuomisto et al. 2017; Ekta and Modi 2018). Several remediation strategies such as bioremediation (Sturman et al. 1995; Gill et al. 2014; Azubuike et al. 2016) and phytoremediation (Arthur et al. 2005; Mosa et al. 2016; Feng et al. 2017; Lajayer et al. 2019) have been applied over the years to mitigate soil contamination with differing degrees of effectiveness. Plant species hold the potential to eliminate/degrade or metabolize a broad range of contaminants via phytoextraction, phytorestoration, phytostabilization, phytodegradation, phytovolatilization, or rhizofiltration (Etim 2012; Martin et al. 2014; Sasse et al. 2018; Rai et al. 2020; Dhaliwal et al. 2020).

Natural attenuation (NA) treatment, biostimulation, and site-specific bio-augmentation have resulted in very low removal/degradation of soil pollutants (Crognale et al. 2020). In recent years, innovations for the remediation of environmental pollutants from soil have gained substantial attention. Amongst them, Electrokinetic Remediation (EKR) is sustainable technology to remove heavy metals, salts, radioactive elements, and organic pollutant from fine-grained and low-permeability soil due to their environmental compatibility, and cost-effectiveness (Klouche et al. 2020a; Pham and Sillanpaa 2020). EKR is an in situ process, so for decontamination, there is no need for soil excavation (De Battisti and Ferro 2007).

Several enhanced electrokinetic remediation technologies have been applied so far, to increase the efficacy of pollutant removal from soil such as Chelating Agent-Enhanced Remediation (Yang et al. 2020), Biosurfactant-Enhanced Electrokinetic Remediation (Tang et al. 2020), Bio-electrokinetic (BEK) Remediation (Sarankumar et al. 2020), Permeable Reactive Barrier (PRB) (Zhao et al. 2016; Yao et al. 2020), Microbial Fuel Cell (MFC)-Enhanced Remediation (Gustave et al. 2020). The current studies on electrokinetic remediation mainly focus on electrokinetic remediation of inorganic and organic pollutants from soil. This chapter emphasizes soil pollutants, electrokinetic-assisted remediation, current development, process, energy consumption, and field applications.

24.2 Soil Pollutants and Pollution

Soil contamination with inorganic substances, including radioactive elements heavy metals, and salts, and organic pollutants, poses threats to human and environment, which in recent years have attracted widespread attention (Sorengard et al. 2020; Wen et al. 2021). The expansion of urbanization and industrial activity has exacerbated significant environmental issues, such as soil contamination, over the last decade (Gnanasundar and Akshai 2020).

24.2.1 Inorganic Contaminants

Soil polluted with inorganic contaminants including radioactive elements, heavy metals, and salts due to certain imbalances and unstoppable anthropogenic processes, such as industrialization, urbanization, and incorrect farming practices pose threats to human health and ecological climate, which in recent years have attracted widespread attention (Singh et al. 2020). The pollution of heavy metals in soil is one of the serious problems and has a huge impact on the environment (Dhaliwal et al. 2020). Usually, heavy metals are found as cations or as retained on soil particles with organic or inorganic bonds. These are responsible for many widespread poisoning activities (Wuana and Okieimen 2011; Tchounwou et al. 2012; Jaishankar et al. 2014; Mao et al. 2016; Palansooriya et al. 2020)."Heavy metals" are a group of elements with an atomic mass of >5 g/cm^3, or >5 times than water (Rajindiran et al. 2015). Lead and arsenic are the soil's major environmental contaminants, so the removal of this metal from the soil is essential in the context of ecological safety

(Selvi et al. 2019; Ait Ahmed 2020). Arsenic contamination in soil is a major problem nowadays and poisoning the human body through crops and vegetables (Shrivastava et al. 2015). With the enhancement of accumulation, heavy metals cause atherosclerosis, melanoma, Alzheimer's disease, Parkinson's disease, etc. (Bakulski et al. 2020). Over the past two decades, substantial research by scientists and experts has concentrated on discovering new ways to eliminate soil pollutants (Cercato and De Donno 2020).

Across the globe, radioactive element contamination of soil and sediments by anthropogenic activities is a major concern. The radioactive substance and waste were produced during the operation of nuclear reactors, uranium mining and milling, nuclear weapons program, nuclear weapons testing, fuel manufacturing units, fuel reprocessing plants, research laboratories working on radionuclides, radioisotope in medicine and industry, accidents and disasters. Huge quantities are produced by coal-fired power plants, which also contained radionuclides elements (Hu et al. 2010; Sharma et al. 2014). Radionuclide-contaminated soils, particularly ^{137}Cs. ^{238}U, ^{239}Pu, and ^{90}Sr, pose a long-term radiation threat to the health of human through exposure via the food chain and other routes (Zhu and Shaw 2000). The primary path of internal radionuclide ingestion in humans is the consumption of food goods tainted with radionuclides (Shaw and Bell 1994).

24.2.2 Organic Contaminants

Soil is a complex environment that supports human activities and ecosystems across a large variety of functions (Upcraft and Guo 2020). The natural ecosystem and public health have been negatively impacted by organic pollutants of soil (Ojuederie and Babalola 2017). The major organic pollutants are Polybrominated Biphenyls (PBBs), Polycyclic Aromatic Hydrocarbons (PAHs), Polychlorinated Biphenyls (PCBs), Polychlorinated dibenzofurans (PCDFs), Polychlorinated dibenzodioxins (PCDDs), organophosphorus and carbamate insecticides (Pesticides), herbicides, fertilizers, and other agriculture product and organic fuels (Gasoline and Diesel).

Organic contaminants contain many insecticides and herbicides that have been used in farming and weed and pest management to fulfill the growing demand for food and feed (Schell et al. 2012; Boudh and Singh 2019; Rajendran et al. 2021). Humans can be affected to pesticides via inhaling soil particles, ingesting soil, and dermal touch (Li 2018). Polychlorinated biphenyls (PCBs) are organic pollutants with hydrophobic properties that inhibit the metabolic process (Burca and Watson 2014). Among the current environmental issues, soil contamination of petroleum (Total Petroleum Hydrocarbon; TPH) is one of the most severe soil pollution problems. The occurrence of petroleum hydrocarbons pollutants in the soil causes major environmental effects and poses a significant risk to humans (Khan et al. 2018a). Petroleum hydrocarbons and their derivatives adversely affect both the environment and human health (Varjani and Upasani 2017; Huang et al. 2019). Dioxin {Polychlorinated dibenzodioxins (PCDDs) and Polychlorinated dibenzofurans (PCDFs)} is an environmental pollutant that is a byproduct of the processes of paper bleaching, herbicide/pesticide production, and incineration of solid/hospital waste (Kimbel et al. 2019; Tu et al. 2021).

24.3 Need for Remediation of Soil Pollutants

Soil is an essential environmental factor that constitutes the ecosystem for the life and growth of human beings (Zhao et al. 2016). The inorganic and organic pollutants in the soil and sediment became very serious worldwide. Such polluted areas are increasing day by day in various countries. There are more than 20 million hectares of land globally polluted by heavy metal (loid)s (Liu et al. 2018). Many of these substances are exceedingly persistent and accumulate beyond acceptable levels in the soil (Ahmad et al. 2017). The pollutants acidify and contaminated the soil and threatening the production of crops, food quality, environmental safety, and public health as well as sustainable expansion (Song et al. 2017). Biological, chemical, physical, and combined processes for remediation have been implemented in recent years to address the problems of contamination of soil and sediments (Khan et al. 2018b). In the majority of situations, the purpose of soil remediation activities is to reduce toxins to levels that are acceptable for usage and to ensure that we're using our land without environmental hazards (Acar and Alshawabkeh 1993).

The best approach to remediation of soil pollutants is the prevention of soil pollution. The soil remediation strategy selected for the polluted soil according to nature, potential hazard, soil characteristics, time, laboratory studies, and feasibility (Lombi and Hamon 2005; Daghan and Ozturk 2015). The remediation of the pollutant from the soil is fundamental for the sustainable development and protection of ecosystems and biodiversity (Stojic et al. 2018). Substantial courtesy has been given to suitable technology for the remediation of harmful contaminants from the land. Among them, electrokinetic (EK) remediation is highlighted because of its versatility and amenability (Andrade and dos Santos 2020). Electrokinetic phenomena (electrosmosis, electrophoresis, electrolysis) in which continuous electricity is produced for the elimination of inorganic and organic contaminants in the polluted soil (Llorente et al. 2014).

24.4 Electrokinetic Assisted Remediation (EKR)

Bioremediation and phytoremediation have been extensively used to improve soils, though it can face some limitations like the term of contaminants, time to be taking in processing (excavation or removal) of contaminants, availability of hyperaccumulator plants, etc. (Mosavat et al. 2012; Couto et al. 2015; Jamil et al. 2015). Electrokinetic (EK) remediation is a new technology for physicochemical remediation which relies on the application of a direct current of low intensity to boost contaminant mobilisation. Since the early 1800s, the concept of electrokinetic remediation has been hypothesized in the context of Electroosmosis. Electrokinetics (EK) uses a low electrical current put in the soil between an anode and a cathode (Fig. 24.1). It was conducted first by the F.F. Reuss in the year 1809 (Reuss 1809; Wall 2010; Biscombe 2017). Electrokinetic remediation is broadly applied to exclude metals, radionuclides, polar inorganic pollutants from soil (Lacatusu et al. 2013). The applied electric potential for EKR is greater than 1 V/cm and the power supply is over than 1 mA/cm^2 (Reddy et al. 2006; Yoo et al. 2015; Li et al. 2019).

In electrokinetic remediation process, the current passes between the electrodes into the soil, which causes several physical and chemical impressions like electrolysis, electromigration, electroosmosis, electrophoresis, electro-oxidation, pH fluctuations, water hydrolysis, etc. (Isosaari et al. 2007; Streche et al. 2018; Head et al. 2020). Numerous studies have reported that electrokinetic remediation is feasible to decontaminate complex toxic contaminants with low power consumption (Cong et al. 2005; Szpyrkowicz et al. 2007; Zheng et al. 2007; Truu et al. 2015; Acosta-Santoyo et al. 2017; Popescu et al. 2017; Meshalkin et al. 2020; Ajiboye et al. 2021).

24.4.1 Electrokinetic Assisted Bioremediation (EKBR)

Electrokinetic bioremediation is an effective technique that can dramatically increase the delivery of nutrients to natural microorganisms and thereby have a substantial opportunity to clean contaminated soils, such as fine-grained soils, which are usually difficult to clean up using conventional methods (Alshawabkeh 2009; Tahmasbian and Sinegani 2016; Karaca et al. 2019; Zhou et al. 2020). The combination of electrokinetic technology and bioremediation allows the absorption of toxins in the form of ions that are also bacterial activity inhibitors. Thus, it allows full remediation of the polluted

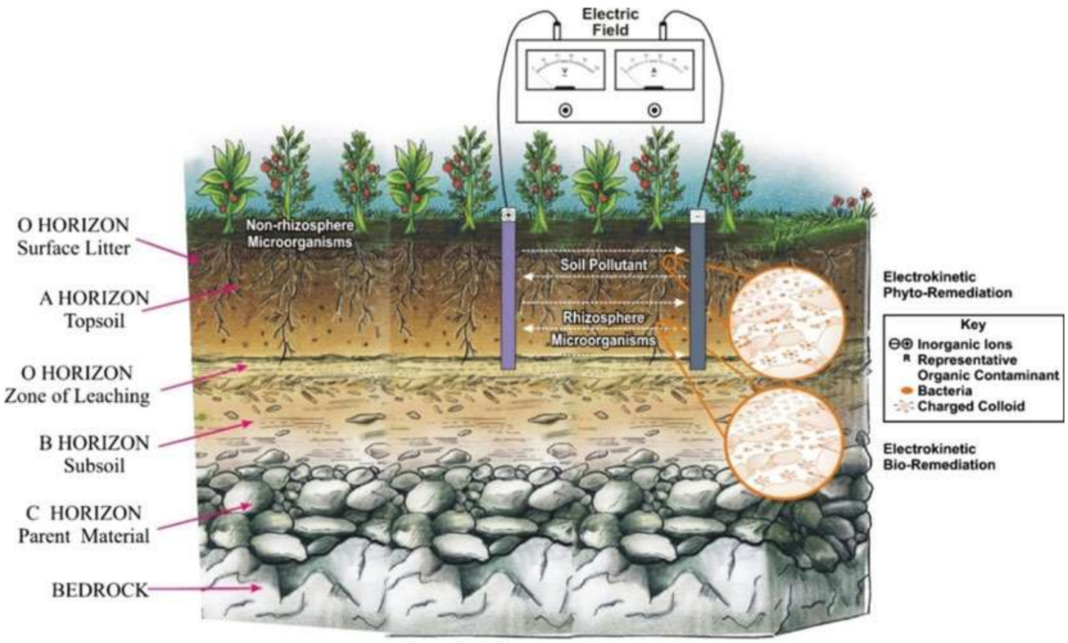

Fig. 24.1 Process of electrokinetic assisted bioremediation and phytoremediation

soil (Chilingar et al. 1997; Gill et al. 2014). The electric field is used in such a remediation procedure to improve the rate of degradation by extending the electrokinetics associated with the transfer of nutrients and adding new bacteria in the absence of indigenous microorganisms (Luo et al. 2005; Dzionek et al. 2016; Ottosen et al. 2019).

Here, a redox reaction involves the electrodes in the presence of bacteria and creates hydrogen ions and oxygen gas at the anode side and hydroxyl ions and hydrogen gas at the cathodes. Hydrogen ions from an acidic presence pass into the cathode via the influence of three processes, namely electroosmotic movement, diffusion, and electromigration. This approach lowers the soil's pH, producing an acidic environment. While hydroxide ions form a fundamental character and move by electromigration and diffusion toward the anode. In electrokinetic bioremediation, the pH of the soil also plays an important role in completing the process. However, bacterial survival and optimal degradation performance are influenced directly by pH (Hassan et al. 2018; Gidudu and Chirwa 2020a).

The oxygen ions can be transferred within the soil and can start an anaerobic biodegradation process because of the high porosity of the silty and sandy soils. While electrical flow often increases the temperature of the polluted soil at a high degree, it has an antagonistic effect on the microorganisms' survival (Virkutyte et al. 2002; Hassan et al. 2016). The cost of electrical power needed for electrokinetic is a big part of the total cost of the electrokinetic-remediation process, according to the literature. Energy expenditure, thus, raises the expense of the bioremediation process and results in the limitation of wide-ranging electrokinetic bioremediation applications (Li et al. 2017; Mao et al. 2019).

24.4.2 Electrokinetic Assisted Phytoremediation (EKPR)

There is an alliance of phytoextractor plants and an electrokinetics system to circumvent the restrictions of conventional phytoremediation for the elimination of both inorganic and organic contaminants from soils. It is termed as "Electrokinetic Assisted Phytoremediation". In this process, a low-voltage electric field (DC) is applied across polluted soil in surrounding area of rising plants to move soluble pollutants out of the soil (Fig. 24.2) (Acar and Alshawabkeh 1993; Virkutyte et al. 2002; O'Connor et al. 2003; Lageman et al. 2005; Sanchez et al. 2020; Siyar et al. 2020). However, little is known about the influence of Electrokinetic-assisted phytoremediation on the biological and physiological properties of soil (Cang et al. 2012). To prevent any harm to the developing plants and soil microflora, the voltage of the electric field and the chemical composition of the electrode shave must be carefully chosen. The electrokinetic assisted phytoremediation technology is capable of remediating soil with mixed contaminants under the proper conditions (Cameselle and Gouveia 2018).

During the electric transient time, hydrogen ions are revealed to accumulate around the anode electrode through water electrolysis. The hydrogen ions lower the pH of the soil around the anode and form an acid front, while the hydroxyl ions raise the pH that produces a base front in the vicinity of the cathode. As an outcome, pollutants are spread around the anode electrode in the acid state and ions transported from the anode to the cathode electrode (Thangavel and Subbhuraam 2004; Dermont et al. 2008). Three electrochemical processes also happen and assist to mobilize soluble pollutants (electroosmosis, electromigration, and electrophoresis) (Kim et al. 2002; Cameselle et al. 2013; Lima et al. 2017).

Amidst, electroosmosis occurs from electrolytic cell's anode to cathode for soil moisture or groundwater. In electromigration, ions and ion compounds are transported to opposite charge electrode. While in electrophoresis, charged particles, or colloid contaminants are embedded in a free state of an electric field and are transported out of the surface (Yeung 2006; Saeedi et al. 2013; Punia and Singh 2018; Ramadan et al. 2018; Klouche et al. 2020b). Usually, the active functioning of phytoremediation–electrokinetic coupled technology depends on the type of current supply, voltage parameters,

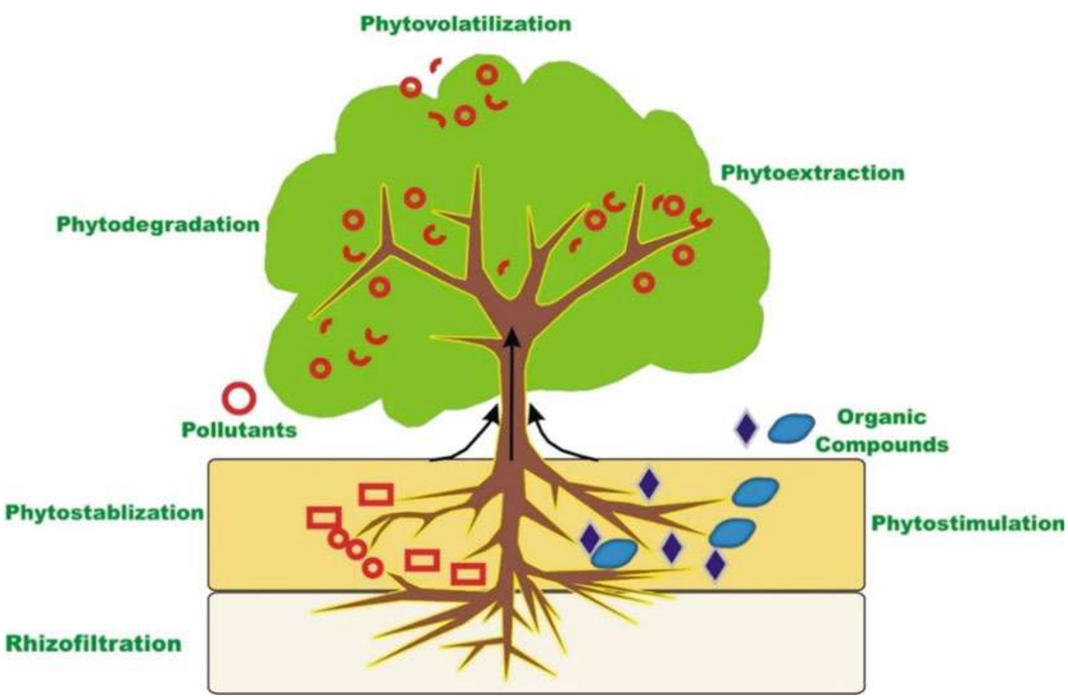

Fig. 24.2 Mechanism of enhanced electrokinetic phytoremediation

pattern of voltage use, pH of the soil, and the addition of promoting factors (Mao et al. 2016). Overall, in this hybrid technology, the plants take positions to eliminate or degrade the contaminants, whereas the electrical flows enhance the plant activity by increasing the bioavailability of pollutants (Hassan et al. 2018) (Table 24.1).

24.5 Source of Energy for Electrokinetic Remediation

In electrokinetic remediation of polluted soil, the electric field is indispensable (Wang et al. 2020). Scientists and researchers evaluated the various energy sources required for the electrokinetic remediation of soil impurities (Vocciante et al. 2016). Usually, an external current source (AC or DC) is actively employed in electrokinetics remediation. Either AC or DC systems with anode and cathode are installed inside the earth. Each electrode (anode and cathode) has a reservoir for the refilling of an ideal electrolytic solution (Kim and Han 2020).

In recent years, some innovations and advances for electrokinetic remediation have been made in the field of energy supplies to achieve better efficiency of pollutant removal from soil and cost-effectiveness. The electrokinetic remediation or process of heavy metals, pesticides, and other organic pollutants was studied on the following power/energy supply systems:

(a) Normal power supply
(b) Solar power supply and,
(c) Microbial fuel cells.

The remediation process can also be triggered by the non stabilised electric current produced by solar panels (Hassan et al. 2018). The solar-based

Table 24.1 Electrokinetic remediation technology for soil pollutant elimination

Electrokinetic technology	Soil pollutant	Observation	References
EKBR	Polycyclic Aromatic Hydrocarbon (PAH)	Removal of PAH (80%) using electrokinetic and *Sphingomonas* sp. L138 and *Mycobacterium frederiksbergense* LB501TG	Wick et al. (2004)
EKBR	Pentadecane	Removal of pentadecane (77.6%) at 0.63 mA/cm^2 after 14 days	Kim et al. (2005)
EKBR	Mercury	Removal of Mercury (78%) by *Lysinibacillus fusiformis* and electrokinetic technique (7 days; 50 V/m)	Azhar et al. (2016)
EKBR	Phenanthrene	Removal of Phenanthrene 65.1% at the anode and 49.9% at cathode using Phe-degrading *Sphingomonas* sp. GY2B	Lin et al. (2016)
EKPR	Zn, Pb, Cu, and Cd	Elimination of heavy metals from polluted soil using Potato plants	Aboughalma et al. (2008)
EKPR	Cd, Cu, Pb, and Zn	Removal of heavy metals using *Brassica juncea* after 40 days	Cang et al. (2011)
EKPR	Cd, Cu, Zn, and Pb	Metal uptake observed from *Brassica napus* and *Nicotiana tabacum* in electrical fields (AC and DC)	Bi et al. (2011)
EKPR	Heavy metals and PAHs	Removal of heavy metal and PAHs using Ryegrass (*Lolium perenne* L.) in AC electric fields	Acosta-Santoyo et al. (2017)
EKPR	Atrazine	Removal of atrazine using Ryegrass (*Lolium perenne* L.) with 0.6 V cm^{-1} DC electric field after 19 days	Sanchez et al. (2020)
EKPR	n-Hexadecane	Removal of n-Hexadecane using Ryegrass after 40 days	Wu et al. (2020b)

*EKPR: Electrokinetic-assisted phytoremediation; EKBR: Electrokinetic-assisted bioremediation system's power consumption is only 50–55% of the DC-powered system (Jeon et al. 2015). Nowadays, it is also important to investigate the applicability of alternative electricity generation and the application of adequate and inexpensive power outputs for energy fields. In most cases, to produce the electric field in the soil for the mobilization and elimination of the pollutants, direct current (DC) is applied over the electrodes. Electrokinetic remediation driven by DC may lead to an eventual expenditure of electrical energy. Solar energy has the ability for electrokinetic remediation, which transforms sunlight into electricity, to avoid the downside of DC-driven systems. Many scientific papers have been released in the last 20 years on electrokinetic remediation of toxic inorganic pollutants powered through Microbial Fuel Cells (MFC). MFC is an inexpensive, environmentally sustainable, and revolutionary bio-electrochemical technology that transforms the chemical energy of waste matter into electrical energy using extracellular-respiring microbes (Logan and Regan 2006; Wu et al. 2020a). The electrokinetic removal of zinc (Zn) and cadmium (Cd) from polluted paddy soil with MFCs were studied (Chen et al. 2015). Zn (12 mg) and cadmium (0.7 mg) were substantially removed from the contaminated soil after 78 days. The efficacy of Cd and Pb removal using Microbial fuel cells (MFCs) was investigated by Habibul et al. (2016) and found that Cd and Pb in the soil mitigated from anode to cathode.

24.6 Electrokinetic Removal of Inorganic Pollutants

Toxic heavy metals and diverse forms of nutrients and salts contain inorganic contaminants that usually arise in the form of dissolved anions and cations (Goldscheider 2010). Heavy metals and metalloids are among the inorganic pollutants of primary concern due to high toxicity at low concentrations. In soil, heavy metals may be either bound to solid phases or readily used for absorption by organisms (Kumar et al. 2016). Electrokinetic remediation (EKR) has emerged as an optimistic and effective method that can be used to eradicate organic and inorganic pollutants from contaminated land (Kim et al. 2011). Among the prominent technologies developed so far for reclamation of heavy metal polluted soil. EKR has become an effective process, especially in soils with low hydraulic conductivity (Cameselle and Gouveia 2018; Beyrami et al. 2020).

Jeon et al. (2015) found that 32 and 27% of arsenic was eliminated from the soil of a former refinery plant located in Janghang, Chungnam, Republic of Korea, by the normal power supply (Direct Current; DC) and solar power supply, respectively. Cr(VI) was removed at 99.8% in 30 min from the soil of China by using photovoltaic solar panels and a DC-DC converter for electrokinetic remediation (Zhang et al. 2015). Hassan et al. (2015) worked on Two Anode Technique (TAT) using solar cells for remediation (electrokinetic) of Copper polluted soil and observed that 75% Cu was eliminated. The highest removal of Cu (92%) was observed near the anode (Table 24.2).

There are significant threats to the environment from the deposition of lead (Pb) in sediments from anthropogenic activities (Mao et al. 2019). Hussein and Alatabe (2019) researched solar energy for electro-kinetic remediation of Baghdad, Iraq's lead (Pb) contaminated soil, and reported that 90.7, 63.3, and 42.8% of lead elimination were accomplished for sandy, sandy loam, and silty loam soils, respectively. Shu et al. (2019) reported that the removal efficiency of manganese (94.74%) and ammonia nitrogen (88.20%) using Pulse Electric field (PE) were higher than Direct Current (DC).

It has become increasingly important to remediate radionuclide-contaminated soils. Traditional methods for remediation of radioactive elements are expensive and less suitable for large-area contamination (Yan et al. 2021). With the application of physicochemical procedures such as soil cleaning, soil flushing, and soil reclamation of polluted soil with radionuclides can be achieved; however, due to the long treatment period and the associated high costs, they do not succeed (Annamalai et al. 2014; Cameselle and Gouveia 2019). Electrokinetic

Table 24.2 Electrokinetic removal of heavy metals from soil

Heavy metal	Soil sample	Solution	Time duration	Removal efficiency (%)	References
Copper	Red Soil	Lactic acid + NaOH	900 h	81%	Zhou et al. (2004)
Arsenic	Arsenic Contaminated	0.1 M $MgSO_4$ 0.1 M HNO_3	28 days	68%	Baek et al. (2009)
Copper	Kaolin	$NaNO_3$, Citric acid-Sodium citrate buffer	04 days	96.60%	Zhao et al. (2016)
Cadmium Copper Nickle Lead Zinc	Kaolinite clay	Citric acid + Calcium chloride	72 h	98.19% 95.24% 98.95% 86.21% 99.01%	Yuan et al. (2016)
Chromium (Cr^{6+})	Industrial soil	The citric acid (CA) and Polyaspartic acid (PASP)	07 days	94.27% with CA and 93.26% with PASP	Fu et al. (2017)
Lead	Saline	Citric acid and EDTA	168 h	31.5%	Ait Ahmed (2020)

remediation of soil is an emerging decontamination technology for radionuclides (Ugaz et al. 1994). Valdovinos et al. (2016) reported electrokinetic remediation of radionuclide-contaminated Phaeozem soil and observed that 61.0% of ^{99m}Tc and 71.8% of ^{24}Na were removed after 04 h. Purkis et al. (2020) observed high remediation efficiencies radionuclides (80 + % for ^{137}Cs and 50+ % for ^{90}Sr) by electrokinetic remediation (Table 24.3).

One of the most dangerous environmental challenges is salty soils, which retain massive and unsustainable quantities of noxious salt pollutants, thereby harming the ecosystem and, human health (Bessaim et al. 2020). Annamalai et al. (2014) studied electrokinetic removal of trace metals, dyes and inorganic salts from polluted agricultural soil with textile effluent and found 84% (Cl^-) and 68% (SO_4^2) removal efficiency.

24.7 Electrokinetic Removal of Organic Pollutants

Soil pollution by toxic persistent organic pollutants (POPs) such as organochlorinated pesticides, halohydrocarbons, polycyclic aromatic hydrocarbons (PAHs) and polybrominated diphenyl ethers poses a major environmental threat (Manz et al. 2001; Ren et al. 2018). Chemical contaminants are released into the atmosphere because of increased industrialization and processing practices. Hydrophobic organic contaminants (HOCs) are lethal and cannot be eliminated by normal attenuation. (Alcantara et al. 2010). Pham et al. (2009) examined ultrasonic enhanced electrokinetics (EK-US) and electrokinetics alone (EK) experiments to remove {fluoranthene (FLU), phenanthrene (PHE) and hexachlorobenzene (HCB)} persistent organic contaminants (POPs) from kaolin and found that PHE and FLU were easily extracted from EK-US compared to HCB.

To remediate petroleum-contaminated soil, Gidudu and Chirwa (2020b) used a DC-driven electrokinetic reactor with biosurfactant as demulsification. Ni et als. (2018) studied the removal of {dichloro-diphenyl-trichloroethane (DDT) and hexachloro-cyclohexane soprocide (HCH)} organochlorine pesticides from the soil and, found that Enhanced EK-Fenton treatment was better than EK-Fenton-coupled technologies (EF) and Individual Electrokinetic (IE). Souza et al. (2016) investigated the elimination of 2,4-

Table 24.3 Electrokinetic elimination of radioactive elements from soil

Radioactive element	Solution	Time duration	Removal efficiency (%)	Current/Energy	References
^{85}Sr (4892 Bq/kg) U (1027 mg/kg)	CH_3COOH (0.4 M)	5 days	89.5% 80.5%	100 mA	Kim et al. (2003)
Co^{2+} and Cs^{+}	Acetic Acid (0.01 M)	15 days	95.2% 84.2%	20 −30 mA	Kim et al. (2008)
^{60}Co (1042.4 Bq/kg) ^{137}Cs (1185.6 Bq/kg)	Nitric Acid (0.01 M)	20 days	99.7% 64.9%	15 mA/cm^2	Kim et al. (2010)
Pu(−)	Citric acid (0.04 M)	60 days	About 0.4 m^3, or 1/6 starting material remediation (1.7 Bq/g)	33 kWh/m^3	Agnew et al. (2011)
Uranium(VI) Red Soil	Citric acid, Ferric chloride	120 h	61.55 ± 0.41%	0.2559 kW	Xiao et al. (2020)

Dichlorophenoxyacetic acid by Electrokinetic Soil Flushing powered with DC and Photovoltaic (PV) solar panels. After 15 days, elimination of 2,4-D reaches 90.2% by DC power and 73.6% PV solar (Table 24.4).

24.8 Electrokinetic Removal of Co-contamination

The mixtures of inorganic and organic contaminants (Co-contamination or Mix contamination) are found commonly in the environment (Alcantara et al. 2012). The carcinogenic and mutagenic capability of co-existed inorganic and organic contaminants affects human health and, habitats (Mohamadi et al. 2019). The simultaneous elimination of co-contaminants using conventional practices e.g. phytoremediation and bioremediation are often problematic from the soil. These co-contaminants exhibit different characteristics, composition, and properties but synergistic impacts (Maturi et al. 2008; Saberi et al. 2018). Electrokinetic remediation (EKR) is the green, sustainable, and eco-friendly technology to ease the elimination of toxic pollutants from mixed contaminated soil (Cang et al. 2012; Chirakkara and Reddy 2013). However, only limited work about Electrokinetic remediation (EKR) of co-contaminants has been performed globally, and to advance the knowledge of many major mechanism-influencing influences, more study is required (Khodadoust et al. 2005; Colacicco et al. 2010; Ammami et al. 2014).

Lu (2020) examined EKR of cadmium-pyrene mixed polluted soil and observed 56.38% pyrene elimination efficiency adjacent to the electrodes due to the combined effect of electrochemical oxidation and bioremediation. Chirakkara et al. (2016) reported the influence of electrokinetic phytoremediation on contaminated soil spiked by organic (phenanthrene and naphthalene) and heavy metals (cadmium, lead and chromium) pollutants and found substantial reduction of contaminants in soil. Reddy et al. (2006) reported the enhanced electrokinetic remediation of PAHs and heavy metals at former Manufactured Gas Plant. Maturi and Reddy (2008) reported the electrokinetic simultaneous remediation of heavy metals and PAHs from low-permeability kaolin soils using cyclodextrins (Table 24.5).

24.9 Conclusion

Soil contamination from inorganic and organic pollutants poses great harm to people and their surroundings. The association of toxic heavy

Table 24.4 Electrokinetic removal of organic pollutants from soil

Organic pollutant	Soil sample	Solution	Time duration	Removal efficiency (%)	References
Chlorobenzene (CB) and trichloroethylene (TCE)	Clayey loam soddy-podzolic soil	Triton X-100, OS-20, ALM-10	45 h and 34 h	Chlorobenzene, (61%) Ttrichloroethylene (85%)	Kolosov et al. (2001)
Naphthalene and 2,4-DNT	Spiked Soil	Carboxymethyl-β-cyclodextrin	14 days	Naphthalene (83%) and 2,4-DNT (89%)	Jiradecha et al. (2006)
2,6-Dichlorophenol	Kaolinite Clay	$CH_3OH + H_3PO_4$ $KH_2PO_4 + H_3PO_4$	110 h	90%	Polcaro et al. (2007)
Benzanthracene Fluoranthene Pyrene	Contaminated Soil	Hexane	7 days	86.56% 89.78% 80.16%	Alcantara et al. (2009)
Hexachlorobenzene Phenanthrene Fluoranthene	Kaolin	Hexane	10 days	63% 84% 90%	Pham et al. (2009)
PAHs (Fluoranthene, Pyrene, and Benzanthracene)	Kaolin clay	1% Tween 80 and 0.1 M Na_2SO_4	23 days	39.06%	Alcantara et al. (2010)
Gasoil	Spiked Soil	0.1 N of Citric acid	15 days	86.7%	Gonzini et al. (2010)
Phenanthrene	Kaolinite	Hydroxypropyl-â-cyclodextrin + Na_2Co_3	6 days	75%	Jeon et al. (2010)
Oxyfluorfen	Field soil	Water	34 days	63%	Risco et al. (2016)
Total Petroleum Hydrocarbons	Rhodamine B Kaolinite	Hydrogen Peroxide	27 days	58.2%	Popescu et al. (2017)

metals, organic pollutants, and pesticides make the circumstance of pollution more complex. In today's world, soil pollutants have become a major problem, and its prevention is thus desperately required to preserve the environment and public health. There is a current interest in discovering technologies for sustainable remediation to remove toxins from the soil. Electrokinetic is a modern effort at enhancing the remediation process and soil decontamination. Electrokinetic-assisted phytoremediation (EKPR) and Electrokinetic-assisted bioremediation (EKBR) are innovative technology to remove heavy metals, total petroleum hydrocarbon content (TPH), pesticides, heavy metals, radioactive elements, and organic pollutant of contaminated soils. The electrical current needed for electrokinetics is Direct Current and Solar powered. Solar energy is a creative power alternative and can be economically viable for electrokinetic enhanced bioremediation and phytoremediation. Electrokinetic bioremediation and, phytoremediation may be an efficient technique for appropriate remediation in-field application.

Table 24.5 Electrokinetic removal of co-contamination from soil

Co-contaminants	Soil sample	Solution	Time duration	Removal efficiency (%)	References
Reactive Black 5 (RB5) and Cr	Kaolinite Clay	K_2SO_4 (0.1 M)	05 days	RB5 (95%)	Ricart et al. (2008)
Lubricant oil and zinc	Railroad soil	0.1 M HNO_3 and 0.1 M $MgSO_4$ + 0.5wt% Tergitol	17 days	Zn (22.1–24.3%) Lubricant oil (45.1–55.0%)	Park et al. (2009)
Lead and Phenanthrene	Kaolin clay Sandy soil	1% Tween 80 and 0.1 M EDTA	30 days	90% 70%	Alcantara et al. (2012)
Kerosene Phenol Metals	Contaminant Clay	Hexane Distilled Water	21 days	Kerosene (49.8%) Phenol (100%) Metals (26.8–92.49%)	Lukman et al. (2013)
Polycyclic Aromatic Hydrocarbons and Metals	The mixture of Kaolinite, Silt, and Sand	Nitric acid (NA)	10–14 days	PAHs (70.3–89.7%); Metals (76.8–99.9%)	Ammami et al. (2014)
Petroleum Diesel and Heavy Metals	Co-contaminated soil	0.10 M KH_2PO_4	21 days	~95% TPH ~50% As ~20% Cu	Lee et al. (2016)
Decabromodiphenyl ether (BDE-209) and Copper	Field soil	Citric acid, Persulfate and methyl-β-cyclodextrin (MCD)	10 days	Cu (92.5%) BDE-209 (85.6%)	Chen et al. (2019)

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