ENVIRONMENTAL SCIENCE ARCHIVES
ISSN: 2583-5092
Volume IV Issue 1 (TPC2), 2025

Received: 2025/02/18
Accepted: 2025/04/23
Published: 2025/05/19

REVIEW

Electrokinetics Bioremediation: Concept, Application and Future Opportunities

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Abstract

Environmental pollution is a gigantic challenge faced by the global community belonging to the present era. The researchers and environmentalists around the globe are working tirelessly to combat and reduce the pollution or contaminants with an aim to make the climatic conditions healthy and fit for the global community. The multiple anthropological, industrial, and environmental events are responsible for escalating the deterioration of the environment and earth. Bioremediation is an environment-friendly and sustainable approach to reducing and regulating naturally present pollutants. It utilizes multiple microbial organisms to break down and detoxify environmental pollutants from polluted mixtures to safeguard the environment and earth. The core principles of bioremediation include a number of important techniques to reduce environmental pollutants, such as adsorption, redox processes, and pH level modification. These approaches seek to lessen the effects of pollutants in the environment. The bioremediation procedure suffers from different drawbacks, like the availability of contaminants and their accessibility to microorganisms, and the adaptation/ modification of native microbes for biodegradation of suitable target contaminants, which are critical factors in bioremediation processes. The effective bulk supply of electron collectors and essential components to the microbes poses significant challenges. These limitations can be mitigated through the integration of bioremediation techniques with electrokinetics (EK), specifically utilizing electrobioremediation technology. This approach involves the use of electricity on a perforated subsurface matrix, which activates the targeted precise movement of desired components. Electrobioremediation harnesses electrokinetic effects to enhance and directionalize the transport of environmental pollutants and microbial populations toward remediation targets. The present manuscript discussed the EK-assisted electrobioremediation technology along with its potential application and challenges.

Keywords: Environmental pollution; Electrobioremediation; Electrokinetics; Bioremediation

Introduction

Environmental pollution is a serious problem faced by the entire globe, and therefore, it attracts serious attempts to protect the weather and earth. Industrial processes release heavy metals, such as antimony, chromium, and mercury, into the soil and aquatic environment; agricultural produce pollutants like aluminum, copper, zinc, nickel, lead, and arsenic; and untreated pollutants from agro-food industries wastewater in river canals also pose environmental risks (Menthneni et al., 2021; Ayilara et al., 2020). Bioremediation is an environmentally friendly and sustainable way to reduce and regulate naturally present pollutants. It utilizes multiple microbial organisms to break down and detoxify environmental pollutants from polluted mixtures to safeguard the environment and the earth. The core principles of bioremediation include a number of important techniques to reduce environmental pollutants, such as adsorption, redox processes, and pH level modification. These tactics seek to lessen the effects of pollutants in the environment (Jain & Arnepalli, 2019). In-situ and ex-situ bioremediation methods are the two primary categories in which contaminants are treated on-site in in-situ remediation, and conversely, ex-situ bioremediation entails removing and handling the contamination independently (Alori et al., 2022). However, its bioremediation procedures suffer from different lacuna: the availability of pollutants and their bioavailability to microorganisms, along with the rapid adaptation of native microbes for the biodegradation of specific contaminants, are critical factors in bioremediation processes. Additionally, the effective bulk supply of electron collectors and essential components to the microbes that facilitate biodegradation poses significant challenges. These limitations can be mitigated through the integration of bioremediation techniques with electrokinetics (EK), specifically utilizing electrobioremediation technology. This approach involves the use of electricity on a perforated subsurface matrix, which activates the targeted movement of desired components.

Electrobioremediation harnesses electrokinetic effects to enhance and directionalize the transport of environmental pollutants and microbial populations towards remediation targets. While identified as an innovative bioremediation strategy, its practical application at contaminated sites is still underlying electrobioremediation technology. Electrokinetic processes can facilitate the movement of contaminants towards electrodes, where they can be degraded or immobilized by microorganisms. This technique is particularly effective for soil having heavy metal impurities, organic pollutants, pesticides, and radioactive elements, addressing the limitations of traditional remediation techniques, such as excavation or chemical treatments, which can be costly and disruptive (Chen et al., 2021). The majority of traditional organic as well as inorganic molecules hazardous to the environment and cleaning technologies, including microbe-assisted remediation, stimulation, oil isolation and containment, venting, and the majority of procedures using chemical-assisted processes, are ineffective in comparison to electrokinetic remediation. They also introduce harmful substances during the treatment procedures and may result in inefficient pollutant eradication (Ossai et al., 2020). Furthermore, low-permeability soils can be remedied both in situ and ex situ using electrokinetic remediation, in contrast to conventional remediation methods (Gidudu & Chirwa, 2022). Electrochemical methods make use of electricity to split ions, ion transport across a permeable barrier, movement, and migration to remove pollutants from contaminated media. Electrokinetics remediation is more effective when pH variations are controlled and highly ionic electrolytes along with compatible electrodes are used collectively with traditional bioremediation procedures (Liu et al., 2022; Gidudu & Chirwa, 2022).

The sustainable remediation technologies have been intensified due to the pressing need to effectively clean soil and groundwater. The present manuscript discusses the integration of electrokinetic principles of electric potential to mobilize numerous compounds or charged particles and microorganisms in the subsurface, independent of hydraulic conductivity, with bioremediation, which involves the degradation of organic pollutants or the attenuation of inorganic compounds through the activity of microorganisms in situ or ex situ.

The main focus of this paper is to assess the current state of comprehension regarding electrokinetic bioremediation and serious assessment of numerous parameters influencing the scalability of mechanisms that govern electrokinetic bioremediation within the subsurface environment, analyzing both micro- and macroscopic scales. Furthermore, this review presents findings of a mathematical design that demonstrates the potential capability of electrokinetics in supplying electron acceptors within plume-scale scenarios, particularly in cases where such acceptors are limiting. It underscores the necessity for future research, particularly in the evaluation of electrokinetic bioremediation under diverse environmental conditions that are found in natural heterogeneous systems.

Bioremediation: Insights into traditional methods

Bioremediation, a process that utilizes microorganisms to remove contaminants from Earth's crust and natural water resources, has gained significant attention since the late 1960s, when George Robinson first demonstrated its effectiveness by using microbes to address an oil spill in Santa Barbara, California. Since the 1980s, this method has been increasingly recognized for its potential in treating hazardous wastes, particularly oil spills (Shannon and Unterman, 1993).

Bioremediation involves the natural abilities of native soil microorganisms, which act as biogeochemical agents to transform complex organic pollutants into simpler inorganic forms or their constituent elements. This transformation, known as mineralization, occurs as microorganisms adhere to soil particles through ionic exchange mechanisms. Typically, soil particles possess a negative charge, allowing for the binding of microbes via ionic bonds involving polyvalent cations. Bioremediation technology aims to reduce, eliminate, contain, or convert hazardous contaminants in various environments, including soils, sediments, water, and air (Adams et al., 2015).

Bioremediation is a precise approach for the treatment of biodegradable pollutants, according to concepts based in general on ex-situ treatment of dumped sites (in pollutant source removal) and in-situ treatment for locations with limited access (requiring the least disturbance and longer time). Bioremediation demands optimum climatic conditions suited for the specific biochemical method and mutual reaction between microbes, pollutants, nutrients, and electronic ions (Sturman et al., 1995). In situ degradation via microbes may be limited by how much of these components are available to natural microbes (Semple et al., 2004). There may be conditions where biodegradation happens in the subsurface condition at a slower pace, which is insufficient to mitigate the challenge at a specific site.

Traditionally, bioremediation is classified into two primary approaches: in-situ and ex-situ remediation, as mentioned in Fig. 1.

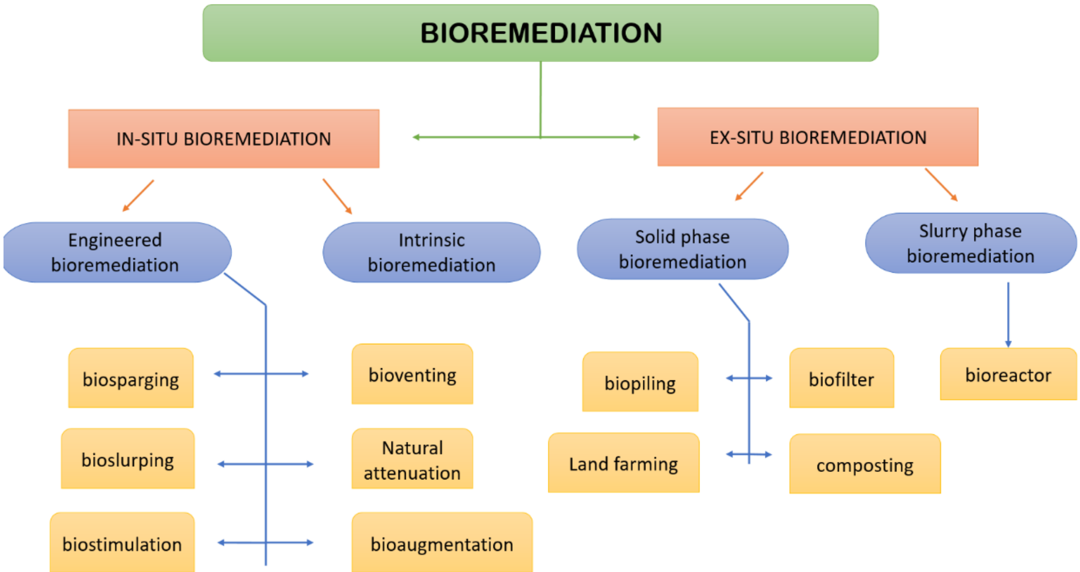

Figure 1. Different traditional approaches used for bioremediation

Direct treatment of pollutants at the pollution site is known as in-situ remediation. This method eliminates the need to dig up or move contaminated materials, allowing the natural bioremediation processes to take place. Intrinsic bioremediation, also known as natural reduction, is a non-invasive technique that uses both aerobic and anaerobic processes to encourage preexisting microbial populations to biodegrade pollutants. In contrast, engineered bioremediation (Bala et al., 2022) involves the following:

1. **Biosparging:** A bioremediation technique that breaks down pollutants by introducing air or oxygen into soil.
2. **Biostimulation:** This method uses nutrients and other materials to promote the breakdown of contaminants.
3. **Bioaugmentation:** A method that uses microorganisms to speed up the bioremediation process.
4. **Bioventing:** This method uses controlled airflow to boost the activity of natural microorganisms while supplying oxygen to unsaturated areas with the aid of nutrients and moisture.
5. **Natural attenuation:** A passive method of pollution removal that takes advantage of natural processes.
6. **Bioslurping:** A method for removing light non-aqueous phase liquids (LNAPLs) from soil and groundwater by using vacuum-enhanced extraction.

Conversely, ex-situ remediation involves removing contaminated items from their original location so they can be treated independently. Following extraction, these materials go through either solid-phase or slurry-phase bioremediation in a controlled setting. While solid-phase bioremediation (Bala et al., 2022) entails the following, slurry-phase bioremediation uses bioreactors that use biological reactions to convert raw materials into particular products, creating the perfect environment for bioremediation under controlled conditions (Davoodi et al., 2020).

1. **Biopiling:** It is a method that uses biological processes to convert soil contaminants into less harmful metabolites.
2. **Composting:** This method uses the microorganisms in compost to get rid of contaminants.
3. **Land farming:** A method that turns ground into a thin layer to treat contaminants.

4. **Biofilter:** A bioreactor packed with an organic matrix (fixed bed) in which active microorganisms capable of degrading pollutants are immobilized.

EKRT Technology

The EKRT (electrokinetics remediation technology) approach utilizes an electric potential gradient to induce a low electric current in contaminated soil via strategically positioned electrodes. This method is effective for both on-site and off-site management, making possible the remediation of low-permeability soils by penetrating deep contaminants. The resulting electric current, influenced by various soil characteristics, promotes physical, chemical, and electrochemical processes that facilitate the movement of contaminants towards the electrodes. Contaminants can then be removed through processes like electrodeposition, adsorption, or by extracting the contaminated electrolyte solution for further treatment and reuse (Vocciante et al., 2021).

Electrokinetics remediation is a cutting-edge method for removing pollutants or contaminants from soil by using three primary processes: 1. Electroosmosis—the mass passage of fluid through porous media; 2. Electromigration—ionic mobility in solution; 3. Electrophoresis—mobility of charged particles, either solubilized or suspended in a porous matrix or fluid, all under a low-density direct current electric field, as shown in Fig. 2. It may be as simple as the water electrolysis at the oppositely charged electrodes (Virkutyte et al., 2002). During electrolysis, water is split into hydronium ions and nascent oxygen, whereas at the cathode side, water is reduced to hydroxyl ions and nascent hydrogen (Jones, et al., 2011). The dissociated ions, hydrogen (H+) and hydroxyl (OH-) ions, moved towards the cathode and anode, generating acid and base fronts (Acar et al., 1993). The migration and osmosis under the electric field, which is not dependent on fluidic conductivity and EK, might be utilized to produce mass flux in zones inaccessible to advective movement (Jones, et al., 2011). The multiple studies elaborate on the different principles of electrokinetics and advocate its application (Virkutyte et al. 2002; Yeung and Gu 2011).

Factors that influence in-situ bioremediation are strictly adapted or meant for specific sizes (Boopathy, 2000) and generally have-

1. Bulk movement of electron acceptors and metabolites to degrading microbes (Simoni et al., 2001);
2. Bioavailability of pollutants (Lohner et al., 2009);
3. Affinity of the microbes for a particular contaminant (Mrozik and Piotrowska-Seget, 2010).

The main objective of EK-bioremediation (EKB) is to combat the above-mentioned shortcoming, enhancing the influence of the EKB approach. This paper also mentions related processes: 1. EKB at the micro and macro level (Wick et al., 2007; Lohner et al., 2009), especially interactions among EKB procedures and the subsurface condition; 2. Mechanisms assisting practical application, e.g., the effect of climatic conditions on EK (e.g., Page and Page, 2002), with an emphasis on bioremediation; and 3. Up-scaling of EKB to a higher level. The combined evaluation of electrokinetics/bioremediation methods and their potential utilities as a sustainable bioremediation method.

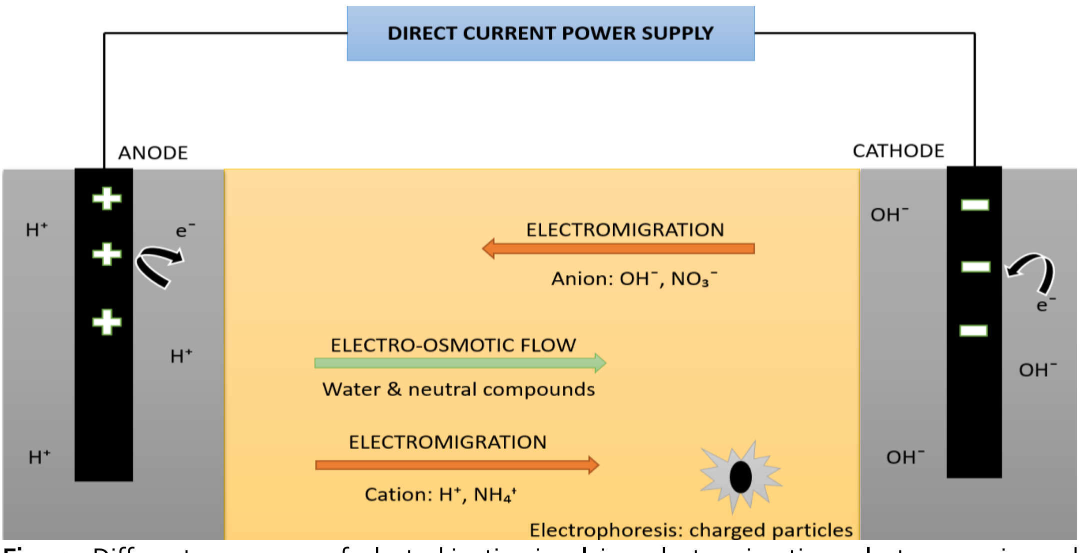

Fig. 2. Different processes of electrokinetics involving electromigration, electroosmosis, and electrophoresis

Subsurface EK-Bioprocesses
Mechanisms of EK-BIO processes at the subsurface level take place on two scales: micro-scale and macro-scale. Micro-scale involves reciprocation between the surface, pollutant, and the environment at the pore level, whereas macro-scale involves such interactions that can be applied for plume-scale remediation. Different processes of micro-scale and macro-scale production are summarized in Table 1.

Table 1. Different processes of micro-scale and macro-scale production

Production	Processes	Description	References
Microscale	Substance transport	In this, bioremediation is based on the bioavailability of contaminants and nutrients by reducing spatial barriers and on the effectiveness of substance properties, with electroosmosis increasing the mobility of hydrophobic contaminants in low-permeability media, but hydrophilic compounds face difficulty because of their mass-to-charge ratio.	Wick et al., 2007; Da Rocha et al., 2009
	Contaminants desorption by EK	It involves the emancipation of contaminants attached to particles present in soil by fluttering the surface charge of molecules which increase the biodegradation.	Maini et al., 2000; Luo et al., 2005; Alshawabkeh et al., 2004
	Effect of EK on viability of the microbial populations	It is based on direct current and show microbes show minimal impacts at low intensity DC (0.3-1 mA cm^2) and they show changes near electrodes when pH changes. Positive effects also involve the formation of favourable oxidizing and reducing zones for biodegradation.	Lear et al., 2004; Wick et al., 2010; Pazos et al., 2012
Macroscale	EK-Bio attenuation	EK-Bio attenuation is an efficient and cost-effective low-impact bioremediation approach, which accelerates the natural diffusion of biodegradable contaminants and offers electron acceptors and microorganisms by increasing electrode quantities and reversing the polarity thereof. The difference in voltages over time and space governs the rates of substance migration, thereby determining the efficiency of biodegradation. Applications encompass ex situ remediation of oil-contaminated soil and enhancement of mixing within groundwater contaminant plumes to promote contact and biodegradation of persistent contaminants.	Li et al., 2010; Huang et al., 2013; Yuan et al., 2013
	EK-Biostimulation	EK-biostimulation transports nutrients and electron acceptors to contaminated areas at speeds exceeding diffusion, thus facilitating the biodegradation of a range of contaminants, including PCE, toluene, and diesel. This approach involves using gaseous products of water electrolysis and solubilizing agents (i.e., surfactants) to enhance bioavailability of contaminants. Experiments show surfactants enhance biodegradation with macro-scale delivery essential for efficacy particularly in soils of different permeability. The application of EK-biostimulation is particularly promising, as low-permeability matrices may hinder the accessibility of bio amendments, thus limiting overall bioremediation efficacy.	Wu et al., 2007; Tiehm et al., 2010; Pazos et al., 2012
	EK-Bioaugmentation	EK-bioaugmentation is only applied to non-permeable soils, where electric field helps the migration of microorganisms and moving flow is mainly forced to flow along macro-pores. The approach provides means for the distribution of active degrader species for contamination treatment, whilst maintaining micro biome integrity through transport. Moreover, surfactants can mitigate sediment attachment problems, and using endospores as a more stable alternative can increase efficacy as well.	Wick et al., 2004; Mao et al., 2012; Lee & Kim., 2010
	EK-Phytoremediation	It is based on the mutual associationship present among the plant and the soil microbial community and targets heavy metal pollution, and enhance remediation without harming plant health.	Cameselle et al., 2013; Cang et al., 2011; Cang et al., 2012

Strategic Approach to Implementing Field-Scale Ek-Biosystems
Field-Scale Ek-Biosystems implementation involves undermentioned approaches:

Electrochemical enhancement of additives

The drifting and flow rate of amendments can be enhanced by optimizing electrochemical variables in electrokinetics. In sandy soil, research indicates a straight and direct association between the voltage potential and the speed of electromigration; in clay, however, a minimum voltage (>0.8 V cm^{-1}) is necessary for the effective penetration of amendments. Control over pH results in the non-uniform distribution and stops the precipitation of amendment (Lohner et al., 2008; Tiehm et al., 2010; Acar et al., 1993). The ionic mobility and mass flux may be impaired due to the electrical neutrality and competitive transport by the addition of nutrients in the mixture. The amendment's chemical form affects its migration when organic and inorganic phosphate react with the metal ions (Gill et al., 2014).

Electrode design and optimization

In order to maintain a higher average voltage gradient across the soil, it is essential to choose such electrode materials that reduce voltage drops at the soil-electrode interface in systems having constant use of voltage for amendments (Mohamedelhassan & Shang, 2001). Although carbon electrodes have been found to be better than steel since they have a small voltage profile drop, they are prone to corrosion at low pH levels. Metal electrodes can be used in conjunction with protective coatings or pH control to minimize corrosion. Coatings that raise surface potential have the potential to hinder the growth of microorganisms—a crucial aspect of EJ-BIO application. Therefore, metal electrodes are preferred for micro-scale production, whereas corrosion-resistant metals like titanium and stainless steel are preferred for macro-scale projects (Gill et al., 2014).

Effective electrode layout

There are many ways to place electrodes, including unidirectional, bidirectional, radial pairs, and radial bidirectional, as mentioned in Fig. 3. These can be used to accomplish various goals, such as radial-pair arrangement, which works well for mixing materials in situ, whereas bidirectional or radial-bidirectional setup works well for the uniform and high-concentration movement of amendment. Other elements to improve electrode arrangement are the absence of metal debris, injection wells, electrode spacing, and polarity reversals (Wu et al., 2013; Luo et al., 2006).

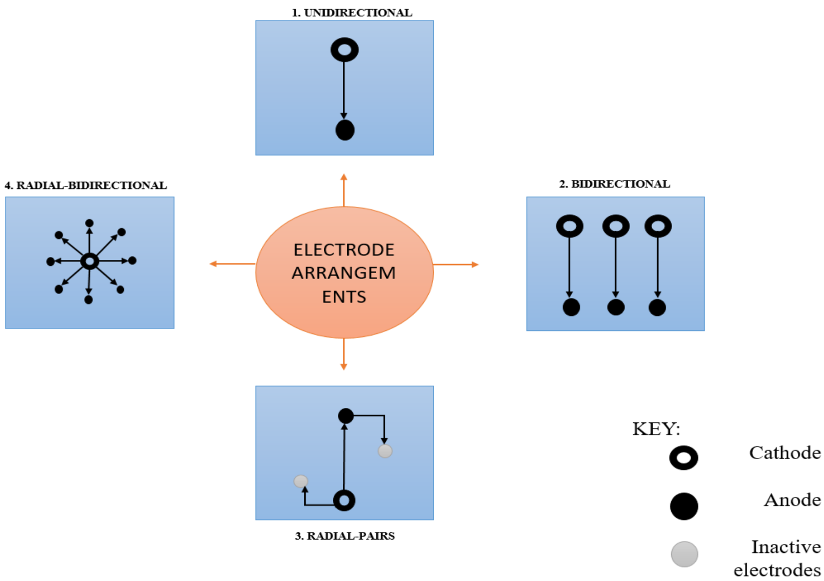

Fig. 3. Different layouts of the EK-Biosystem. Different arrangements of electrodes are depicted that are generally used in field layout.

Subsurface Environmental Processes: Key influencers of EK-Bio

Environmental factors influence the EK process and the effectiveness of their application; therefore, adjusting the treatment to the environment is crucial for controlling electrode effects and anticipating and maintaining the EK process. The electrolyte, such as soil moisture or groundwater chemistry, which is a medium for current; the earth layer that affects the EK process; water parameters that add advection as an extra transport vector; physical variability that can change migration rates; and the mixed nature of contaminants present at many sites are the main environmental factors that affect EK-BIO.

Interplay between EK and Electrolyte Characteristics

The pure water functions as an electrolyte, and on application of an electric field to porous media, such as soil or aquifers, the system's capacity to sustain the electric field depends on the ion concentration (Alshawabkeh & Acar, 1996). These ions mostly come from man-made sources and the disintegration of minerals in the geological matrix. The ionic features and electrochemical properties are strongly influenced by the type of rock or soil (Reddy & Saichek, 2003). Different types of rock and soil can cause variations in electrolyte conductivity, which can result in modest voltage gradients that impede electromigration (Li et al., 2013). Higher ion concentrations increase electric current flow, increasing power consumption. Unsaturated soils favor saturated areas with higher conductivity. Electroosmosis changes moisture distribution, raising electrical resistance. Electro-dewatering may induce water stress, affecting microorganism growth. Rotational or bidirectional modes of EK application can distribute moisture more effectively (Gill et al., 2014).

Dynamics of EK and Geological Strata

Electroosmotic flow in a geological matrix is determined by the percentage of fine-grained sediments having net surface charge. Because of their high surface charge density, clays and silts have the highest electroosmotic permeability (Acar et al., 1995). Electrolyte conductivity and pH have an impact on the zeta potential, a measurement of charge (Vane & Zang, 1997). A counterflow is provided by electroosmosis, which prevents negatively charged modifications from migrating. Consequently, for EK-BIO applications, boosting electrical conductivity works better (Wu et al., 2007).

EK-BIO can affect the carbonate mineral content, which is the main factor governing the pH buffering power of land (Ouhadi et al., 2010). Stress reactions can be lessened, and neutral pH conditions for a negative zeta potential can be maintained by minimizing pH variations at the electrodes. However, the soil buffering capacity may vary geographically due to the uneven distribution of carbonate minerals. The pH buffering may be impacted by cation exchange, which may result in a decrease in bioaccessible fractions (Reddy & Saichek, 2003; Andrews et al., 2005).

EK's Role in Hydrodynamics System

Groundwater flow in saturated medium- to high-permeability zones can have a major effect on EK processes. Nutrient dispersion and electron acceptor delivery into contaminated phases are examples of EK and hydraulic flow combinations. Although efficient against hydraulic gradients, electromigration diminishes with increasing flow rate (Godschalk & Lageman, 2005). At perpendicular hydraulic flow (30 cm h^{-1}), a nitrate electromigration rate of 20.4 $cm^2\ V^{-1}\ h^{-1}$ was attained (Lohner et al., 2008; Tiehm et al., 2010).

EK and Physical Inconsistencies

Assessing EK processes in physical inconsistencies or heterogeneity systems is essential for the technology's field-scale implementation. Due to distinct mechanisms, EK-enhanced movement of ions across selectively permeable membrane barriers is larger as compared to dispersion and diffusion (Reynolds et al., 2008). According to EK theory, spatial variations in porosity and tortuosity, along with a larger negative osmotic pressure in the low permeability section, cause the speed of material migration to decrease across the permeability gradient (Wu et al., 2007).

EK and Contaminants

Both organic and inorganic pollutants frequently make up environmental contamination, necessitating the use of various remediation techniques. Both can be eliminated concurrently using electrochemical kinetics (EK); however, it can be difficult to remove organic and heavy metals without the use of facilitating agents. EDTA and cyclodextrin or non-ionic surfactants are necessary for a successful removal (Maturi & Reddy, 2006; Maini et al., 2000). Sequential procedures could be used in EK-BIO, where organic contaminants are treated after the elimination of inorganic contaminants (Cang et al., 2007), while pH management can improve community survival, heavy metals can impede microbial growth.

Various Applications of EK-Bioremediation

EK-Bioremediation ha following important applications

Genomic Advances in Microbial Research

The microbial communities that are engaged in bioremediation processes are being augmented by the developments in microbial ecology and genetics. There are different pathways and methods by which these communities assimilate the contaminants and help in the reimposition of the ecosystem by discovering and describing those contaminants (Xue et al., 2024). Moreover, genetically engineered organisms can be created to target particular pollutants and thrive in particular environmental conditions. Bioremediation and intervention techniques can be optimized by using genomic data to forecast how the microbes will react to changes in their environment (Patel Desai & Thakur, 2024).

Bioinformatics and Simulation Techniques

The effect of environmental changes on microbes can be speculated by the use of bioinformatics and computational modeling. The alliance of various biosensors and advanced learning tools, generally known as bioinformatics, can improvise the working strategy of various bioremediation techniques. The Internet of Things (IoT) devices, when paired with EK, can provide continuous monitoring of various parameters such as pH, temperature, etc., whereas biosensors provide real-time data of the pollutants in the environment (Oyewusi et al., 2024).

Engineering and Bioreactor Design

The novel bioreactor design, which includes bioelectrochemical systems and membrane bioreactors, is efficient for removing contaminants within a short period of time (Orzechowska et al., 2024). Optimization and scalability of bioremediation under controlled conditions are part of recent advancements in the field of EK-BIO (Sandoval-Herazo et al., 2024).

Microbial Enhancement

Biostimulation and bioaugmentation are the techniques that can improve the microbial activity and speed up the process of contaminant degradation. Biostimulation involves the supply of essential biomolecules or electron acceptors that will help bacterial populations to grow along with the degradation of contaminants simultaneously, whereas bioaugmentation involves the addition of such specific microorganisms that optimize the metabolic pathways for degrading contaminants (Omenna et al., 2024).

Improving Observation Methods

DNA-based markers, radioisotope probing, and remote sensing are some monitoring techniques that can improve the observation of microbial dynamics and contaminant transformation. The incorporation of the internet and artificial intelligence has made the technologies cost-effective, scalable, and easily accessible (Ukhurebor et al., 2021).

Current Progress of EK-Bioremediation

Following progressions have been reported in the field of EK-Bioremediation

Genetically modified microbes

Bioremediation fields have taken significant changes due to current developments in genetic engineering by the involvement of CRISPR-Cas9 technology (Sahoo et al., 2022). Microbial strains that can effectively break down the pollutants have been developed by genetic engineering (Adetunji et al., 2024). With the help of these technologies, microbial genomes are modified and designed to create such pathways that can target specific toxins and adjust to environmental changes. Such types of altered microbes have shown an increase in effective bioremediation by boosting enzyme activity, substrate selectivity, and an increase in stress tolerance (Verde-zoto-Prado et al., 2024).

Microbial communities

Despite depending on the microbial strains, researchers have emphasized microbial community engineering. This method is known as microbial community engineering (Bustamante-Torres et al., 2023). This technique involves the breakdown of various pollutants through the synergistic interactions between the various bacteria. The purpose of this technique is to deal with the contaminants to a larger extent and to increase the potency of bioremediation in dealing with pollutants by inducing metabolic pathways into these communities (Adetunji et al., 2024).

Phytoremediation synergy and bioelectrochemical system

Phytoremediation involves consolidation of microbial and plant species for the removal of contaminants (Khan et al., 2023; Prasad, 2024). Plants provide favourable conditions for the microbial breakdown and uptake of pollutants in their rhizosphere. Likewise, in bioelectrochemical systems (BES), microbial metabolism and electrochemical processes are combined for the removal of contaminants. BES involves catalysis of redox reactions on electrode surfaces, and microorganisms produce electrical currents that remove pollutants (Baek & Lee, 2024).

Nano-engineering

It includes the use of nano-size particles and composites to increase the effectiveness of contaminant removal procedures. These nanomaterials make the pollutants reactive by supplying electron acceptors and nutrients, and they act as microbial cell transporters to increase the spread of microbial cells (Kuppan et al., 2024).

Computational biology and omics techniques

Applying comprehensive databases on environmental factors is known as computational techniques and omics technology. Metagenomics, metatranscriptomics, and metaproteomics are some examples (Mohanty et al., 2024).

Conclusions and Future Prospects

EKB is a crucial approach for degrading and neutralizing many pollutants belonging to soil as well as underground water. It holds high potential for bioremediation in matrices with poor permeability and diverse types where other remediation procedures did not work. In the present manuscript, different methods related to EKB suitable to different situations were elaborated. The EKB methods are highly dependent on the host geological matrix. During the ex-situ process in the natural condition, multiple biochemical procedures lead to fluctuation in pH, voltage, and moisture level that might adversely affect the bioremediation process and must be considered on a site-specific basis. The material and configuration of the electrode should be carefully selected to achieve optimum results from the EKB treatment. The mathematical model of targeted pollutant of groundwater, together with better designing of processes related to bioremediation of groundwater, may optimize output of EKB with less time and at economic cost. There is a high need for research to evaluate the response of these techniques to the complexity of specific field-scale applications. These include: A better understanding of the effect of natural aquifer settings on EKB processes like underground water movement and differential properties related to electrolyte mixture, geological texture, and physical nature. The EKB influence on new organic and inorganic pollutants as well as mixtures should be studied to broaden the horizon and application of these techniques. More studies should be undertaken on combining EKB with available remediation approaches, namely chemical oxidation/reduction and phytoremediation. There should be critical focus on electrode composition/design and optimizing processes to make these processes large-scale applications, like field-scale as well as industrial-scale, and the effects of EKB on different microbial species. There is a high need at the present time for finalizing guidelines regarding EKB use at the field scale as well as industrial-scale application for the proper safety of the community.

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Author Contributions

HS, KS and JK conceived the concept; HS, KS and JK wrote and approved the manuscript.

Acknowledgements

Not applicable.

Funding

Not applicable.

Availability of data and materials

Not applicable.

Competing interest

The authors declare no competing interests.

Ethics approval

Not applicable.

Citation: Singh H, Sapehia K and Kumar J (2025) Electrokinetics Bioremediation: Concept, Application and Future Opportunities. Environmental Science Archives 4(1): 260-273.