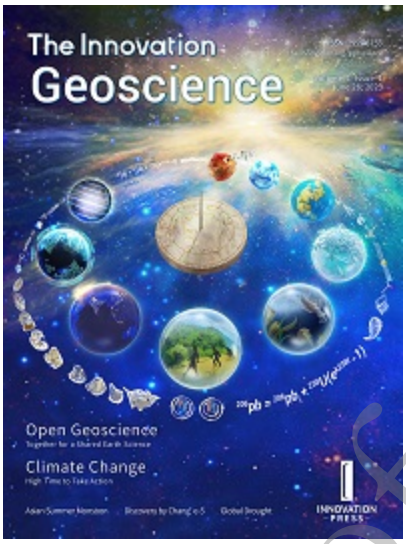

Direct Current Electric Field Modulation of Mass Transport in Soils: A Comprehensive Review

Journal:	*The Innovation Geoscience*
Manuscript ID	XINNgeoscience-2025-0144.R2
Manuscript Type:	Review
Keywords:	Electrokinetics, mass transport, pore fluid, interfacial effects 3 49, Electrokinetics mass transport pore fluid interfacial effects 3 49

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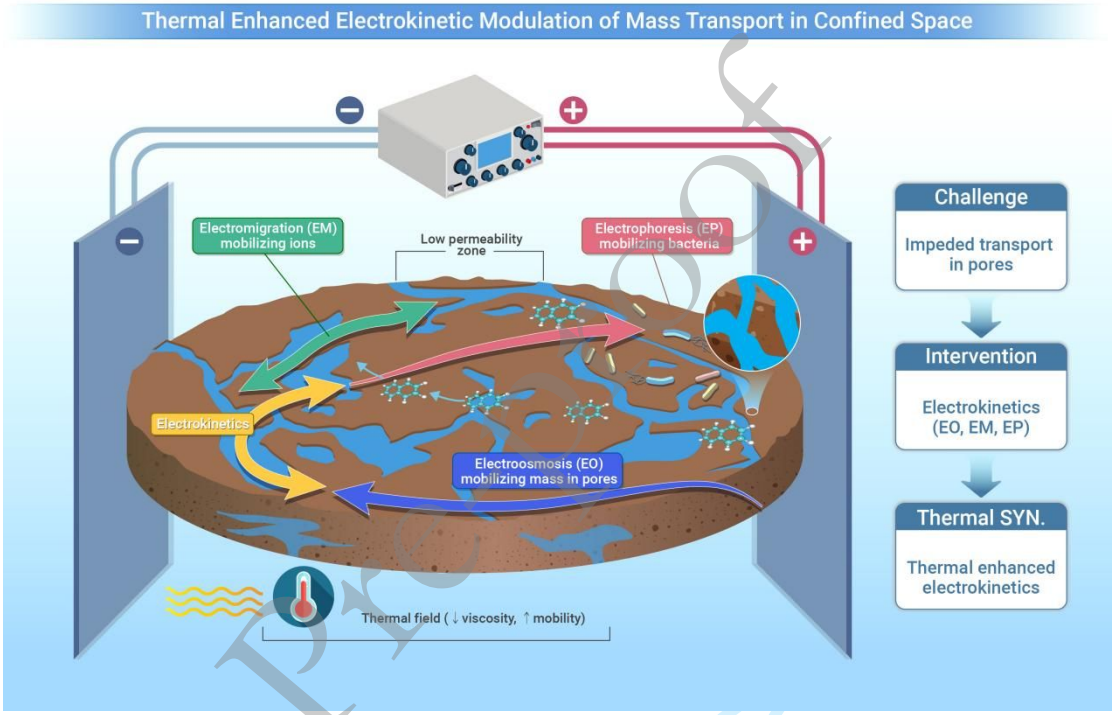
GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- Electric fields drive electromigration, electroosmosis, and electrophoresis to boost transport.
- Thermal fields added tune properties, improving delivery of compounds and microbes.
- Synergy of electro- and thermo- overcomes microscale barriers, enhancing remediation.
- Future strategies include engineered microbiomes and optimized ecosystem services.

Key Words：Electrokinetics; mass transport; pore fluid; interfacial effects

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SUBJECT AREA: Environment & Ecology

ABSTRACT

Mass transport within the Earth critical zone is fundamental to sustaining ecosystem functions. This process is governed by a complex interplay of natural factors, including soil, microbial, and chemical properties. However, mass transport is often impeded by microscale barriers in low-permeability soils, restricting the mobility of microorganisms and compounds, thereby limiting essential processes from biogeochemical cycling to resource recovery. Among various intervention strategies, the application of a direct current electric field induces electrokinetic phenomena electromigration (EM), electroosmosis (EO), and electrophoresis (EP), that act in concert to mobilize pore fluids and enhance the co-transport of compounds and biodegrading microbes. This review synthesizes how electrokinetic fields enhance mass transport in soils. It systematically resolves the electrokinetic-driven interactions within the microbe-matrix-compound triad, analyzing the distinct electrokinetic effects on bacterial deposition and transport at interfaces, as well as on compound sorption and desorption. We elucidate how the interplay of electric and chemical mechanisms governs the transport dynamics, with EO serving as a universal driver, while EM and EP preferentially facilitate ion and bacterial transport in nano- and micro- pores, respectively. Furthermore, the synergistic effect of superimposed thermal fields is examined for its role in tuning key physical properties to further improve delivery efficiency. We provide perspectives on future research priorities, which include targeted microbiome engineering and in situ sustainable mining applications. This synthesis aims to provide a systematic strategy for deploying electrokinetic interventions to overcome transport barriers and enhance ecosystem services in both natural and engineered environments.

INTRODUCTION

Mass transport within the earth critical zone is fundamental to sustaining ecosystem functions,[1] yet this process is often severely impeded by microscale barriers in low-permeability soils.[2] These barriers restrict the mobility of microorganisms and compounds, thereby limiting essential processes from biogeochemical cycling to contaminant degradation and resource recovery.[3,4] Although indigenous soil microbial communities harbor degraders of compounds like polycyclic aromatic hydrocarbons (PAHs), their efficacy is critically limited by physical constraints in heterogeneous pore networks.[5] Preferential flow in natural soils results in hydraulic isolation of low-permeability zones, which severely restricts microbial and compound mobility.[6] In these areas, the disconnected physical gaps hinder microbial uptake and become a critical bottleneck for biodegradation.[7] Consequently, strategies to enhance the co-transport of both compounds and microbial degraders in confined soil matrices are essential to facilitate microbial activities and elevate soil ecological functions.

To address the limits in confined space, direct current (DC) electric field-triggered electrokinetic phenomena have been efficient.[8] Electromigration (EM) directs the motion of dissolved ions, electrophoresis (EP) propels suspended charged particles or colloids, and electroosmosis (EO) drives the plug-shaped pore fluid along charged surfaces.[9] Collectively, these phenomena govern efficient, directional transport of solutes and particulates within constrained environments, offering a targeted strategy with minimal environmental disturbance.[10–12] These phenomena enhanced the mobilization of compounds such as metal, PAHs, perfluorooctanoic acid (PFOA) by up to 46%,[13] and the transport of bio-degraders such as *Pseudomonas fluorescens* LP6a by up to 60%.[14] In addition, the integration of a thermal field significantly augments these electrokinetic transport processes by modifying fluid viscosity, ionic mobility, surface charge, etc.[15] The coupled fields provide promising transport strategies in the soil confinement pore networks.

Electric and thermal fields exert significant influence over microbial degradation pathways for compounds, underscoring their promise as bioremediation enhancers.[16] However, research examining the concomitant application of electric and thermal fields remains notably fragmented and incomplete. Comprehensive review of how thermally augmented electrokinetics regulates the entire mass transport remains absent. This deficiency extends to understanding the dynamic interplay and potential synergies between thermally enhanced transport and microbial physiological responses. The current lack of this integrated mechanistic understanding fundamentally impedes the rational design, predictive modeling, and effective optimization of advanced coupled electro-thermal remediation strategies for complex contaminated matrices.

This study conducts a systematic review and critical analysis of existing scientific literature, focusing on the influencing factors and mechanisms of electrokinetics, and the coupling with thermal fields, with the aspect of bacteria and compound transport, respectively. By integrating these aspects, this study analyzes the mechanisms of mass transport with EM, EP, and EO, as well as their integration with the thermal field. Based on the analysis, this paper proposes that potential research interest in the dynamic coupling effects on the microbes-matrix-compounds interactions, and emphasizes the application potential of thermal effects in

optimizing electro-transport efficiency. This paper provides systematic references for theoretical innovations and engineering optimizations in electro-biological synergistic remediation technologies.

DRIVING FACTORS OF MASS TRANSPORT IN TRANSPORT IN NATURAL SYSTEMS

As a central indicator of the biodegradation, bioavailability is defined as the rate of a compound's mass transfer to microbial cells relative to their intrinsic catabolic potential, which underscores the importance of mass transport in degradation. It is determined by compound accessibility and biodegrader activity (Figure 1), in which bacterial deposition and compound release controlled accessibility becomes a critical premise.[17] Constraint on mobility reduces bioavailability, hence hindering the essential first step toward productive biodegradation.[18,19] This chapter explores the interplay of physicochemical, biological, and environmental parameters as driving factors in both natural and external intervention approaches.

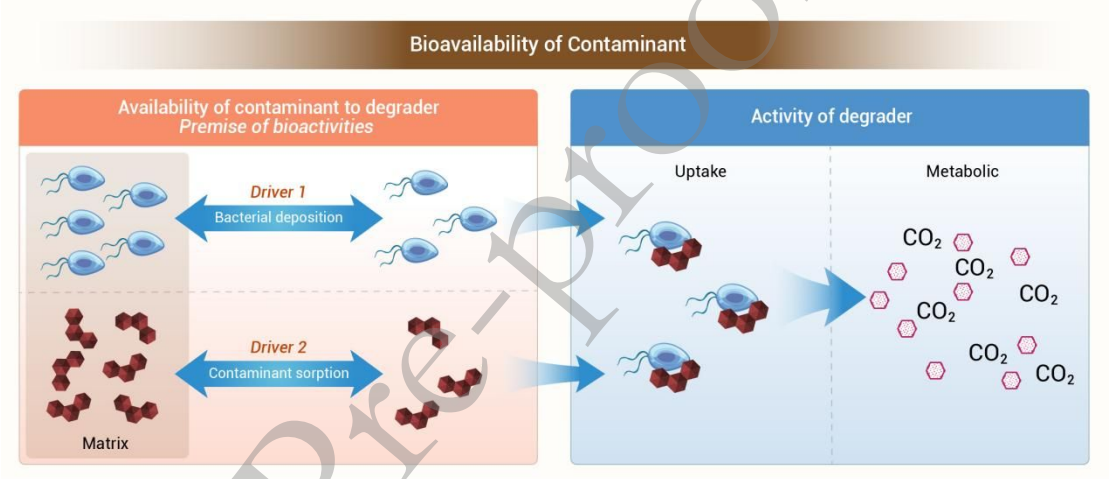

Figure 1. Conceptualization of the processes driving the bioavailability of compounds.

Natural driving factors

Bio-accessibility in the inherent complex soil systems is governed by the interaction of soil-microbe-chemical, including multiple processes of microbe deposition-transport, chemical sorption-desorption, etc.[20]

Soil properties.

The pore-liquid coupled micro-environment synergistically regulates the transport pathways and efficiency of both bacteria and compounds.[21,22] Specifically, solid-phase properties, such as the zeta potential, play a crucial role alongside liquid-phase characteristics, including the dielectric constant, viscosity, etc.[23] These factors collectively perform as the media of compound sorption-desorption and bacterial deposition-transport

processes (Figure 2).[24,25]

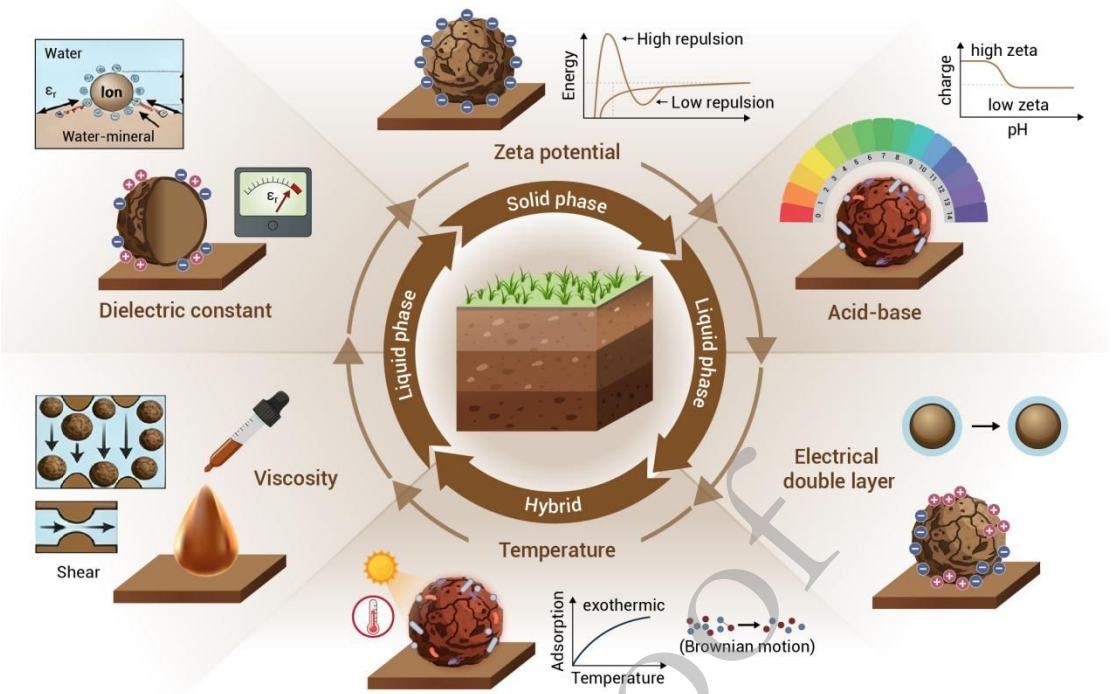

Figure 2. Drivers of mass transport in the natural environment.

From the perspective of the liquid phase, solution chemistry affects the migration efficiency by modulating interfacial interactions.[26,27] Changes in solution chemistry are manifested in three key parameters: changes in ionic strength significantly affect the thickness of the bilayer,[28] which in turn alters the electrostatic interactions;[29] acid-base interactions affect the sorption strength by modulating the surface charge density;[30] and the presence of organic matter may both inhibit the retention by competing for sorption sites[31] and alter the interfacial hydrophobicity to promote attachment.[32] These variations in compound parameters make the liquid-phase environment critical in regulating mass transport.[33]

From the perspective of the solid phase, the physical structural characteristics of porous media establish the fundamental framework for compound and bacterial migration. Particle size distributions directly determine the characteristic parameters of the pore structure.[34] Consequently, microbial and compound transport is typically accessible in coarse-grained media as loam soils, while highly constrained in fine-grained clay soils.[35] This confinement effect is further enhanced with increasing surface roughness,[36] as rough surfaces provide more contact sites.[37] Moreover, the pore structure is not static in the natural state, and biofilm formation dynamically changes pore geometry and surface properties,[38] thereby continuously adjusting microbial and compound deposition.[39]

Microbial properties.

Bacterial migration and distribution in environmental systems are synergistically governed by their surface chemistry, structural features, and intrinsic physiological status (Figure

3).[40] Surface physicochemical properties such as zeta potential and hydrophobicity, critically dictate cell-matrix and cell-cell interactions.[41] Concurrently, structural properties including cell morphology, Gram-stain type, growth phase, further modulate bacterial aggregation, and retention.[42]

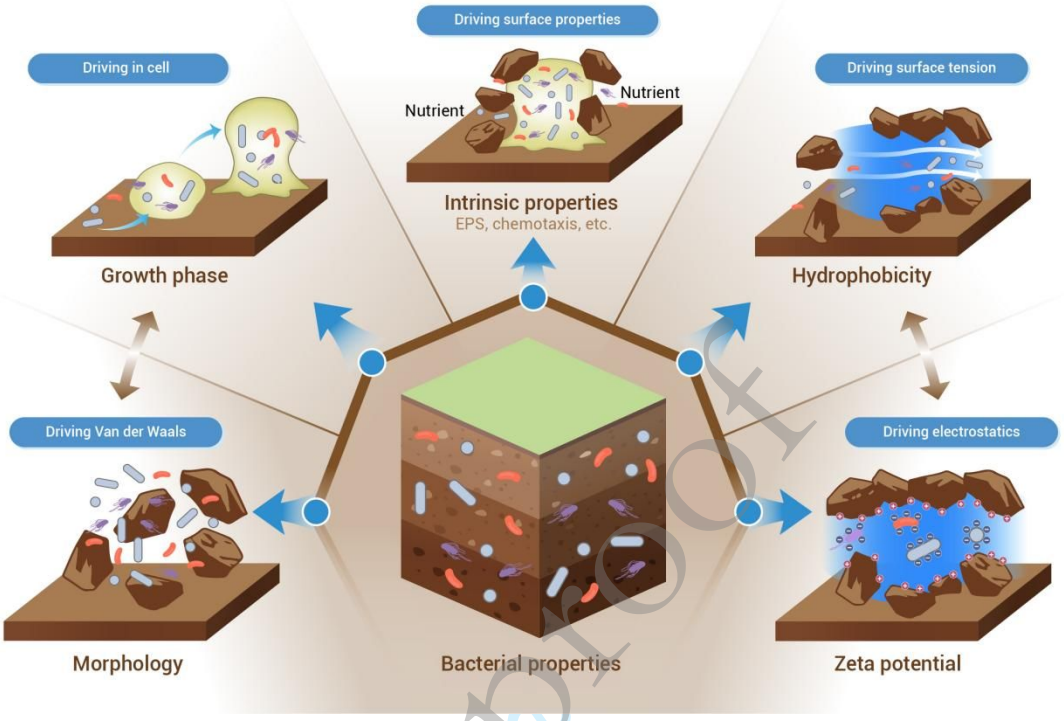

Figure 3. Bacterial physicochemical characteristics on transport.

Regarding surface chemistry, the initial deposition of single bacterial cells onto a matrix prior to biofilm formation is primarily governed by colloidal interactions. As defined in the classical Derjaguin, Landau, Vervey, and Overbeek (DLVO) theory, the electrostatic repulsion counteracts with van der Waals attraction to determine bacterial deposition.[43] The electrostatic repulsion generally originates from the typically negatively charged bacteria and matirx.[44,45] Reduction in surface charge reduces electrostatic repulsion by up to 25% in typical sand matrix to increase bacterial deposition.[46,47] Van der Waals forces refer to the universal short-range attractions between molecules, which include orientation, induction and dispersion forces. Van der Waals attraction is evaluated using surface free energy derived from multi-solvent contact angles. The attractive energy differs by 32% between hydrophobic and hydrophilic cells when interacting with sand.[48]

Beyond surface chemistry, bacterial structural properties and physiological statuses play critical roles in modulating these physicochemical interactions and transport dynamics. Bacterial structural properties e.g., growth status and morphology play critical roles in the variations of physicochemical properties. Differed growth phase or nutrient starvation, can significantly alter surface charge or cell size, thereby shifting the net DLVO interaction energy.[49,50] Meanwhile, morphological characteristics of bacteria e.g., size and shape affect transport behavior by altering settling velocity and diffusion capacity.[51] A significant

physical sieving effect occurs when the ratio of bacterial size to media pore size ≥ 0.05.[52–54]

Compound properties.

The survival and growth stages of bacteria are highly dependent on their interaction with carbon, nitrogen sources, and other essential elements.[55,56] The accessibility of these elements for bacterial uptake are strongly governed by the physicochemical properties of compounds, such as solubility, ionization, and polarity, etc.[57]

Firstly, the water solubility of compounds determines the rate of compounds to transport with the pore water. The solubility can be quantitatively described by the octanol-water partition coefficient ($log\ K_{ow}$). For instance, polycyclic aromatic hydrocarbons (PAHs) with low solubility $log\ K_{ow} > 4$, tend to strongly adsorb onto soil organic matter and biofilms, thereby exhibiting significantly reduced transport compared to highly soluble compounds like sulfamethoxazole with $log\ K_{ow} < 3$.[58]

Secondly, compound ionizability profoundly affects its partitioning between pore water and the soil matrix, thereby governing sorption-desorption kinetics and subsequent transport.[59] For instance, perfluorooctanesulfonic acid (PFOS) and perfluorooctanoic acid (PFOA) ionize to form anionic species, the electrostatic repulsion greatly enhances their mobility.[60] On the other hand, cationic species (e.g., Methylene Blue, Crystal Violet) are strongly retained by negatively charged soil colloids via electrostatic attraction, resulting in limited mobility. Weakly ionization compounds such as Polychlorinated Biphenyls strongly adsorb onto soil organic matters, resulting in limited transport.[61]

Moreover, the polarity of compounds, representing the symmetry of the intramolecular charge, regulates interfacial sorption of compounds to the soil matrix through hydrogen bonding or van der Waals forces.[62] Highly polarity compounds (e.g., phenols, chlorinated hydrocarbons) readily adsorb to clay minerals or biofilms through hydrogen bonding. For instance, phenol with polarity index 4.3 in underground coal gasification wastewater exhibited 50% greater adsorption on the surface of fine-particle residue (particle size <0.15 mm) than non-polar alkanes, yielding a partition coefficient K_d of 4.5 L kg^{-1}. Conversely, non-polar compounds (e.g., mineral oils) rely primarily on van der Waals forces to undergo sorption onto organic carbon.[63]

External intervention

To overcome the severe mass transport constraints inherent in confined soil matrices, remediation strategies inducing hydraulic, electric, and thermal fields have been extensively investigated.[64,65] While hydraulic flow is highly efficient for delivering bulk fluids into loose porous matrices, its efficacy is strictly limited in compact or low-permeability soils. To address this limitation, electric fields can be applied to drive inner-surface fluids via electrokinetics and directly mobilize bacteria and contaminants.[66] Furthermore, thermal fields serve to increase molecular kinetic energy and weaken the interfacial interactions of bacteria and compounds with the soil matrix, thereby potentially amplifying both hydraulic

and electric effects.[67] Consequently, this section introduces these three primary intervention approaches individually, followed by a comprehensive discussion of their synergistic interactions.

Hydraulic field intervention.

Hydraulic flow governs the spatiotemporal distribution of microbes and compounds by controlling their transport and interactions. For microbial transport, pore-scale hydrodynamics and shear forces dictate cellular deposition/transport, thereby governing functional biomass retention. For compound transport, advection and multiscale dispersion dominate mass transfer, where variations in velocity and residence time alter retention kinetics.[68] Crucially, the efficiency of both processes is ultimately constrained by media heterogeneity, which dictates the breakthrough behaviors of cells and solutes under shifting pressure gradients.[69]

For microbial transport in high-permeability matrix, increasing the imposed pressure gradient markedly improves penetration and the advance of microbial fronts. Column experiments show that raising the Darcy velocity boosts breakthrough peaks and substantially shortens the time to first arrival. In coarse media, longitudinal dispersion grows nearly linearly with pore velocity, reflecting advection-dominated transport under well-formed parabolic profiles, uniform shear, and fewer filtration sites reduce mechanical straining and enhance advective delivery.[70]

For compounds transport, in high-permeability sands, transport is dominated by advection, producing piston-like breakthroughs with much less tailing. However, in low-permeability, fine-grained soils, low permeability and high tortuosity suppress pore velocities. Underdeveloped flow and bottleneck control intensify mechanical retention and tailing, lowering breakthrough peaks and inflating apparent dispersion and retention parameters, even when the pressure gradient is increased.[71]

Electric field intervention.

Electrokinetic remediation, introduced in the late 1980s and first deployed for heavy-metal removal in 1992, utilizes direct current (DC) fields to mobilize and concentrate soil compounds. The process is governed by three coupled, interacting mechanisms,[72] electroosmosis (EO) drives pore-water flow, electromigration (EM) transports ions along field lines, and electrophoresis (EP) moves charged colloids and cells. The interplay between these mechanisms can either reinforce or counteract transport efficiency; for instance, bacterial deposition increases when electroosmotic shear exceeds electrophoretic resistance, and decreases under the reverse conditions (Figure 4). Crucially, because the electric field establishes directional transport independent of hydraulic conductivity, electrokinetics is uniquely effective in low-permeability media such as clays and fine sediments.

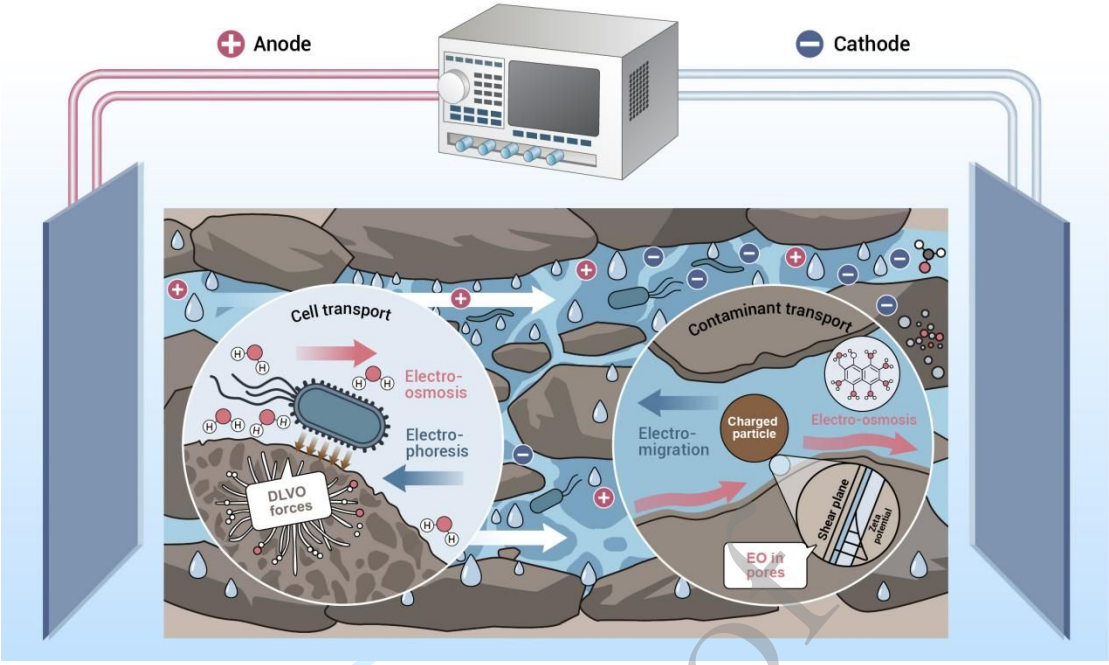

Figure 4. Schematic diagram of electroosmosis, electrophoresis, and hydraulic flow.

External fields drive electroosmotic pore-water flow, while electrophoresis concentrates charged bacteria near electrodes, boosting mobility in low-permeability media. Weak fields (0.5-1.0 $V \cdot cm^{-1}$) stimulate metabolism; elevated dehydrogenase activity can raise phenanthrene degradation by up to ~60%. Cathodic H_2 acts as an electron donor, enhancing anaerobic respiration and accelerating reductive dehalogenation. Some Gram-positive bacteria (e.g., *Lysinibacillus varians* GY32) form centimeter-scale conductive protein networks enabling long-distance electron transfer, extending this capability beyond Gram-negatives.[73,74] Coupled electro-biological treatments outperform standalone approaches, achieving higher removals of compounds such as total petroleum hydrocarbons.[75]

For dissolved compounds, EO supplies directional bulk flow that moves neutrals and colloid-bound species, while EM accelerates ion migration, improving capture or delivery to reactive zones.[76] In low-permeability media, this decouples transport from hydraulic conductivity, yielding more uniform, controllable fluxes. Moderate fields can substantially increase solute migration rates, sharpen breakthrough, and reduce tailing by mitigating mechanical retention and bypassing tortuous paths. For ionic compounds, EM enables focused removal or in situ treatment at electrodes or reactive barriers, which depends on balancing EO and EM with site geochemistry, while careful electrode and electrolyte management limits by-products and sustains stable transport.[77]

Thermal field intervention.

Thermal-effect coupled remediation effectively overcomes transport limitations in low-

permeability porous media by modulating the physicochemical and interfacial rheological properties at solid-liquid-biological interfaces.[78,79] Heating of 25–80°C include a 30% reduction in pore-water viscosity, and a threefold increase in the diffusion coefficient of ionized compounds like PFOA, and a 30%-50% decrease in DLVO-driven microbial sorption, collectively improving bacterial migration rates by up to 145%.[80–82]

Heating improves microbial transport by reducing fluid viscosity, widening nanoscale conduits, and weakening attractive forces between cells and matrix,[83,84]hence resulting in declined attachment and increased microbial breakthrough in fine-grained matrices. Beyond these physical fluid alterations, moderate thermal fields impact the rheological properties of biological interfaces. Specifically, elevated temperatures can trigger a phase transition in bacterial extracellular polymeric substances (EPS), shifting them from a rigid, highly adhesive hydrogel state to a more fluid, viscoelastic state.[85] Heat can also stimulate metabolism and community restructuring, which supports enhanced biodegradation of compounds such as erythromycin.[86]

For compounds, thermal fields enhance their mobility by decreasing viscosity, expanding nanoporous pathways, and increasing diffusion coefficients, thereby accelerating desorption from solids and transport through tight pore networks.[87] For ionic and polar compounds such as PFOA, a threefold rise in diffusion under moderate heating translates to faster mass transfer across interfacial barriers.[88] Moreover, this thermally driven desorption mechanism is increasingly being explored for emerging contaminants, such as the mobilization of strongly bound nanoplastics and microplastics from complex soil aggregates. The elevated thermal kinetic energy effectively overcomes their high-affinity hydrophobic and van der Waals interactions with soil organic matter.[89]

ELECTROKINETIC ENHANCEMENT OF MASS TRANSPORT IN SOILS

Electrokinetic remediation offers significant advantages by simultaneously controlling bacterial deposition and compound release. It preserves soil microbiome structure and function, sustaining biodegradation capacity.[90–92] Field-induced multi-physics including ion migration, electroosmosis, and electrophoresis, jointly drive directional transport of compounds and microbes.[93,94] By altering solid–liquid interfacial conditions such as pH, ionic strength, electrokinetic modulation of compound retention and microbial interfacial behavior can be regulated.[95,96] Through the multi-field coupling mechanism, the electric field modulates microbe-substrate-compound interfacial interactions, enhancing the efficiency of compound migration and transformation (Figure 5).

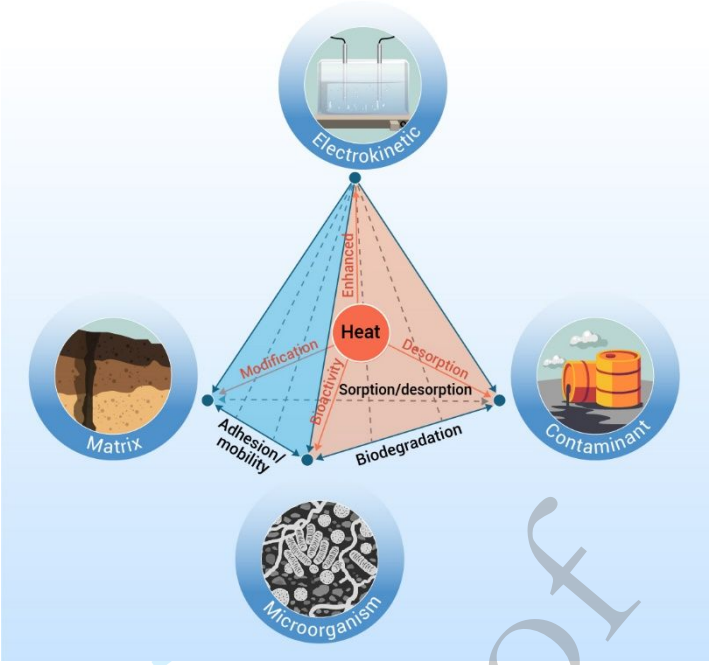

Figure 5. Schematic diagram of the impact of electric effects on soil system interactions.

Electrokinetic-driven microbe-matrix-compound interactions

Electrokinetic remediation simultaneously controls bacterial deposition and compound release while preserving soil microbiome structure and function, retaining innate biodegradation potential.[97] This technique enhances mass transport through field-induced synergies including EO, EM, and EP, which facilitate directional movement of charged compounds, microorganisms, and ions.[98] These processes modify interfacial physicochemical conditions, such as electric double-layer structure and surface charge, to regulate compound sorption-desorption and microbial adhesion. Joule heating nonlinearly influences mass transfer by altering medium viscosity and diffusion coefficients.[99] Through electro-chemo-biological coupling, electric fields optimize microbe-matrix-compound interactions, significantly improving the efficiency of compound migration and transformation.[100–102]

Electrokinetic driven microbe-matrix interactions. The physicochemical, structural, and surface characteristics of the bacteria and solid synergistically regulate the direction and extension of electric field have been investigated.[103] Surface charge is the primary factors determining the direction (i.e., deposition or transport) electric field effects.[104,105] Electric fields enhance high-charge species transport (e.g., *Pseudomonas fluorescens* LP6a, *Sphingomonas* species S3, etc.) while suppressing low-charge species (e.g., *Pseudomonas putida* KT2440, *Rhodococcus opacus* X9, etc.).[106–108] Structural features including cell morphology and Gram type, intrinsic features including growth phase and EPS, and surface hydrophobic features are the key factors determining the extent of

electric field effects.[109,110] These results underscore the capacity of applied electric fields to augment microbial degradation efficiency.

Electrokinetic driven matrix-compound interactions. The electric field induced electroosmotic pore water flow and electro-migration of drives dissolved and suspended compounds transport.[111,112] This process increases the transport flux of key substances by several orders of magnitude,[113] ensuring their efficient delivery in low-permeable zones. In this process, the inherent properties of the matrix significantly influence the efficacy of the aforementioned electric field-driven effects. For example, the removal efficiency of compounds in high-permeable sandy soil is significantly higher than in low-conductive loamy soil,[114] highlighting the importance of the matrix as an interaction medium. The pore water chemical environment modulates the transport and mixing efficiency of charged compounds through Coulombic interactions, thereby governing the degradation kinetics.[115]

Electrokinetic effects on bacterial deposition and transport

Electrokinetic phenomena at the solid-liquid interface are key to regulate bacterial transport in complex heterogeneous environments,[116] in addition to the classical attractive forces depicted by DLVO theories.[117,118] The presence of DC fields overcomes the temporary restricted transport of microbes in the areas with permeable pore networks (Figure 6). Soil and microbial properties interfere the electrokinetic effects, involving mechanisms of electroosmosis, electrophoresis, integrated to the DLVO interactions.

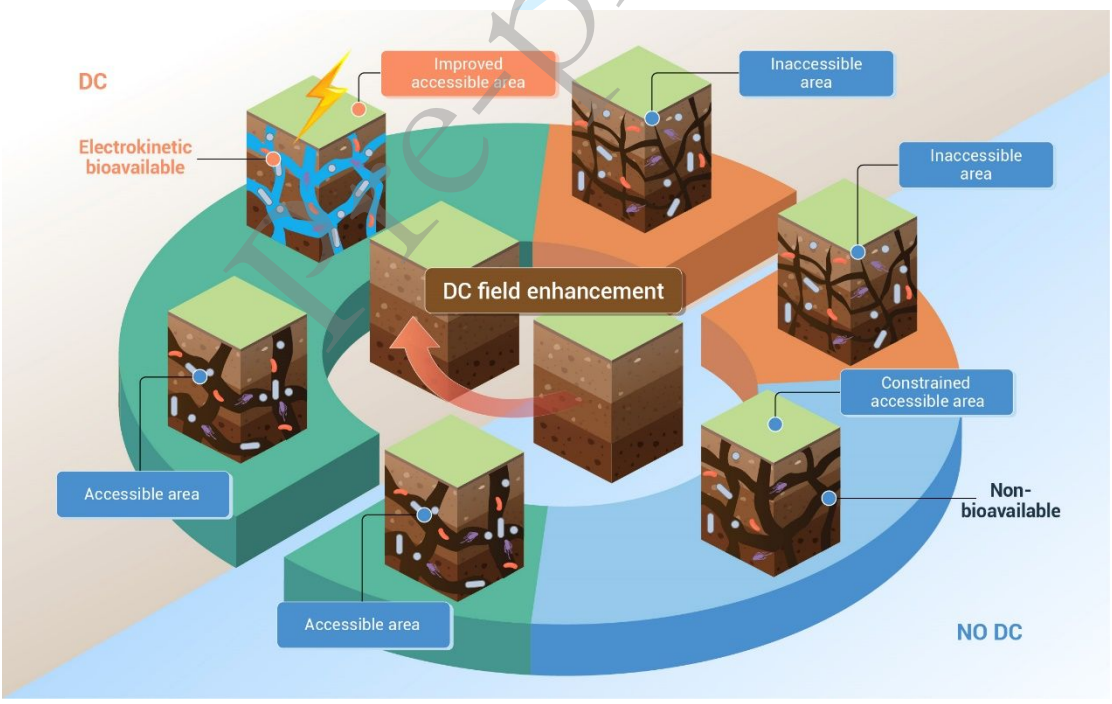

Figure 6. Direct current improvement on the mass transport in the temporarily restricted accessible areas.

Therefore, this section will systematically explore the dual role of electrokinetic in bacterial transport at heterogeneous solid-liquid interfaces: we will analyze its macro-observable effects on bacterial deposition and migration behavior, and then delve into the underlying

physical mechanisms and dominant forces driving these phenomena, with the aim of elucidating the physical basis of electrokinetic in regulating bacterial environmental behavior.

Electrokinetic transport of bacteria.

In heterogeneous solid-liquid interface environments, the application of an external DC electric field has been widely observed to exert significant and complex regulatory effects on initial bacterial transport.[119] These electrokinetic effects manifest themselves in observable, non-random changes in the spatial distribution, adhesion strength, movement trajectory, and retention time of bacteria at the interface. Its form and degree depend heavily on the electric field parameters, interface properties, and solution chemical environment.[120,121]

Electric-field strength critically regulates bacterial deposition on heterogeneous surfaces.[122] Specific DC fields can reduce initial adhesion efficiency and surface coverage by > 85%.[92] Quartz Crystal Microbalance with Dissipation (QCM-D) reveals field-induced shifts in vibration frequency (Δf), and dissipation energy (ΔD) of the sensor posed to piezoelectric effect, with the $\Delta f/\Delta D$ indicating real-time changes in viscoelastic rigidity of bacterial attachments under external electric field.[123–125] Electrolyte concentration modulates outcomes: low ionic strength often promotes field-enhanced deposition, whereas high salinity can weaken or reverse the effect.[126]

Electric fields reshape near-interface and porous-media migration paths, rates, and directions. Under DC fields, populations migrate non-randomly, predominantly toward the cathode, with subpopulations moving anode-ward, revealing spatial differentiation tied to surface-charge heterogeneity.[127] Directional differentiation arises from heterogeneous bacterial surface charges. Tuning field parameters suppresses local pH swings and stabilizes migration flow patterns.[128,129] Field effects are time-dependent: short-term exposure enhances directed transport, whereas prolonged exposure can reduce migration efficiency by up to 95%.[130]

Physicochemical heterogeneity at solid–liquid interfaces underpins the strong spatial variability of electrokinetic effects. Microscale variations in charge, wettability, and roughness yield distinct deposition preferences, adhesion strengths, and migration resistances under the same field.[122,125] Oppositely charged patches show elevated local deposition; like-charged regions inhibit deposition or induce desorption.[92,122] At the interface between hydrophobic and hydrophilic patches, bacterial migration trajectories are often observed to undergo significant deflection or retention.[131] Interface-sensitive tools and microscopy show that spatial bacterial distributions correlate strongly with substrate heterogeneity.

Table 1 summarizes the electrokinetic migration behaviors of typical bacterial strains and colloidal particles in different porous and microscale matrices. For bacterial species including *Pseudomonas fluorescens* LP6a, *Sphingomonas* sp. S3, *Pseudomonas putida*

KT2440 and *Rhodococcus opacus* X9 in sand media, the dominant electrokinetic mechanisms involve electroosmosis and electrophoresis, which exhibit distinct effects on cell deposition, ranging from complete deposition reduction to substantial deposition enhancement with varied efficiency magnitudes. For colloidal particles spanning nanometer to micrometer bioparticles and nanoprobes in microsystems and polydimethylsiloxane wells, multiple electrokinetic phenomena such as electrophoresis, dielectrophoresis, electroosmosis, electrorotation and electroalignment dominate the transport process, achieving efficient particle throughput and precise directional alignment, with corresponding migration performance and relevant research references listed for each category.

Meanwhile, electrolysis occurs in pore water and aqueous solutions under the electric field. Oxidation reactions take place at the anode, releasing H^+ and O_2 and leading to localized acidification; reduction reactions occur at the cathode, generating OH^- and H_2 and forming alkaline microenvironments. Electrolytic products and extreme pH values impose concentration-dependent effects on soil microorganisms. Moderate hydrogen produced at the cathode acts as an electron donor to facilitate anaerobic respiration and reductive dehalogenation metabolism of microorganisms, and enhance the degradation capacity of functional bacteria.[132] In contrast, extreme pH conditions, high levels of reactive oxygen species and accumulated bubbles derived from electrolysis damage microbial cell membranes, inhibit intracellular enzyme activity and bacterial proliferation, and markedly weaken microbial functions. Long-term electrode polarization and continuous electrolysis also reshape the soil microenvironment, further causing differentiation of microbial community structure and altering the coupling efficiency between mass transfer and biodegradation.[133]

422 **Table 1. Summary of typical electrokinetic transport cases of particles.**

Category	Species	Matrix	Dominant electrokinetic	EK efficiency	References
Bacteria strains	*Pseudomonas fluorescens* LP6a	sand	Electroosmosis enhances deposition Electrophoresis reduced deposition	100% reduced deposition	Shan et al.[104]
	Sphingomonas sp. S3	sand		40% reduced deposition	
	Pseudomonas putida KT2440	sand		584% enhanced deposition	
	Rhodococcus opacus X9	sand		66% enhanced deposition	
Colloidal particles	Bioparticles	microsystems	electrophoresis and/or dielectrophoresis	10^6 particles per second	Porro et al.[134]
	nanoprobe	Polydimethylsiloxane well	electroosmosis, electrophoresis, electrorotation, electroalignment	2.7 μm s^{-1} precise alignment of the particle	Li et al.[135]

Interfacial mechanical mechanism of bacterial transport.

With the presence of DC fields, electrophoretic force (F_{EP}) and electroosmotic shear force (F_{EOF}) constitute the dominant electromechanical mechanisms regulating bacterial transport and deposition, in addition to the classical (extended-) DLVO forces, to determine the bacterial transport.[122,125]

F_{EP} drives charged cells toward the electrode of opposite sign under the Columbic force.[136,137] It explains population-level directed transport and intra-population migration divergence. Directional divergence arises from heterogeneity in single-cell surface charge, altering F_{EP} direction/magnitude.[127,137] EOF-driven by field-dragged counter-ions in the EDL moves bulk liquid along surfaces, complementing or competing with F_{EP}.[136,138] EOF often carries bacteria cathodically with the flow (~0.6 cm h^{-1}), enabling co-migration of compounds, cells, and nutrients.[118]

In the critical region near the interface (micrometer scale), the velocity gradient generated by EOF velocity gradients impose tangential F_{EOF} that pose shear force to increase the probability of strong adhesion.[92,122] Generally, in neutral environments, the opposite directions of F_{EOF} and F_{EP} lead to intrinsic competitions.[122] Their instantaneous balance is the core mechanism that governs interfacial outcomes of enhanced deposition-transport.[107,108] Deposition is significantly inhibited[92] when F_{EOF} is greater than F_{EP}. Conversely, the dominance of F_{EP} enhances deposition efficiency. This competitive model quantitatively explains the deposition phenomenon dependent on electric field strength.[107,108]

In addition to the electrokinetic forces, electric fields also reshape the interaction energy by influencing the EDL, ionic strength, etc.[71,107] According to the XDLVO theory, irreversible bacterial deposition must overcome the primary energy barrier formed by electrostatic repulsion.[122,125] The application of electric fields significantly compresses the EDL, especially at low ionic strength (I) conditions. This compression lowers barrier height/range, explaining deposition promotion in low-salt conditions.[125] Fields may adjust van der Waals and acid-base components, deepening the secondary minimum. This underpins transitions from loosely to tightly bound states under prolonged exposure.[130]

Furthermore, the electrokinetics is influenced by the environmental factors, such as heterogeneity, wettability, solution chemistry etc. (i) The physicochemical heterogeneity creates spatially varying field gradients and ζ, producing vortices, acceleration, and stagnation in microscopic EOF, which deflect, accelerate, or stall bacterial trajectories;[131] (ii) Wettability alters hydrophobic interactions and slip/boundary conditions, tuning F_{EOF} and interfacial energy and intensifying spatial complexity,[131] (iii) the balance and strength of the above driving forces are dynamically regulated by solution chemistry, electric field parameters.[126] (iv) Electrolyte ionic strength I is a key solution parameter: at low I, the EDL is thicker, the electric field compression effect is significant (promoting deposition), and high ζ enhances EOF.[125,136]

Electrokinetic effects on compound sorption and desorption

Interactions between compounds and solid geological adsorbents play a crucial role in determining the persistence, fate, and exposure of pollutants to environmental and human. The sorption-release of compounds is influenced by three rate-limiting steps: (i) diffusion from bulk liquid to matrix, (ii) molecular diffusion across the aqueous film layer, and (iii) intra-particle diffusion to nano-pores. Progressive binding renders residual hydrophobes less leachable and less bio-accessibility.[139] Specifically, by directly targeting these steps, electric fields provide strong driving forces that overcome conventional diffusion limits.

EM can efficiently drive charged compound ions (such as heavy metal ions Cd^{2+}, Pb^{2+}, or organic ions such as phenol salts) through the water boundary layer (step iii) and accelerate their transport in the pore network (step ii) or even nanoscale channels (step i). This is essentially achieved by enhancing the desorption of compounds from sorption sites and their transport to the electrode region.

Electroosmosis drives the overall movement of pore water, not only promoting convective diffusion of desorbed compounds in the water phase (steps ii and iii) and flushing sorption sites, but also potentially affecting mass transfer within nanopores by altering local hydrodynamic conditions (step i).

The electric field and its induced accompanying processes can significantly influence the interaction forces between compounds and adsorbents. For example, the strongly acidic environment (low pH) in the anode region typically weakens the electrostatic attraction between cationic compounds and negatively charged sorption sites, promoting their desorption; whereas the high pH environment in the cathode region may enhance the sorption of anionic compounds or trigger the precipitation of heavy metals.

Additionally, the electric field may directly alter the surface charge density and double layer structure of the adsorbent, thereby regulating the intensity of non-electrostatic sorption mechanisms such as hydrophobic interactions and complexation/chelation. The sorption and release of PAH in various sorbents can be investigated by kinetic[140–142] and thermodynamic (e.g., Gibbs free energy of sorption, ΔG^{o}) approaches (Figure 7).[143,144]

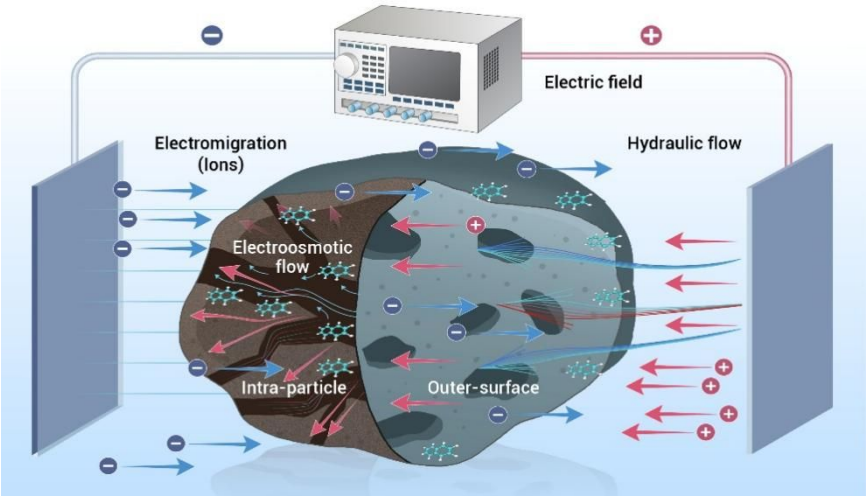

Figure 7. Schematic diagram of the theoretical mechanism of electrokinetic effects on compound sorption and desorption.

Electrokinetic transport of compounds.

Applying external DC fields to heterogeneous environmental interfaces exerts significant and multifaceted regulation on the sorption–desorption behavior of compounds.[126–128] This electrokinetic influence is reflected in measurable, non-random alterations in sorption rate, equilibrium capacity, desorption kinetics, final release quantity, and spatial distribution of compounds at interfaces.[149] These changes are strongly governed by electric field parameters, compound properties, interfacial characteristics, and solution chemistry.[150,151]

Typical application cases of electrokinetic technology in contaminated soil remediation are summarized in Table 2 to provide detailed process parameters and performance data for representative scenarios, including non-ionizable organics, ionizable organics, and inorganic contaminants. Electrode layout and voltage/field strength directly determine the dominant electrokinetic transport behavior. For non-ionizable organic compounds such as phenanthrene and diesel, EO acts as the primary driving force. For ionizable organic contaminants e.g., PFOA and 2,4-D, EM becomes dominant due to charge dissociation at outer surface of matrix, while electroosmotic flow dominates in nano-pores. In inorganic systems involving heavy metals, rare earth ions, and radionuclides, EM governs ion transport, and field strengths of 0.3-1.0 $V \cdot cm^{-1}$ achieve stable removal efficiencies of 65%-95%. Soil matrix type strongly influences EK performance: lateritic red soil and kaolin exhibit high EM efficiency for ionic rare earth and radioactive elements, whereas silt soil and garden soil favor EO-driven organic mobilization. This systematic comparison clarifies the adaptability of EK parameters to different contaminant categories and soil types, validating technical operability and universality across engineering scenarios.

Electric field strength plays a critical role in modulating compound sorption efficiency. On carbonaceous materials such as exfoliated graphite, the sorption rate of phenanthrene (PHE) can increase by up to 7-fold under an applied field.[145,146] In contrast, PHE sorption is often suppressed on mineral adsorbents. For heavy metals, electric currents markedly reduce their retention on solid phases. At a low current density of 0.5 mA cm^{-2}, concentrations of copper and cadmium rapidly decreased by 74% and 80% within the first three days.[152,153] Competitive sorption selectivity between compounds can also be altered by the electric field, shifting preferential uptake among co-existing substances, while solution chemistry further modulates the overall sorption response.[154,155]

DC electric fields strongly promote the desorption and release of various bound compounds. For example, on carbonaceous materials, the electric field reduced the desorption rate of PHE by more than 99%.[146] EOF has been observed to strongly release hydrophobic compounds from low-permeability areas, increasing the release flux of phthalates by 1.4-1.8 fold compared to conventional water flow.[147] For heavy metals, the desorption efficiency under an electric field is often significantly better than just compound acidification.[152] The desorption process often shows a phased pattern, showing how the

electric field gradually overcomes interface resistance.[153] The marked acceleration in desorption kinetics is manifested by faster attainment of desorption equilibrium and a significant increase in the final desorption yield.[133,135] Under specific conditions, desorption inhibition may also be observed.[156]

Rare earth elements are critical strategic metals, yet conventional mining of ion-adsorption deposits causes severe environmental harm and has been banned. Wang et al. introduced electrokinetic mining (EKM), a novel approach using electric fields to direct and recover rare earth ions. Through multi-scale validation and key innovations such as conductive polymer electrodes and intermittent power supply, the team achieved over 95% recovery in a 5,000-ton industrial test, while cutting reagent use, extraction time, and ammonia emissions by 80%, 70%, and 95%, respectively.[157,158] This milestone demonstrates the successful scaling of EKM from concept to industrial reality.

Table 2. Summary of typical electrokinetic remediation cases for contaminated soil, including electrode configuration, field parameters, dominant mechanisms, and removal efficiency.

Category	Compound	Matrix	Electrode layout	Voltage	Dominant electrokinetic	Removal rate	References
Non-ionizable organic compounds	Phenanthrene	Garden soil	Parallel platinum plate electrodes	1 V·cm^{-1}	EO	Up to 94.4%	Yue et al. [159]
	Diesel	Kaolin clay	Graphite plate electrodes (10×10×1 cm); daily polarity reversal	0.5-1.5 V·cm^{-1}	EO	Up to 36%	
Ionizable organic compounds	PFOA	Activated carbon	Parallel platinum plate electrodes	1-3 V cm^{-1}	EO and EM	Up to 38%	Shan et al.[160]
	2,4-D	Silt soil	Carbon felt anode; stainless steel cathode;	10.5 V	EM	87.1%	Jackman et al.[161]
Inorganic compounds	Cr^{6+}, U^{6+}, As^{3+}, Cd^{2+}, Pb^{2+}	Red soil, clay, sand	Lab EK cell; graphite + Ti	0.3–1.0 V·cm^{-1}	EM	65%–95%	Annamalai et al.[76]
	Rare earth ions	Lateritic red soil	Conductive polymer; 2.0 m×2.0 m grid	0.3–0.6 V·cm^{-1}	EM	>95%	
	Sr-90, Cs-137, U	kaolin	Lab-scale EK cell; electrode spacing 2–10 cm	0.5–1.0 V·cm^{-1}	EM	70%–90%	

Electrokinetic fundamentals governing compound sorption.

Sorption-desorption dynamics at heterogeneous interfaces are governed by the coupling of electrokinetic processes and electric field induced chemical reactions.[127,128]

EOF is adsorbent-dependent: an electric field drives double-layer counter-ions, generating tangential flow along charged surfaces, while the direction is set by the zeta potential.[127,131] In strong adsorbents with well-developed microporosity, EOF drives hydrophobes into diffusion-limited pores, increasing contact frequency and residence time at sorption sites[163]. Conversely, on weakly adsorbing or non-microporous minerals, EOF acts mainly via shear, scouring interfacial compounds, inhibiting sorption and promoting desorption.[145] EOF intensity is nonlinearly modulated by porosity, particle size, ionic strength, and interfacial hydrophobicity, explaining media-dependent EOF effects.[164–166]

EM is the primary driver of directed transport for charged compounds.[167] For weakly adsorbed ions (e.g., NO_3^-), EM efficiently drives interface-to-bulk migration, dominating rapid removal. However, f or strongly adsorbed or precipitable ions (e.g., Pb^{2+}, Cd^{2+}), EM efficacy hinges on prior compound desorption. Once desorbed, EM supplies sustained, directed transport toward target electrodes and suppresses re-sorption. This mechanism enables high removals (≥ 94%) for species such as phenol and acetic acid.[162] Thus, intrinsic sorption strength sets the prerequisite for EM effectiveness.[167]

Electrode-induced pH fronts are the key switch governing sorption-desorption equilibria.[137,138] Anodic acidity promotes cationic metal desorption via (i) surface protonation, (ii) H^+ competition for sites, and (iii) acid dissolution of metal-bearing minerals[133,135]. This explains the phenomena rapid anode-zone metal decline, desorption surpassing simple acidification, and the necessity of forced acidification. Conversely, cathodic alkalinity (pH > 10) promotes anion desorption (e.g., CrO_4^{2-}, AsO_4^{3-}) via repulsion/OH^- competition but induces cation precipitation/re-sorption, limiting cathode-zone removal.[134,137]

Intrinsic heterogeneity strongly shapes the spatial expression of these mechanisms.[140] Conductivity contrasts distort local fields, degrading EOF/EM uniformity and efficiency. Mineralogical differences in buffering, surface charge, and reactivity cause divergent local pH evolution and responses.[154,170] Priority EOF pathways formed in large pores or high-permeability zones result in spatial segregation of compound migration and reaction.[172] Highly sorptive domains act as traps via irreversible sorption or precipitation.[173]

Key optimization strategies were developed based on the above mechanistic understanding. Forced acidification supplies sufficient H^+ to overcome buffering and sustain strong acidity, maximizing protonation and mineral dissolution.[152,155] Complexation/solubilization forms stable, soluble complexes that lower sorption affinity, raise solubility, and resist re-sorption/precipitation, boosting EOF/EM transport.[174,175] Targeted delivery/activation of oxidants or reductants under electric fields transforms speciation and mobility.[146,147] Electrode manipulation (e.g., mobile anodes) optimizes acid-front coverage and efficiency; physical barriers isolate electrode extremes or block

bypass/interference paths.[150]

THERMAL EFFECTS ON ELECTROKINETIC DELIVERY

The efficiency of electrokinetic delivery is often limited by factors such as high liquid viscosity and strong particle-surface adhesion forces.[179] Recent studies have shown that thermal effects can significantly enhance electrokinetic delivery by altering key physicochemical properties of the system[80] (Figure 8). Temperature variations can reduce liquid viscosity and dielectric constant while increasing zeta potentials of both particles and porous media surfaces. These changes lead to a reduction in matrix attractive forces and an enhancement of electrokinetic forces, thereby improving particle transport efficiency.[180]

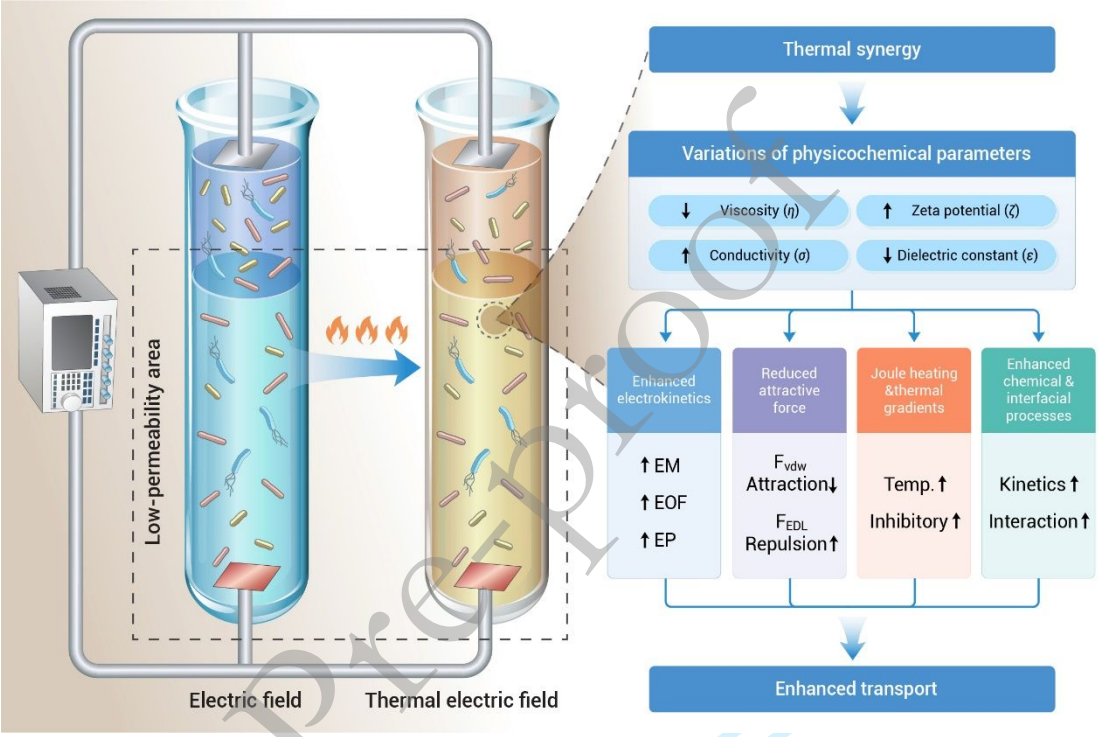

Figure 8. Theoretical diagram of the effect of thermal effects on electrokinetic transport.

Mechanisms of thermal-electric coupling

While uniform thermal interventions mitigate fundamental mass transfer barriers, the integration of direct current (DC) electric fields introduces highly non-linear multiphysics coupling. Thermal effects exert multifaceted and profound influences on the electrokinetic transport process, with the core mechanism originating from temperature-induced alterations in fundamental physicochemical properties. Although elevated temperatures significantly reduce liquid viscosity (η) and directly impact conductivity and Zeta potential, the latter of which is associated with temperature-dependent electrical double layer (EDL) structure. the true complexity emerges from internal heat generation. These changes in physical properties directly accelerate the core processes of electrokinetic transport: EOF velocity and EM rate.[181]

Beyond altering bulk fluid properties, recent research highlights that the superimposed thermal field exerts profound physiological stress on biological colloids. Elevated temperatures induce dynamic shifts in bacterial morphological characteristics and extracellular polymeric substance (EPS) secretion. These morphological adaptations alter the effective cellular radius and surface charge density, directly modifying their electrophoretic mobility and re-calibrating the interaction energy landscape at the microbe-matrix interface. Concurrently, elevated temperatures generally enhance chemical reaction kinetics and interfacial mass transfer processes, thereby accelerating compound sorption/desorption on the medium or degradation reactions.

In actual EK systems driven by direct current (DC), the Joule heating effect is the primary heat source, with its influence far exceeding uniform heating. Numerical simulations have for the first time systematically revealed the positive feedback loop between electrical conductivity and temperature triggered by Joule heating, a key mechanism completely overlooked in traditional isothermal models. More importantly, Joule heating induces significant temperature gradients within the system, and these gradients themselves become a new important driving force capable of inducing thermal convection.

In heterogeneous porous media at the site scale, this non-uniform heating process is highly complex, manifesting as dynamic stages such as preferential heating of low-permeability zones, rapid heating of intermediate regions, temperature decline, and the movement and reheating of thermal zones. The dynamic behavior of ions leads to their non-uniform redistribution, which in turn dominates heating rates and spatial temperature patterns.[182] Soil heterogeneity represented by clay content, pH, organic matter content and electrical conductivity critically governs electric field distribution, mass transport and remediation performance in electrokinetic systems: high clay content increases soil pore tortuosity and particle adsorption to distort the electric field and hinder electroosmotic and electrophoretic migration; near-neutral pH of 6.0–7.5 maintains stable zeta potential and uniform electric field, while extreme acidity or alkalinity induces particle aggregation and inhibits contaminant transport; high organic matter coats mineral surfaces, sequesters pollutants, distorts electric field lines and suppresses pollutant desorption and migration; moderate electrical conductivity within 50–200 mS/m sustains concentrated electric fields and efficient mass transport, whereas excessively high conductivity causes current leakage and energy loss and reduces remediation selectivity, and overall, soils with moderate clay content (10%–20%), low organic matter (<2%), near-neutral pH and properly regulated conductivity yield the most stable electric field and optimal remediation efficiency, while abnormal parameter levels lead to pore blockage, pollutant immobilization and deteriorated electrokinetic treatment outcomes.[182]

Enhanced mass transport and remediation

Building upon the spatiotemporal multiphysics coupling mechanisms, thermal effects exert complex regulatory effects on the migration and removal efficiency of target compounds in complex media. Rather than merely accelerating simple diffusion, the synergistic action of thermal and electric fields fundamentally alters interfacial interactions. Recent advances

further reveal that this synergistic thermal-electric field profoundly impacts the transport and reactivity of complex, naturally occurring geo-sorbents, such as pyrogenic carbon. For instance, the electrokinetic mobilization of dissolved black carbon (DBC) from wildfire residues is significantly enhanced under thermal gradients. The elevated temperatures not only increase DBC solubility, but also accelerate its redox-driven interactions with reactive soil minerals, such as manganese oxides, thereby overcoming transport bottlenecks in heterogeneous or boreal forest soil profiles.

In zeolite column experiments, the combined action of a direct current (DC) electric field and heating significantly promoted the migration of perfluorooctanoic acid (PFOA) by reducing viscosity and altering sorption kinetics (reducing sorption by 37%-38%).[81,82] In contaminated site remediation, the Joule heating effect of direct current is one of the key pathways for activating persulfates; as voltage increases, the activation pathway of persulfates transitions from a single electrode reaction to a coupled electrode, chemical, and thermal reaction, significantly improving the removal efficiency of compounds (e.g., MCB) from 57% to 95%. while alternating current (AC) can only influence persulfates through Joule heating, with efficiency far lower than DC.[181] At the nanoscale, the regulation of ion current rectification ratio by temperature gradients to enhance rectification effects demonstrate the potential of thermal effects as an additional important transport driving force beyond potential gradients.[183,184]

Table 3 summarizes the thermal enhancement and inhibition effects across three typical temperature scenarios in electrokinetic remediation systems. At 25°C–40°C, moderate heating reduces medium viscosity, raises the absolute zeta potential, weakens particle aggregation, and markedly accelerates electroosmotic flow and electrophoretic migration, with only slight impacts on microbial activity and negligible restriction on mineral colloid transport. In the medium temperature range of 40°C–80°C for thermo-electrokinetic coupled bioremediation, thermal effects further improve pore water fluidity, facilitate contaminant desorption from soil particles, and promote long-distance colloid migration; meanwhile, elevated temperature inhibits microbial viability and metabolism and accelerates the thermal decomposition of organic matter. Under thermal treatment coupled remediation conditions above 80°C, strong thermal convection strengthens pollutant volatilization and desorption, and mineral lattice activation facilitates the release of insoluble pollutants; nevertheless, severe adverse impacts occur, including nearly complete microbial inactivation, extensive carbonization of soil organic matter, irreversible destruction of medium pore structure, and the potential production of volatile toxic by-products, with corresponding literature references provided for each temperature regime.

Table 3. Variation of thermal enhancement and inhibition effects in electrokinetic remediation under different temperature ranges.

Scenarios	Temperature	Thermal enhancement	Thermal inhibition	References
mineral colloids Microbial cells Organic matter	25–40℃	Reduced medium viscosity and increased zeta potential boosted EO and EP	Slight influence on microbial physiological activity	Yang et al.[185]
Thermo-electrokinetic coupled bioremediation	40–80℃	Improve pore water fluidity and enhanced desorption of contaminants promoted colloidal transport	Heating accelerated organic matter thermal decomposition while suppressed microbial viability	Shan et al.[186]
Thermal coupled remediation	>80℃	Thermal convection of pore water enhanced pollutant desorption; activation of partial mineral lattices promoted the release of insoluble pollutants	Microorganisms were almost completely inactivated; massive carbonization caused irreversible damage to the pore structure of the medium	Deng et al.[187]

Understanding the impact of thermal effects provides important insights for optimizing electric drive technology, but it also presents challenges. On one hand, thermal effects can be actively leveraged to enhance efficiency: for example, in microfluidics, the Joule heating effect has been successfully utilized to achieve thermal cycling control in microchannel PCR, eliminating the need for an external heater;[188] in capillary zone electrophoresis, regulating the axial temperature gradient generated by Joule heating through a voltage ramp strategy can suppress peak broadening caused by thermal diffusion, thereby optimizing separation efficiency. On the other hand, thermal effects often lead to a sharp increase in energy consumption while accelerating the process. Therefore, optimizing voltage, current density, and operational strategies to balance efficiency and energy consumption is crucial. Additionally, complex non-uniform heating phenomena in heterogeneous media and the Joule heating positive feedback loop[182] all highlight the importance of monitoring and controlling temperature distribution in applications. Numerous studies[81,82,184] have developed predictive models, providing indispensable theoretical tools for understanding and regulating the impact of thermal effects and

designing novel thermoelectric coupling devices.

CONCLUSIONS AND PERSPECTIVES

This review synthesizes the electrokinetic enhancement of mass transport as a pivotal strategy to overcome the pervasive challenge of mass transfer limitations in low-permeability subsurface environments. By systematically deconvoluting the tripartite interaction among microbes, soil matrices, and contaminants under electric fields, we have identified electroosmosis as a universal transport driver, with electromigration and electrophoresis preferentially facilitating ionic and bacterial translocation, respectively. The superposition of thermal gradients further augments delivery efficiency by modulating fluid properties and interfacial interactions. Electro-bioremediation exemplifies a promising integrated strategy, leveraging these mechanisms for efficient, low-disturbance soil restoration.

Fundamental research should focus on coupled multi-physical processes involving interactions among electrical, thermal, hydraulic, chemical, and biological pathways. In situ characterization techniques enable real-time tracking of micro-interfacial processes, including charge transfer, species transformation, and colloid behavior at soil–microbe–contaminant interfaces. Long-term electric field exposure can reshape soil microbiome structure, functional gene expression, and ecological interactions, which require systematic investigation. Insights from community coalescence and cross-feeding networks further clarify how electro-driven forces modulate microbial assembly, stability, and functional resilience over extended operation.

For engineering applications, priority should be given to optimizing key electric field parameters including intensity, waveform, and electrode configuration to improve adaptability to heterogeneous soil environments. Practical strategies must consider energy efficiency, cost balance, and long-term operational stability. Integrating electrokinetics with bioremediation, permeable reactive barriers, and other innovative technologies enhances mass transfer, contaminant degradation, and mineralization efficiency. Intelligent voltage regulation based on real-time feedback of soil properties further promotes robust, scalable, and sustainable field implementation.

Targeted microbiome engineering via electric field regulation provides a controllable strategy for directional assembly of functional microbial communities. By adjusting electric field intensity, polarity reversal frequency and waveform, electric fields can be used as selective driving forces to enrich electroactive strains, stabilize syntrophic interactions, and enhance the colonization of functional degraders in low-permeability soils. Drawing on the principles of microbial community coalescence, top-down and bottom-up ecological coselection can be realized to coordinate dominant and rare populations for synergistic degradation.[189] Furthermore, modular design of synthetic microbial consortia enables metabolic division of labor, where electro-stimulated functional bacteria efficiently degrade contaminants with the aid of cross-feeding networks.[190] Future efforts should focus on constructing electrically tailored complex communities with high stability and colonization

resistance, enabling precise and resilient microbiome regulation.[191]

Artificial intelligence driven adaptive voltage control enables intelligent optimization against soil heterogeneity and improves remediation efficiency. Real-time monitoring of soil pH, redox potential, contaminant concentration, current density and electroosmotic flow provides high-quality input data for predictive models. Training datasets can be established from laboratory experiments, field pilots and high-throughput sensors to realize dynamic optimization of voltage, waveform and electrode layout. This intelligent framework reduces energy consumption while strengthening mass transport and contaminant removal.[192] Engineering breakthroughs rely on low-cost in situ sensors, edge-computing modules and flexible electrode arrays, enabling long-term autonomous regulation of electrokinetic remediation systems.

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FUNDING AND ACKNOWLEDGMENTS

This work was supported by the Natural Science Foundation of China (Grant Nos. 42277011 & 42477015). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

AUTHOR CONTRIBUTIONS

Wentao Jiao: Conceptualization, Data curation, Formal analysis, Funding acquisition, Supervision, Validation, Visualization, Writing - original draft; **Peng Luo**: Data curation, Formal analysis, Investigation, Methodology, Writing - original draft; **Yajun Wang**: Investigation, Methodology, Software, Validation, Writing - review & editing; **Yuting Guo**: Methodology, Resources, Software, Validation, Visualization, Writing - original draft; **Conghui Zhang**: Methodology, Resources, Software, Validation, Visualization; **Jianfeng Liu**: Methodology, Resources, Validation, Visualization, Writing - review & editing; **Lezhuo Li**: Methodology, Resources, Software, Validation, Writing - review & editing; **Yongping Shan**: Conceptualization, Data curation, Funding acquisition, Validation, Visualization, Writing - original draft, Writing - review & editing; **Bin Liu**: Conceptualization, Resources, Software, Validation, Writing - review & editing.

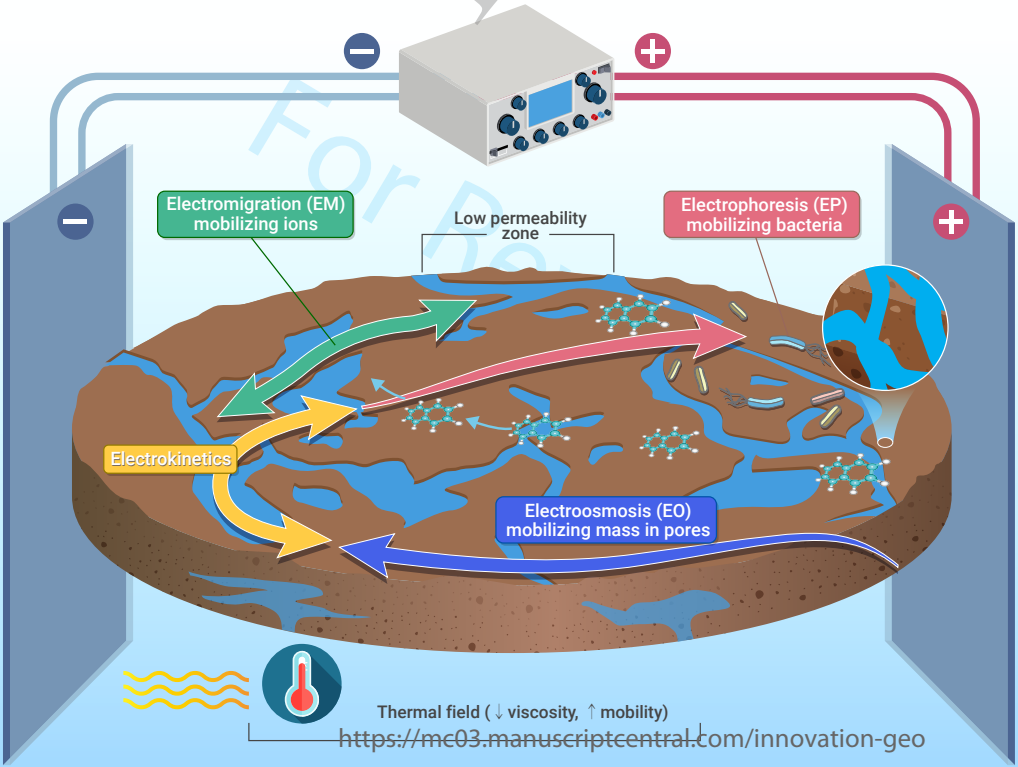
DECLARATION OF INTERESTS

The authors declare no competing interests.

DATA AND CODE AVAILABILITY

No new data were created or analyzed in this study.

Thermal Enhanced Electrokinetic Modulation of Mass Transport in Confined Space



Challenge

Impeded transport in pores

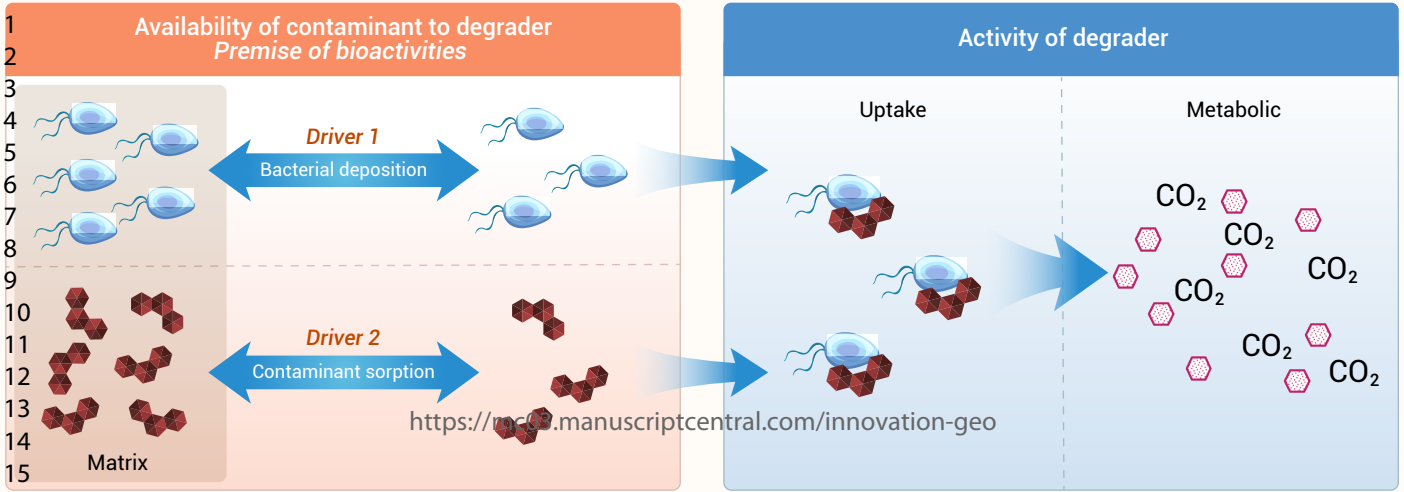
Intervention

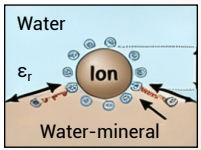
Electrokinetics (EO, EM, EP)

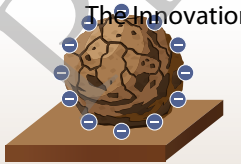
Thermal SYN.

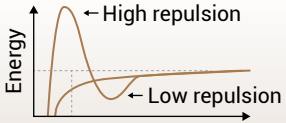
Thermal enhanced electrokinetics

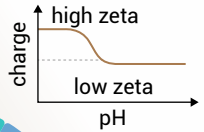
Bioavailability of Contaminant











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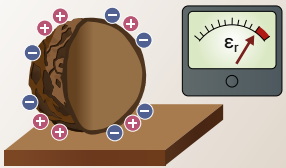
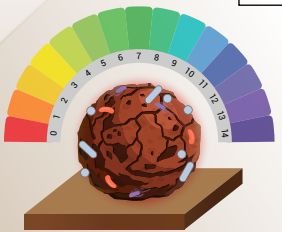


Dielectric constant



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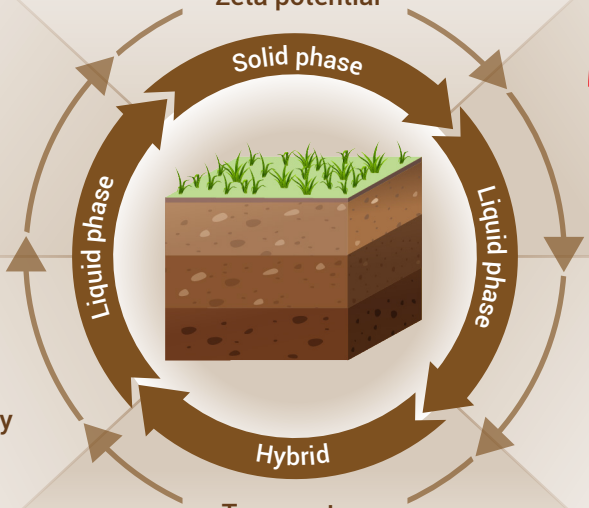

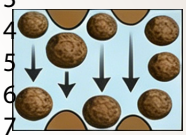

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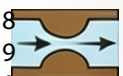

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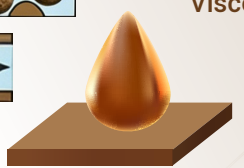
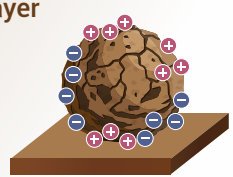
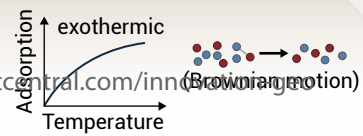
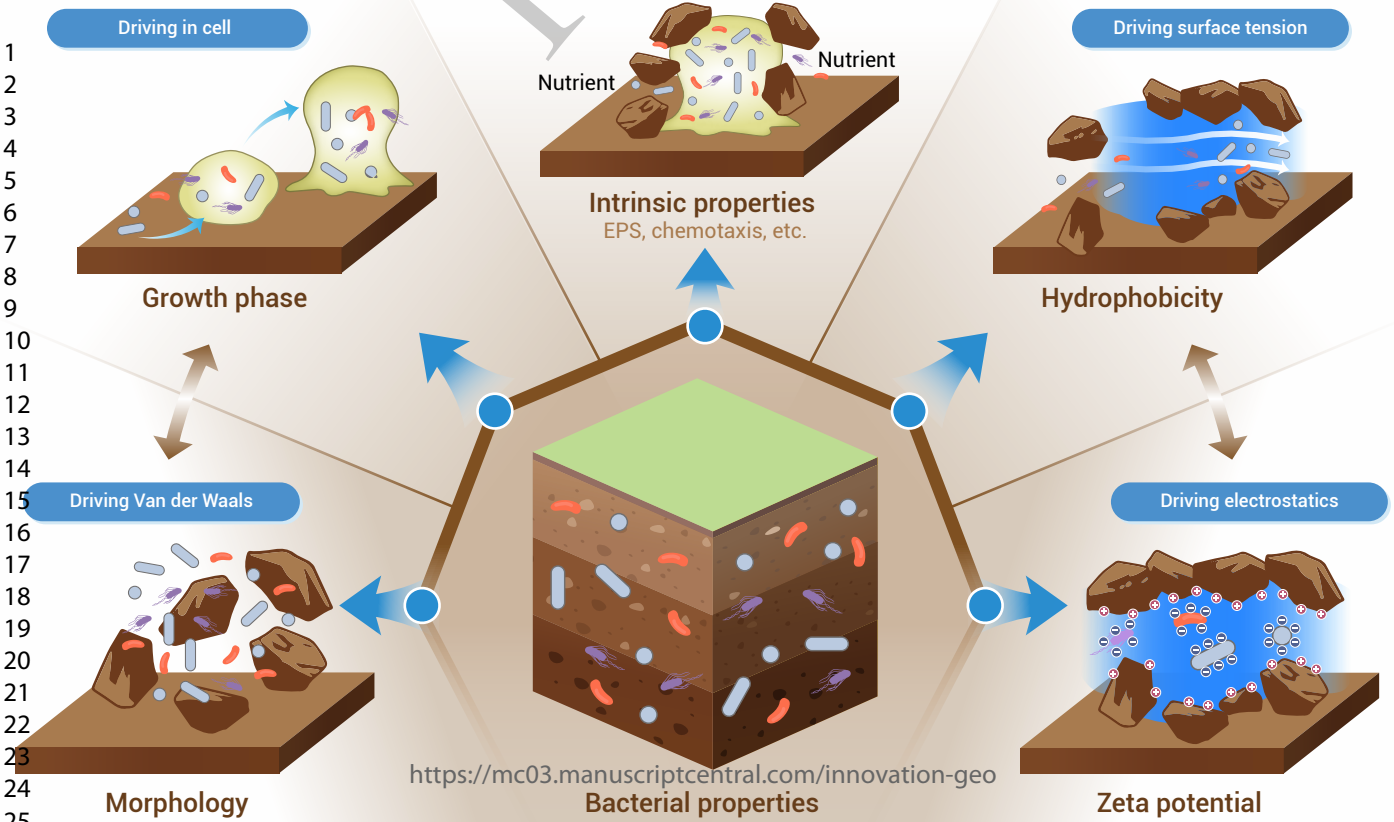


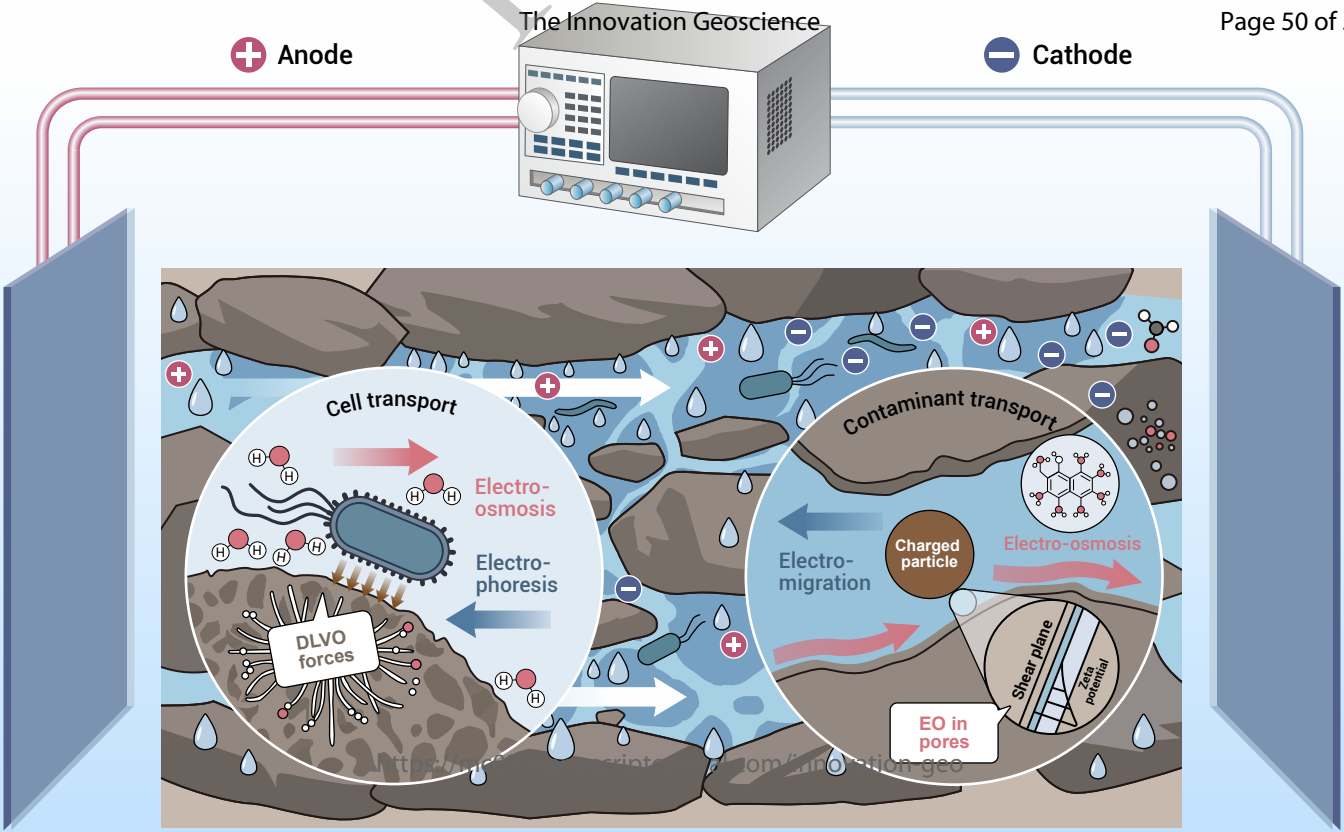
Electrical double layer

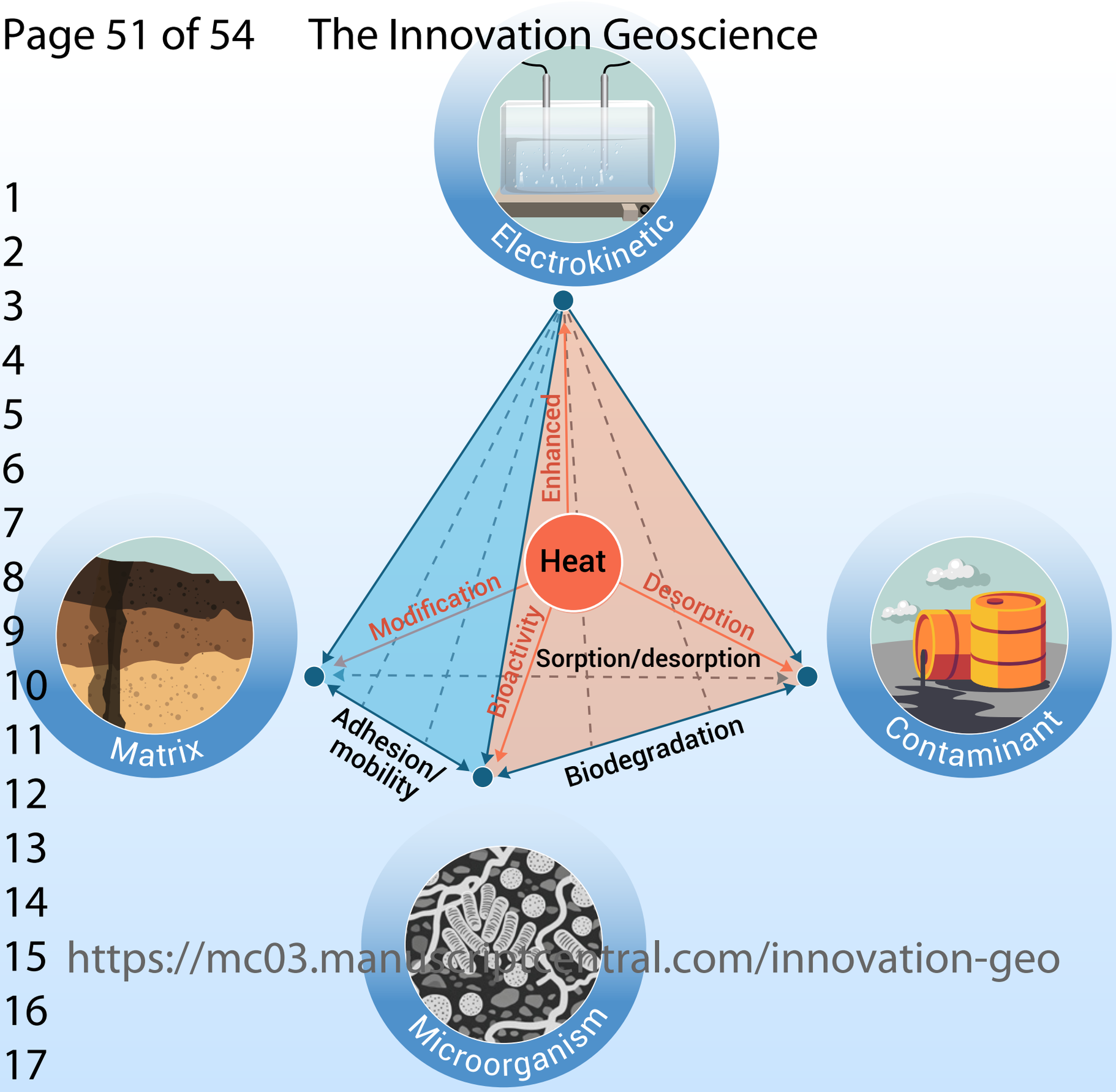


Temperature




Driving surface properties
Driving in cell
Nutrient
Nutrient
Driving surface tension
Intrinsic properties
EPS, chemotaxis, etc.
Growth phase
Hydrophobicity
Driving Van der Waals
Driving electrostatics
https://mc03.manuscriptcentral.com/innovation-geo
Morphology
Bacterial properties
Zeta potential


Anode
Cathode
Cell transport
Electro-osmosis
Electro-phoresis
DLVO forces
Contaminant transport
Electro-migration
Charged particle
Electro-osmosis
Shear plane
Zeta potential
EO in pores


Electrokinetic
Matrix
Contaminant
Microorganism
Heat
Enhanced
Modification
Desorption
Bioactivity
Sorption/desorption
Adhesion/
mobility
Biodegradation