Hapres | Journal of Sustainability Research

sustainability.hapres.com

Review

Advances in Sustainable Soil Health Restoration through Chemical Biological Physical Integrated and Nano Remediation Techniques

Kiran Keshyagol [1], U. Satisha Prabhu [2], Pavan Hiremath [2,*], B. M. Gurumurthy [2], Y. M. Shivaprakash [2], G. Divya Deepak [2], Suhas Kowshik [2]

[1] Department of Mechatronics, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal 576104, India; kiran2.mitmpl2022@learner.manipal.edu, mekeshyagol@gmail.com (KK)

[2] Department of Mechanical and Industrial Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal 576104, India; satisha.prabhu@manipal.edu (USP); gurumurthy.bm@manipal.edu (BMG); prakash.ym@manipal.edu (YMS); divya.deepak@manipal.edu (GDD); suhas.kowshik@manipal.edu (SK)

* Correspondence: Pavan Hiremath, Email: pavan.hiremath@manipal.edu

ABSTRACT

Land degradation, caused by pollution, salinization, erosion, and nutrient loss, undermines food security, the resilience of climate systems, and the health of ecosystems. This review provides an assessment of distinct advanced techniques used for soil remediation which include chemical, biological, physical, integrated, and nano remediation. Some chemical methods like gypsum reclamation, electrokinetic remediation, and advanced oxidation processes (AOPs) focus on the mobilization and breakdown of contaminants, achieving high removal efficiencies epitomized by heavy metals and organics. Other methods, such as phytoremediation, bioaugmentation, and mycoremediation, enhance soil fertility and employ restorational biology while inventive methods like Microbially-Induced Calcite Precipitation (MICP) bolster soil strength. Some of the physical processes are soil flushing and thermal desorption which can efficiently remove pollutants, but energy costs are high. Integrated techniques, notably the application of biochar and electro-bioremediation, demonstrate synergistic enhancement with soil structure and bioremediation performance. Nano-remediation provides unparalleled efficiency for pollutant removal but using nano-zero valent iron (nZVI), nanoclays, and graphene oxide (GO) poses unchartered ecological threats. From the comparison, it is clear that the sustainable remedial approach requires a multifaceted hybrid methodology tailored to the specific site conditions.

KEYWORDS: soil; soil health; sustainability; soil remediation; soil organic carbon (SOC)

Open Access

Received: 19 Apr 2025

Accepted: 11 Aug 2025

Published: 02 Sep 2025

INTRODUCTION

Soils are fundamental to terrestrial ecosystems and perform essential functions including food production, water filtration, carbon sequestration, and biodiversity support [1]. In addition, healthy soils also act as natural reservoirs—storing moisture within their pore networks—thereby enhancing drought resilience and buffering ecosystems against climate variability [2]. These functions are critical not only for agricultural sustainability but also for broader climate adaptation and land restoration goals. However, decades of anthropogenic activities—especially industrialization, mining, improper waste disposal, and unregulated urban expansion—have led to widespread soil contamination, rendering vast land areas unfit for safe ecological or agricultural use [3,4]. This industrial legacy has created a pressing global challenge: how to remediate contaminated soils efficiently and sustainably while unlocking their potential for future productive use.

The scale of the problem is substantial. Over 10 million contaminated sites globally are estimated to contain hazardous levels of pollutants, including heavy metals (e.g., Pb, Cd, As), petroleum hydrocarbons, pesticides, polychlorinated biphenyls (PCBs), and emerging contaminants like microplastics and pharmaceuticals [5]. Many of these sites are classified as brownfields—land areas abandoned or underutilized due to real or perceived contamination. In Europe alone, more than 2.8 million potentially contaminated sites have been identified, of which over 342,000 require urgent remediation [6]. Many concentrated in aging industrial corridors and urban zones. In rapidly developing nations such as India [7] and China [8], informal industrial operations and inadequate regulatory oversight have further intensified the spread of pollutants into peri-urban and even rural landscapes [9]. The contamination of soils with toxic compounds poses serious risks to human health, biodiversity, and environmental sustainability [10]. Furthermore, contaminated soils compromise essential functions such as water retention, microbial diversity, and fertility, perpetuating land degradation and limiting future land use options [11]. The reclamation and rehabilitation of these polluted soils is thus central not only to ecosystem restoration but also to achieving broader sustainability goals, including safe urban development, environmental justice, and land reuse planning [12,13]. In this context, soil remediation which refers to the process of removing, stabilizing, or transforming contaminants in soil to restore it for safe use. The technologies have evolved rapidly to address the complex chemical and physical heterogeneity of industrially contaminated sites. Techniques such as electrokinetic remediation [14], AOPs [15], soil washing [16], and thermal desorption have demonstrated high removal efficiencies for heavy metals, organics, and mixed pollutants [17,18]. Simultaneously, biological approaches such as phytoremediation [19], bioaugmentation [20], and mycoremediation [21] offer ecosystem-compatible alternatives, while nano-enabled technologies (e.g., nZVI, nanoclays, and GO composites) represent the frontier of precision decontamination [22,23].

However, the practical deployment of these methods is often limited to small to medium-scale sites, primarily due to economic and logistical constraints. Many remediation techniques, particularly those involving energy input or specialized reagents, are not viable at the scale of industrial agriculture, which typically spans hundreds to thousands of hectares. This limitation raises a critical issue previously underemphasized in the literature: Given this disconnect, a key goal of modern remediation science is to bridge the gap between high-efficiency industrial remediation methods and scalable, agriculture-compatible solutions. One promising avenue lies in reclaiming remediated brownfield sites for safe agricultural reuse. While mainstream agriculture may not adopt energy-intensive remediation approaches, brownfields cleaned to safe standards can be transitioned into urban farms, community gardens, and peri-urban food production zones. This concept of "brownfield-to-greenfield" conversion supports the growing trend of urban agriculture and land circularity, aligning well with the United Nations Sustainable Development Goals (SDGs). In this context, the objective of this review is to provide a holistic, comparative assessment of advanced soil remediation strategies by examining their mechanisms, effectiveness, sustainability, and alignment with global climate-resilient agriculture and SDGs.

The review is guided by three key hypotheses:

Hypothesis 1 (H1). *Integrated remediation approaches, such as the combination of biochar with microbial or electrokinetic systems, provide enhanced and more sustainable outcomes than single-method applications*;

Hypothesis 2 (H2). *Nano-remediation methods offer high contaminant removal efficiency but raise environmental and regulatory concerns that need careful evaluation*;

Hypothesis 3 (H3). *Remediation practices based on circular economy principles and ecosystem-based management are more likely to ensure long-term soil health*

While large-scale agricultural deployment of advanced remediation technologies remains economically prohibitive, these methods hold promise in the targeted rehabilitation of contaminated soils in peri-urban zones, smallholder farming systems, and urban agriculture. Additionally, the transformation of brownfields into arable land offers a sustainable pathway for increasing food production capacity without expanding agricultural frontiers, particularly in land-scarce regions. Thus, the methods reviewed herein, though originally designed for industrial remediation, may serve as critical enablers for selective agricultural land reuse and climate-smart urban development.

An Overview of Climate Change and Its Impact on Soil and Agriculture

Climate change is a critical global challenge, significantly affecting agriculture, soil quality, and ecosystems. Chaotic rainfall patterns bring drought to some regions and floods to others, eroding fertile soil and disrupting agricultural systems. Melting glaciers raise sea levels, submerging low-lying areas and contaminating freshwater with saltwater [24]. Torrential rains result in waterlogging, washing away topsoil, and hindering root development, while salinization from rising sea levels and poor irrigation renders soil unfarmable [25]. Increased atmospheric CO_2 and higher temperatures amplify the greenhouse effect, accelerating global warming. This creates drier conditions, fueling desertification and prolonged droughts, which strain water resources and reduce crop yields [26]. SOC disperses more easily, and nutrient-rich topsoil erodes under heavy rainfall and storms, lowering fertility and productivity. Excess moisture from flooding disrupts root respiration and microbial activities, while nutrient loss through leaching and volatilization further weakens soils [27]. Climate change also reduces photosynthesis due to high temperatures and water scarcity, affecting crop yields [28]. Degraded soils and nutrient-depleted crops lead to diminished food quality and security, exacerbating hunger and affecting livestock [29]. Figure 1 shows the impact of climate on soil and agriculture [30,31]. Addressing these challenges requires adopting eco-friendly farming methods, managing water resources, reducing soil erosion, cultivating climate-resilient crops, and lowering greenhouse gas emissions. Implementing these measures can create sustainable ecosystems, maintain healthy soils, and support long-term agricultural productivity.

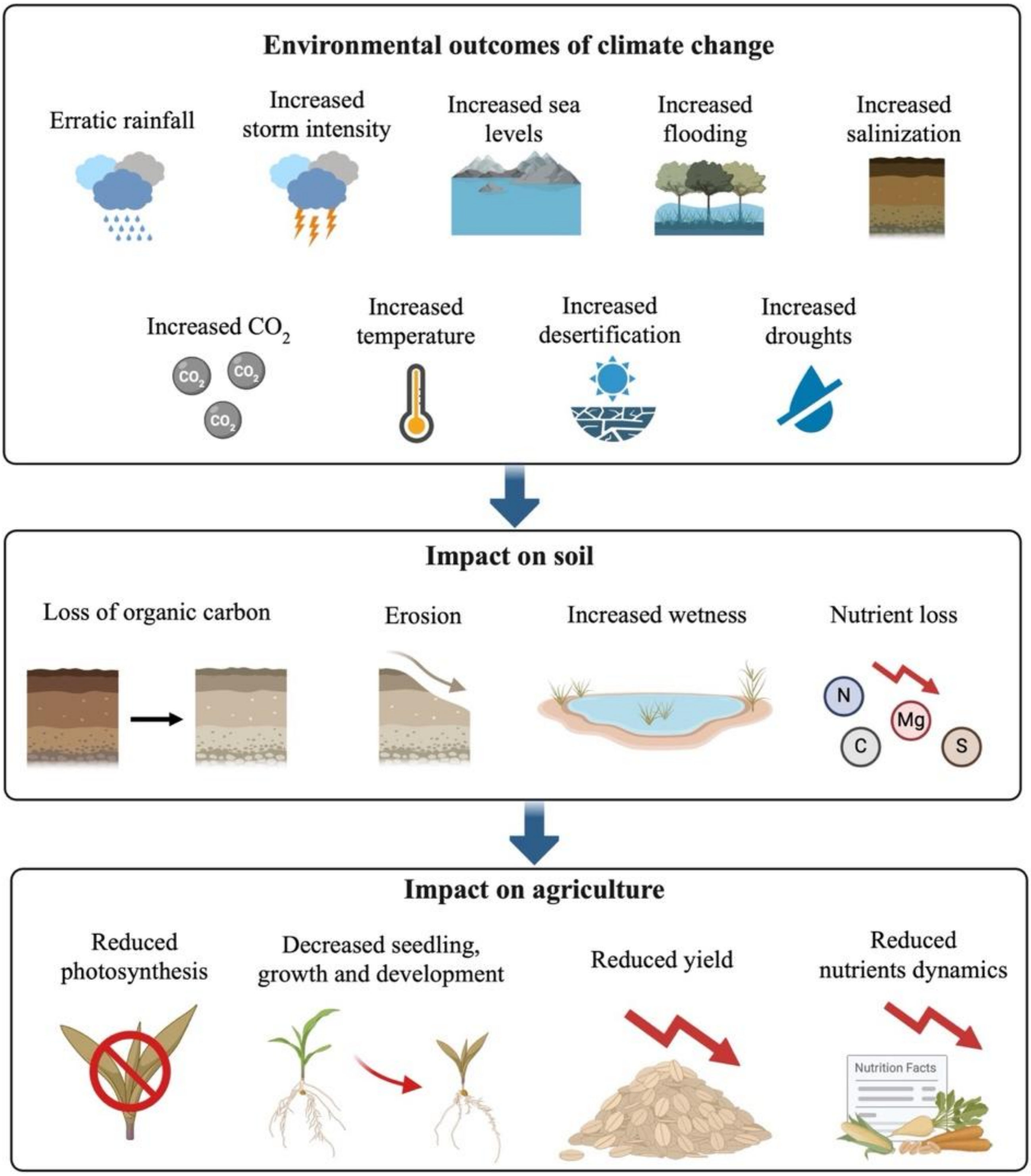

Figure 1. The environmental outcomes of climate change and their impact on soil and hence impact on agriculture (Created in BioRender. DEPARTMENT, B. (2025) https://BioRender.com/t42b146).

Introduction to Soil Functions and Ecosystem Importance

Figure 2 shows the Functions of soil, it serves as the cornerstone of terrestrial ecosystems, performing a wide range of functions that are essential for life on Earth. It is a critical resource for agriculture, enabling crop growth and securing food production while also contributing to broader environmental sustainability goals [32]. Beyond agriculture, soil acts as a natural filter, purifying water and regulating the Earth's hydrological cycles [33]. It plays a pivotal role in climate regulation by sequestering carbon dioxide and mitigating greenhouse gas emissions, which helps combat climate change [34]. These processes highlight soil's vital contribution to ecosystem stability, biodiversity conservation, and human well-being. The multifunctionality of soil is evident in its diverse roles. The soil supports the provision of food, fiber, and fuel by supplying essential nutrients for plant growth, ensuring food security and raw materials for human needs [35]. Soil serves as a carbon sink, storing large amounts of organic carbon and contributing to climate mitigation [36]. It also filters pollutants and improves water quality, ensuring clean water for ecosystems and human use. Through nutrient cycling, soil recycles key elements like nitrogen, phosphorus, and potassium, making them available for plants and other organisms. Furthermore, soil provides a habitat for a vast array of microorganisms, fungi, and fauna, all of which are crucial for maintaining soil health and ecosystem functions [37]. It regulates food availability, quality, and security by preserving fertility and productivity, while its biodiversity serves as a reservoir for pharmaceuticals and genetic resources essential for medicine and biotechnology. Soil also provides the foundation for human infrastructure, offering structural stability for buildings and roads, and supplies essential raw materials like clay, sand, and gravel for construction [38]. Additionally, soil plays a cultural role by preserving archaeological artifacts and providing landscapes for recreation, thus contributing to cultural heritage and identity. The Food and Agriculture Organization (FAO) emphasizes the importance of these functions for sustainable development and environmental health [39]. However, soil degradation through erosion, nutrient depletion, and contamination poses significant threats to these critical functions. The FAO's International Year of Soils campaign in 2015 highlighted the urgency of addressing soil degradation and promoted sustainable practices such as conservation tillage, crop rotation, and organic amendments [40]. These measures are essential for preserving soil health and ensuring its ability to continue supporting future generations.

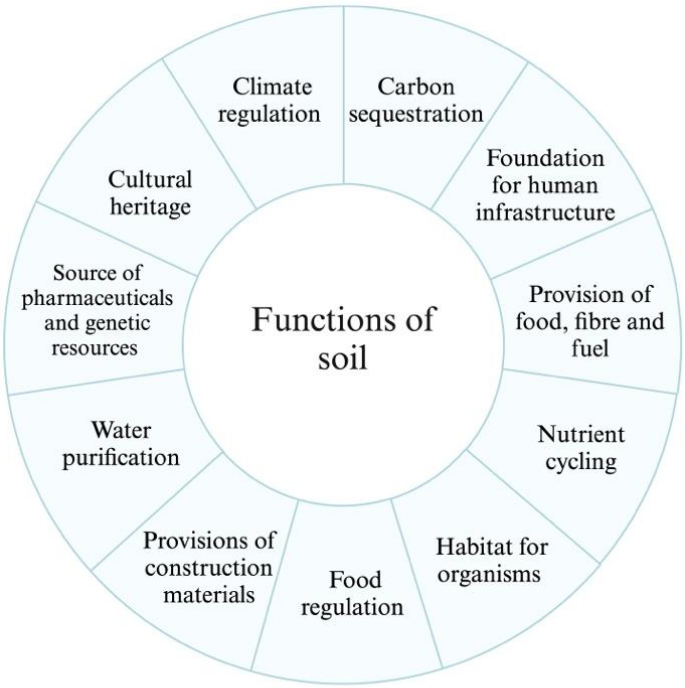

Figure 2. The infographic shows the Functions of soil.

Soil Health Indicators: The Role of SOC

SOC, is a key indicator of soil health, reflecting its quality, fertility, and ability to sustain life [41]. As a major component of soil organic matter (SOM), SOC plays a critical role in regulating physical, chemical, and biological soil properties, supporting agricultural productivity and ecosystem sustainability while aiding in climate change mitigation through carbon sequestration. Physically, SOC enhances soil structure, porosity, and water retention by forming stable aggregates, reducing erosion risk, and lowering bulk density, making soil easier to cultivate. Chemically, SOC stores essential nutrients like nitrogen, phosphorus, and sulfur, gradually releasing them through decomposition [42]. It improves cation exchange capacity (CEC), nutrient retention, and pH buffering, fostering optimal conditions for plant roots and microbial activity. Biologically, SOC fuels microbial diversity and activity, driving nutrient cycling, organic matter decomposition, and disease suppression, thus sustaining a balanced and resilient soil ecosystem [43]. SOC interacts with soil properties in a feedback loop: improved structure boosts aeration, stimulating microbial activity that replenishes SOC through decomposition, while nutrient release from SOC supports plant growth, further adding organic inputs. Factors influencing SOC are shown in Figure 3. which include geological attributes (soil type, mineralogy), physical properties (porosity, moisture), biological activity (microbes, earthworms), and chemical properties (pH, CEC). Climate variables (rainfall, temperature) and land use practices like agriculture and forestry also affect SOC levels. Effective management practices, such as conservation tillage, crop rotation, organic amendments, and controlled irrigation, are crucial for maintaining SOC. Enhancing SOC levels by minimizing soil disturbance and increasing organic inputs ensures long-term soil health, resilience against climate change, and sustainable agricultural systems.

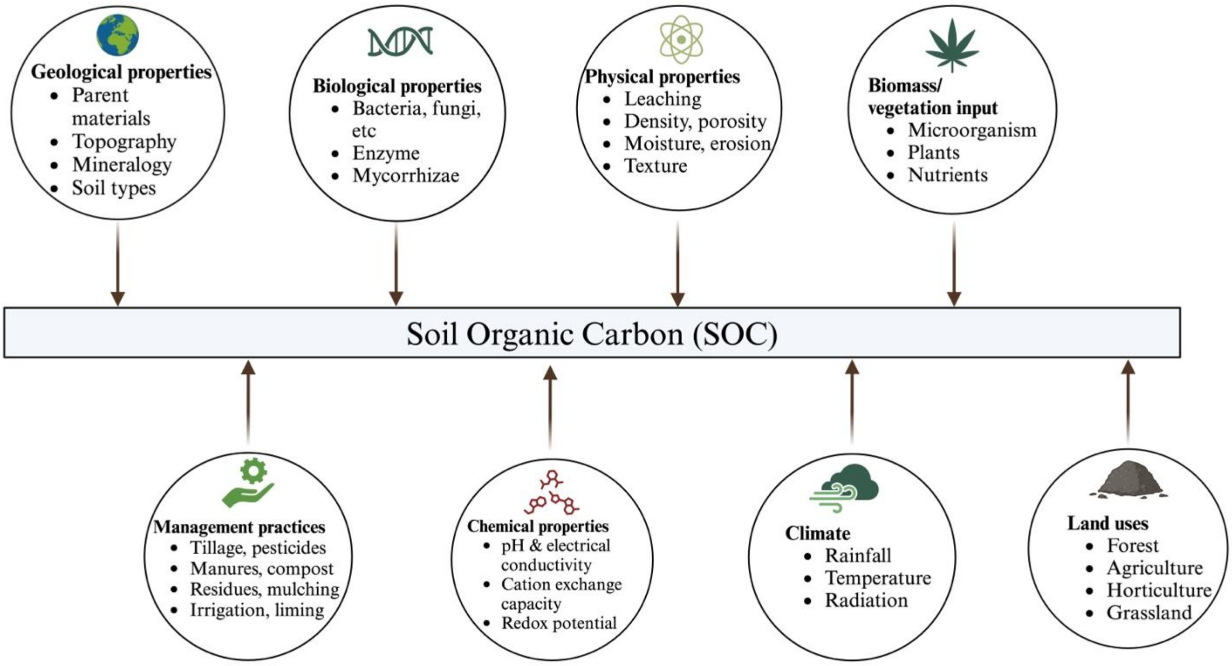

Figure 3. Factors affecting the concentration of SOC in soils (Created in BioRender. DEPARTMENT, B. (2025) https://BioRender.com/e16e568).

Microbial and fungal communities are essential for decomposing organic matter, releasing nutrients, and maintaining soil fertility, particularly in the O and A soil horizons. These layers, however, are highly susceptible to degradation due to deforestation, overgrazing, and intensive agriculture [44]. Soil degradation manifests as erosion, nutrient depletion, salinization, compaction, organic matter loss, and contamination, all of which reduce productivity and disrupt ecosystems. Erosion, driven by wind and water, depletes nutrient-rich topsoil and leads to sedimentation in water bodies. Salinization, often caused by poor irrigation and fertilizer overuse, degrades soil structure and nutrient availability [45]. Nutrient depletion from monocropping and excessive fertilizer use reduces microbial activity and increases dependency on chemical inputs. Compaction limits water infiltration and root growth, while contamination from pollutants renders soil infertile. Degraded soils exacerbate climate change by reducing carbon sequestration and releasing greenhouse gases like nitrous oxide. Loss of microbial biodiversity further diminishes soil recovery [46]. Figure 4 shows the effects of soil salinity on plants.

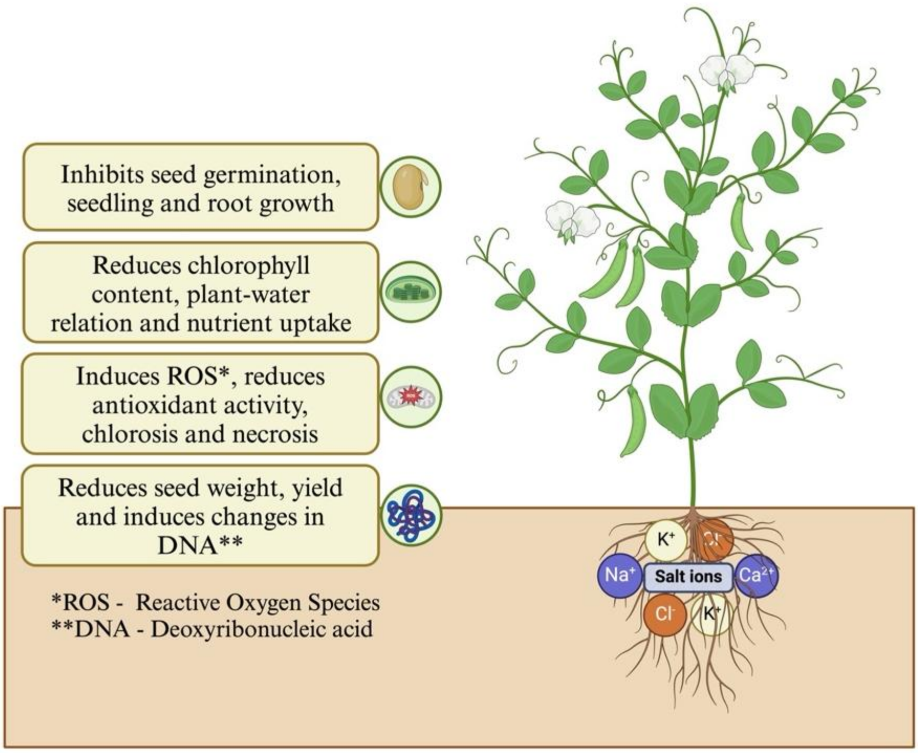

Figure 4. Shows the effects of soil salinity on plants. (Created in BioRender. DEPARTMENT, B. (2025) https://BioRender.com/d51v629).

METHODOLOGY

Literature Search Strategy and Inclusion Criteria

The methodology adopted for this review involved a comprehensive examination of existing literature on advancements in soil remediation techniques. Emphasis was placed on evaluating advanced remediation strategies for their effectiveness in restoring degraded soils. Each method was critically analyzed based on environmental impact, practical applicability, and alignment with sustainability goals. Figure 5 presents the PRISMA flow diagram illustrating the study selection process, including identification, screening, and eligibility assessment of 212 studies sourced from major academic databases. The review predominantly incorporates recent publications, while foundational concepts are supported by earlier seminal works, as reflected in Figure 6.

Figure 5. PRISMA flow diagram illustrating the study selection process for the systematic review of soil remediation techniques.

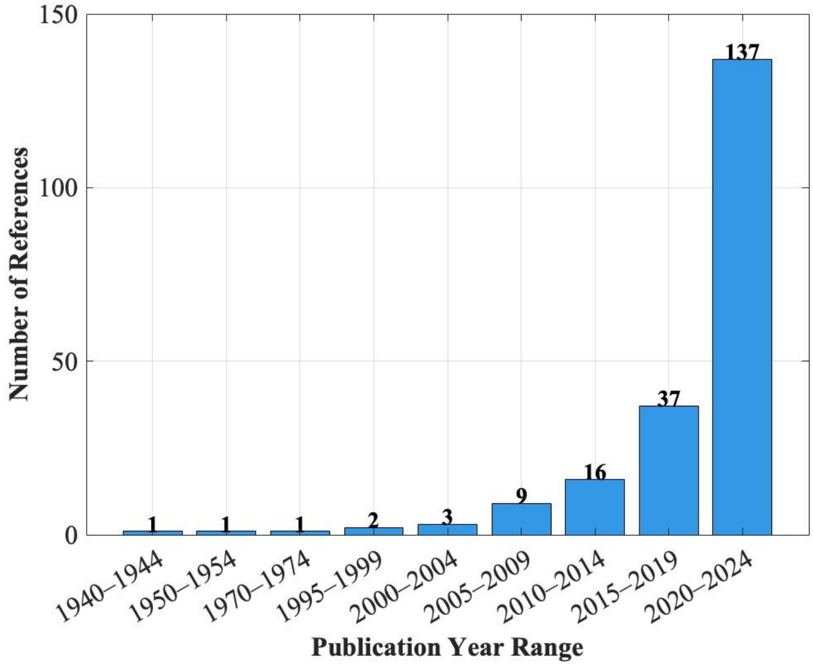

Figure 6. Shows the publication year of literature used in this manuscript (studies grouped by 5-year publication intervals).

The regenerative methods such as cover cropping, compost addition, and reduced tillage are highly effective at restoring soil structure and microbial function, they are not sufficient for soils contaminated with industrial pollutants (e.g., heavy metals, petroleum hydrocarbons, persistent organic compounds). In such cases, remediation techniques—physical, chemical, or biological—must be employed first to remove or immobilize toxic contaminants before soil can be safely returned to use ecological function. These techniques are therefore most relevant in brownfield reclamation, urban agriculture on legacy-contaminated lands, or conversion of derelict industrial zones into productive green spaces. For the current review, soil remediation techniques are classified as shown in Figure 7.

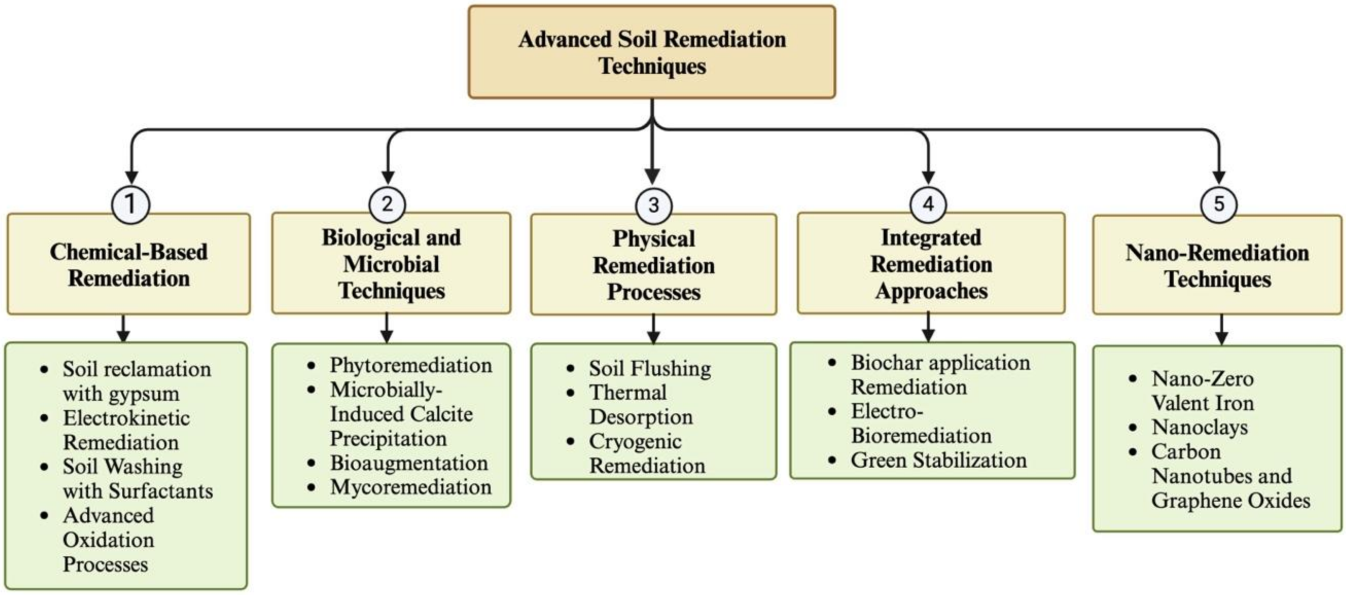

Figure 7. Soil remediation methods categorized by principle, benefits, and limitations.

Chemical-Based Remediation

Soil Reclamation with Gypsum

Gypsum, or calcium sulfate dihydrate ($CaSO_4{\cdot}2H_2O$), is widely used for reclaiming salt-affected sodic soils, particularly in areas with high soil salinity and low rainfall [47]. Its primary benefit is replacing sodium ions in the soil with calcium ions, which improves soil structure, reduces compaction, and increases permeability [47]. Sodium is leached away by rain or irrigation, enhancing soil moisture retention and creating a healthier environment for plant roots and beneficial microbes [48]. Gypsum provides essential nutrients, such as calcium for root development and sulfur for protein synthesis and enzymatic activities, boosting soil fertility and crop production. It also reduces soil crusting, enhances water infiltration, and mitigates salt build-up in salinized irrigation systems, which is vital for steep or eroding terrains [49]. While gypsum is highly effective, its success depends on proper management practices, including correct application rates based on soil salinity, sodicity levels, and crop requirements [50]. Over-application may lead to imbalances in calcium and magnesium or excessive nutrient leaching. Regular monitoring of soil properties, such as pH, electrical conductivity, and exchangeable sodium percentage (ESP), is essential to ensure optimal results and sustainable soil health [51]. Soil reclamation with gypsum entails a fundamental chemical reaction wherein the calcium ions (Ca^{2+}) contained in gypsum, displace the sodium ions (Na^{+}) present in soil particles. The sodium ions that were displaced, get washed away in the form of soluble sodium sulfate (Na_2SO_4) in water. This process can be illustrated as follows:

Gypsum dissociates in water to release calcium ions (Ca^{2+}) and sulfate ions (SO_4^{2-})

$$CaSO_4 \cdot 2H_2O \rightarrow Ca^{2+} + SO_4^{2-} + 2H_2O \quad (1)$$

The calcium ions from gypsum displace the sodium ions on the soil exchange sites (sodium-bound clay particles)

$$2Na\text{-}clay + Ca^{2+} \rightarrow Ca\text{-}clay + 2Na^{+} \quad (2)$$

The displaced sodium ions combine with sulfate ions in the soil solution to form sodium sulfate, which is water-soluble and can be leached out of the root zone:

$$2Na^{+} + SO_4^{2-} \rightarrow Na_2SO_4 \quad (3)$$

$$CaSO_4 \cdot 2H_2O + 2Na\text{-}clay \rightarrow Ca\text{-}clay + Na_2SO_4 + 2H_2O \quad (4)$$

This reaction improves soil structure by replacing sodium with calcium, leading to better aggregation of soil particles, increased permeability, and enhanced soil health.

A recent study titled “A quantitative assessment of the dynamic process and potential capacity of using gypsum to reclaim sodic soil”, published in the Journal of Soils and Sediments in May 2023 [52], provides an in-depth analysis of gypsum’s effectiveness in ameliorating sodic soils. The research involved leaching sodic soil columns with gypsum solutions of varying concentrations to monitor changes in soil properties and ion dynamics. The findings indicated that gypsum application significantly reduced soil pH, ESP, and sodium adsorption ratio (SAR), thereby improving soil structure and permeability. The study also highlighted the efficient utilization of calcium ions from gypsum in replacing exchangeable sodium, emphasizing the importance of appropriate gypsum application rates tailored to specific soil conditions. This case study underscores the potential of gypsum as a viable amendment for sodic soil reclamation, offering valuable insights for optimizing its use in soil management practices.

Electrokinetic Remediation

Electrokinetic remediation is an advanced in-situ soil remediation technique that uses a low-intensity direct current electric field to mobilize and extract contaminants from soil, particularly in fine-grained soils like clay and silt, which are challenging to remediate using traditional methods [53,54]. The process is driven by three primary mechanisms: electromigration, where charged ions move toward electrodes under the electric field; electroosmosis, which facilitates water movement toward the cathode, carrying dissolved contaminants; and electrophoresis, involving the migration of charged particles such as colloids or microbial cells [55]. Redox reactions at the electrodes further enhance the breakdown of certain organic pollutants [56].

A recent study titled “Controlled Ion Transport in the Subsurface: A Coupled Advection-Diffusion-Electromigration System”, published on August 9, 2023 [57], explores the application of electrokinetic remediation for groundwater pollution. The research introduces a coupled advection-diffusion-electromigration system to control ion transport in subsurface environments, utilizing the Lattice-Boltzmann-Poisson method for simulations in various porous media. The study establishes an ion transport regime classification based on the Peclet number and a novel Electrodiffusivity index, identifying four transport regimes: large channeling, uniform flow, small channeling, and no flow.

Soil Washing with Surfactants

Soil washing with surfactants is an advanced remediation method that employs aqueous solutions containing surfactants to remove contaminants from soil [58]. Surfactants, or surface-active agents, lower surface tension, enhancing the desorption and mobilization of hydrophobic organic compounds and heavy metals [59]. This technique is particularly effective for soils contaminated with petroleum hydrocarbons, pesticides, polychlorinated biphenyls (PCBs), and metals.

The process involves applying a surfactant solution to contaminated soil, where the surfactants form micelles that encapsulate hydrophobic pollutants, solubilizing them in water. This enables contaminants to detach from soil particles [60] and remain suspended in the washing solution. Heavy metals are removed via ion exchange or complexation with the surfactants [61]. The contaminated solution is collected, and pollutants are separated and treated, while the surfactant solution can be recycled for reuse. Nonionic surfactants, such as Tween and Triton, are commonly used due to their low toxicity and efficiency in solubilizing hydrophobic pollutants [62]. Anionic surfactants like sodium dodecyl sulfate are effective for both metals and organic pollutants, while cationic surfactants are less frequently used due to their tendency to adsorb onto soil particles. Soil washing with surfactants is versatile and effective for various contaminants [63].

A recent study reported by Zhao et al, in 2024 [64] provides a comprehensive review of surfactant-enhanced soil washing techniques for remediating oil-contaminated soils. The study examines various surfactants, including synthetic surface-active agents and biosurfactants, and their effectiveness in enhancing the solubilization, desorption, and separation of petroleum hydrocarbons from soil matrices. Key findings highlight that surfactant-enhanced soil washing can significantly improve the removal of hydrophobic organic contaminants, with efficiency influenced by factors such as surfactant type, concentration, soil properties, and contaminant characteristics. The authors also discuss the environmental implications of surfactant use, emphasizing the need for selecting biodegradable and environmentally friendly surfactants to minimize secondary pollution.

AOPs

AOPs are cutting-edge chemical treatments designed to degrade organic and inorganic soil contaminants using highly reactive hydroxyl radicals (·OH) [65]. These radicals are non-selective and capable of breaking down complex pollutants, such as petroleum hydrocarbons, pesticides, and volatile organic compounds (VOCs), into harmless substances like carbon dioxide and water [66]. The key mechanisms involve oxidative cleavage, dehydrogenation, and mineralization, which destabilize pollutants and convert them into simpler compounds [58,67]. Hydroxyl radicals can be generated through various methods, including Fenton's reaction (using hydrogen peroxide and iron salts), ozone oxidation enhanced by ultraviolet (UV) light, photocatalysis with UV and titanium dioxide, and electrochemical oxidation [68]. The process begins with introducing the oxidant into contaminated soil, followed by radical generation, pollutant breakdown, and post-treatment monitoring to ensure remediation effectiveness [69]. AOPs are versatile, effective for organic pollutants and some inorganic contaminants, and adaptable for complex mixtures. Their advantages include high efficiency, minimal toxic residue production, and scalability. However, they are cost-intensive and require specialized equipment and precise pH control for optimal performance [70]. Soil conditions, such as low permeability or high organic matter, can reduce effectiveness by consuming hydroxyl radicals prematurely [71].

A recent study highlighted the use of homogeneous and heterogeneous AOP systems for remediating creosote-contaminated soils. Homogeneous systems using sodium persulfate and ferrous ions showed high removal efficiencies for polycyclic aromatic hydrocarbons (PAHs), while heterogeneous systems with clay-based iron catalysts enabled catalyst recovery and reuse, showcasing AOPs' potential in soil remediation [72]. Simultaneously, another recent review, "Recent Developments in AOPs for Organics Removal in Water and Wastewater Treatment," [73] provides insights into the latest advancements in AOP technologies for managing organic pollutants in water. It covers methods such as photocatalysis, Fenton-based processes, ozonation, and sulfate radical-based oxidation. Innovations in catalytic materials and the integration of unconventional methods have significantly improved the efficiency of AOPs. Given their operational cost and complexity, AOPs are largely confined to industrial sites or small contaminated zones and are not applicable to broad-acre farming systems.

Biological and Microbial Techniques

Phytoremediation

Phytoremediation is a sustainable soil remediation technique that uses plants to extract, stabilize, or degrade contaminants in soil, water, and air [74]. This eco-friendly method effectively treats pollutants such as heavy metals, organic compounds, and radionuclides, particularly in sites where traditional remediation methods are costly or impractical [75]. Phytoremediation performance varies widely depending on pollutant type, plant species, and conditions. The field studies on heavy metal–contaminated soils have shown that certain plants can extract on the order of 50–60% of metals like lead over several months [76]. Likewise, for organic pollutants such as petroleum hydrocarbons, phytoremediation using appropriate plant species (e.g., maize) can degrade or remove roughly 50–70% of total petroleum hydrocarbons under controlled conditions [76]. Key processes include phytoextraction, where plants absorb contaminants into harvestable biomass; phytostabilization, which immobilizes pollutants to prevent leaching and erosion; phytodegradation, involving enzymatic breakdown of organic pollutants by plants and microbes; phytovolatilization, which releases absorbed volatile compounds into the atmosphere in less harmful forms; and rhizome-filtration, where plant roots filter contaminants from water sources [77]. The plant selection must align with site-specific conditions and pollutant types [78]. Advancements in phytoremediation include genetic engineering to create plants with enhanced pollutant uptake and tolerance, the use of microbial symbionts like mycorrhizal fungi to improve nutrient and contaminant processing [19,70], and hybrid methods combining phytoremediation with techniques like soil washing or electro-kinetics. These developments enhance its efficiency and broaden its applicability, making phytoremediation a vital tool for sustainable soil remediation and ecological restoration [79]. Table 1 provides a comparison between biological and microbial techniques discussed in this article.

After the Chornobyl nuclear disaster, phytoremediation was employed using sunflowers to remove radioactive isotopes from contaminated soil and water. Sunflowers demonstrated a high capacity for absorbing cesium-137 and strontium-90, reducing soil toxicity and enabling safer environmental conditions. This case highlights the potential of phytoremediation for managing heavy metal and radioactive contamination in agricultural and industrial sites [80].

Microbially-Induced Carbonate Precipitation (MICP) Process for Soil Strengthening

MICP is an innovative biogeochemical process that utilizes microbial activity to enhance soil properties by inducing the precipitation of calcium carbonate ($CaCO_3$) [81]. As depicted in Figure 8 the process is driven by urease-producing microorganisms, such as cyanobacteria, which facilitate the hydrolysis of urea ($CO(NH_2)_2$) into ammonia (NH_3) and carbon dioxide (CO_2) [82]. This enzymatic reaction increases the pH of the surrounding environment by producing ammonium (NH_4^+) and hydroxide (OH^-) ions. The elevated pH enables the conversion of dissolved carbon dioxide into carbonate ions (CO_3^{2-}), which then react with calcium ions (Ca^{2+}) present in the soil or are added externally to precipitate calcium carbonate in the form of calcite. The precipitated calcite binds soil particles together, filling voids and pores within the soil matrix. This transformation converts loose, untreated soil into a denser and more stable material, significantly improving its mechanical properties, including strength, durability, and erosion resistance [83]. The treated soil becomes more compact and cohesive due to the formation of calcite bridges between particles [76,84]. The effectiveness of the process depends on factors such as the uniform distribution of microorganisms, the availability of calcium and urea, and environmental conditions like temperature and pH. The process requires careful optimization to ensure efficient calcite precipitation and soil stabilization [85].

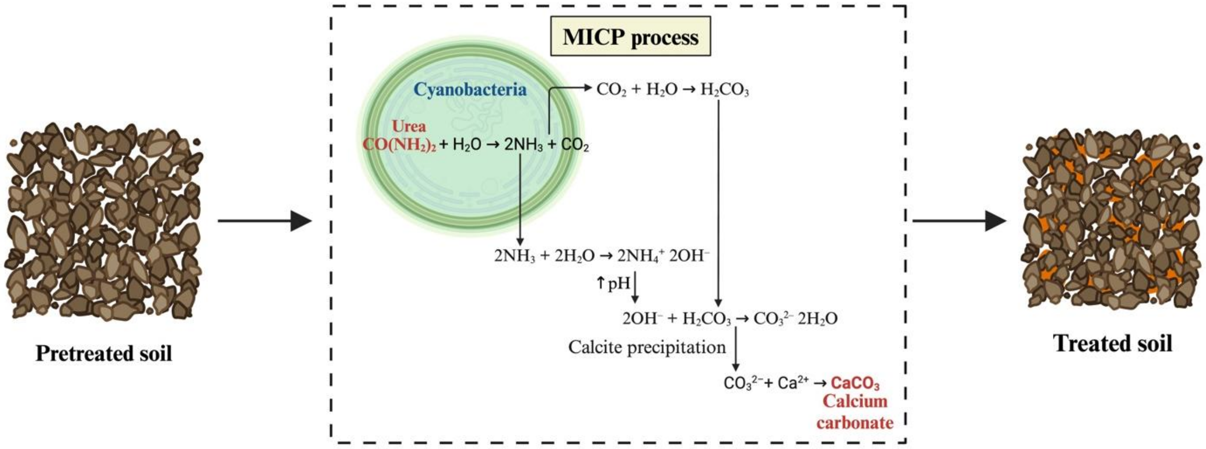

Figure 8. MICP Process representation (Created in BioRender. DEPARTMENT, B. (2025) https://BioRender.com/t42b146) [86].

Bioaugmentation

Bioaugmentation is a biological remediation strategy involving the introduction of specific microorganisms into contaminated soils to enhance the degradation or transformation of pollutants [87]. These microorganisms are chosen for their ability to metabolize contaminants such as hydrocarbons, pesticides, heavy metals, and other hazardous compounds. This technique is particularly useful when the native microbial community lacks the metabolic capacity or sufficient populations to remediate the site effectively [88]. The bioaugmentation process starts with analyzing the contaminants and site conditions, followed by selecting microorganisms, often bacteria or fungi, tailored to the specific pollutants. These microbes are introduced into the soil, typically as liquid or solid formulations, and environmental conditions such as pH, oxygen, and nutrients are optimized to support their activity [89]. The introduced microbes then metabolize the pollutants through enzymatic processes, breaking them down into less harmful compounds. In some cases, bioaugmentation is combined with bio-stimulation, which involves adding nutrients to enhance microbial activity further [90]. Bioaugmentation offers several benefits, including cost-effectiveness, environmental friendliness, and the ability to target specific contaminants. It is particularly suitable for in-situ applications, preserving soil structure and minimizing the need for excavation [91].

Mycoremediation

Myco-remediation is an eco-friendly remediation method that uses fungi to degrade or transform environmental pollutants in soil and water [84,92]. Fungi, such as *Pleurotus* spp., *Trametes versicolor*, and *Phanerochaete chrysosporium*, are chosen for their robust enzymatic systems, including lignin peroxidase, manganese peroxidase, and laccase [93]. These enzymes effectively break down pollutants like hydrocarbons, pesticides, dyes, PAHs, and synthetic polymers [94]. The fungi are cultivated on substrates such as sawdust or compost and introduced into contaminated areas, where they metabolize organic pollutants into less harmful compounds or mineralize them into carbon dioxide and water [95]. For heavy metals, fungi use biosorption and bioaccumulation to immobilize contaminants, reducing their mobility. Myco-remediation has several advantages, including its ability to degrade a wide range of pollutants, low cost due to the use of agricultural byproducts, and applicability in both in-situ and ex-situ scenarios [88,96]. It also enhances soil health through nutrient cycling and structural improvements and is effective in extreme environmental conditions where other methods fail [97]. However, the process can be slow and is influenced by environmental factors like temperature, moisture, and pH. Additionally, incomplete mineralization of pollutants and the disposal of contaminated fungal biomass pose challenges [98]. Table 1 gives the case studies on biological and microbial remediation techniques.

Table 1. Case studies on biological and microbial remediation techniques.

Case Study	Contaminants	Environment	Key Findings	Key Technologies Used	Remediation Efficiency	Challenges Encountered	Reference
Phytoremediation of Heavy Metals Using Echinacea Purpurea	Petroleum Hydrocarbons	Polluted Soil	Echinacea purpurea effectively reduced petroleum hydrocarbon concentrations in contaminated soils; bioaugmentation enhanced remediation efficiency.	Phytoremediation supported by bioaugmentation	Significant contaminant reduction	Soil heterogeneity; maintaining plant health in contaminated conditions.	[20]
MICP for Soil Strengthening: A Micro to Macro Scale Study	N/A	Sandy Soils	MICP treatment improved soil strength; micro-scale experiments informed macro-scale applications, optimizing treatment protocols.	MICP	Enhanced soil strength	Controlling uniformity of carbonate precipitation; scaling up from laboratory to field applications.	-
Bioaugmentation-Assisted Mycoremediation of Heavy Metal Contaminated Soil	Heavy Metals, Metalloids	Landfill-Contaminated Soil	Fungal consortia enhanced the removal of heavy metals from contaminated soils; bioaugmentation improved remediation efficiency compared to control treatments.	Bioaugmentation and Mycoremediation	Up to 48% metal removal	Soil physicochemical variability; maintaining fungal activity over time.	[99]
Mycoremediation of Organic Pollutants Using Fungal Strains	Organic Pollutants	Contaminated Ecosystems	Fungal strains demonstrated high degradation rates of organic pollutants; mycoremediation is considered a promising technology for environmental cleanup.	Mycoremediation	Up to 98.4% degradation	Environmental conditions affecting fungal activity; scalability of treatment methods.	[21]
MICP Treatment of Lead-Contaminated Loess	Lead (Pb)	Loess Soil	MICP effectively reduced lead bioavailability in contaminated loess; biochar addition enhanced microbial activity and carbonate precipitation.	MICP with biochar amendment	Improved remediation efficiency	Toxicity of lead to microbial activity; optimizing biochar properties for enhanced performance.	[100]

Physical Remediation Processes

Soil Flushing

Leaching is a method of soil healing that allows the user to eliminate already existing soil from the vadose zone, as seen in the Figure 9, as well as the saturated zone, aiming to eliminate probable pollutants within the soil [101]. The efficiency is dependent on the parameters of the soil such as the permeability and porosity, which govern the movement of flushing agents. Even though soil flushing can be an effective remediation technique, there are limitations such as low permeability soils, pollutants that have diffused into areas that are not allowed, and that can hinder its success pollutant levels [102].

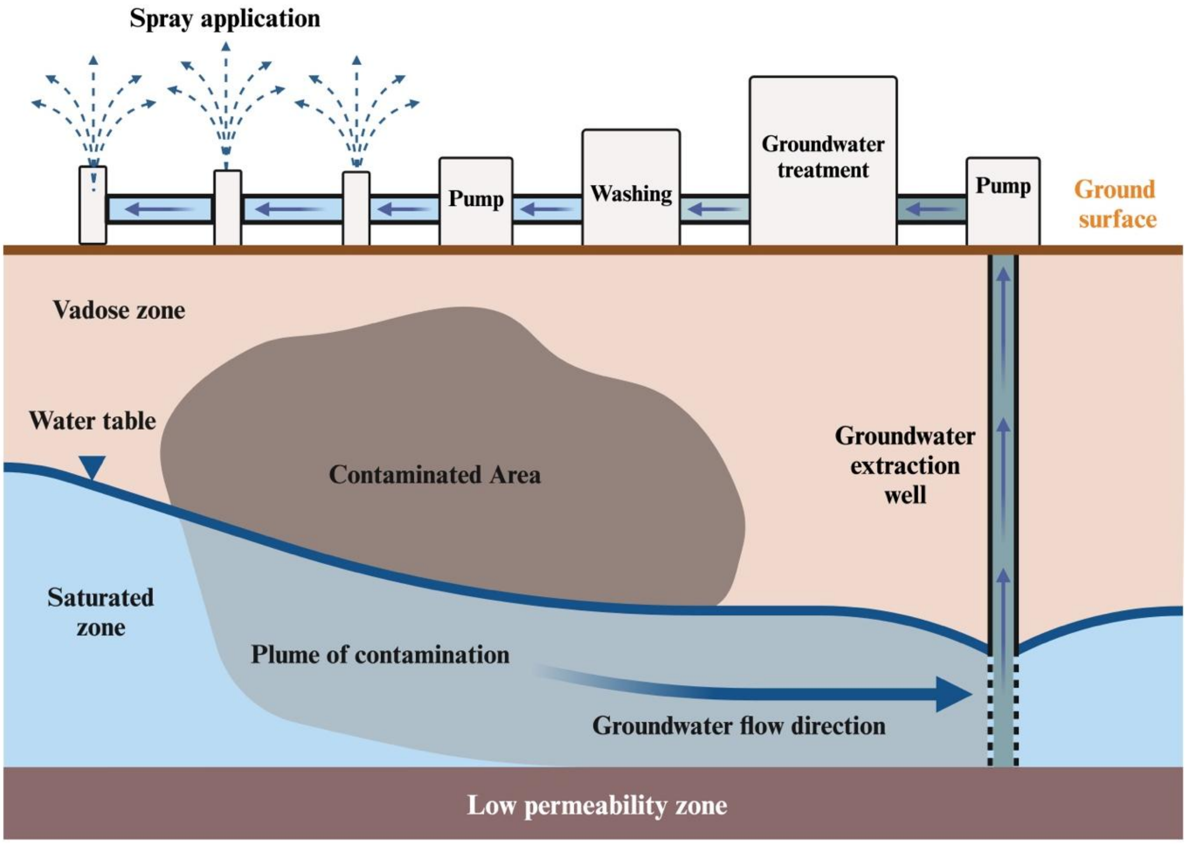

Figure 9. Soil flush technique (Created in BioRender. DEPARTMENT, B. (2025) https://BioRender.com/t42b146) [97,103].

Although soil flushing is often associated with groundwater remediation, recent pilot studies have demonstrated its feasibility in agricultural soil contexts, particularly in sandy loam soils contaminated with heavy metals. For example, Klik et al. (2021) performed column-scale flushing on contaminated agricultural soil and achieved significant amount of removal of Cu, Pb, and Zn using sewage-sludge derived washing agents, simultaneously improving soil fertility and microbial health post-treatment [104]. These examples underscore that, while uncommon in mainstream farming, soil flushing can be adapted for localized agricultural contamination scenarios under specific conditions [105].

Thermal Desorption

Thermal desorption is a soil remediation technique that uses controlled heat to volatilize and remove organic and some inorganic contaminants [106]. By elevating soil temperature, this method targets pollutants with low boiling points, such as hydrocarbons, VOCs, SVOCs, and certain pesticides, which are evaporated, captured, and treated. It is classified into Low-Temperature Thermal Desorption (LTTD), operating at 90 °C to 320 °C, ideal for volatile and semi-volatile compounds, and High-Temperature Thermal Desorption (HTTD), above 320 °C, suitable for persistent pollutants like PCBs. LTTD preserves soil integrity, while HTTD may alter soil properties [107]. Thermal desorption is effective for treating organic contaminants and offers a relatively quick treatment process with flexible application in situ or ex-situ. However, the method is energy-intensive, making it costly, and high temperatures can affect soil fertility and structure [108]. It is less effective for non-volatile contaminants like heavy metals. Recent innovations include microwave-assisted heating, hybrid systems that combine thermal desorption with other remediation techniques, and the use of renewable energy to improve energy efficiency and sustainability [109]. Table 2 gives case studies on soil flushing and thermal desorption methods.

Table 2. Case studies on soil flushing, and thermal desorption.

Case Study	Contaminants	Environment	Key Findings	Key Technologies Used	Remediation Efficiency	Challenges Encountered	References
Electrokinetic Soil Flushing with Facing Rows of Electrodes	2,4-Dichlorophenoxyacetic acid	Pilot Plant Soil	Effective removal of 2,4-D from soil using electrokinetic soil flushing with facing rows of electrodes; achieved significant contaminant reduction.	Electrokinetic soil flushing	High removal efficiency	Scale-up challenges; energy consumption considerations.	[110]
Thermal Desorption of PFAS-Contaminated Soil	Per- and Polyfluoroalkyl Substances (PFAS)	Laboratory-Scale Study	Thermal desorption effectively removed PFAS from contaminated soil at temperatures around 350 °C; higher temperatures increased removal efficiency.	Thermal desorption	High removal efficiency	Energy-intensive process; potential formation of volatile byproducts.	[109]
Thermal Desorption of PAH-Contaminated Soil	PAHs	Industrial Site Soil	Thermal desorption at temperatures between 300–500 °C successfully reduced PAH concentrations; soil properties were altered post-treatment.	Thermal desorption	Effective remediation	Soil quality degradation; need for post-treatment soil amendments.	[111]
Thermal Desorption of Mixed Organic Contaminants	Petroleum Hydrocarbons, PAHs	Industrial Site Soil	Applied thermal desorption to soil contaminated with mixed organic pollutants; achieved significant contaminant reduction, facilitating site redevelopment.	Thermal desorption	Significant contaminant reduction	High energy consumption; management of off-gas emissions.	[112]
Thermal Desorption of Chlorinated Organic Compounds	Chlorinated Organic Compounds	Industrial Site Soil	Thermal desorption effectively remediated soil contaminated with chlorinated organics; and met regulatory cleanup levels.	Thermal desorption	Effective remediation	Potential release of toxic byproducts; ensuring complete contaminant removal.	[113]
Thermal Desorption of Dioxin-Contaminated Soil	Dioxins	Industrial Site Soil	HTTD successfully reduced dioxin concentrations in contaminated soil; required careful temperature control to prevent byproduct formation.	Thermal desorption	High removal efficiency	Strict temperature control is needed; the potential formation of secondary pollutants.	[113]

Integrated Remediation Approaches

Biochar Application

The sustainable agricultural innovation that incorporates biochar in the soil in order to retain its long-term productivity is known as biochar application [107]. Biochar is produced through the heat treatment of organic material in an oxygen-deprived setting which results in locking carbon which transforms biochar into a useful soil-enhancing product [109]. Biochar makes particles such as wood, crop residues, and animal manure [114]. One of the best uses of biochar is its ability to enhance the structure of soil and retain moisture [115]. Biochar's pored composition serves as an air channel for the soil which promotes the retention of water, as a result, biochar is great to use with other sandy soils that fail to retain water [116]. Enhanced water retention helps plants sustain themselves during droughts and as a result, the frequency of irrigation is reduced [117]. Another great benefit that biochar provides is the higher concentration of nutrients and for improving soil quality. Biochar possesses a large surface area and an increased CEC which allows it to withhold nitrogen, phosphorus, and potassium within the soil rather than letting these nutrients leach [118]. Biochar also plays a very important role in increasing microbial activity and the diversity of soil [119]. Enhanced water retention helps sustain the plants during droughts as a result the required frequency of irrigation is reduced. Increased activity of the microbes improves the fertility of the soil and aids the growth of the plants [120].

The soil remediation procedure involving biochar application involves complex chemical processes that typically encompass physical, biological, and chemical interactions [121,122]. Below is a simplified representation of the key chemical reactions associated with biochar's role in soil remediation, particularly in binding and immobilizing contaminants and enhancing nutrient dynamics.

Nutrient Retention and Cation Exchange: Biochar has a high CEC and can adsorb nutrients, such as ammonium (NH_4^+) and potassium (K^+), making them available to plants over time:

$$\text{Biochar-Cation Exchange Site} + NH_4^+ \rightarrow \text{Biochar} - NH^{4+} \quad (5)$$

$$\text{Biochar-Cation Exchange Site} + K^+ \rightarrow \text{Biochar} - K \quad (6)$$

Heavy Metal Immobilization: Biochar can immobilize heavy metals, such as lead (Pb^{2+}), cadmium (Cd^{2+}), or arsenic (As^{3+}), by binding them to its surface through ion exchange or precipitation:

$$\text{Biochar-OH} + Pb^{2+} \rightarrow \text{Biochar-O-Pb} + H^+ \quad (7)$$

For arsenic, precipitation with calcium ions (from biochar or other sources) can occur:

$$Ca^{2+} + 2AsO_4^{3-} \rightarrow Ca_3(AsO_4)_2 \text{ (Calcium Arsenate Precipitate)} \quad (8)$$

Soil pH Buffering: Biochar, especially if derived from alkaline feedstocks, can neutralize acidic soils by releasing hydroxide ions (OH^-):

$$\text{Biochar-}CO_3^{2-} + 2H^+ \rightarrow H_2CO_3 \text{ (Carbonic Acid)} \quad (9)$$

$$H_2CO_3 \rightarrow H_2O + CO_2 \text{ (Gas Release)} \quad (10)$$

Organic Pollutant Adsorption: Biochar's porous structure adsorbs organic pollutants like pesticides or hydrocarbons, reducing their bioavailability:

$$\text{Organic Pollutant} + \text{Biochar-Pore Surface} \rightarrow \text{Biochar-Pollutant Complex} \quad (11)$$

Carbon Sequestration: Biochar contributes to long-term carbon sequestration by stabilizing carbon in a recalcitrant form:

$$\text{Biomass} \rightarrow \text{Biochar} + \text{Volatile gasses} + \text{Bio} - \text{oils} \quad (12)$$

These reactions illustrate biochar's multifunctional role in soil remediation, addressing issues like nutrient loss, contamination, acidity, and poor carbon storage. Table 3 gives case studies on biochar remediation.

Table 3. Case studies on biochar for environmental remediation.

Case Study	Contaminants	Environment	Key Findings	Key Technologies Used	Remediation Efficiency	Challenges Encountered	References
Biochar as a Green Sorbent for Remediation of Polluted Soils and Water	Heavy Metals, Organic Pollutants	Soil and Water	Biochar effectively immobilizes heavy metals and organic pollutants, reducing their bioavailability and environmental risks.	Biochar derived from various feedstocks	Significant reduction in contaminant mobility	Variability in biochar properties based on feedstock and production conditions.	[123]
Production, Characterization, and Environmental Remediation Application of Phosphorus-Rich Biochar/Hydrochar	Heavy Metals	Aquatic and Soil Environments	Phosphorus-rich biochar exhibits high adsorption capacity for heavy metals, suitable for remediating water and soils.	Phosphorus-rich biochar/hydrochar	Enhanced heavy metal adsorption	Optimization of production methods for stability and efficacy.	[124]
The Role of Modified Biochar for the Remediation of Coal Mining Contaminated Soil	Heavy Metals	Mine-Impacted Soils	Modified biochar composites immobilize pollutants and improve soil health, with various modification methods enhancing biochar performance.	Functionalized biochar composites	Effective heavy metal immobilization	Long-term effects on soil ecosystems need evaluation.	[125]
Evaluation of Sustainable Green Materials: Pinecone in Permeable Adsorptive Barriers for Remediation of Groundwater	Lead (Pb^{2+}), Methylene Blue	Groundwater Systems	Pinecone-derived biochar in adsorptive barriers effectively reduces Pb^{2+} concentrations in groundwater.	Permeable adsorptive barriers	Significant reduction in Pb^{2+} levels	Optimization of production parameters for consistency.	[126]
Selective Copper Recovery from Ammoniacal Waste Streams Using a Systematic Biosorption Process	Copper (Cu)	Industrial Wastewater	Sustainable biosorbents, including biochar, demonstrated high selectivity and efficiency in recovering copper from waste streams.	Biosorption using biochar	High copper recovery	The impact of co-occurring ions on selectivity needs optimization.	[127]

Electro-Bioremediation

Electro-bioremediation is an advanced hybrid soil remediation technique that combines electrokinetic processes with bioremediation to enhance the degradation or removal of contaminants [128]. This innovative approach leverages the strengths of both methods: the ability of electrokinetics to mobilize contaminants and nutrients through an electric field, and the metabolic capabilities of microorganisms to degrade or transform these contaminants into less harmful compounds [129]. Electro-bioremediation is particularly effective for treating a wide range of organic pollutants, such as hydrocarbons and pesticides, as well as inorganic contaminants like heavy metals [130]. Electro-bioremediation offers several advantages over conventional methods [131]. It enhances the efficiency of bioremediation by ensuring the even distribution of nutrients, contaminants, and microbial populations across the treatment zone, particularly in low-permeability soils like clay, where diffusion is limited. The electric field accelerates the degradation process, reducing the time required for remediation [132,133].

A recent study titled “Electro-bioremediation of nitrate and arsenite polluted groundwater” [134] explores the application of this method for treating groundwater contaminated with nitrate and arsenite. The research demonstrates that electro-bioremediation effectively reduces concentrations of these pollutants, leveraging the synergistic effects of electrokinetic transport and microbial activity. Another study, “Electro-bioremediation: An Advanced Remediation Technology for the Treatment of Textile Dye-Contaminated Soil,” discusses the use of electro-bioremediation to address soil contamination from textile dyes. The research highlights the process’s efficiency in degrading complex organic compounds present in dyes, facilitated by the combined action of electric fields and microbial degradation. Similarly, Table 4 gives comprehensive details of recent case studies on Electro-Bioremediation.

Table 4. Electro-bioremediation case studies.

Case Study	Contaminants	Environment	Key Findings	Key Technologies Used	Remediation Efficiency	Challenges Encountered	Source
Electro-bioremediation of nitrate and arsenite-polluted groundwater	Nitrate, Arsenite	Groundwater	Demonstrated effective reduction of nitrate and arsenite concentrations using combined electrokinetic and bioremediation techniques.	Electrodes with controlled DC current	~85% nitrate reduction	High energy requirements and uneven contaminant transport.	[134]
An advanced remediation technology for the treatment of textile dye-contaminated soil	Textile Dyes	Soil	Enhanced degradation of complex organic compounds in textile dyes through the synergistic effects of electric fields and microbial activity.	Electrodes, biosurfactants	~90% dye degradation	Managing microbial viability in highly polluted conditions.	[135]
Enhancement of Bioremediation enhanced	Hydrocarbons	Soil	Provided an overview of the applicability of electrokinetic methods in enhancing bioremediation of hydrocarbon-contaminated soils.	Electrodes, nutrient amendments	~75% hydrocarbon removal	Limited effectiveness in heterogeneous soils.	[136]
Electrokinetic bioremediation of hydrocarbon-contaminated soil	Hydrocarbons	Soil	Achieved significant reduction in hydrocarbon concentrations by applying an electric field to stimulate microbial degradation.	Controlled DC electric fields	~80% hydrocarbon removal	Potential for soil heating and moisture loss.	[137]
Electro-bioremediation of heavy metal-contaminated soil	Heavy Metals	Soil	Enhanced removal of heavy metals through the combined application of electrokinetic and bioremediation processes, improving metal mobility and microbial activity.	Electrokinetic gradient, chelating agents	~85% heavy metal removal	Long treatment times for deeply contaminated soils.	[138]
Electrokinetic-enhanced bioremediation of chlorinated solvents	Chlorinated Solvents	Groundwater	Improved degradation rates of chlorinated solvents by integrating electrokinetic transport with microbial dechlorination.	Electrodes, reductive microbes	~90% solvent degradation	Limited microbial activity in extreme pH or salinity conditions.	[139]
Electro-bioremediation of PAHs in soil	PAHs	Soil	The increased degradation efficiency of PAHs in the soil through the application of an electric field to enhance microbial activity.	Controlled electric fields, nutrient inputs	~88% PAH removal	Energy-intensive process, requiring careful electrode spacing.	[140]

Electrokinetic bioremediation of diesel-contaminated clay soil	Diesel	Soil	Effective remediation of diesel-contaminated clay soil by combining electrokinetic treatment with bioremediation, resulting in significant contaminant reduction.	Electrokinetic system with amendments	~85% diesel reduction	Challenges in dealing with low-permeability clay soils.	[141]
Electro-bioremediation of perchlorate-contaminated soil	Perchlorate	Soil	Enhanced perchlorate degradation in soil by applying an electric field to stimulate microbial reduction processes.	Electrodes, perchlorate-reducing microbes	~90% perchlorate degradation	Difficulties in maintaining microbial activity over long periods.	[142]
Electrokinetic-enhanced bioremediation of phenol-contaminated soil	Phenol	Soil	Increased removal rates of phenol from contaminated soil through the synergistic effects of electrokinetic transport and microbial degradation.	Electrokinetic gradient, microbial inoculants	~82% phenol removal	Potential for electrode corrosion and secondary by-products.	[143]

Green Stabilization

Green stabilization is an eco-friendly soil remediation and stabilization technique that utilizes vegetation, natural additives, and microbial interactions to improve soil structure, reduce erosion, and immobilize contaminants [144]. This approach leverages natural processes involving plant roots, organic materials, and soil microorganisms to achieve stabilization and remediation sustainably [145]. Plants with extensive root systems, such as grasses and shrubs, bind soil particles, prevent erosion, and reduce the mobility of contaminants. These roots also enhance soil structure by increasing organic matter and facilitating aeration and water infiltration [146]. In addition to vegetation, natural additives like biochar, compost, and natural clays are incorporated to improve soil cohesion, nutrient content, and contaminant immobilization. Soil microorganisms play a crucial role by transforming and immobilizing pollutants, enhancing nutrient cycling, and improving soil fertility [147]. In some cases, chemical stabilization occurs as plants and microbes interact to sequester heavy metals and other pollutants, transforming them into less bioavailable forms. Green stabilization is widely applied in scenarios such as erosion control on slopes, riverbanks, and construction sites, where it prevents soil loss and improves stability [148]. It is also effective for immobilizing contaminants, and reducing the leaching of heavy metals and organic pollutants into groundwater. Table 5 gives case studies on green stabilization.

Table 5. Case studies on green stabilization for environmental remediation.

Case Study	Contaminants	Environment	Key Findings	Key Technologies Used	Remediation Efficiency	Challenges Encountered	Source
Green and Sustainable Remedial Strategy for Contaminated Site	Heavy Metals, Organic Pollutants	Urban Brownfield Site	Developed a green remediation strategy achieving compliance with regulations while minimizing environmental impact.	Phytoremediation, in-situ stabilization	Effective contaminant reduction	Long-term monitoring is required to ensure effectiveness.	[149]
Environmental Impacts of Stabilization and Solidification Technologies	Heavy Metals	Industrial Waste Sites	Assessed environmental impacts of stabilization technologies using life cycle assessment; identified benefits and drawbacks of S/S methods.	Stabilization and solidification	Identified potential benefits	Need for comprehensive life cycle assessments.	[150]
Green and Sustainable Remediation in the USA	Various Contaminants	Multiple Sites across the USA	Analyzed the policy framework and case studies of GSR; highlighted governmental roles in promoting sustainable remediation practices.	Green remediation (in-situ, ex-situ)	Enhanced understanding of GSR	Variability in policy adoption across regions.	[151]

Nano-Remediation Techniques

Nano Zero Valent Iron (nZVI)

nZVI is an advanced remediation technology employing nanoscale iron particles, less than 100 nanometers in size, to treat contaminants in soil and groundwater [152]. With a high surface area and strong reactivity, nZVI is particularly effective in degrading organic pollutants, immobilizing heavy metals, and addressing persistent contaminants like chlorinated solvents and pesticides [153]. The primary remediation mechanism involves redox reactions, where the zero-valent iron donates electrons to transform or reduce pollutants into less toxic forms while oxidizing itself to ferrous or ferric ions [154]. The nanoscale nature of nZVI allows for penetration into porous media, making it effective in treating contaminants in diverse soil and groundwater matrices [155]. Its advantages include high reactivity, versatility across a range of pollutants, and the ability to perform in situ applications, minimizing site disruption and reducing remediation costs. Additionally, nZVI performs well in anaerobic or low-pH environments [156].

While nano-scale materials (e.g., nanoscale zero-valent iron) show high reactivity in lab settings, their efficacy in real soils is often limited by issues like particle aggregation, rapid oxidation, and persistence in the environment. Such aggregation can drastically reduce the available reactive surface area and nanoparticle mobility [157]. Moreover, field deployments have revealed challenges with higher costs and only comparable performance relative to conventional bulk materials, along with uncertainties about long-term ecotoxicity and human health risks [157].

Nanoclays

Nanoclays, derived from naturally occurring clays, are nanostructured materials known for their layered structure, high surface area, and remarkable adsorptive and catalytic properties [158]. These properties make them effective in soil remediation by adsorbing, immobilizing, and degrading contaminants such as heavy metals, organic pollutants, and persistent chemicals [159]. The remediation process involves adsorption, ion exchange, and catalytic reactions [160]. Nanoclays' layered structure provides abundant active sites for binding pollutants, and their ion exchange capabilities allow the replacement of harmful ions with less harmful ones, stabilizing contaminants and reducing mobility. Functionalized nanoclays, such as organo-clays or polymer-clay composites, are further tailored to target specific pollutants and catalyze the breakdown of complex organic molecules into less toxic forms [161]. Nanoclays are advantageous due to their high adsorption capacity, environmental friendliness, cost-effectiveness, and versatility in both in-situ and ex-situ remediation strategies [162]. They also improve soil properties, enhancing its structure and water retention, contributing to both remediation and agricultural productivity [163].

Carbon Nanotubes (CNTs) and Graphene Oxides (GO)

CNTs and GO are advanced nanomaterials with remarkable properties such as high surface area, mechanical strength, and strong adsorptive capabilities, making them highly effective for soil remediation [164]. These materials can target a range of contaminants, including heavy metals, hydrocarbons, pesticides, and pharmaceuticals [165]. Their remediation mechanisms include adsorption, catalytic degradation, and immobilization. The high surface area and functional groups of CNTs and GO provide active sites for adsorbing contaminants [166]. Heavy metals are removed through chemical bonding or ion exchange, while organic pollutants are adsorbed via π-π interactions, hydrophobic effects, or van der Waals forces [167]. Additionally, these nanomaterials serve as catalysts in AOPs, breaking down complex pollutants into less toxic compounds [168].

Table 6 gives the case studies that highlight the significant potential of nanomaterials for environmental remediation, focusing on soil and water pollutants. Nanomaterials, such as metal and metal oxide nanoparticles, demonstrate enhanced pollutant removal capabilities compared to conventional methods, but environmental and health risks remain a concern.

Table 6. Case studies on nano-remediation techniques.

Case Study	Contaminants	Environment	Key Findings	Key Technologies Used	Remediation Efficiency	Challenges Encountered	References
Advancement in Nanomaterials for Environmental Pollutants Remediation	Various Pollutants	Soil and Water	Nanomaterials enhance pollutant removal compared to conventional techniques; potential environmental risks exist.	Metal and metal oxide nanoparticles	Enhanced pollutant removal	Environmental and health risks of nanomaterials; need for sustainable synthesis methods.	[169]
Nanoremediation of Polluted Environment: Current Scenario and Case Studies	Organic Compounds, Heavy Metals	Soil and Water	TiO_2 nanoparticles degrade organic compounds under sunlight; silver oxide nanoparticles treat microbial contamination.	TiO_2 and silver oxide nanoparticles	Effective degradation of organic pollutants and microbes	Potential toxicity and scalability of nanoparticles.	[170]
Removal of Industrial Dye and Pharmaceutical products using Nano and Micron-Sized PS Rough Particles Studded with Pt Nanoparticles	Methylene Blue, Tetracycline	Wastewater	Platinum-studded PS particles achieved 100% removal of methylene blue and tetracycline; performance was influenced by particle size and concentration.	Platinum (Pt) nanoparticles	Complete removal of contaminants	Optimization of particle size and scalability for different contaminants.	[171,172]
End-to-End Integrated Simulation for Predicting the Fate of Contaminant and Remediating Nanoparticles	Trichloroethylene (TCE)	Groundwater	The modeling framework simulated contaminant and nZVI behavior in groundwater, aiding remediation design.	nZVI	Predictive modeling effectiveness	Complexity of subsurface environments; need for field data validation.	
Synthesis of nZVI/PVP Nanoparticles for Bioremediation Applications	Pathogenic Microorganisms	Soil and Water	Zero-valent iron nanoparticles stabilized with PVP exhibited antimicrobial activity; suggested for bioremediation applications.	Zero-valent iron (nZVI) with PVP	Antimicrobial activity observed	The stability and long-term effects of nanoparticles need further study.	

For example, TiO_2 and silver oxide nanoparticles effectively degrade organic compounds and treat microbial contamination, particularly under sunlight. However, potential toxicity and scalability challenges must be addressed. Platinum-studded PS particles have achieved 100% removal of industrial dyes like methylene blue and pharmaceuticals like tetracycline, showcasing the efficiency of size-optimized nanoparticles. However, scalability and particle size optimization for diverse contaminants remain challenges. nZVI is particularly effective in groundwater remediation, as demonstrated through predictive modeling of TCE behavior, aiding in the design of effective remediation strategies. Nevertheless, the complexity of subsurface environments necessitates field data validation. Further, nZVI stabilized with PVP shows antimicrobial properties, suggesting potential for bioremediation of pathogenic microorganisms in soil and water. Despite its promise, the long-term stability and ecological impacts of such nanoparticles require further exploration. These case studies underscore the transformative potential of nanomaterials in environmental remediation while highlighting the need for sustainable synthesis methods and risk mitigation strategies to ensure safe and effective applications.

The Table 7 provides a comparison of various remediation techniques. Chemical-based techniques like electrokinetic remediation and AOPs offer high efficiency for removing heavy metals, hydrocarbons, and organics but often come with high energy demands and operational costs. On the other hand, biological approaches, including phytoremediation and myco-remediation, emphasize eco-friendly and cost-effective solutions, though they are often time-consuming and limited by environmental conditions. Physical remediation processes, such as thermal desorption and soil flushing, are highly effective for specific contaminants like VOCs and hydrocarbons, yet they require significant resource inputs, including energy and water. Integrated approaches, such as biochar-amended remediation and electro-bioremediation, combine techniques to enhance efficiency and sustainability but necessitate precise optimization to maximize effectiveness. Emerging nano-remediation techniques show great promise due to their high reactivity and versatility. Materials like nZVI and GO demonstrate exceptional pollutant removal capabilities, especially for heavy metals and organic pollutants. However, concerns regarding cost, stability, and potential environmental risks associated with nanoparticle use remain critical challenges.

Table 7. Comprehensive comparison of all the soil remediation techniques discussed in this article.

Category	Technique	Mechanism	Target Pollutants	Advantages	Limitations	References
Chemical-Based Remediation	Electrokinetic Remediation	Uses electric fields to mobilize contaminants via electromigration, electroosmosis, and electrophoresis.	Heavy metals, hydrocarbons.	Effective in low-permeability soils; in-situ application.	High energy demand; pH imbalances near electrodes.	[173,174]
	Soil Washing with Surfactants	Surfactants mobilize and remove hydrophobic contaminants by forming micelles.	Hydrocarbons, heavy metals, organics.	Effective for hydrophobic pollutants; can recover surfactants.	Limited by soil type; surfactant recovery can be costly.	[58]
	AOPs	Generates hydroxyl radicals to degrade organic pollutants via chemical or photochemical oxidation.	Hydrocarbons, VOCs, pesticides.	Fast, versatile, and effective for organic pollutants.	Energy-intensive; requires chemical handling.	[175]
Biological and Microbial Techniques	Phytoremediation	Plants extract, degrade, or stabilize pollutants in soil.	Heavy metals, hydrocarbons, organics.	Eco-friendly, cost-effective, and enhances soil fertility.	Time-consuming; depth limited to root systems.	[176,177]
	MICP	Microorganisms precipitate calcite to immobilize heavy metals.	Heavy metals, radionuclides.	Stabilizes soil structure; reduces pollutant mobility.	Limited to specific microbial strains and site conditions.	[178–181]
	Bioaugmentation	Introduces specific microorganisms to degrade pollutants.	Organics, hydrocarbons, pesticides.	Targets specific pollutants; enhances biodegradation.	Competition with native microbes; requires nutrient supplementation.	-
	Mycoremediation	Uses fungi to degrade organic contaminants or immobilize metals.	Hydrocarbons, heavy metals, pesticides.	Effective for recalcitrant pollutants; eco-friendly.	Slow process; limited to specific environmental conditions.	[92,93]
Physical Remediation Processes	Soil Flushing	Flushes contaminants using water or chemical solutions to extract pollutants.	Heavy metals, salts, hydrocarbons.	Effective for a wide range of pollutants; can be combined with other methods.	High water demand; requires effluent treatment.	[182,183]
	Thermal Desorption	Heats soil to volatilize and remove organic pollutants.	VOCs, SVOCs, hydrocarbons, PCBs.	Fast and effective for volatile pollutants.	Energy-intensive; alters soil properties.	[106,184,185]
	Cryogenic Remediation	Freezes soil to immobilize and extract volatile pollutants.	VOCs, hydrocarbons.	Prevents pollutant migration; effective for volatile contaminants.	High energy costs; are limited by soil type and contaminant.	[186–188]
Integrated Remediation Approaches	Biochar-Amended Remediation	Uses biochar to adsorb contaminants and improve soil fertility.	Heavy metals, hydrocarbons, organics.	Enhances soil health; cost-effective and eco-friendly.	Limited adsorption for some pollutants; biochar disposal is required.	[189]
	Electro-Bioremediation	Combines electric fields with microbial activity to enhance contaminant degradation.	Organics, hydrocarbons, metals.	Accelerates biodegradation; effective in low-permeability soils.	Requires optimized microbial and electrical conditions.	[190]
	Green Stabilization	Uses plants, microbes, and natural additives to stabilize contaminants and reduce erosion.	Heavy metals, hydrocarbons.	Eco-friendly, restores vegetation, and cost-effective.	Time-consuming; limited for heavily contaminated sites.	[191]
Nano-Remediation Techniques	nZVI	Reduces and immobilizes pollutants through redox reactions.	Heavy metals, halogenated organics.	Highly reactive; cost-effective for metals.	Short lifespan; potential secondary pollution from iron oxides.	[192]
	Nanoclays	Adsorbs pollutants via ion exchange and immobilization.	Heavy metals, hydrocarbons, organics.	Eco-friendly, enhances soil structure.	Limited catalytic potential for some organics.	[193]
	CNTs	Adsorbs and degrades contaminants through catalytic and physical interactions.	Organics, heavy metals.	High adsorption capacity; durable.	Expensive; prone to aggregation.	[194,195]
	GO	Adsorbs and degrades pollutants via oxidation and adsorption mechanisms.	VOCs, heavy metals, hydrocarbons.	Versatile, easily functionalized.	Costly; environmental risks if not managed properly.	[196,197]

Table 8 provides a detailed overview of soil remediation techniques, their environmental risks, key concerns, and mitigation strategies. Chemical-based and biological remediation techniques emphasize the importance of precise application and monitoring to minimize secondary contamination and disruption of native microbial communities. Physical and nano-remediation methods, though effective, underline the need for careful assessment of their long-term environmental impacts, particularly in maintaining soil structure and preventing nanoparticle toxicity. Energy-intensive methods and their reliance on fossil fuels pose a significant challenge, advocating for a shift toward renewable energy integration and optimization of energy use. The integration of remediation with sustainable farming practices showcases the importance of balancing soil recovery efforts with agricultural productivity. Additionally, waste management strategies, focusing on the sustainable disposal and recycling of residues, highlight a critical area for reducing secondary pollution and enhancing environmental outcomes. There is a need for multi-disciplinary approaches that combine technological advancements, renewable energy solutions, and sustainable farming practices. Addressing these challenges requires robust policies, stakeholder collaboration, and adaptive management frameworks to ensure the success of remediation efforts while promoting environmental sustainability and resilience.

Table 8. Environmental risks and mitigation strategies in advanced soil remediation.

Technique	Environmental Risks	Key Concerns	Mitigation Strategies	References
Chemical-Based Remediation	Residual byproducts in soil/water; potential secondary contamination affecting soil microbiota and water sources.	Improper application or overuse of chemicals.	Use controlled dosing; conduct risk assessments before application.	[198]
Biological Remediation	Disruption of native microbial communities; incomplete remediation leaving pollutants partially untreated.	Introduction of non-native microorganisms or fungi.	Use site-specific organisms; monitor microbial balance post-remediation.	[199,200]
Physical Remediation	Alteration of soil structure, porosity, and moisture retention; depletion of water resources.	Thermal desorption reduces fertility; soil flushing generates contaminated effluents.	Monitor soil health post-treatment; recycle water from flushing; adopt minimal impact methods.	[201]
Nano-Remediation	Nanoparticle leaching into water; bioaccumulation and toxicity to soil and aquatic life.	Uncertainty about long-term environmental impacts.	Conduct comprehensive risk assessments; use biodegradable nanomaterials.	[202]
Energy-Intensive Methods	High energy inputs lead to carbon footprints; and potential greenhouse gas emissions.	Dependence on fossil fuels in energy-intensive regions.	Use renewable energy sources; optimize energy use in remediation technologies.	[198,203]
Integration with Farming	Potential inhibition of crop growth; reduced effectiveness of sustainable farming practices.	Conflict between remediation agents and sustainable methods like crop rotation.	Balance application of agents with crop needs; integrate holistic approaches.	[204,205]
Waste Management	Residues like contaminated water and spent biochar require proper disposal or further treatment.	Risk of secondary pollution from unmanaged waste.	Develop sustainable disposal and recycling methods for residues.	[206,207]

RESULTS AND DISCUSSION

The evaluation of individual and integrated soil remediation techniques reveals distinct performance characteristics across varying soil types and contaminant profiles. Chemical methods such as gypsum reclamation showed high efficacy in sodic soil improvement by lowering the ESP and enhancing soil permeability. Studies by [47–52] support these findings, demonstrating reductions in both soil pH and SAR post-treatment with gypsum amendments. These outcomes align with Hypothesis 1, which proposes that targeted chemical interventions can significantly improve soil structure and hydraulic conductivity. Biological methods, especially phytoremediation and microbial augmentation, demonstrated sustainability and ecological balance. For example, the use of *Echinacea purpurea* in petroleum-contaminated soils led to significant pollutant reduction, supported by recent evidence [20].

Electro-bioremediation emerged as a particularly effective hybrid approach, achieving up to 90% degradation of persistent organic pollutants such as textile dyes and hydrocarbons. This synergy of electrokinetic stimulation with microbial action supports Hypothesis 1, indicating superior performance of integrated methods over standalone techniques. Likewise, biochar application—especially when enriched with microbial or nutrient amendments—significantly improved SOC content, microbial biomass, and nutrient retention [123].

The immobilization of heavy metals through sorption and pH regulation further confirms its multifunctional utility. Nano-remediation strategies, including the use of nZVI and GO, consistently achieved over 85–90% removal efficiency of contaminants such as chlorinated solvents and heavy metals in lab-scale studies. While these outcomes affirm Hypothesis 2 regarding the high removal efficiency of nano-materials, they also raise valid concerns about ecological toxicity, nanoparticle persistence, and regulatory constraints—thus partially refuting the blanket applicability of such methods without thorough risk assessment. The MICP not only stabilized heavy metals but also improved soil shear strength and erosion resistance. These methods are consistent with long-term fertility enhancement, validating Hypothesis 3, which emphasizes the benefits of ecosystem-based approaches.

The evaluation of individual and integrated soil remediation techniques reveals distinct performance characteristics across varying soil types and contaminant profiles. Chemical methods, such as gypsum reclamation, showed high efficacy in sodic soil improvement by lowering the ESP and enhancing soil permeability. Studies by [47–52] support these findings, demonstrating reductions in both soil pH and SAR post-treatment with gypsum amendments. These outcomes align with Hypothesis 1, which proposes that targeted chemical interventions can significantly improve soil structure and hydraulic conductivity. Electro-bioremediation emerged as a particularly effective hybrid approach, achieving up to 90% degradation of persistent organic pollutants such as textile dyes and hydrocarbons. This synergy of electrokinetic stimulation with microbial action supports Hypothesis 1, indicating superior performance of integrated methods over standalone techniques. Biological methods, especially phytoremediation and microbial augmentation, demonstrated sustainability and ecological balance. For example, the use of *Echinacea purpurea* in petroleum-contaminated soils led to significant pollutant reduction, supported by recent evidence [20]. Likewise, biochar application—especially when enriched with microbial or nutrient amendments—significantly improved SOC content, microbial biomass, and nutrient retention [123]. The immobilization of heavy metals through sorption and pH regulation further confirms its multifunctional utility. Nano-remediation strategies, including the use of nZVI and GO, consistently achieved over 85–90% removal efficiency of contaminants such as chlorinated solvents and heavy metals in lab-scale studies. While these outcomes affirm Hypothesis 2 regarding the high removal efficiency of nano-materials, they also raise valid concerns about ecological toxicity, nanoparticle persistence, and regulatory constraints—thus partially refuting the blanket applicability of such methods without thorough risk assessment. The MICP not only stabilized heavy metals but also improved soil shear strength and erosion resistance. These methods are consistent with long-term fertility enhancement, validating Hypothesis 3, which emphasizes the benefits of ecosystem-based approaches.

Comparison with Literature and Sustainability Considerations

The comparative matrix (Table 7) illustrates that while physical and chemical remediation methods offer rapid results, biological and integrated strategies are more aligned with sustainability and SDG frameworks. Physical approaches such as thermal desorption are effective but energy-intensive, limiting their feasibility in low-resource settings. Biological methods, although slower, enhance long-term resilience and support soil biodiversity. These observations are in line with findings by [121,122] who advocate for combining multiple techniques tailored to site-specific soil profiles.

CONCLUSIONS

The review presents a comprehensive assessment of chemical, biological, physical, integrated, and nano-based soil remediation strategies, emphasizing their comparative efficiencies, environmental sustainability, and practical applicability. The following key conclusions are drawn:

- Chemical remediation methods such as gypsum amendment and AOPs are effective in rapidly improving soil structure and removing heavy metals or organics, but they may lead to secondary impacts and require careful dosage control.
- Biological techniques, particularly phytoremediation, bioaugmentation, and MICP, offer long-term benefits by enhancing soil fertility and ecosystem functioning, although they are often limited by time and environmental conditions.
- Physical methods like soil flushing and thermal desorption provide high contaminant removal efficiency but are resource-intensive and less sustainable for widespread agricultural application.

- Integrated approaches, such as electro-bioremediation and biochar-assisted remediation, deliver synergistic benefits by improving both remediation efficiency and soil health. These are particularly suitable for site-specific and multi-contaminant scenarios.
- Nano-remediation techniques, notably using nZVI, GO, and nanoclays, demonstrate superior contaminant removal in laboratory conditions. However, they present ecological and regulatory challenges that must be addressed before large-scale deployment.
- Hypotheses tested in this review were largely validated, confirming that integrated and ecosystem-based methods are superior in sustainability and long-term applicability, while nano-remediation demands further environmental scrutiny.

Directions for Future Research

- Field-scale validation of nano-remediation techniques under varying soil textures and climatic conditions is needed to assess scalability and ecological risks.
- Development of standardized protocols for integrating biological and electrochemical methods to optimize performance in heterogeneous soils.
- Life-cycle assessments (LCA) and cost-benefit analyses should be conducted to determine the economic feasibility of combined and nano-based remediation methods.
- Policy frameworks and risk assessment models must evolve to regulate and safely implement advanced materials in agricultural soil remediation.
- Exploration of AI-driven monitoring systems, smart sensors, and IoT technologies for real-time decision-making in site-specific soil recovery.

DATA AVAILABILITY

All data contained within the article.

AUTHOR CONTRIBUTIONS

Conceptualization: KK; Methodology: KK and PH; Writing—Original draft preparation: KK and PH; Validation: USP, BMG, YMS, GDD and SK Writing—Reviewing and Editing; all authors; Supervision: PH.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

FUNDING

This research is not funded by any internal or external agencies.

AKNOWLEDGEMT

All authors gratefully acknowledge the Department of Biotechnology, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, India, for providing access to the BioRender software tool used to create the figures and infographics presented in this manuscript.

REFERENCES

1. Smith P, Cotrufo MF, Rumpel C, Paustian K, Kuikman PJ, Elliott JA, et al. Biogeochemical cycles and biodiversity as key drivers of ecosystem services provided by soils. Soil. 2015;1(2):665-85. doi: 10.5194/soil-1-665-2015.
2. Yudina A, Kuzyakov Y. Dual nature of soil structure: The unity of aggregates and pores. Geoderma. 2023;434:116478. doi: 10.1016/j.geoderma.2023.116478.
3. Omo-Okoro P, Ofori P, Amalapridman V, Dadrasnia A, Abbey L, Emenike C. Soil pollution and its interrelation with interfacial chemistry. Molecules. 2025;30(12):2636. doi: 10.3390/molecules30122636.
4. Alemu EB. Evaluating the environmental impacts of industrialization and urbanization on groundwater quality: A comprehensive review of methodological approaches in Ethiopia. Green Energy Environ Tech. 2025. doi: 10.2139/ssrn.5285703.
5. Khalid S, Shahid M, Niazi NK, Murtaza B, Bibi I, Dumat C. A comparison of technologies for remediation of heavy metal contaminated soils. J Geochem Explor. 2017;182:247-68. doi: 10.1016/j.gexplo.2016.11.021.
6. European Environment Agency. Progress in the Management of Contaminated Sites (Indicator). Copenhagen (Denmark): European Environment Agency; 2022.
7. Ahmad N, Pandey P. Spatio-temporal distribution, ecological risk assessment, and multivariate analysis of heavy metals in Bathinda District, Punjab, India. Water Air Soil Pollut. 2020;231(8):431. doi: 10.1007/s11270-020-04767-9.
8. Cao B, Sun Z, Bai D, Kong L, Zhang X, Chen J, et al. The identification of soil heavy metal sources and environmental risks in industrial city peri-urban areas: A case study from a typical peri-urban area in western Laizhou, Shandong, China. Sustainability. 2024;16(11):4655. doi: 10.3390/su16114655.
9. Gong Y, Zhao D, Wang Q. An overview of field-scale studies on remediation of soil contaminated with heavy metals and metalloids: Technical progress over the last decade. Water Res. 2018;147:440-60. doi: 10.1016/j.watres.2018.10.024.
10. Hou D, Jia X, Wang L, McGrath SP, Zhu YG, Hu Q, et al. Global soil pollution by toxic metals threatens agriculture and human health. Science. 2025;388(6744):316-21. doi: 10.1126/science.adr5214.
11. Boularbah A, Aloo BN, Benidire L, Neina D, Lahlali R. Soil health and contamination: Processes, remediation, and impacts on food security. In: Innovative Approaches in Environmental Health Management: Processes, Technologies, and Strategies for a Sustainable Future. Cham (Switzerland): Springer; 2025; p. 87-111. doi: 10.1007/978-3-031-81966-7_4.
12. Zhang L, Wang Y, Ding Q, Shi Y. Current status and prospects of ecological restoration and brownfield reuse research based on bibliometric analysis: A literature review. Land (Basel). 2025;14(6):1185. doi: 10.3390/land14061185.

13. Sobieraj, Metelski D. Analysis of technologies for the reclamation of illegal landfills: A case study of the relocation and management of chromium and arsenic contamination in Łomianki (Poland). Sustainability. 2025;17(7):2796. doi: 10.3390/su17072796.
14. Abou-Shady A, El-Araby H. Soil electrokinetic remediation to restore mercury-polluted soils: A critical review. Chemosphere. 2025;377:144336. doi: 10.1016/j.chemosphere.2025.144336.
15. Zeng W, Yao B, Zhou Y, Yang J, Zhi D. Combination of electrochemical advanced oxidation and biotreatment for wastewater treatment and soil remediation. J Environ Sci. 2025;150:36-53. doi: 10.1016/j.jes.2024.02.036.
16. Saqr AM, Pant RR, Alao JO, Chaurasia PK, Abdelkebir B, Abd-Elmaboud ME. Soil remediation through washing and flushing: bibliometric trends, technical review, and future prospects. Environ Earth Sci. 2025;84(14):401. doi: 10.1007/s12665-025-12386-y.
17. Zhao H, Cui W, Yang Y, Li S, Song F, Wang M, et al. Surfactant-functionalized fly ash from waste into wealth: Collaboratively scavenge of heavy metals and antibiotics from multi-pollutant wastewater. Sep Purif Technol. 2025;375:133862. doi: 10.1016/j.seppur.2025.133862.
18. Ma Y, He C, Yang L, Liu X, Wang F. Effective remediation of benzo [a] anthracene contaminated soil by combination of low-temperature thermal desorption and advanced oxidation. Chem Eng J. 2025;511:162166. doi: 10.1016/j.cej.2025.162166.
19. Kumar K, Shinde A, Aeron V, Verma A, Arif NS. Genetic engineering of plants for phytoremediation: Advances and challenges. J Plant Biochem Biotechnol. 2023;32(1):12-30. doi: 10.1007/s13562-022-00776-3.
20. Wojtowicz K, Steliga T, Kapusta P. Evaluation of the effectiveness of bioaugmentation-assisted phytoremediation of soils contaminated with petroleum hydrocarbons using Echinacea purpurea. Appl Sci. 2023;13(24):13077. doi: 10.3390/app132413077.
21. Akpasi SO, Anekwe IM, Tetteh EK, Amune UO, Shoyiga HO, Mahlangu TP, et al. Mycoremediation as a potentially promising technology: Current status and prospects—A review. Appl Sci. 2023;13(8):4978. doi: 10.3390/app13084978.
22. Tian H, Liang Y, Yang D, Sun Y. Characteristics of PVP–stabilised NZVI and application to dechlorination of soil–sorbed TCE with ionic surfactant. Chemosphere. 2020;239:124807. doi: 10.1016/j.chemosphere.2019.124807.
23. López-Rodríguez D, Micó-Vicent B, Jordán-Núñez J, Bonet-Aracil M, Bou-Belda E. Uses of nanoclays and adsorbents for dye recovery: A textile industry review. Appl Sci. 2021;11(23):11422. doi: 10.3390/app112311422.
24. Uprety DC, Reddy VR, Mura JD. Climate Change and Agriculture. Singapore: Springer; 2019. doi: 10.1007/978-981-13-2014-9.
25. Temple PH, Rapp A. Landslides in the Mgeta area, Western Uluguru Mountains, Tanzania. Geografiska Annaler: Series A, Physical Geography. 1972;54(3–4):157-93. doi: 10.1080/04353676.1972.11879864.
26. Yoro KO, Daramola MO. CO_2 emission sources, greenhouse gases, and the global warming effect. In: Advances in Carbon Capture. Amsterdam,

(Netherlands): Elsevier; 2020. p. 3-28. doi: 10.1016/B978-0-12-819657-1.00001-3.

27. Lal R. Soil erosion and the global carbon budget. Environ Int. 2003;29(4):437-50. doi: 10.1016/S0160-4120(02)00192-7.
28. Hussain S, Ulhassan Z, Brestic M, Zivcak M, Zhou W, Allakhverdiev SI, et al. Photosynthesis research under climate change. Photosynth Res. 2021;150(1–3):5-19. doi: 10.1007/s11120-021-00861-z.
29. Smith P, Calvin K, Nkem J, Campbell D, Cherubini F, Grassi G, et al. Which practices co-deliver food security, climate change mitigation and adaptation, and combat land degradation and desertification? Glob Chang Biol. 2020;26(3):1532-75. doi: 10.1111/gcb.14878.
30. Karavolias NG, Horner W, Abugu MN, Evanega SN. Application of gene editing for climate change in agriculture. Front Sustain Food Syst. 2021;5:685801. doi: 10.3389/fsufs.2021.685801.
31. Bibi F, Rahman A. An overview of climate change impacts on agriculture and their mitigation strategies. Agriculture. 2023;13(8):1508. doi: 10.3390/agriculture13081508.
32. Kopittke PM, Berhe AA, Carrillo Y, Cavagnaro TR, Chen D, Chen QL, et al. Ensuring planetary survival: The centrality of organic carbon in balancing the multifunctional nature of soils. Crit Rev Environ Sci Technol. 2022;52(23):4308-24. doi: 10.1080/10643389.2021.2024484.
33. Keesstra S, Sannigrahi S, López-Vicente M, Pulido M, Novara A, Visser S, et al. The role of soils in regulation and provision of blue and green water. Philos Trans R Soc B: Biol Sci. 2021;376(1834):20200175. doi: 10.1098/rstb.2020.0175.
34. Lal R, Monger C, Nave L, Smith P. The role of soil in regulation of climate. Philos Trans R Soc B: Biol Sci. 2021;376(1834):20210084. doi: 10.1098/rstb.2021.0084.
35. Valentine J, Clifton-Brown J, Hastings A, Robson P, Allison G, Smith P. Food vs. fuel: the use of land for lignocellulosic ‘next generation’ energy crops that minimize competition with primary food production. GCB Bioenergy. 2012;4(1):1-19. doi: 10.1111/j.1757-1707.2011.01111.x.
36. Sommer R, Bossio D. Dynamics and climate change mitigation potential of soil organic carbon sequestration. J Environ Manage. 2014;144:83-7. doi: 10.1016/j.jenvman.2014.05.017.
37. Prasad S, Malav LC, Choudhary J, Kannojiya S, Kundu M, Kumar S, et al. Soil microbiomes for healthy nutrient recycling. In: Current Trends in Microbial Biotechnology for Sustainable Agriculture. Singapore: Springer; 2020; p. 1-21. doi: 10.1007/978-981-15-6949-4_1.
38. Iyiola AO, Babafemi OP, Ogundahunsi OE, Ojeleye AE. Food security: A pathway towards improved nutrition and biodiversity conservation. In: Biodiversity in Africa: Potentials, Threats and Conservation. Singapore: Springer Nature; 2022; p. 79-107. doi: 10.1007/978-981-19-3326-4_4.
39. Pawlak K, Kołodziejczak M. The role of agriculture in ensuring food security in developing countries: Considerations in the context of the problem of sustainable food production. Sustainability. 2020;12(13):5488. doi: 10.3390/su12135488.

40. Eugenio NR, Nachtergaele F, Biancalani R, Emiliano M, Benedetti F, Li L. Working together for soils: The longstanding collaboration between FAO and the IUSS. In: Soil science in Italy. Cham (Switzerland): Springer International Publishing; 2024. p. 649-53. doi: 10.1007/978-3-031-52744-9_35.
41. Adamsone-Fiskovica A, Grivins M. Understanding the potential of sustainability turn in farming: Review of sociotechnical adoption factors of agri-environmental cropping practices. Renew Agric Food Syst. 2024;39:e16. doi: 10.1017/S1742170524000085.
42. Lal R. Soil organic matter and water retention. Agron J. 2020;112(5):3265-77. doi: 10.1002/agj2.20282.
43. Bi X, Chu H, Fu M, Xu D, Zhao W, Zhong Y, et al. Distribution characteristics of organic carbon (nitrogen) content, cation exchange capacity, and specific surface area in different soil particle sizes. Sci Rep. 2023;13(1):12242. doi: 10.1038/s41598-023-38646-0.
44. Condron L, Stark C, O'Callaghan M, Clinton P, Huang Z. The role of microbial communities in the formation and decomposition of soil organic matter. In: Soil microbiology and sustainable crop production. Dordrecht (Netherlands): Springer; 2010. p. 81-118. doi: 10.1007/978-90-481-9479-7_4.
45. Mukhopadhyay R, Sarkar B, Jat HS, Sharma PC, Bolan NS. Soil salinity under climate change: Challenges for sustainable agriculture and food security. J Environ Manage. 2021;280:111736. doi: 10.1016/j.jenvman.2020.111736.
46. Lampridi M, Sørensen C, Bochtis D. Agricultural sustainability: A review of concepts and methods. Sustainability. 2019;11(18):5120. doi: 10.3390/su11185120.
47. Gangwar P, Singh R, Trivedi M, Tiwari RK. Sodic soil: Management and reclamation strategies. In: Environmental concerns and sustainable development. Singapore: Springer; 2020. p. 175-90. doi: 10.1007/978-981-13-6358-0_8.
48. Abdolvand Y, Sadeghiamirshahidi M. Soil stabilization with gypsum: A review. J Rock Mech Geotech Eng. 2024;16(12):5278-96. doi: 10.1016/j.jrmge.2024.02.007.
49. Shruthi, Prakash NB, Dhumgond P, Goiba PK, Laxmanarayanan M. The benefits of gypsum for sustainable management and utilization of acid soils. Plant Soil. 2024;504(1–2):5-28. doi: 10.1007/s11104-024-06907-0.
50. Singh YP, Arora S, Mishra VK, Bhardwaj AK. Regaining the agricultural potential of sodic soils and improved smallholder food security through integration of gypsum, pressmud and salt tolerant varieties. Agroecology and Sustainable Food Systems. 2022;46(3):410-31. doi: 10.1080/21683565.2021.2015735.
51. Wakeel A, Ishfaq M. Potash Use and Dynamics in Agriculture. Berlin Heidelberg (Germany): Springer; 2021. doi: 10.1007/978-981-16-6883-8.
52. Zhang W, Zhang W, Wang S, Sun Z, Liu J, Li Y, et al. A quantitative assessment of the dynamic process and potential capacity of using gypsum to reclaim sodic soil. J Soils Sediments. 2023;23(8):3082-95. doi: 10.1007/s11368-023-03535-6.

53. Akansha J, Thakur S, Chaithanya MS, Gupta BS, Das S, Das B, et al. Technological and economic analysis of electrokinetic remediation of contaminated soil: A global perspective and its application in Indian scenario. Heliyon. 2024;10(2):e24293. doi: 10.1016/j.heliyon.2024.e24293.
54. El-Mehalmey WA, Alkordi MH. Electrokinetic remediation technique for soil contaminants. In: Nanoremediation. Amsterdam (Netherlands): Elsevier; 2023. p. 229-58. doi: 10.1016/B978-0-12-823874-5.00005-X.
55. Abou-Shady A, Yu W. Recent advances in electrokinetic methods for soil remediation. A critical review of selected data for the period 2021–2022. Int J Electrochem Sci. 2023;18(8):100234. doi: 10.1016/j.ijoes.2023.100234.
56. Panizza M, Cerisola G. Direct and mediated anodic oxidation of organic pollutants. Chem Rev. 2009;109(12):6541-69. doi: 10.1021/cr9001319.
57. Tang K, Bo Z, Li Z, Da Wang Y, McClure J, Su H, et al. Controlled ion transport in the subsurface: A coupled advection–diffusion–electromigration system. Phys Fluids. 2024;36(6):067137. doi: 10.1063/5.0213161.
58. Mao X, Jiang R, Xiao W, Yu J. Use of surfactants for the remediation of contaminated soils: A review. J Hazard Mater. 2015;285:419-35. doi: 10.1016/j.jhazmat.2014.12.009.
59. Rasheed T, Shafi S, Bilal M, Hussain T, Sher F, Rizwan K. Surfactants-based remediation as an effective approach for removal of environmental pollutants—A review. J Mol Liq. 2020;318:113960. doi: 10.1016/j.molliq.2020.113960.
60. Bolan S, Padhye LP, Mulligan CN, Alonso ER, Saint-Fort R, Jasemizad T, et al. Surfactant-enhanced mobilization of persistent organic pollutants: Potential for soil and sediment remediation and unintended consequences. J Hazard Mater. 2023;443:130189. doi: 10.1016/j.jhazmat.2022.130189.
61. Wołowicz A, Staszak K, Hubicki Z. Effect of anionic surfactants on the heavy metal ions removal by adsorption onto ion exchangers—batch and column studies. J Water Process Eng. 2023;53:103792. doi: 10.1016/j.jwpe.2023.103792.
62. Cheng M, Zeng G, Huang D, Yang C, Lai C, Zhang C, et al. Advantages and challenges of Tween 80 surfactant-enhanced technologies for the remediation of soils contaminated with hydrophobic organic compounds. Chem Eng J. 2017;314:98-113. doi: 10.1016/j.cej.2016.12.135.
63. Koundal M, Singh AK, Sharma C. Study on the effect of imidazolium ionic liquid as a modulator of corrosion inhibition of anionic surfactant sodium dodecyl sulfate (SDS) on mild steel in sodium chloride solution. J Mol Liq. 2022;350:118561. doi: 10.1016/j.molliq.2022.118561.
64. Zhao Y, Sun Y, Sun H, Zuo F, Kuang S, Zhang S, et al. Surfactant-based chemical washing to remediate oil-contaminated soil: The state of knowledge. Toxics. 2024;12(9):648. doi: 10.3390/toxics12090648.
65. Mukherjee J, Lodh BK, Sharma R, Mahata N, Shah MP, Mandal S, et al. Advanced oxidation process for the treatment of industrial wastewater: A review on strategies, mechanisms, bottlenecks and prospects. Chemosphere. 2023;345:140473. doi: 10.1016/j.chemosphere.2023.140473.
66. Ndibewu PP, Mramba AS, Makgopa K, Sibali LL. Nanoelectrocatalysts-Enhanced methods for removal of volatile organic compounds in wastewater.

In: Nanoelectrocatalysts for Energy and Water Treatment. Cham (Switzerland): Springer Nature; 2024. doi: 10.1007/978-3-031-55329-5_13.
67. Ayoub K, van Hullebusch ED, Cassir M, Bermond A. Application of advanced oxidation processes for TNT removal: A review. J Hazard Mater. 2010;178(1–3):10-28. doi: 10.1016/j.jhazmat.2010.02.042.
68. Dai M, Niu Q, Wu S, Lin Y, Biswas JK, Yang C. Hydroxyl radicals in ozone-based advanced oxidation of organic contaminants: A review. Environ Chem Lett. 2024;22(6):3059-106. doi: 10.1007/s10311-024-01772-w.
69. Tijani JO, Fatoba OO, Madzivire G, Petrik LF. A review of combined advanced oxidation technologies for the removal of organic pollutants from water. Water Air Soil Pollut. 2014;225(9):2102. doi: 10.1007/s11270-014-2102-y.
70. Mahbub P, Duke M. Scalability of advanced oxidation processes (AOPs) in industrial applications: A review. J Environ Manage. 2023;345:118861. doi: 10.1016/j.jenvman.2023.118861.
71. Pandis PK, Kalogirou C, Kanellou E, Vaitsis C, Savvidou MG, Sourkouni G, et al. Key points of advanced oxidation processes (AOPs) for wastewater, organic pollutants and pharmaceutical waste treatment: A mini review. ChemEngineering. 2022;6(1):8. doi: 10.3390/chemengineering6010008.
72. Magalhães VM, Aranha RM, Mendes GP, Soares LC, Yoshikawa NK, Nascimento CA, et al. Homogeneous and heterogeneous advanced oxidation processes: Treatability studies on artificially contaminated soils with creosote. Water Air Soil Pollut. 2022;233(1):29. doi: 10.1007/s11270-022-05498-9.
73. Calenciuc C, Fdez-Sanromán A, Lama G, Annamalai S, Sanromán A, Pazos M. Recent developments in advanced oxidation processes for organics-polluted soil reclamation. Catalysts. 2022;12(1):64. doi: 10.3390/catal12010064.
74. Bhat SA, Bashir O, Haq SA, Amin T, Rafiq A, Ali M, et al. Phytoremediation of heavy metals in soil and water: An eco-friendly, sustainable and multidisciplinary approach. Chemosphere. 2022;303:134788. doi: 10.1016/j.chemosphere.2022.134788.
75. Evangelou MWH, Papazoglou EG, Robinson BH, Schulin R. Phytomanagement: Phytoremediation and the production of biomass for economic revenue on contaminated land. In: Phytoremediation. Cham (Switzerland): Springer International Publishing; 2015. p. 115-32. doi: 10.1007/978-3-319-10395-2_9.
76. Nemati B, Baneshi MM, Akbari H, Dehghani R, Mostafaii G. Phytoremediation of pollutants in oil-contaminated soils by Alhagi camelorum: Evaluation and modeling. Sci Rep. 2024;14(1):5502. doi: 10.1038/s41598-024-56214-y.
77. Bolan NS, Park JH, Robinson B, Naidu R, Huh KY. Phytostabilization: A green approach to contaminant containment. Adv Agron. 2011;112:145-204. doi: 10.1016/B978-0-12-385538-1.00004-4.
78. Barwise Y, Kumar P. Designing vegetation barriers for urban air pollution abatement: A practical review for appropriate plant species selection. NPJ Clim Atmos Sci. 2020;3(1):12. doi: 10.1038/s41612-020-0115-3.
79. Eapen S, D'Souza SF. Prospects of genetic engineering of plants for phytoremediation of toxic metals. Biotechnol Adv. 2005;23(2):97-114. doi: 10.1016/j.biotechadv.2004.10.001.

80. Dushenkov S, Mikheev A, Prokhnevsky A, Ruchko M, Sorochinsky B. Phytoremediation of radiocesium-contaminated soil in the vicinity of Chernobyl, Ukraine. Environ Sci Technol. 1999;33(3):469-75. doi: 10.1021/es980788.
81. Jiang L, Xia H, Wang W, Zhang Y, Li Z. Applications of microbially induced calcium carbonate precipitation in civil engineering practice: A state-of-the-art review. Constr Build Mater. 2023;404:133227. doi: 10.1016/j.conbuildmat.2023.133227.
82. Wong PY, Mal J, Sandak A, Luo L, Jian J, Pradhan N. Advances in microbial self-healing concrete: A critical review of mechanisms, developments, and future directions. Sci Total Environ. 2024;947:174553. doi: 10.1016/j.scitotenv.2024.174553.
83. Konstantinou C, Wang Y. Unlocking the potential of microbially induced calcium carbonate precipitation (MICP) for hydrological applications: A review of opportunities, challenges, and environmental considerations. Hydrology. 2023;10(9):178. doi: 10.3390/hydrology10090178.
84. Mujah D, Shahin MA, Cheng L. State-of-the-art review of biocementation by microbially induced calcite precipitation (MICP) for soil stabilization. Geomicrobiol J. 2017;34(6):524-37. doi: 10.1080/01490451.2016.1225866.
85. Wang Y-N, Li S-K, Li Z-Y, Garg A. Exploring the application of the MICP technique for the suppression of erosion in granite residual soil in Shantou using a rainfall erosion simulator. Acta Geotech. 2023;18(6):3273-85. doi: 10.1007/s11440-022-01791-3.
86. Omoregie AI, Palombo EA, Nissom PM. Bioprecipitation of calcium carbonate mediated by ureolysis: A review. Environ Eng Res. 2020;26(6):200379. doi: 10.4491/eer.2020.379.
87. Cycoń M, Mrozik A, Piotrowska-Seget Z. Bioaugmentation as a strategy for the remediation of pesticide-polluted soil: A review. Chemosphere. 2017;172:52-71. doi: 10.1016/j.chemosphere.2016.12.129.
88. Lebeau T. Bioaugmentation for in situ soil remediation: How to ensure the success of such a process. In: Bioaugmentation, Biostimulation and Biocontrol. Berlin, Heidelberg (Germany): Springer; 2011; p. 129-86. doi: 10.1007/978-3-642-19769-7_7.
89. Tyagi M, da Fonseca MMR, de Carvalho CCCR. Bioaugmentation and biostimulation strategies to improve the effectiveness of bioremediation processes. Biodegradation. 2011;22(2):231-41. doi: 10.1007/s10532-010-9394-4.
90. Megharaj M, Ramakrishnan B, Venkateswarlu K, Sethunathan N, Naidu R. Bioremediation approaches for organic pollutants: A critical perspective. Environ Int. 2011;37(8):1362-75. doi: 10.1016/j.envint.2011.06.003.
91. Juwarkar AA, Singh SK, Mudhoo A. A comprehensive overview of elements in bioremediation. Rev Environ Sci Biotechnol. 2010;9(3):215-88. doi: 10.1007/s11157-010-9215-6.
92. Kumar A, Yadav AN, Mondal R, Kour D, Subrahmanyam G, Shabnam AA, et al. Myco-remediation: A mechanistic understanding of contaminants alleviation from natural environment and future prospect. Chemosphere. 2021;284:131325. doi: 10.1016/j.chemosphere.2021.131325.

93. Dinakarkumar Y, Ramakrishnan G, Gujjula KR, Vasu V, Balamurugan P, Murali G. Fungal bioremediation: An overview of the mechanisms, applications and future perspectives. Environ Chem Ecotoxicol. 2024;6:293-302. doi: 10.1016/j.enceco.2024.07.002.
94. Saravanan A, Kumar PS, Vo DVN, Jeevanantham S, Karishma S, Yaashikaa PR. A review on catalytic-enzyme degradation of toxic environmental pollutants: Microbial enzymes. J Hazard Mater. 2021;419:126451. doi: 10.1016/j.jhazmat.2021.126451.
95. Gupta G, Maurya S, Jha PN, Chauhan PS. Valorization of spent mushroom substrate (SMS) as a sustainable approach to remediation of xenobiotic compounds in groundwater—A comprehensive review. Groundw Sustain Dev. 2024;26:101290. doi: 10.1016/j.gsd.2024.101290.
96. Noman E, Al-Gheethi A, Mohamed RMSR, Talip BA. Myco-remediation of xenobiotic organic compounds for a sustainable environment: A critical review. Top Curr Chem. 2019;377(3):17. doi: 10.1007/s41061-019-0241-8.
97. Navina BK, Velmurugan NK, Kumar PS, Rangasamy G, Palanivelu J, Thamarai P, et al. Fungal bioremediation approaches for the removal of toxic pollutants: Mechanistic understanding for biorefinery applications. Chemosphere. 2024;350:141123. doi: 10.1016/j.chemosphere.2024.141123.
98. Baghel P, Sakhiya AK, Kaushal P. Influence of temperature on slow pyrolysis of Prosopis Juliflora: An experimental and thermodynamic approach. Renew Energy. 2022;185:538-51. doi: 10.1016/j.renene.2021.12.053.
99. Hassan A, Pariatamby A, Ossai IC, Hamid FS. Bioaugmentation assisted mycoremediation of heavy metal and/metalloid landfill contaminated soil using consortia of filamentous fungi. Biochem Eng J. 2020;157:107550. doi: 10.1016/j.bej.2020.107550.
100. He P, Guo J, Zhang S. Investigating the potential of microbially induced carbonate precipitation combined with modified biochar for remediation of lead-contaminated loess. Sustainability. 2024;16(17):7550. doi: 10.3390/su16177550.
101. Ghorbani Y, Franzidis JP, Petersen J. Heap leaching technology – current state, innovations and future directions: A review. Miner Process Extr Metall Rev. 2015. doi: 10.1080/08827508.2015.1115990.
102. Kwon JH, Ji MK, Kumar R, Islam MM, Khan MA, Park YK, et al. Recent advancement in enhanced soil flushing for remediation of petroleum hydrocarbon-contaminated soil: A state-of-the-art review. Rev Environ Sci Biotechnol. 2023;22(3):679-714. doi: 10.1007/s11157-023-09657-0.
103. Baldissarelli DP, Vargas GDLP, Korf EP, Galon L, Kaufmann C, Santos JB. Remediation of soils contaminated by pesticides using physicochemical processes: A brief review. Planta Daninha. 2019;37:e019184975. doi: 10.1590/s0100-83582019370100054.
104. Klik B, Gusiatin ZM, Kulikowska D. Quality of heavy metal-contaminated soil before and after column flushing with washing agents derived from municipal sewage sludge. Sci Rep. 2021;11(1):15773. doi: 10.1038/s41598-021-95441-5.

105. Guo X, Chen C, Wu QT, Wei Z. Field experiments to assess the remediation efficiency of metal-contaminated soil by flushing with ferric chloride followed by applying amendments. Sci Total Environ. 2023;868:161592. doi: 10.1016/j.scitotenv.2023.161592.
106. Zhao C, Dong Y, Feng Y, Li Y, Dong Y. Thermal desorption for remediation of contaminated soil: A review. Chemosphere. 2019;221:841-55. doi: 10.1016/j.chemosphere.2019.01.079.
107. Liu H, Ma S, Zhang X, Yu Y. Application of thermal desorption methods for airborne polycyclic aromatic hydrocarbon measurement: A critical review. Environ Pollut. 2019;254:113018. doi: 10.1016/j.envpol.2019.113018.
108. Zhu L, Shen D, Luo KH. A critical review on VOCs adsorption by different porous materials: Species, mechanisms and modification methods. J Hazard Mater. 2020;389:122102. doi: 10.1016/j.jhazmat.2020.122102.
109. Sörengård M, Lindh A-S, Ahrens L. Thermal desorption as a high removal remediation technique for soils contaminated with per- and polyfluoroalkyl substances (PFASs). PLoS ONE. 2020;15(6):e0234476. doi: 10.1371/journal.pone.0234476.
110. Risco C, López-Vizcaíno R, Sáez C, Yustres A, Cañizares P, Navarro V, et al. Remediation of soils polluted with 2,4-D by electrokinetic soil flushing with facing rows of electrodes: A case study in a pilot plant. Chem Eng J. 2016;285:128-36. doi: 10.1016/j.cej.2015.10.011.
111. Biabani R, Ferrari P, Vaccari M. Best management practices for minimizing undesired effects of thermal remediation and soil washing on soil properties. A review. Environ Sci Pollut Res. 2023;30(47):103480-95. doi: 10.1007/s11356-023-29656-6.
112. Lee SH, Kim SO, Lee SW, Kim MS, Park H. Application of soil washing and thermal desorption for sustainable remediation and reuse of remediated soil. Sustainability. 2021;13(22):12523. doi: 10.3390/su132212523.
113. Wang B, Wu A, Li X, Ji L, Sun C, Shen Z, et al. Progress in fundamental research on thermal desorption remediation of organic compound-contaminated soil. Waste Dispos Sustain Energy. 2021;3(2):83-95. doi: 10.1007/s42768-021-00071-2.
114. Hameed R, Abbas A, Khan I, Balooch S, Iqbal B, Nazir MM, et al. Biochar-assisted remediation of contaminated soils under changing climate. In: Biochar-Assisted Remediation of Contaminated Soils under Changing Climate. Amsterdam (Netherlands): Elsevier; 2024. p. 377-420. doi: 10.1016/B978-0-443-21562-9.00015-3.
115. Chen ZS, Liu T, Dong JF, Chen G, Li Z, Zhou JL, et al. Sustainable application for agriculture using biochar-based slow-release fertilizers: A review. ACS Sustain Chem Eng. 2022;11(1):1-12. doi: 10.1021/acssuschemeng.2c05691.
116. Kumar P, Singhania RR, Sumathi Y, Kurrey NK, Chen CW, Patel AK, et al. Investigating innovative techniques for biochar modification to enhance the removal of heavy metals from aqueous environments: A comprehensive review. Clean Technol Environ Policy. 2024:1-23. doi: 10.1007/s10098-024-02962-4.

117. Sakhiya AK, Anand A, Kaushal P. Production, activation, and applications of biochar in recent times. Biochar. 2020;2(3):253-85. doi: 10.1007/s42773-020-00047-1.
118. Atkinson CJ. How good is the evidence that soil-applied biochar improves water-holding capacity? Soil Use Manag. 2018;34(2):177-86. doi: 10.1111/sum.12413.
119. Gorovtsov AV, Minkina TM, Mandzhieva SS, Perelomov LV, Soja G, Zamulina IV, et al. The mechanisms of biochar interactions with microorganisms in soil. Environ Geochem Health. 2020;42(8):2495-518. doi: 10.1007/s10653-019-00412-5.
120. Fu Q, Zhao H, Li H, Li T, Hou R, Liu D, et al. Effects of biochar application during different periods on soil structures and water retention in seasonally frozen soil areas. Sci Total Environ. 2019;694:133732. doi: 10.1016/j.scitotenv.2019.133732.
121. Beesley L, Moreno-Jiménez E, Gomez-Eyles JL, Harris E, Robinson B, Sizmur T. A review of biochars' potential role in the remediation, revegetation and restoration of contaminated soils. Environ Pollut. 2011;159(12):3269-82. doi: 10.1016/j.envpol.2011.07.023.
122. Zama EF, Reid BJ, Arp HPH, Sun GX, Yuan HY, Zhu YG. Advances in research on the use of biochar in soil for remediation: A review. J Soils Sediments. 2018;18(7):2433-50. doi: 10.1007/s11368-018-2000-9.
123. Murtaza G, Ahmed Z, Eldin SM, Ali I, Usman M, Iqbal R, et al. Biochar as a green sorbent for remediation of polluted soils and associated toxicity risks: A critical review. Separations. 2023;10(3):197. doi: 10.3390/separations10030197.
124. Ge Q, Dong C, Wang G, Zhang J, Hou R. Production, characterization and environmental remediation application of emerging phosphorus-rich biochar/hydrochar: A comprehensive review. RSC Adv. 2024;14(45):33649-65. doi: 10.1039/D4RA03333G.
125. Chandra S, Medha I, Tiwari AK. The role of modified biochar for the remediation of coal mining-impacted contaminated soil: A review. Sustainability. 2023;15(5):3973. doi: 10.3390/su15053973.
126. El-Shafey SE, Obada MK, El-Shamy AM, Mohamed WS. Silica/klucel nanocomposite as promising durable adsorbent for lead removal from industrial effluents. Sci Rep. 2024;14(1):26095. doi: 10.1038/s41598-024-74680-2.
127. Nicomel NR, Otero-Gonzalez L, Williamson A, Ok YS, Van Der Voort P, Hennebel T, et al. Selective copper recovery from ammoniacal waste streams using a systematic biosorption process. Chemosphere. 2022;286:131935. doi: 10.1016/j.chemosphere.2021.131935.
128. Hassan I, Mohamedelhassan E, Yanful EK, Yuan Z-C. A review article: Electrokinetic bioremediation current knowledge and new prospects. Adv Microbiol. 2016;06(01):57-72. doi: 10.4236/aim.2016.61006.
129. Wick LY, Shi L, Harms H. Electro-bioremediation of hydrophobic organic soil-contaminants: A review of fundamental interactions. Electrochim Acta. 2007;52(10):3441-8. doi: 10.1016/j.electacta.2006.03.117.

130. Moghadam MJ, Moayedi H, Sadeghi MM, Hajiannia A. A review of combinations of electrokinetic applications. Environ Geochem Health. 2016;38(6):1217-27. doi: 10.1007/s10653-016-9795-3.
131. Li WW, Yu HQ. Electro-assisted groundwater bioremediation: Fundamentals, challenges and future perspectives. Bioresour Technol. 2015;196:677-84. doi: 10.1016/j.biortech.2015.07.074.
132. Barba S, Villaseñor J, Rodrigo MA, Cañizares P. Biostimulation versus bioaugmentation for the electro-bioremediation of 2,4-dichlorophenoxyacetic acid polluted soils. J Environ Manage. 2021;277:111424. doi: 10.1016/j.jenvman.2020.111424.
133. Saxena G, Thakur IS, Kumar V, Shah MP. Electrobioremediation of contaminants: Concepts, mechanisms, applications and challenges. In: Combined Application of Physico-Chemical & Microbiological Processes for Industrial Effluent Treatment Plant. Singapore: Springer; 2020. p. 291-313. doi: 10.1007/978-981-15-0497-6_14.
134. Ceballos-Escalera A, Pous N, Chiluiza-Ramos P, Korth B, Harnisch F, Bañeras L, et al. Electro-bioremediation of nitrate and arsenite polluted groundwater. Water Res. 2021;190:116748. doi: 10.1016/j.watres.2020.116748.
135. Annamalai S, Sundaram M. Electro-bioremediation: An advanced remediation technology for the treatment and management of contaminated soil. In: Bioremediation of Industrial Waste for Environmental Safety. Singapore: Springer; 2020. p. 183-214. doi: 10.1007/978-981-13-3426-9_8.
136. Yuan Y, Guo S, Li F, Wu B, Yang X, Li X. Coupling electrokinetics with microbial biodegradation enhances the removal of cycloparaffinic hydrocarbons in soils. J Hazard Mater. 2016;320:591-601. doi: 10.1016/j.jhazmat.2016.07.043.
137. Yang SY, Lai CY, Zhao HP. Trichloroethylene detoxification in low-permeability soil via electrokinetic-enhanced bioremediation technology: Long-term feasibility and spatial-temporal patterns. J Hazard Mater. 2025;484:136743. doi: 10.1016/j.jhazmat.2024.136743.
138. Carrick J. Technology Based Academic Entrepreneurship: How Little We Know. 2016. Available from: https://www.researchgate.net/publication/305400456. Accessed on 15 Jun 2025.
139. Wang D, He JM, Knuteson JA. Concentration–time exposure index for modeling soil fumigation under various management scenarios. J Environ Qual. 2004;33(2):685-94. doi: 10.2134/jeq2004.6850.
140. Zeng Y, Hung Y, Chen M, Peng C, Tzen JTC, Liu J. Simultaneous refolding, purification, and immobilization of recombinant Fibrobacter succinogenes 1,3-1,4-β-D-glucanase on artificial oil bodies. J Chem Technol Biotechnol. 2009;84(10):1480-5. doi: 10.1002/jctb.2205.
141. Taherian A, Yazdi M, Danaei I, Zad A. The effect of Triton X100 and Tween 80 surfactants on diesel removal from soil using electrokinetic remediation. Int J Environ Sci Technol. 2025;22(3):1577-90. doi: 10.1007/s13762-024-05895-z.
142. Chair K, Bedoui A, Bensalah N, Saez C, Fernandez-Morales FJ, Cotillas S, et al. Treatment of soil-washing effluents polluted with herbicide oxyfluorfen by

combined biosorption–electrolysis. Ind Eng Chem Res. 2017;56(8):1903-10. doi: 10.1021/acs.iecr.6b04977.
143. Suni S, Malinen E, Kosonen J, Silvennoinen H, Romantschuk M. Electrokinetically enhanced bioremediation of creosote-contaminated soil: Laboratory and field studies. J Environ Sci Health, Part A. 2007;42(3):277-87. doi: 10.1080/10934520601134213.
144. Xu DM, Fu RB, Wang JX, Shi YX, Guo XP. Chemical stabilization remediation for heavy metals in contaminated soils on the latest decade: Available stabilizing materials and associated evaluation methods—A critical review. J Clean Prod. 2021;321:128730. doi: 10.1016/j.jclepro.2021.128730.
145. Lavanya MB, Viswanath DS, Sivapullaiah PV. Phytoremediation: An eco-friendly approach for remediation of heavy metal-contaminated soils-A comprehensive review. Environ Nanotechnol Monit Manag. 2024;22:100975. doi: 10.1016/j.enmm.2024.100975.
146. Latifi N, Horpibulsuk S, Meehan CL, Abd Majid MZ, Tahir MM, Mohamad ET. Improvement of problematic soils with biopolymer—An environmentally friendly soil stabilizer. J Mater Civ Eng. 2017;29(2):04016204. doi: 10.1061/(ASCE)MT.1943-5533.0001706.
147. Olaniran A, Balgobind A, Pillay B. Bioavailability of heavy metals in soil: Impact on microbial biodegradation of organic compounds and possible improvement strategies. Int J Mol Sci. 2013;14(5):10197-228. doi: 10.3390/ijms140510197.
148. Seshadri B, Bolan NS, Naidu R. Rhizosphere-induced heavy metal(loid) transformation in relation to bioavailability and remediation. J Soil Sci Plant Nutr. 2015;15(2):524-48. doi: 10.4067/S0718-95162015005000043.
149. Reddy KR, Chirakkara RA. Green and sustainable remedial strategy for contaminated site: Case study. Geotech Geol Eng. 2013;31(6):1653-61. doi: 10.1007/s10706-013-9688-5.
150. Hossain MU, Wang L, Chen L, Tsang DC, Ng ST, Poon CS, et al. Evaluating the environmental impacts of stabilization and solidification technologies for managing hazardous wastes through life cycle assessment: A case study of Hong Kong. Environ Int. 2020;145:106139. doi: 10.1016/j.envint.2020.106139.
151. Sang Y, Wang F, Shao X, Zhu L, Yan Z, Guo G. Comprehensive study on green and sustainable remediation in the USA: Policy system and case experiences. Environ Sci Pollut Res. 2022;29(55):83526-35. doi: 10.1007/s11356-022-21242-6.
152. Zhao X, Liu W, Cai Z, Han B, Qian T, Zhao D. An overview of preparation and applications of stabilized zero-valent iron nanoparticles for soil and groundwater remediation. Water Res. 2016;100:245-66. doi: 10.1016/j.watres.2016.05.019.
153. Ahmad S, Liu X, Tang J, Zhang S. Biochar-supported nanosized zero-valent iron (nZVI/BC) composites for removal of nitro and chlorinated contaminants. Chem Eng J. 2022;431:133187. doi: 10.1016/j.cej.2021.133187.
154. Latif A, Sheng D, Sun K, Si Y, Azeem M, Abbas A, et al. Remediation of heavy metals polluted environment using Fe-based nanoparticles: Mechanisms, influencing factors, and environmental implications. Environ Pollut. 2020;264:114728. doi: 10.1016/j.envpol.2020.114728.

155. Stefaniuk M, Oleszczuk P, Ok YS. Review on nano zerovalent iron (nZVI): From synthesis to environmental applications. Chem Eng J. 2016;287:618-32. doi: 10.1016/j.cej.2015.11.046.
156. Liu Y, Wang J. Reduction of nitrate by zero valent iron (ZVI)-based materials: A review. Sci Total Environ. 2019;671:388-403. doi: 10.1016/j.scitotenv.2019.03.317.
157. Komárek M. Perspectives of soil nanoremediation: the case of nano zerovalent iron and metal(loid) contaminants. NPJ Mater Sustain. 2024;2(1):8. doi: 10.1038/s44296-024-00013-z.
158. Zhang T, Wang W, Zhao Y, Bai H, Wen T, Kang S, et al. Removal of heavy metals and dyes by clay-based adsorbents: From natural clays to 1D and 2D nano-composites. Chem Eng J. 2021;420:127574. doi: 10.1016/j.cej.2020.127574.
159. Nazir MS, Mohamad Kassim MH, Mohapatra L, Gilani MA, Raza MR, Majeed K. Characteristic properties of nanoclays and characterization of nanoparticulates and nanocomposites. In: Nanoclay Reinforced Polymer Composites: Nanocomposites and Bionanocomposites. Singapore: Springer; 2016. p. 35-55. doi: 10.1007/978-981-10-1953-1_2.
160. Awasthi A, Jadhao P, Kumari K. Clay nano-adsorbent: structures, applications and mechanism for water treatment. SN Appl Sci. 2019;1(9):1076. doi: 10.1007/s42452-019-0858-9.
161. Iravani R, An C, Adamian Y, Mohammadi M. A review on the use of nanoclay adsorbents in environmental pollution control. Water Air Soil Pollut. 2022;233(4):109. doi: 10.1007/s11270-022-05580-2.
162. Nagaraju K, Prasad TNVK, Munaswamy V, Ramu YR. Nanoclay and its importance. Curr J Appl Sci Technol. 2021;40(13):71-81. doi: 10.9734/cjast/2021/v40i1331395.
163. Tang J, Tang L, Feng H, Zeng G, Dong H, Zhang C, et al. pH-dependent degradation of p-nitrophenol by sulfidated nanoscale zerovalent iron under aerobic or anoxic conditions. J Hazard Mater. 2016;320:581-90. doi: 10.1016/j.jhazmat.2016.07.042.
164. Punetha VD, Rana S, Yoo HJ, Chaurasia A, McLeskey Jr JT, Ramasamy MS, et al. Functionalization of carbon nanomaterials for advanced polymer nanocomposites: A comparison study between CNT and graphene. Prog Polym Sci. 2017;67:1-47. doi: 10.1016/j.progpolymsci.2016.12.010.
165. Khan ZU, Kausar A, Ullah H. A review on composite papers of graphene oxide, carbon nanotube, polymer/GO, and polymer/CNT: Processing strategies, properties, and relevance. Polym Plast Technol Eng. 2016;55(6):559-81. doi: 10.1080/03602559.2015.1098693.
166. Chen X, Oh WD, Lim TT. Graphene- and CNTs-based carbocatalysts in persulfates activation: Material design and catalytic mechanisms. Chem Eng J. 2018;354:941-76. doi: 10.1016/j.cej.2018.08.049.
167. Li G, Du R, Cao Z, Li C, Xue J, Ma X, et al. Research progress in graphene-based adsorbents for wastewater treatment: Preparation, adsorption properties and mechanisms for inorganic and organic pollutants. C (Basel). 2024;10(3):78. doi: 10.3390/c10030078.

168. Kurian M. Advanced oxidation processes and nanomaterials-A review. Clean Eng Technol. 2021;2:100090. doi: 10.1016/j.clet.2021.100090.
169. Asghar N, Hussain A, Nguyen DA, Ali S, Hussain I, Junejo A, et al. Advancement in nanomaterials for environmental pollutants remediation: A systematic review on bibliometrics analysis, material types, synthesis pathways, and related mechanisms. J Nanobiotechnology. 2024;22(1):26. doi: 10.1186/s12951-023-02151-3.
170. Thangadurai D, Chakrabarty M, Sangeetha J. Nanoremediation of polluted environment: Current scenario and case studies. In: Handbook of Nanomaterials and Nanocomposites for Energy and Environmental Applications. Cham (Switzerland): Springer International Publishing; 2020. p. 1-16. doi: 10.1007/978-3-030-11155-7_72-1.
171. Khan F, Shekhar C, Mondal T, Sabapathy M. Rapid removal of methylene blue and tetracycline by rough particles decorated with Pt nanoparticles. J Nanopart Res. 2024;26(1):4. doi: 10.1007/s11051-023-05904-1.
172. Xing G-W, Gao J, Wang H, Liu Y-C. New fluorophore and its applications in visualizing polystyrene nanoplastics in bean sprouts and HeLa cells. Molecules. 2023;28(20):7102. doi: 10.3390/molecules28207102.
173. Han D, Wu X, Li R, Tang X, Xiao S, Scholz M. Critical review of electro-kinetic remediation of contaminated soils and sediments: Mechanisms, performances and technologies. Water Air Soil Pollut. 2021;232(8):335. doi: 10.1007/s11270-021-05182-4.
174. Khan NT, Jameel N, Khan MJ. A Brief Overview of Contaminated Soil Remediation Methods. 2018. Available from: www.tsijournals.com. Accessed on 15 Jun 2025.
175. Verma S, Verma P, Bag AG, Changade NM. Reviewing soil contaminant remediation techniques. Int J Environ Clim Change. 2024;14(5):115-34. doi: 10.9734/ijecc/2024/v14i54175.
176. Kafle A, Timilsina A, Gautam A, Adhikari K, Bhattarai A, Aryal N. Phytoremediation: Mechanisms, plant selection and enhancement by natural and synthetic agents. Environ Advances. 2022;8:100203. doi: 10.1016/j.envadv.2022.100203.
177. Lacalle RG, Becerril JM, Garbisu C. Biological methods of polluted soil remediation for an effective economically-optimal recovery of soil health and ecosystem services. J Environ Sci Public Health. 2020;4(2):112-33. doi: 10.26502/jesph.96120089.
178. Zhang C, Wu D, Ren H. Bioremediation of oil contaminated soil using agricultural wastes via microbial consortium. Sci Rep. 2020;10(1):9188. doi: 10.1038/s41598-020-66169-5.
179. Taher AM, Saeed IO. Bioremediation of contaminated soil with crude oil using two different bacteria. AIP Conf Proc. 2022;2398:040027. doi: 10.1063/5.0094117.
180. Nagy KK, Takács K, Németh I, Varga B, Grolmusz V, Molnár M, et al. Novel enzymes for biodegradation of polycyclic aromatic hydrocarbons identified by metagenomics and functional analysis in short-term soil microcosm experiments. Sci Rep. 2024;14(1):11608. doi: 10.1038/s41598-024-61566-6.

181. Ayilara MS, Babalola OO. Bioremediation of environmental wastes: The role of microorganisms. Front Agronomy. 2023;5:1183691. doi: 10.3389/fagro.2023.1183691.
182. Zhou Q, Sun F, Liu R. Joint chemical flushing of soils contaminated with petroleum hydrocarbons. Environ Int. 2005;31(6):835-9. doi: 10.1016/j.envint.2005.05.039.
183. Zhang H, Xu Y, Kanyerere T, Wang Y, Sun M. Washing reagents for remediating heavy-metal-contaminated soil: A review. Front Earth Sci (Lausanne). 2022;10:901570. doi: 10.3389/feart.2022.901570.
184. Aparicio JD, Raimondo EE, Saez JM, Costa-Gutierrez SB, Alvarez A, Benimeli CS, et al. The current approach to soil remediation: A review of physicochemical and biological technologies, and the potential of their strategic combination. J Environ Chem Eng. 2022;10(2):107141. doi: 10.1016/j.jece.2022.107141.
185. Wang M, Kong D, Liu L, Wen G, Zhang F. In situ conductive heating for thermal desorption of volatile organic-contaminated soil based on solar energy. Sustainability. 2024;16(19):8565. doi: 10.3390/su16198565.
186. Filler DM, Van Stempvoort DR, Leigh MB. Remediation of frozen ground contaminated with petroleum hydrocarbons: Feasibility and limits. In: Permafrost Soils. Berlin, Heidelberg (Geymany): Springer; 2009; p. 279-301. doi: 10.1007/978-3-540-69371-0_19.
187. Camenzuli D, Freidman BL. On-site and in situ remediation technologies applicable to petroleum hydrocarbon contaminated sites in the Antarctic and Arctic. Polar Res. 2015;34(1):24492. doi: 10.3402/polar.v34.24492.
188. Chaudhary DK, Kim J. New insights into bioremediation strategies for oil-contaminated soil in cold environments. Int Biodeterior Biodegradation. 2019;142:58-72. doi: 10.1016/j.ibiod.2019.05.001.
189. Li H, Yang L, Mao Q, Zhou H, Guo P, Agathokleous E, et al. Modified biochar enhances soil fertility and nutrient uptake and yield of rice in mercury-contaminated soil. Environ Technol Innov. 2023;32:103435. doi: 10.1016/j.eti.2023.103435.
190. Li F, Li J, Tong M, Xi K, Guo S. Effect of electric fields strength on soil factors and microorganisms during electro-bioremediation of benzo[a]pyrene-contaminated soil. Chemosphere. 2023;341:139845. doi: 10.1016/j.chemosphere.2023.139845.
191. Islam MM, Saxena N, Sharma D. Phytoremediation as a green and sustainable prospective method for heavy metal contamination: A review. RSC Sustain. 2024;2(5):1269-88. doi: 10.1039/D3SU00440F.
192. Li S, Wang W, Liang F, Zhang W. Heavy metal removal using nanoscale zero-valent iron (nZVI): Theory and application. J Hazard Mater. 2017;322:163-71. doi: 10.1016/j.jhazmat.2016.01.032.
193. Da Silva Neto LD, Maged A, Gabriel R, Lins PV, Haneklaus NH, Hlawitschka MW, et al. Nanoclays in water treatment: Core concepts, modifications, and application insights. J Water Process Eng. 2024;67:106180. doi: 10.1016/j.jwpe.2024.106180.

194. Wang Y, Pan C, Chu W, Vipin AK, Sun L. Environmental remediation applications of carbon nanotubes and graphene oxide: Adsorption and catalysis. Nanomaterials. 2019;9(3):439. doi: 10.3390/nano9030439.
195. Zhang W, Zeng Z, Liu Z, Huang J, Xiao R, Shao B, et al. Effects of carbon nanotubes on biodegradation of pollutants: Positive or negative? Ecotoxicol Environ Saf. 2020;189:109914. doi: 10.1016/j.ecoenv.2019.109914.
196. Rana K, Kaur H, Singh N, Sithole T, Siwal SS. Graphene-based materials: Unravelling its impact in wastewater treatment for sustainable environments. Next Mater. 2024;3:100107. doi: 10.1016/j.nxmate.2024.100107.
197. Anegbe B, Ifijen IH, Maliki M, Uwidia IE, Aigbodion AI. Graphene oxide synthesis and applications in emerging contaminant removal: A comprehensive review. Environ Sci Eur. 2024;36(1):15. doi: 10.1186/s12302-023-00814-4.
198. Smith P, Martino D, Cai Z, Gwary D, Janzen H, Kumar P, et al. Greenhouse gas mitigation in agriculture. Philos Trans R Soc B: Biol Sci. 2008;363(1492):789-813. doi: 10.1098/rstb.2007.2184.
199. Arnold SM, Hickey WJ, Harris RF, Talaat RE. Integrated chemical and biological remediation of atrazine-contaminated aqueous wastes. ACS Symp Ser. 1998;683(16):177-88. doi: 10.1021/bk-1998-0683.ch016.
200. Tyagi P, Agate S, Velev OD, Lucia L, Pal L. A critical review of the performance and soil biodegradability profiles of biobased natural and chemically synthesized polymers in industrial applications. Environ Sci Technol. 2022;56(4):2071-95. doi: 10.1021/acs.est.1c04710.
201. Diaz AM, Baragaño D, Menéndez-Aguado JM, Norén A, Fedje KK, Espín E, et al. Enhanced remediation of organotin compounds and metal(loid)s in polluted sediments: Chemical stabilization with mining-wastes and nZVI versus physical soil washing. J Environ Manage. 2025;373:123602. doi: 10.1016/j.jenvman.2024.123602.
202. Ji M, AL-Huqail AA, Majdi A, Liu H, Ali I, Marzouki R. Remediation of mine polluted soil with nano-enhanced materials: Development of extreme learning machine approaches. Chemosphere. 2022;307:135772. doi: 10.1016/j.chemosphere.2022.135772.
203. Li H, Muhammad F, Yan Y, Zhang M, Jiao B, Yu L, et al. Electrokinetic remediation of heavy metals from municipal solid waste incineration fly ash pretreated by nitric acid. R Soc Open Sci. 2018;5(8):180372. doi: 10.1098/rsos.180372.
204. Sikiru S, Abioye KJ, Adedayo HB, Adebukola SY, Soleimani H, Anar M. Technology projection in biofuel production using agricultural waste materials as a source of energy sustainability: A comprehensive review. Renew Sustain Energy Rev. 2024;200:114535. doi: 10.1016/j.rser.2024.114535.
205. Souza MC, Cruz JC, Cesila CA, Gonzalez N, Rocha BA, Adeyemi JA, et al. Recent trends in pesticides in crops: A critical review of the duality of risks-benefits and the Brazilian legislation issue. Environ Res. 2023;228:115811. doi: 10.1016/j.envres.2023.115811.

206. Kumar M, Ambika S, Hassani A, Nidheesh PV. Waste to catalyst: Role of agricultural waste in water and wastewater treatment. Sci Total Environ. 2023;858:159762. doi: 10.1016/j.scitotenv.2022.159762.
207. Chormare R, Moradeeya PG, Sahoo TP, Seenuvasan M, Baskar G, Saravaia HT, et al. Conversion of solid wastes and natural biomass for deciphering the valorization of biochar in pollution abatement: A review on the thermo-chemical processes. Chemosphere. 2023;339:139760. doi: 10.1016/j.chemosphere.2023.139760.

How to cite this article:
Keshyagol K, Prabhu US, Hiremath P, Gurumurthy BM, Shivaprakash YM, Deepak GD, et al. Advances in sustainable soil health restoration through chemical biological physical integrated and nano remediation techniques. J Sustain Res. 2025;7(3):e250056. https://doi.org/10.20900/jsr20250056.