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Systematic Review

A Systematic Review of Integrative Approaches for the Multidimensional Analysis of Sustainable Soil Rehabilitation

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Abstract

Soil contamination represents a pervasive and multifaceted threat to environmental integrity, public health, and sustainable land use. In response to this challenge, this systematic review synthesizes recent advancements in sustainable soil remediation techniques, with an emphasis on bioremediation, nature-based solutions (NBSs), innovative physicochemical methods, and multidimensional assessment frameworks. Utilizing the adapted PRISMA methodology, 3222 peer-reviewed articles published between 2015 and 2025 were initially identified, with 53 studies selected for in-depth evaluation based on methodological rigor, innovation, and relevance to sustainability. The findings reveal a pronounced research trajectory toward biologically mediated remediation strategies, including microbial bioremediation, phytoremediation, and vermiremediation, as well as hybrid systems that incorporate biochar and nano-enabled materials to enhance efficacy. Concurrently, emerging physicochemical techniques, such as stepped steam heating and composite stabilization using fly ash demonstrate potential for high-efficiency contaminant immobilization with reduced environmental trade-offs. The integration of computational tools, particularly machine learning for remediation optimization, and the application of life cycle assessment (LCA) and Multi-Criteria Decision Analysis (MCDA), are redefining how sustainability is quantified and operationalized. In addition to technical innovation, the review underscores critical policy and socio-economic dimensions, including regulatory fragmentation, funding asymmetries, and stakeholder engagement. Comparative analyses of EU and US regulatory frameworks highlight the impact of governance structures on implementation scalability and public acceptance. The review concludes by advocating for a paradigm shift toward holistic, transdisciplinary remediation approaches that are ecologically resilient, economically viable, and socially just aligned with the Sustainable Development Goals (SDG 15.3) and the Paris Agreement. This review provides a comprehensive and integrative perspective on the current state and future directions of sustainable soil remediation, offering a strategic foundation for researchers, policymakers, and practitioners engaged in the restoration of contaminated lands.

Keywords: sustainable remediation; contaminated soils; remediation techniques; multidimensional; soil remediation

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1. Introduction

Soil remediation refers to the processes used to remove, reduce, or neutralize contaminants in soil to restore its health and functionality. With increasing industrialization, agricultural activities, and urbanization, soil pollution has become a critical environmental challenge, threatening ecosystems, food security, and human health [1]. Effective soil remediation is essential for environmental protection, sustainable land use, and compliance with global sustainability goals such as the United Nations' Sustainable Development Goals (SDGs) [2].

To provide an up-to-date and structured overview of this fast-evolving field, the present work was conducted as a systematic review, following an adapted PRISMA methodology (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) and a set of predefined identification, screening, eligibility, and inclusion criteria, which are detailed in Section 2.

Various remediation technologies have been developed to address different types of soil contaminants, including heavy metals, petroleum hydrocarbons, pesticides, and industrial chemicals. These methods can be broadly classified into physical, chemical, and biological approaches, each with distinct advantages and limitations [3,4]. Additionally, remediation strategies can be categorized as in situ (on-site treatment) or ex situ (off-site treatment), with in situ methods generally being more cost-effective and less disruptive [4,5].

It should be noted that, as also reflected in the composition of the studies analyzed in this review (Section 3.2), the published literature on soil remediation is markedly weighted toward heavy-metal contamination, relative to organic pollutants and other contaminant classes; this imbalance is discussed further as a limitation.

Recent trends emphasize green and sustainable remediation, which prioritizes eco-friendly techniques that restore soil quality while minimizing secondary environmental impacts [6,7]. Among these, bioremediation, phytoremediation, and nature-based solutions (NBSs) have gained attention for their ability to enhance ecosystem services while degrading pollutants [2,8]. Furthermore, innovative approaches such as biochar application and soil engineering in vivo demonstrate the potential for multidisciplinary solutions to soil contamination [9,10].

The scale of the problem is substantial: soil contamination has been documented across industrialized, agricultural, and urban regions worldwide, with heavy metals, petroleum hydrocarbons, and industrial chemicals identified among the most prevalent pollutant classes, and with impacts that extend to food security, ecosystem services, and human health [11]. The geographical distribution and severity of contamination vary considerably by region, reflecting differences in industrial history, mining activity, agricultural intensity, and regulatory oversight, underscoring the need for internationally comparable, context-sensitive remediation strategies.

Figure 1 illustrates the global distribution of regions with documented soil contamination, highlighting broad patterns associated with mining and smelting, industrial and urban activities, and agricultural intensification. These patterns underscore the need for remediation strategies tailored to site-specific contamination and regional regulatory contexts.

This paper explores key soil remediation technologies, focusing on their mechanisms, applications, and sustainability. The following sections discuss bioremediation techniques, sustainable soil management, nature-based solutions, soil engineering, and biochar applications in detail.

Historically, the development of these approaches has followed a discernible trajectory, closely linked to the evolving regulatory and social response to industrial pollution. Early remediation practice relied primarily on physicochemical treatments, such as soil washing and thermal desorption, reflecting an initial, engineering-driven response to point-source contamination. From the 2000s onward, biologically mediated techniques, including microbial bioremediation [8] and phytoremediation [12], gained traction as lower-cost, less disruptive alternatives, paralleling the emergence of soil engineering approaches that integrate microbiology and geotechnical science [9]. Over the past decade, growing societal and policy commitment to climate and biodiversity goals has driven a shift toward nature-based solutions [2], sustainable soil management practices [1], and biochar-based amendments [10], while the 2020s have seen the further integration of green and sustainable remediation frameworks [6,7], mirroring the broader socio-political emphasis on the Sustainable Development Goals and international climate policy. The following subsections examine these approaches in turn.

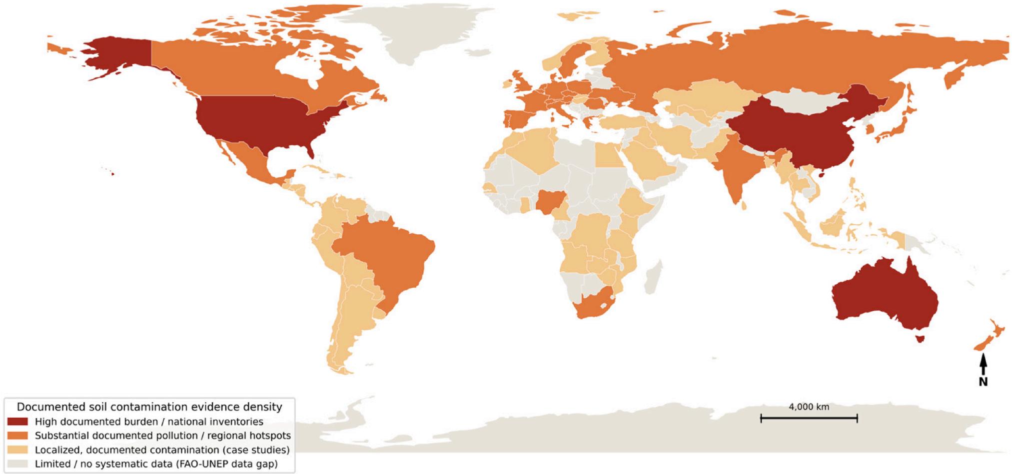

Figure 1. Global distribution of documented soil contamination evidence, compiled from national inventories, reported contaminated sites, and the case-study literature summarized in the FAO and UNEP Global Assessment of Soil Pollution. Adapted from FAO and UNEP [11].

Bioremediation is a cost-effective and environmentally friendly approach that utilizes microorganisms, plants, and fungi to degrade or immobilize soil contaminants [13]. It is particularly effective for organic pollutants such as petroleum hydrocarbons, pesticides, and chlorinated solvents. This is particularly relevant for petroleum-hydrocarbon-contaminated soils, where composting-based approaches have been shown to enhance both microbial activity and contaminant degradation [14], and for pesticide-contaminated sites, where technology selection must additionally account for treatment cost and the formation of transformation products [15].

Microorganisms, including bacteria and fungi, break down contaminants through metabolic processes such as aerobic and anaerobic degradation [8]. Key factors influencing microbial bioremediation include: bioavailability of pollutants (enhanced by surfactants or chemotaxis); nutrient availability (often requiring nitrogen and phosphorus supplementation); and environmental conditions (pH, temperature, moisture).

Phytoremediation uses plants to extract, stabilize, or degrade contaminants. Different mechanisms include: phytoextraction (uptake and accumulation of metals); phytostabilization (reducing contaminant mobility); and rhizodegradation (microbial degradation in the root zone).

Hyperaccumulator plants, such as *Brassica juncea* (Indian mustard) for heavy metals, are particularly effective [12].

Despite its advantages, bioremediation faces limitations, such as slow degradation rates and limited applicability to high concentration pollutants. Strategies to improve efficiency include: bioaugmentation (introducing specialized microbial strains); genetic engineering of microbes for enhanced degradation; and combined treatments (e.g., electrokinetics with bioremediation) [16].

Sustainable soil management is critical for maintaining soil fertility, biodiversity, and carbon sequestration [1]. Key practices include: organic farming (reducing chemical inputs); cover cropping and crop rotation (preventing erosion); and agroforestry (enhancing soil structure and carbon storage).

NBSs leverage natural processes to restore degraded soils while providing additional ecosystem benefits [2]. Examples include: constructed wetlands for filtering contaminants; permeable reactive barriers using natural minerals; and afforestation and reforestation to stabilize contaminated sites.

As for innovative approaches, the literature indicates soil engineering and biochar integrating microbiology, geochemistry, and civil engineering to rehabilitate soils while addressing multiple environmental challenges [9]. Applications include: microbially induced calcite precipitation (MICP) for soil stabilization; biocementation to immobilize heavy metals; and carbon sequestration through microbial activity.

Biochar, a carbon-rich material produced from biomass pyrolysis, improves soil properties by: enhancing nutrient retention; immobilizing heavy metals; and promoting microbial activity [10]. Beyond metal immobilization, organic amendments such as biochar and compost have also been applied to mitigate petroleum-hydrocarbon contamination, although their net effect can range from contaminant immobilization to unintended remobilization depending on soil and amendment characteristics [17].

Soil remediation is essential for mitigating pollution and ensuring sustainable land use. While traditional methods (e.g., soil washing, landfilling) remain relevant, bioremediation, nature-based solutions, and innovative technologies (biochar, soil engineering) offer sustainable alternatives. Future research should focus on scaling up green remediation techniques and integrating them into policy frameworks [11]. By adopting holistic and multidisciplinary approaches, we can achieve long-term soil health and environmental sustainability.

2. Materials and Methods

The systematic review was conducted following the adapted PRISMA methodology (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) to ensure a structured and transparent research process. The methodology was divided into four key phases, identification, screening, eligibility, and inclusion, with the aim of synthesizing the relevant scientific literature on sustainable remediation of contaminated soils through multidimensional approaches.

The search strategy was designed to capture peer-reviewed publications from January 2015 to January 2025, ensuring a comprehensive and up-to-date coverage of the research landscape.

Consistent eligibility criteria were applied across all databases to ensure homogeneity in the initial screening. The search was restricted to English language documents and to peer-reviewed journal articles, including original research articles, review papers, and book chapters.

To ensure the relevance and quality of the selected studies, the keywords in Table 1 and the combination of keywords in Table 2 were used. The keyword set was deliberately kept narrow and thematically focused (Table 1) to preserve precision and minimize the retrieval of tangential literature; broader or more technique-specific terms were intentionally excluded at the search stage, as they will be captured downstream through the topical classification presented in Table 4 and Figure 6. This trade-off between search sensitivity and specificity is acknowledged as a methodological choice rather than an oversight, and is further discussed as a limitation.

Table 1. Keywords used in the database searches.

A	Sustainable remediation
B	Contaminated soils
C	Remediation Techniques
D	Multidimensional
E	Soil remediation

Table 2. Keyword combinations in the database searches using the Boolean operator "and".

Combinations			
A	B		
A	C		
A	D		
A	E		
A	B	C	
A	B	C	D

A total of 3222 papers was collected by comprehensive database searches over SCOPUS, Web of Science, and ScienceOpen. In addition, 5 papers were manually found from other sources like reference lists and expert recommendations.

All the papers were checked, and 2815 articles were eliminated using the predefined exclusion criteria. The reasons for the eliminations were: Date: A total of 481 articles were published outside the defined timeframe from January 2015 to January 2025; Document Type: 175 papers were excluded due to being non-peer-reviewed formats (e.g., editorials, conference abstracts); Source Type: A total of 2130 entries were excluded for being from irrelevant or low-impact sources; Language: A total of 26 non-English articles were excluded; Other: A total of 3 articles were excluded for various anomalies (e.g., duplicates not flagged by software); Off-topic: No articles were excluded for being thematically irrelevant at this stage.

After the said elimination, 407 papers remained for further assessment.

In the first screening stage, the full texts of 412 articles were assessed for eligibility. This total comprised 407 articles retrieved through the systematic database search conducted between January 2015 and January 2025, together with five additional articles identified through parallel searching and recommendations from experts and supervisors. Although these five articles were published outside the predefined timeframe, they were retained because they provided relevant evidence for the review and were subsequently included among the 53 studies selected for the qualitative synthesis. Following the second, semi-automatic screening, 359 articles remained. The main reasons for exclusion at this stage were that the studies focused primarily on agriculture rather than soil remediation or did not address sustainability from a multidimensional perspective, concentrating instead on a single dimension of the problem. Of the 359 articles retained after semi-automatic screening, the final 53 studies were selected for in-depth, qualitative synthesis based on three complementary eligibility criteria: (i) methodological rigor, i.e., a clearly described experimental or analytical design; (ii) technical or conceptual innovation relative to established remediation practice; and (iii) explicit relevance to sustainability, defined as addressing environmental, economic, and/or social dimensions of remediation rather than a single-dimension technical outcome. Studies that satisfied the topical scope but did not meet these three criteria jointly were retained for contextual background but excluded from the in-depth synthesis reported in Section 3.

After all those checks, 53 studies turned out to be the only ones that meet the criteria and were therefore taken to feed into the qualitative synthesis part. The sources were thus

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classified as primary sources, and they were on such topics as sustainable soil remediation techniques, a variety of assessment frameworks, and policy contexts.

The documents were thus grouped under the primary source category, and the topics they were about were sustainable methods of soil remediation, a range of assessment frameworks, and policy contexts.

The adapted PRISMA Flow Diagram derived from the research is presented on Figure 2. The PRISMA 2020 checklist is available in Supplementary File S1. This review was conducted without prospective registration or a publicly available protocol.

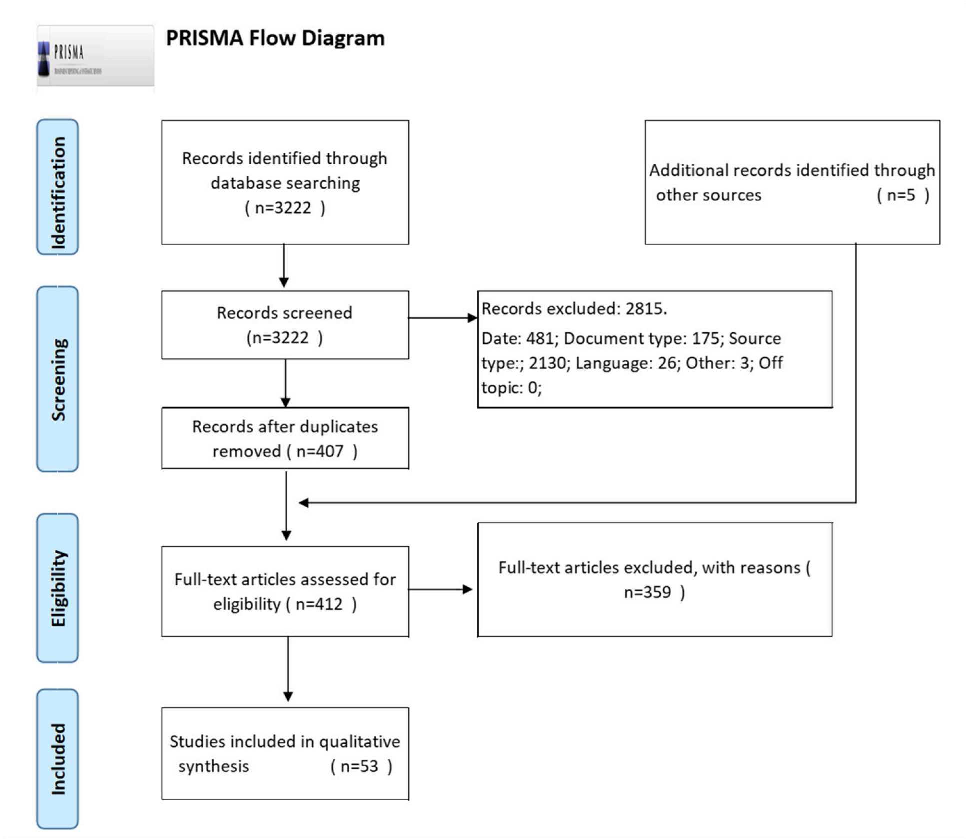

Figure 2. Adapted PRISMA Flow Diagram.

3. Results and Discussion

3.1. Analysis of the Review and Selection of Studies

The findings reveal a strong research focus on biological and physicochemical remediation techniques, particularly phytoremediation, bioremediation, and hybrid approaches. Emerging trends highlight the integration of nanotechnology, computational modeling, and circular economy principles to enhance remediation efficiency while minimizing environmental trade-offs. These 53 documents turned out to be the only ones that meet the criteria and were therefore taken to feed into systematic review. The documents were thus classified as primary sources, and they were on topics such as sustainable soil remediation techniques, a variety of assessment frameworks, and policy contexts.

Figure 3 indicates an increasing trend in the quantity of articles concerning sustainable soil remediation from the early 2020s to the end of the studied time period. Moreover, the growth after 2020 denotes the increased interest of the scholarly and policy communities which probably results from a raised level of environmental awareness and the compliance of the directions of the global sustainable development agenda. It should be noted that no article from 2025 appears in Figure 3, as the database search was conducted only through

January 2025 and therefore captures only a partial, early snapshot of that year's output rather than its full annual publication volume; consequently, 2025 was excluded from the year-on-year trend comparison to avoid an artificial apparent decline.

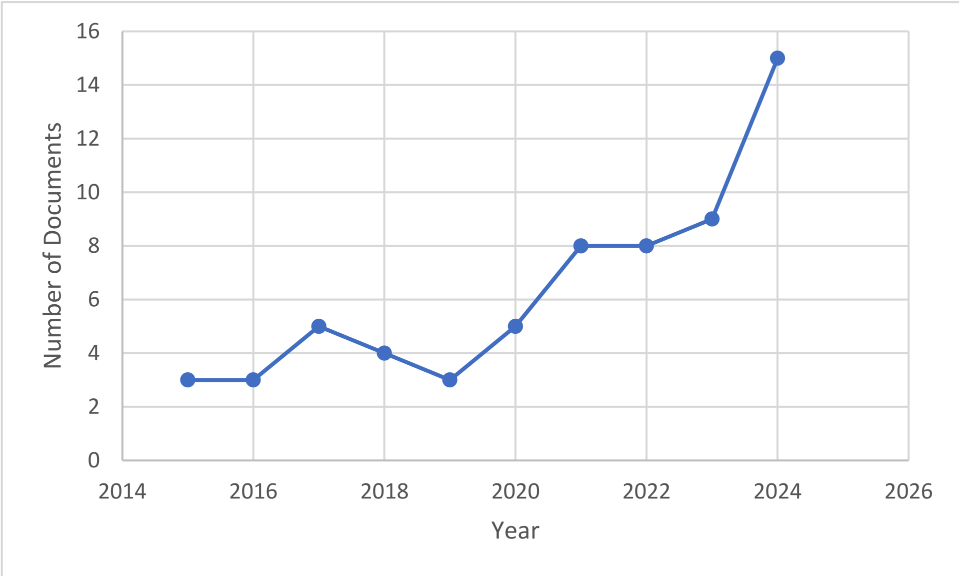

Figure 3. Number of documents per year among the 53 studies selected for the systematic review (2015–2025).

Figure 4 presents the key contributing authors to the retrieved group of papers. Specifically, two authors, Ok, Y.S. and Tsang, D.C.W., who were responsible for five documents each, come out on top, thereby evincing the pivotal function of these scientists in the area of multidisciplinary soil remediation. A few authors form a powerful set of collaborators who work together in the three fields of sustainability science, geochemistry, and environmental engineering.

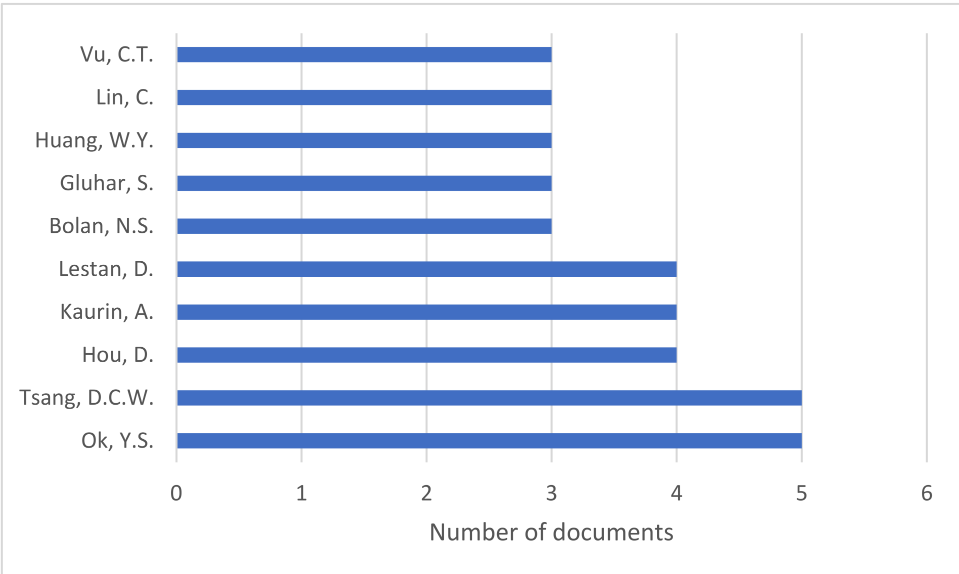

Figure 4. Document count for authors responsible for 3 or more studies among the 53 selected papers.

Figure 5 illustrates the distribution of the most common funding sources taken from the analyzed studies. The National Key Research and Development Program and the National Natural Science Foundation of China are the leading sources seen here. The

European Commission and European Regional Development Fund (ERDF) though the European Union's structural and investment funds, also have a significant contribution in research that is driving innovation in soil restoration.

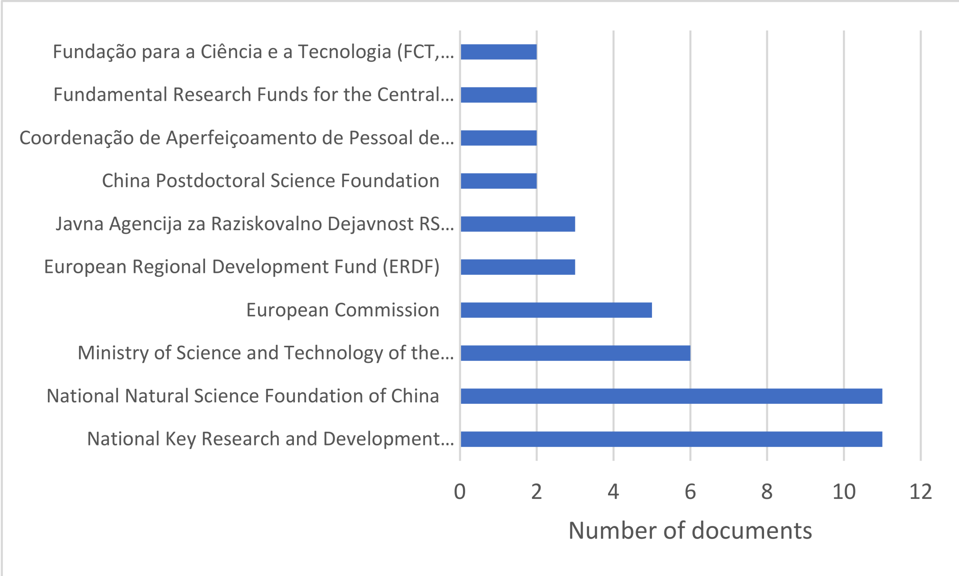

Figure 5. Document count by up to 10 funding sponsors among the 53 selected studies [1,18–34].

Table 3 reviews 53 peer-reviewed articles that were published from the year 2015 to 2025 (including the manually added articles outside the designated timeframe), and these papers show a fast-growing area of concern—that of soil sustainability. It is observable that the majority of the sources are really brand new since many of the studies (over 50%) were from the last 5 years (2020 to 2024), thus establishing the topic as one of the priority research themes. Importantly, the publishing outlets where the papers were released are quite varied, embracing both traditional environmental journals and other disciplines. Journals such as the *Journal of Hazardous Materials*, *Environmental Pollution*, *Science of the Total Environment*, and *Journal of Environmental Management* are just some examples of the main disseminators and they demonstrate the sustainable remediation issue in light of multiple aspects from environmental chemistry to engineering, soil science, and sustainability studies. Together, the bibliographical features chosen in the literature not only confirm the broad conducting of the review systematically but also show the direction of the field towards the research of the transdisciplinary, innovation-driven, and policy-relevant type. The scope of this area is based on a large number of secure data that is the subject for critical synthesis; at the same time, it is necessary to have ecologically approachable restoration principles for meeting global sustainability goals in the future. Examples include SDG 15.3 and the Paris Agreement.

Table 3. Selected studies for systematic review.

Ref.	Contaminant/Study Focus	Country	Soil Type	Main Results	Year
[35]	Arsenic	Australia	Mining-impacted soil	Hydrochar/Fe-encapsulated materials immobilized As	2023
[24]	Arsenic	China (Hong Kong)	As-containing soil	Blast slag/cement blends achieved sustainable As stabilization	2021
[36]	Arsenic	Italy	Industrial soil	Cannabis/*Brassica juncea* showed limited phytoremediation potential for As	2022

Table 3. *Cont.*

Ref.	Contaminant/Study Focus	Country	Soil Type	Main Results	Year
[21]	As, Cd, Pb, Zn	South Korea	Multi-contaminated soil	Different biochars showed contaminant-specific (im)mobilization mechanisms	2021
[37]	As, Hg, PAHs	Spain	Industrial soil	Fe-nanoparticle carbon foams remediated co-contaminated soils	2024
[20]	As, metals	Slovenia	Multi-metal soil	Pilot-scale simultaneous removal of As and toxic metals	2022
[38]	As, Zn, Pb	Brazil	Smelting-impacted soil	Biochar-nZVI immobilized multiple metals from smelting activity	2022
[39]	Cadmium	China	Cd-contaminated soil	Vermicomposting reduced Cd toxicity, improved microbial community	2024
[40]	Cadmium	China	Cd-contaminated soil	Spermidine/activated carbon boosted *Salix integra* phytoextraction	2022
[41]	Cadmium	Czech Republic	Heavily contaminated soil	Biochar enhanced *Salix smithiana* phytoextraction potential	2022
[42]	Cd, Cu	China	Polluted soil	Bacteria-inoculated biochar enhanced Cd/Cu immobilization and enzyme activity	2020
[43]	Chromium	China/Japan	Cr-amended soil	Elevated temperature altered Cr mobility and speciation	2024
[18]	Chromium (Cr VI)	China	Sludge-amended soil	Sludge char/soil mineral co-aging enhanced Cr(VI) reduction	2024
[44]	Chromium (Cr VI)	China	Cr(VI)-contaminated soil	Biochar-supported nZVI improved washing efficiency and agent recovery	2024
[45]	Chromium (Cr VI)	China	Cr(VI)-contaminated soil	AC electrochemical washing achieved sustainable Cr(VI) removal	2022
[46]	Chromium (Cr VI)	China	Seasonally frozen soil	Aging enhanced Cr(VI) reduction/immobilization in cold regions	2021
[47]	General (decision tool)	Brazil	Contaminated soil (general)	Proposed MCDA-based sustainability weighting tool for remediation choice	2024
[32]	General (framework)	Taiwan	Contaminated soil (case study)	Developed GSR evaluation framework, standards, and toolkit	2016
[48]	General (monitoring)	South Korea	Contaminated soil	Soil enzymes proposed as sustainable monitoring indicators	2020
[1]	General (review)	Australia	General (interdisciplinary review)	Proposed interdisciplinary framework for sustainable soil use/management	2020
[2]	General (review)	Netherlands	Degraded land (review)	Demonstrated superior ecosystem service benefits of NBS in land management	2018
[9]	General (review)	USA/UK	General (soil engineering review)	Reviewed biogeochemical soil engineering for multifunctional solutions	2011
[49]	General (thermal)	China	Contaminated soil	LCA-based decision-making for regional thermal remediation	2023
[50]	Heavy metals	China	Wastewater/soil	Novel AC electrochemistry decontaminated metals sustainably	2023
[51]	Heavy metals	Malaysia	Polluted soil	Selected bacteria species enabled biotechnical heavy metal remediation	2017
[52]	Hg, As	Spain	Brownfield soil	Characterized microbiome of Hg/As-polluted brownfield	2023
[53]	Lead	India/USA	Pb-contaminated soil	Moringa seed cake biochar acted as novel Pb-binding amendment	2023
[54]	Lead	Lebanon	Pb-contaminated soil	*Opuntia ficus*-indica extracts removed Pb; harvest phase mattered	2023
[55]	Lead	USA	Urban soil	Ash-based blends reduced Pb bioaccessibility, protected public health	2024
[30]	Mercury	China	Hg-contaminated soil	Sulfur-modified rice husk biochar offered green Hg remediation	2018

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Table 3. *Cont.*

Ref.	Contaminant/Study Focus	Country	Soil Type	Main Results	Year
[33]	Mercury	China	Hg-contaminated soil	Citric acid facilitated more efficient thermal Hg treatment	2015
[56]	Mercury	China	Hg-contaminated soil	$FeCl_3$ enabled Hg removal at reduced treatment temperature	2014
[57]	Mercury	Spain	Hg-contaminated soil	Thermal desorption achieved sustainable Hg remediation	2016
[58]	Metals (general)	China	Wetland soil	Lignin-based poly(acrylic acid) reduced heavy metal mobility	2019
[29]	Metals (general)	China (Hong Kong)	Metal/chelant-contaminated soil	Food waste compost interacted favorably with metal-chelant complexes	2018
[31]	Metals (general)	China (Hong Kong)	Contaminated soil/sediment	Assessed sustainability likelihood across remediation options	2017
[19]	Metals (general)	China/Canada	Biochar-amended soil	Biochar type/aging method affected long-term metal immobilization	2022
[59]	Metals (general)	Greece	Mining-impacted soil	Diasporic bauxite showed potential for sustainable remediation	2017
[60]	Metals (general)	India	Metal-contaminated soil	Reviewed electrokinetic remediation roadmap and sustainability gaps	2024
[22]	Metals (general)	Slovenia	Garden/urban soil	EDTA-washed soil in gardens reduced toxicity hazards	2021
[26]	Metals (general)	Slovenia	Metal-contaminated soil	Biodegradable chelants matched EDTA efficiency with lower impact	2020
[28]	Metals (general)	Slovenia	EDTA-washed soil	Multi-substrate respiration/enzyme activity assessed post-washing recovery	2018
[61]	Multi-metal	China	Agricultural soil	Fly ash + intercropping immobilized metals, restored soil fertility	2024
[62]	nZVI (general)	Brazil	Contaminated soil/groundwater	Reviewed sustainability trade-offs of nZVI; flagged persistence/bioaccumulation risks	2024
[8]	Organic pollutants (general)	India	General (review)	Framework for assessing ecological sustainability of in situ bioremediation	2009
[63]	PAHs	Austria	PAH-contaminated soil	Compost/biochar altered microbial communities and PAH sorption/degradation	2018
[64]	PAHs	Iran	PAH-contaminated soil	Green solvent + RSM optimized continuous-flow remediation	2024
[25]	Pb, As	China	Contaminated soil	Red mud-enhanced cement remediated Pb and As jointly	2020
[23]	Pb, Zn, Cd	China	Contaminated soil	Red mud-derived binders achieved sustainable stabilization/solidification	2021
[65]	PCBs	Portugal/Denmark	PCB-contaminated soil	Electroremediation + Fe nanoparticles; efficacy varied by soil type	2015
[66]	PCBs	Portugal/Denmark	PCB-contaminated soil	Fe nanoparticles + electric current treated PCB suspension	2015
[67]	Salts/heavy metals	China	Saline soil	Solar evaporator enabled combined salt separation and metal remediation	2024
[27]	Zinc	China	Zn-contaminated soil	Rice straw biochar + Al_2O_3 improved Zn immobilization	2019

Table 3 summarizes the 53 selected studies by contaminant focus, geographic origin, soil type, and principal findings, rather than by bibliographic details alone, to allow direct comparison of technique performance across contexts. Full bibliographic information for each reference is provided in the Reference list.

Figure 6 identifies the distribution of remediation techniques in the 53 research articles that are part of the systematic review. The data indicates that there is a great focus on bioremediation (n = 14) and phytoremediation (n = 10), which are in line with the continuously growing scientific and practical interest in natural-based and biologically mediated solutions. Physicochemical methods (n = 9) and biochar applications (n = 7) also account for the majority of current studies and are usually directed at improved contaminant immobilization and soil health restoration. Although slightly smaller, the number of studies that looked into hybrid approaches (n = 6), electrokinetic remediation (n = 4), and soil engineering (n = 3) strategies are still worth noticing as they show a shift toward unified and interdisciplinary ways.

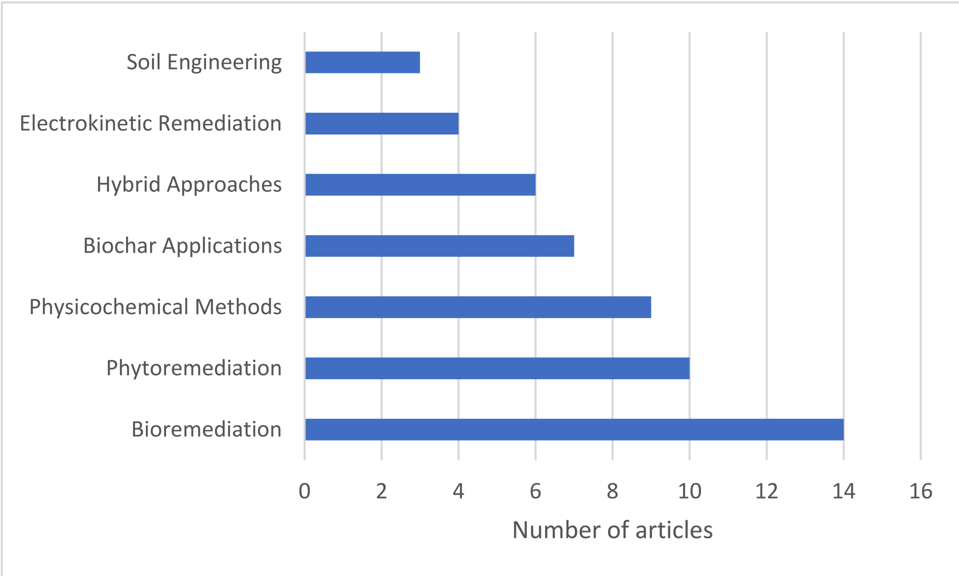

Figure 6. Number of articles by remediation techniques, among the 53 selected documents.

Figure 7 illustrates the temporal evolution in the number of remediation techniques cited per article, highlighting trends in methodological diversification over the years. The use of bioremediation (n = 14) and phytoremediation (n = 10) has been consistent since 2016. These methods become the major sustainable remediation methods, and this is mainly because of their eco-friendly characteristics and inherent ability to be a part of nature-based solutions. The share of physicochemical methods (n = 9) seems to stay stable; however, their predominance in the most recent years is slightly overshadowed, which could be associated with a transition to less invasive and more renewing alternatives. They are biochar-based interventions and hybrid models that have seen growing user adoption, especially the time after 2020, showing a tendency of synergistic soil amendments in the wake of the stronger circular economy principle and in line with multifunctionality. Electrokinetic and soil engineering are two such technologies, which although are used less frequently, have a certain tendency of being used in special cases to unlock unused resources.

Adding to the above temporal aspects, Figure 8 divides the 53 articles by sustainable development dimensions discussed. The environmental dimension is the only one that has been positively addressed in all 53 articles. Only 16 articles give a complete triple bottom line view; in other words, they consider a wider triple bottom line of environmental, economic, and social concerns. The majority of the papers (n = 21) are still eco-centric; hence, the lack of holistic evaluation frameworks is an ongoing issue. Furthermore, few papers (n = 6) include social aspects, such as the involvement of stakeholders, or public acceptance, which is a flaw in the dissemination aspect. Again, those rigid analyses suggest that the models of the future should be more multidimensional and context aware.

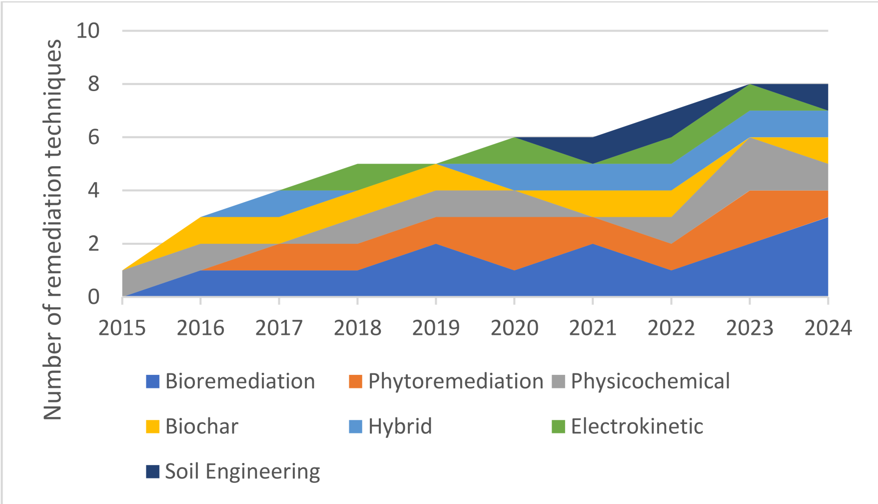

Figure 7. Evolution in the number of remediation techniques cited per article among the 53 selected studies.

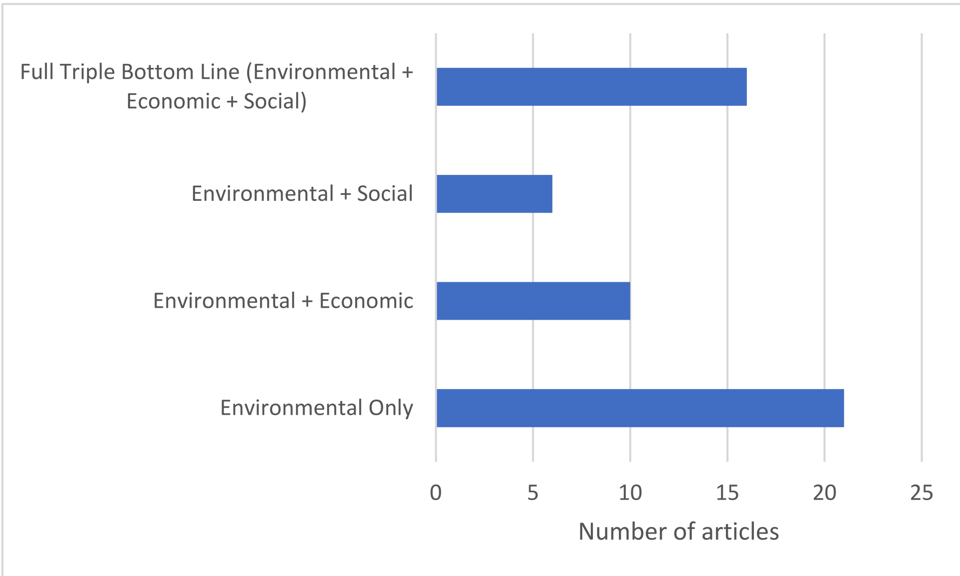

Figure 8. Sustainability dimensions addressed in the 53 reviewed articles.

Table 4 presents the type of remediation and contaminant treated in the 53 articles. Contamination by Cadmium (Cd), lead (Pb), and arsenic (As) turned out to be an emerging issue among the studies, receiving frequent attention revealing the inconveniences that these elements bring and how they still linger in the regions that industries have negatively impacted. Metal products of bioremediation, phytoremediation, and biochar-based approaches were noticeable for the problems that appeared to define the emerging issues of low-impact environmental management following the general orientation towards low-impact eco-friendly interventions. In one example, biochar showed high psi values and at the same time operated in almost all areas of contaminants due to the gas adsorption capability, the enhancement of microbial activity, and the soil amendment properties. By contrast, it was observed that thermal desorption was kept primarily for mercury (Hg) and arsenic which are contaminants whose intrinsic chemical property requires high temperature volatization for effective remediation (extracting and concentrating mercury or arsenic with a hot gas or airflow).

Table 4. Type of remediation and contaminant treated.

Contaminant(s)	Type of Remediation	Number of Articles	Example Techniques/Notes
Cadmium (Cd)	Bioremediation, Phytoremediation, Biochar, Electroremediation	11	*Salix integra*, vermicomposting, biochar enhancement
Lead (Pb)	Phytoremediation, Stabilization, Electroremediation, Biochar	10	Red mud binders, EDTA washing, Moringa seed biochar
Arsenic (As)	Biochar, Soil Washing, Thermal Desorption, Bioremediation	9	Fe nanoparticles, thermal with $FeCl_3$, plant extraction
Chromium (Cr(VI))	Soil Washing, Biochar, Electrochemical, Hybrid Methods	8	Nano-zero-valent iron, stepped heating, electrochemical treatments
Zinc (Zn)	Biochar, Stabilization, Phytoremediation	6	Zn immobilization with Al_2O_3, biochar-rice straw
Mercury (Hg)	Thermal Desorption, Biochar, Green Amendments	5	Citric acid thermal treatment, sulfur-modified biochar
Multi-metal (e.g., Cd, Pb, Zn, As)	Hybrid Approaches, Biochar, Phytoremediation	9	Fly ash + intercropping, red mud binders
PAHs (Polycyclic Aromatic Hydrocarbons)	Soil Washing, Biochar, Electroremediation	4	Green solvents, iron nanoparticles with electric current
PCBs (Polychlorinated Biphenyls)	Electroremediation with Nanoparticles	2	Electroremediation + Fe NPs
General Heavy Metals (non-specific)	Bioremediation, Biochar, Soil Engineering	10	Compost interactions, bacteria inoculated biochar
Organic contaminants (general)	Bioremediation, Soil Engineering, NBS	3	Microbial respiration, compost-based treatments
Salts/Salinity/Soil Degradation	Phytoremediation, Soil Amendment, Solar Interface	2	Artificial phytoremediation evaporator

Additionally, the review also discusses the shifting of the focus of hybrid and electrochemical approaches from only multi-metal or complex pollution scenarios to processes such as electroremediation or nanoparticle-assisted techniques, suggesting an emergent trend toward integrative, systems-based remediation. On the other hand, the report showed that organic pollutants, such as PAHs and PCBs, received relatively less attention and only a few studies used electroremediation or nanoparticle-assisted techniques, insinuating that there is a certain research potential in terms of tracking and treating organic contaminants as part of the sustainability framework. This pattern is consistent with the broader literature, which continues to identify persistent technological constraints and a comparatively fragmented evidence base for PAH remediation specifically [3,68], suggesting that the underrepresentation observed here reflects the composition of the reviewed corpus rather than a genuine scarcity of research on organic contaminants.

The research also confirms the fact that the problem of soil salinization and general degradation of soil resources receives, in general, very little attention from scientists. Nevertheless, the introduction of innovative technologies like artificial solar phytoremediation systems goes a long way in verifying groundbreaking, interdisciplinary innovations that can be used to bring out broader soil functionality restoration. The overall findings of this study are in line with the realization of the need for contaminant-specific remediation strategies that are environmentally accommodating, technically possible, and possess long-term ecosystem resilience.

From this table, we can make another analysis of the type of contaminants referred to in the different reviewed articles. Figure 9 shows that the majority of the articles is dedicated to remediating metals.

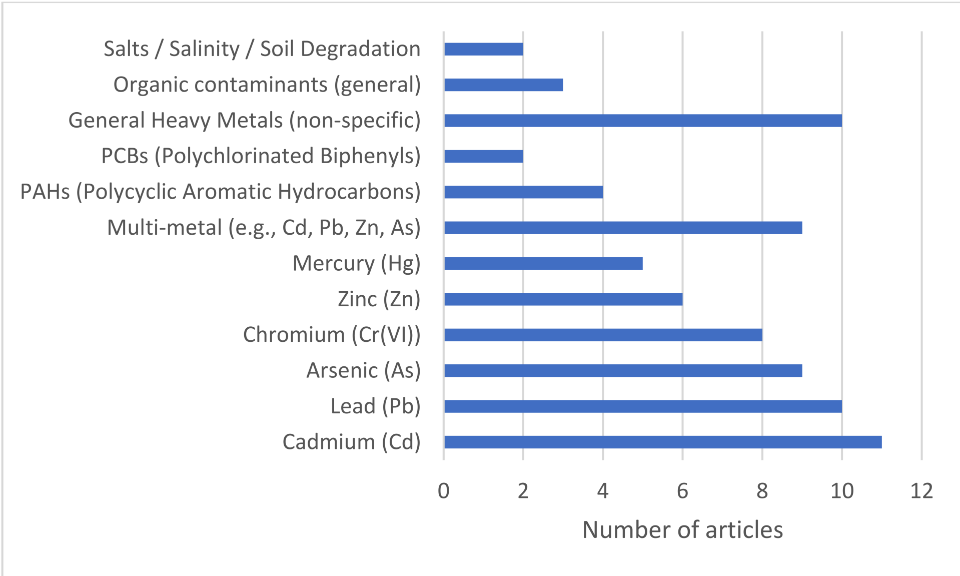

Figure 9. Number of articles addressing each contaminant type among the 53 selected articles.

3.2. Analysis of the Remediation Research and Techniques Used

3.2.1. Bioremediation and Phytoremediation

Recent studies demonstrate significant progress in microorganism-assisted and plant-based remediation, with novel applications improving heavy metal and organic pollutant removal.

The most significant advances have been observed in the field of microorganism-assisted bioremediation and phytoremediation. Study [34] demonstrated that *Eisenia fetida* has a high potential for vermiremediation in soils contaminated with heavy metals, favoring the reduction in toxicity and the improvement in soil structure. In addition, ref. [40] explored the application of *Salix integra* treated with spermidine and activated charcoal, showing a substantial improvement in cadmium phytoextraction capacity.

Another relevant focus was the interaction between biochar and soil microbiota. Ref. [44] demonstrated that the addition of nanoiron-supported biochar enhances the removal of Cr(VI), improving the effectiveness of contaminated soil washing processes. These advances reinforce the need for blended approaches to maximize the efficiency of contaminated soil rehabilitation.

3.2.2. Innovative Physicochemical Techniques

The evolution of physicochemical techniques has also proved crucial for sustainable remediation. Ref. [61] demonstrated the feasibility of stabilization with fly ash in conjunction with a plant intercropping system (*Zanthoxylum bungeanum-Lolium perenne*), resulting in significant heavy metal immobilization and restoration of soil fertility.

On the other hand, ref. [69] introduced a new method of stepped steam heating for the simultaneous stabilization of lead and arsenic, eliminating antagonistic effects often observed in traditional treatments. This approach has shown high efficiency, while minimizing environmental impacts associated with aggressive chemical methods.

Additionally, ref. [62] analyzed the sustainability of the use of zero-valent nanoiron for soil and groundwater remediation, identifying challenges related to nanoparticle persistence and bioaccumulation. This study underlines the need for additional research on the long-term impacts of these techniques.

3.3. Assessment Frameworks, Policy, and Socio-Economic Aspects

3.3.1. Multidimensional Sustainability Assessment

The integration of environmental, economic, and social criteria was widely discussed in the studies analyzed. Ref. [47] proposed a decision model to assess the sustainability of contaminated soil remediation, highlighting the importance of tools such as Multi-Criteria Decision Analysis (MCDA) and Life Cycle Assessment (LCA) to compare different remediation strategies. These findings are consistent with the recent literature emphasizing that sustainable remediation strategies increasingly draw on circular economy principles alongside LCA to reconcile technical performance with resource recovery and long-term environmental cost [70].

Another relevant contribution was presented by [49], who applied life cycle assessment in heat treatments for regionalized remediation of contaminated soils. The results indicate that, although highly effective, this approach requires complementary strategies to mitigate energy costs and greenhouse gas emissions.

Additionally, ref. [61] reinforced the need to consider the social impact of interventions, promoting solutions that involve local communities and increase public acceptance of sustainable techniques.

3.3.2. Policy Barriers

For the political barriers, articles that focus on systems and limits of contaminants in the respective legislation were analyzed (Table 5).

Table 5. Policy barriers.

Aspect	European Union (EU)	United States (US)	Key Challenges
Legal Framework	EU Soil Strategy 2030, Green Deal (binding targets)	CERCLA (Superfund), RCRA (state-level flexibility)	**Fragmentation:** EU harmonizes standards; US relies on state-led enforcement.
Contaminant Limits	Strict Pb (300 mg/kg), Cd (3 mg/kg) in Directive 2004/35/EC	EPA regional benchmarks (e.g., Pb 400 mg/kg residential)	**Inconsistencies:** EU's precautionary principle vs. US risk-based thresholds
Funding Mechanisms	LIFE Programme (€5.4B for 2021–2027)	Superfund Trust Fund (taxes + polluter-pays)	**Underfunding:** US Superfund backlog: 1300+ sites [62]
Sustainability Mandates	Mandatory LCA for remediation projects [47]	Voluntary Green Remediation (EPA 2020)	**Compliance Costs:** EU's LCA adds 15–20% to project costs [49]

The EU prioritizes strict, top-down precautionary standards paired with mandatory life cycle requirements and public funding for sustainable innovation trading higher short-term compliance costs for uniform standards. Conversely, the US uses a decentralized, risk-based system powered by polluter-pays liability, offering flexibility, but running into legal bottlenecks, site backlogs, and variable state enforcement [57]. Despite differences in their regulatory frameworks, both the EU and the US face challenges related to regulatory consistency, long-term funding, liability, and the integration of sustainability criteria into remediation decision-making.

3.3.3. Socio-Economic Trade-Offs

To analyze the socio-economic challenges, key remediation techniques identified in the selected literature were evaluated. As shown in Table 6, the economic implications of remediation technologies extend beyond direct treatment costs. Biochar-based approaches may involve relatively high initial costs but can provide longer-term benefits, whereas phytoremediation generally requires lower initial investment but entails longer treatment periods and continued monitoring [38,40]. Socio-economic trade-offs are also context-dependent: thermal treatments may face greater acceptance constraints in urban areas due to concerns over emissions, while biochar application may be more favorably perceived in rural settings because of its potential benefits for soil fertility [30,57]. Employment effects further differentiate these approaches, as electrokinetic remediation requires specialized expertise but may generate limited local employment, whereas phytoremediation can be more labor-intensive and provide greater opportunities for community involvement [36,60].

Table 6. Economic trade-offs.

Technique	Cost (€/ton)	Timeframe	Social Acceptance	Economic Viability
Biochar + nZVI	120–150	2–5 years	High (farmers prefer C sequestration)	Moderate (high material costs)
Phytoremediation	50–80	5–10 years	Low (land use conflicts)	High (low-tech, but slow)
Electrokinetics	200–300	1–3 years	Medium (noise/energy concerns)	Low (energy-intensive)
Thermal Desorption	400–600	<1 year	Very Low (air pollution fears)	Site-specific (only for Hg/PAHs)

In the EU, incentives for sustainable remediation practices, including tax incentives for biochar application [10], together with greater harmonization of LCA-based assessment frameworks for cross-border projects [47], could facilitate the adoption of sustainable approaches. In the US, strengthening Superfund financing through polluter-pays mechanisms [62] and promoting more structured stakeholder participation in remediation decision-making, drawing on community-based approaches such as the Stratoni Greece model [59], could help address financial and social barriers to implementation.

Globally, sustainable remediation should align with international sustainability goals, including SDG 15.3, while promoting knowledge transfer through frameworks such as Taiwan's GSR Toolkit [32]. Despite regulatory differences, approaches such as biochar and phytoremediation can balance economic, environmental, and social benefits, although scalability remains a challenge. Future progress will require integrating technological innovation, including AI-based tools, with flexible regulatory frameworks to ensure economically viable, socially equitable, and environmentally resilient remediation [1,2].

3.3.4. Future Trends and Challenges

The review identified a growing trend towards the use of hybrid approaches, which combine different techniques to maximize the effectiveness of remediation. However, challenges such as economic viability, long-term environmental impact, and international regulation remain barriers to large-scale implementation. It should be noted that the policy comparison developed in Section 3.3.2 is centered on the EU and US regulatory frameworks, which dominate the underlying literature; progress on internationally harmonized regulation, and a stronger research and policy presence from other regions, such as Latin

America, Africa, and parts of Asia beyond China, represent an important direction for future work and were identified as a gap rather than a finding of this review.

The integration of computational tools, including machine learning for optimization of remediation techniques [71], and the development of new sustainable materials, such as functionalized biochar [44], represent promising directions for future investigations. Nanomaterial-based and hybrid physicochemical–biological strategies are similarly gaining traction for pesticide-contaminated sites, where technology selection increasingly needs to balance treatment cost, contaminant transformation products, and overall process sustainability [15].

4. Conclusions

The systematic review of this article explains the interesting and diversified field of sustainable soil remediation, stating the fact that without advanced technologies, ecological principles, and socio-political frameworks becoming part of the solution, one of the most urgent environmental challenges of our time can hardly be solved. The evolution from the traditional, resource-intensive techniques of soil treatment to the more elaborate, eco-centered, and systems-based methods is more than just a change in the way we think about and make real soil recovery.

In addition, various biological methods involving microbiological organisms, plants, and worms come out as the top contenders for the achievement of environmental regeneration. For instance, the boosting of *Salix integra* by using bio-chemical inputs and the joint deployment of *Eisenia fetida* and the heavy metals removal test represent the ways through which natural means can be strong enough to achieve ecological rehabilitation goals. Further, the making of biochar, using nanotechnology like nZVI or nanoiron, is not only a low-cost method for contaminant immobilization but is also a great way to improve soil health, although there are rising issues related to the persistence of nanoparticles and biosafety.

Physicochemical approaches, however, also made considerable progress, wherein the new ways of undertaking activities, e.g., stepped steam heating and hybrid stabilization systems, break away from the past environmentally aggressive treatments. When rightly customized and combined, these techniques represent a quick and easily implemented approach for the mitigation of hazard scenarios, mostly situations with high environmental contamination and toxicity.

It is the holistic evaluation of such methods through life cycle assessment (LCA) and Multi-Criteria Decision Analysis (MCDA) that will determine the future of these methods. These tools are particularly useful in making comparisons and assessments through the social, environmental, and economic spheres which allows the choosing of only sound technical and locally suitable strategies. This article featured education and the role of people as a first step toward reaching social and environmental justice, especially in parts of the world that suffer from land use disputes or have been left with an industrial legacy.

However, the review has also pointed out major obstacles that have set back the wide use of sustainable remediation practices, such as regulatory fragmentation, funding constraints, and socio-economic trade-offs. The inconsistency between EU's precautionary rules and US's risk-flexibility is a case in point, demonstrating the lack of synergy amongst the countries, which in turn, detracts from transboundary knowledge sharing and sustainability synchronization. Furthermore, the economic gap between low-cost, time-consuming procedures like phytoremediation and capital-intensive quick actions results in difficult choices of cost–benefit equilibrium, scalability, and public acceptance.

But this is not the end of the story; more needs to be done in order to deal with the present situation and prevent such events from happening in the future. Many experts believe that hybridization and computational intelligence should become a part of future remediation technologies, which will lead the way in reducing the environmental pollution and protecting the environment. To the same extent, the introduction of machine learning in prioritizing the sites of concern, the optimization of technological methods, and real-time tracking of the environment promises a new level of precise, applicable, and economical deployment of resources. Similarly, the production of novel sustainable materials, such as functionalized biochar's and bioinspired geopolymers, is a concrete step toward increasing the effectiveness of the materials and achieving circularity.

This synthesis is based on 53 peer-reviewed studies published between 2015 and 2025 across environmental, geochemical, and engineering journals. The evidence base is geographically concentrated, with most studies originating from China, the United States, and selected European Union member states, including Spain, Slovenia, and Portugal, while Latin America, Africa, and South and Southeast Asia are sparsely represented. The reviewed studies are also predominantly supported by national or supranational funding programs, particularly in China and the European Union (Section 3.1). Moreover, most investigations were conducted at the laboratory or pilot scale, with relatively limited evidence from full-scale field applications. These geographic and methodological constraints limit the transferability of the findings and caution against generalizing the conclusions to large-scale, real-world soil remediation programs. While this body of literature illustrates the depth and diversification of current research, it does not constitute an exhaustive or globally representative sample: the reviewed studies concentrate on a limited number of geographic and regulatory contexts and are skewed toward heavy-metal contamination. The conclusions presented here should therefore be read as an evidence-based synthesis of current research directions and priorities, rather than as a globally comprehensive assessment of soil remediation practice at scale.

In short, advancing sustainable soil remediation requires integrating technological innovation, such as hybrid physicochemical–biological treatments and computational optimization tools, with coherent science–policy synergy, spanning immediate contaminant mitigation and long-term systemic transitions. Achieving land degradation neutrality, environmental justice, and the broader aims of SDG 15.3 and the Paris Agreement will depend on closing the geographic, regulatory, and methodological gaps identified in this review, particularly the underrepresentation of regions beyond the EU and the US and of contaminant classes beyond heavy metals.

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Abbreviations

The following abbreviations are used in this manuscript:

SDG	Sustainable Development Goals
ERDF	European Regional Development Fund

References

1. Hou, D.; Bolan, N.S.; Tsang, D.C.; Kirkham, M.B.; O'Connor, D. Sustainable soil use and management: An interdisciplinary and systematic approach. *Sci. Total Environ.* **2020**, *729*, 138961. [CrossRef] [PubMed]
2. Keesstra, S.; Nunes, J.; Novara, A.; Finger, D.; Avelar, D.; Kalantari, Z.; Cerdà, A. The superior effect of nature based solutions in land management for enhancing ecosystem services. *Sci. Total Environ.* **2018**, *610–611*, 997–1009. [CrossRef] [PubMed]
3. Kuppusamy, S.; Thavamani, P.; Venkateswarlu, K.; Lee, Y.B.; Naidu, R.; Megharaj, M. Remediation approaches for polycyclic aromatic hydrocarbons (PAHs) contaminated soils: Technological constraints, emerging trends and future directions. *Chemosphere* **2017**, *168*, 944–968. [CrossRef] [PubMed]
4. 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*, 440–460. [CrossRef] [PubMed]
5. Liu, L.; Li, W.; Song, W.; Guo, M. Remediation techniques for heavy metal-contaminated soils: Principles and applicability. *Sci. Total Environ.* **2018**, *633*, 206–219. [CrossRef] [PubMed]
6. Grifoni, M.; Franchi, E.; Fusini, D.; Vocciante, M.; Barbafieri, M.; Pedron, F.; Rosellini, I.; Petruzzelli, G. Soil Remediation: Towards a Resilient and Adaptive Approach to Deal with the Ever-Changing Environmental Challenges. *Environments* **2022**, *9*, 18. [CrossRef]
7. Rehman, Z.U.; Junaid, M.F.; Ijaz, N.; Khalid, U.; Ijaz, Z. Remediation methods of heavy metal contaminated soils from environmental and geotechnical standpoints. *Sci. Total. Environ.* **2023**, *867*, 161468. [CrossRef] [PubMed]
8. Pandey, J.; Chauhan, A.; Jain, R.K. Integrative approaches for assessing the ecological sustainability of in situ bioremediation. *FEMS Microbiol. Rev.* **2009**, *33*, 324–375. [CrossRef] [PubMed]
9. DeJong, J.T.; Soga, K.; Banwart, S.A.; Whalley, W.R.; Ginn, T.R.; Nelson, D.C.; Mortensen, B.M.; Martinez, B.C.; Barkouki, T. Soil engineering in vivo: Harnessing natural biogeochemical systems for sustainable, multi-functional engineering solutions. *J. R. Soc. Interface* **2011**, *8*, 1–15. [CrossRef] [PubMed]
10. Rawat, J.; Saxena, J.; Sanwal, P. Biochar: A Sustainable Approach for Improving Plant Growth and Soil Properties. In *Biochar—An Imperative Amendment for Soil and the Environment*; IntechOpen: London, UK, 2019. [CrossRef]
11. FAO; UNEP. Environmental, Health and Socio-Economic Impacts of Soil Pollution. In *Global Assessment of Soil Pollution: Report*; FAO: Rome, Italy, 2021; p. 846. Available online: https://www.fao.org/3/cb4894en/online/src/html/chapter-04-3.html (accessed on 12 May 2025).
12. Ali, H.; Khan, E.; Sajad, M.A. Phytoremediation of heavy metals—Concepts and applications. *Chemosphere* **2013**, *91*, 869–881. [CrossRef] [PubMed]
13. Azubuike, C.C.; Chikere, C.B.; Okpokwasili, G.C. Bioremediation techniques–classification based on site of application: Principles, advantages, limitations and prospects. *World J. Microbiol. Biotechnol.* **2016**, *32*, 180. [CrossRef] [PubMed]
14. Chen, M.; Xu, P.; Zeng, G.; Yang, C.; Huang, D.; Zhang, J. Bioremediation of soils contaminated with polycyclic aromatic hydrocarbons, petroleum, pesticides, chlorophenols and heavy metals by composting: Applications, microbes and future research needs. *Biotechnol. Adv.* **2015**, *33*, 745–755. [CrossRef] [PubMed]
15. Sarker, A.; Shin, W.S.; Al Masud, A.; Nandi, R.; Islam, T. A critical review of sustainable pesticide remediation in contaminated sites: Research challenges and mechanistic insights. *Environ. Pollut.* **2024**, *341*, 122940. [CrossRef] [PubMed]
16. Cameselle, C.; Gouveia, S. Electrokinetic remediation for the removal of organic contaminants in soils. *Curr. Opin. Electrochem.* **2018**, *11*, 41–47. [CrossRef]
17. Hoang, S.A.; Sarkar, B.; Seshadri, B.; Lamb, D.; Wijesekara, H.; Vithanage, M.; Liyanage, C.; Kolivabandara, P.A.; Rinklebe, J.; Lam, S.S.; et al. Mitigation of petroleum-hydrocarbon-contaminated hazardous soils using organic amendments: A review. *J. Hazard. Mater.* **2021**, *416*, 125702. [CrossRef] [PubMed]
18. Lin, C.; Guo, Q.; Dong, B.; Xu, Z. Co-aging process of sludge char and soil minerals affects electron-donating and mediating capacities for the reduction of Cr(VI). *J. Environ. Chem. Eng.* **2024**, *12*, 114031. [CrossRef]
19. Yang, X.; Wang, L.; Guo, J.; Wang, H.; Mašek, O.; Wang, H.; Bolan, N.S.; Alessi, D.S.; Hou, D. Aging features of metal(loid)s in biochar-amended soil: Effects of biochar type and aging method. *Sci. Total. Environ.* **2022**, *815*, 152922. [CrossRef] [PubMed]
20. Arteaga, J.F.M.; Gluhar, S.; Kaurin, A.; Lestan, D. Simultaneous removal of arsenic and toxic metals from contaminated soil: Laboratory development and pilot scale demonstration. *Environ. Pollut.* **2022**, *294*, 118656. [CrossRef] [PubMed]

21. El-Naggar, A.; Chang, S.X.; Cai, Y.; Lee, Y.H.; Wang, J.; Wang, S.-L.; Ryu, C.; Rinklebe, J.; Ok, Y.S. Mechanistic insights into the (im)mobilization of arsenic, cadmium, lead, and zinc in a multi-contaminated soil treated with different biochars. *Environ. Int.* **2021**, *156*, 106638. [CrossRef] [PubMed]
22. Gluhar, S.; Kaurin, A.; Finžgar, N.; Gerl, M.; Kastelec, D.; Lestan, D. Demonstrational gardens with EDTA-washed soil. Part I: Remediation efficiency, effect on soil properties and toxicity hazards. *Sci. Total. Environ.* **2021**, *792*, 149060. [CrossRef] [PubMed]
23. Wang, F.; Xu, J.; Yin, H.; Zhang, Y.; Pan, H.; Wang, L. Sustainable stabilization/solidification of the Pb, Zn, and Cd contaminated soil by red mud-derived binders. *Environ. Pollut.* **2021**, *284*, 117178. [CrossRef] [PubMed]
24. Li, J.-S.; Chen, L.; Zhan, B.; Wang, L.; Poon, C.S.; Tsang, D.C. Sustainable stabilization/solidification of arsenic-containing soil by blast slag and cement blends. *Chemosphere* **2021**, *271*, 129868. [CrossRef] [PubMed]
25. Wang, L.; Chen, L.; Guo, B.; Tsang, D.C.; Huang, L.; Ok, Y.S.; Mechtcherine, V. Red mud-enhanced magnesium phosphate cement for remediation of Pb and As contaminated soil. *J. Hazard. Mater.* **2020**, *400*, 123317. [CrossRef] [PubMed]
26. Gluhar, S.; Kaurin, A.; Lestan, D. Soil washing with biodegradable chelating agents and EDTA: Technological feasibility, remediation efficiency and environmental sustainability. *Chemosphere* **2020**, *257*, 127226. [CrossRef] [PubMed]
27. Wu, P.; Cui, P.; Alves, M.E.; Peijnenburg, W.J.; Liu, C.; Zhou, D.; Wang, H.; Ok, Y.S.; Wang, Y. Interactive effects of rice straw biochar and γ-Al_2O_3 on immobilization of Zn. *J. Hazard. Mater.* **2019**, *373*, 250–257. [CrossRef] [PubMed]
28. Kaurin, A.; Lestan, D. Multi-substrate induced microbial respiration, nitrification potential and enzyme activities in metal-polluted, EDTA-washed soils. *Environ. Pollut.* **2018**, *243*, 238–245. [CrossRef] [PubMed]
29. Beiyuan, J.; Tsang, D.C.; Bolan, N.S.; Baek, K.; Ok, Y.S.; Li, X.-D. Interactions of food waste compost with metals and metal-chelant complexes during soil remediation. *J. Clean. Prod.* **2018**, *192*, 199–206. [CrossRef]
30. O'Connor, D.; Peng, T.; Li, G.; Wang, S.; Duan, L.; Mulder, J.; Cornelissen, G.; Cheng, Z.; Yang, S.; Hou, D. Sulfur-modified rice husk biochar: A green method for the remediation of mercury contaminated soil. *Sci. Total. Environ.* **2018**, *621*, 819–826. [CrossRef] [PubMed]
31. Chen, S.S.; Taylor, J.S.; Baek, K.; Khan, E.; Tsang, D.C.; Ok, Y.S. Sustainability likelihood of remediation options for metal-contaminated soil/sediment. *Chemosphere* **2017**, *174*, 421–427. [CrossRef] [PubMed]
32. Huang, W.-Y.; Hung, W.; Vu, C.T.; Chen, W.-T.; Lai, J.-W.; Lin, C. Green and sustainable remediation (GSR) evaluation: Framework, standards, and tool. A case study in Taiwan. *Environ. Sci. Pollut. Res.* **2016**, *23*, 21712–21725. [CrossRef] [PubMed]
33. Ma, F.; Peng, C.; Hou, D.; Wu, B.; Zhang, Q.; Li, F.; Gu, Q. Citric acid facilitated thermal treatment: An innovative method for the remediation of mercury contaminated soil. *J. Hazard. Mater.* **2015**, *300*, 546–552. [CrossRef] [PubMed]
34. Andleeb, S.; Naseer, A.; Liaqat, I.; Sirajuddin, M.; Utami, M.; Alarifi, S.; Ahamed, A.; Chang, S.W.; Ravindran, B. Assessment of growth, reproduction, and vermi-remediation potentials of *Eisenia fetida* on heavy metal exposure. *Environ. Geochem. Health* **2024**, *46*, 290. [CrossRef] [PubMed]
35. Haris, M.; Netherway, P.; Eshtiaghi, N.; Paz-Ferreiro, J. Arsenic immobilization in soil affected by mining waste using waste-derived functional hydrochar and iron-encapsulated materials. *J. Environ. Qual.* **2023**, *52*, 161–172. [CrossRef] [PubMed]
36. Picchi, C.; Giorgetti, L.; Morelli, E.; Landi, M.; Rosellini, I.; Grifoni, M.; Franchi, E.; Petruzzelli, G.; Barbafieri, M. Cannabis sativa L. and *Brassica juncea* L. grown on arsenic-contaminated industrial soil: Potentiality and limitation for phytoremediation. *Environ. Sci. Pollut. Res.* **2022**, *29*, 15983–15998. [CrossRef] [PubMed]
37. Janeiro-Tato, I.; Rodríguez, E.; Lopez-Anton, M.A.; Baragaño, D.; Arrojo, L.; Parra-Benito, P.; Peláez, A.I.; Gallego, J.R. Bio-based carbon foams assembled with Fe nanoparticles for simultaneous remediation of As, Hg and PAHs in co-contaminated industrial soils. *Environ. Sci. Nano* **2024**, *11*, 2683–2692. [CrossRef]
38. dos Santos, F.H.; Soares, M.B.; Alleoni, L.R.F. Pristine and biochar-supported nano zero-valent iron to immobilize As, Zn and Pb in soil contaminated by smelting activities. *J. Environ. Manag.* **2022**, *321*, 116017. [CrossRef] [PubMed]
39. Huang, L.; Meng, Y.; Pan, B.; Pan, B.; Wei, J.; Ding, J.; Deng, Y.; Su, X.; Yuan, Z.; Zhang, M. Multidimensional effects of green waste vermicomposting on cadmium contaminated soil ecosystems: From physicochemical properties to microbial communities. *J. Hazard. Mater.* **2024**, *480*, 136429. [CrossRef] [PubMed]
40. Yin, Z.; Yu, J.; Han, X.; Wang, H.; Yang, Q.; Pan, H.; Lou, Y.; Zhuge, Y. A novel phytoremediation technology for polluted cadmium soil: *Salix integra* treated with spermidine and activated carbon. *Chemosphere* **2022**, *306*, 135582. [CrossRef] [PubMed]
41. Pračke, K.; Száková, J.; Tlustoš, P. Biochar applications enhance the phytoextraction potential of *Salix smithiana* [Willd.] (willow) in heavily contaminated soil: Potential for a sustainable remediation method? *J. Soils Sediments* **2022**, *22*, 905–915. [CrossRef]
42. Tu, C.; Wei, J.; Guan, F.; Liu, Y.; Sun, Y.; Luo, Y. Biochar and bacteria inoculated biochar enhanced Cd and Cu immobilization and enzymatic activity in a polluted soil. *Environ. Int.* **2020**, *137*, 105576. [CrossRef] [PubMed]
43. Zhao, R.; Zhang, X.; Zhou, Y.; Li, J.; Guo, B.; Oyama, K.; Tokoro, C. Influence of elevated temperature on the species and mobility of chromium in ferrous sulfate-amended contaminated soil. *J. Environ. Manag.* **2024**, *356*, 120457. [CrossRef] [PubMed]
44. Yuan, Z.; Peng, A.; Chu, Z.; Zhang, X.; Huang, H.; Mi, Y.; Xia, D.; Wu, X.; Ye, Z.; Tao, Y.; et al. Sustainable remediation of Cr(VI)-contaminated soil by soil washing and subsequent recovery of washing agents using biochar supported nanoscale zero-valent iron. *Sci. Total. Environ.* **2024**, *921*, 171107. [CrossRef] [PubMed]

45. Xie, Y.; Lu, L.; Chen, B. Asymmetrical alternating current electrochemically-mediated washing method for sustainable remediation of Cr(VI)-contaminated soil. *J. Hazard. Mater.* **2022**, *437*, 129088. [CrossRef] [PubMed]
46. Hou, R.; Wang, L.; Shen, Z.; Alessi, D.S.; Hou, D. Simultaneous reduction and immobilization of Cr(VI) in seasonally frozen areas: Remediation mechanisms and the role of ageing. *J. Hazard. Mater.* **2021**, *415*, 125650. [CrossRef] [PubMed]
47. Braun, A.B.; Visentin, C.; Thomé, A. Design of a central tool for sustainability evaluation and weighting to decision-making support of contaminated soils remediation. *J. Environ. Manag.* **2024**, *351*, 119624. [CrossRef] [PubMed]
48. Lee, S.-H.; Kim, M.-S.; Kim, J.-G.; Kim, S.-O. Use of Soil Enzymes as Indicators for Contaminated Soil Monitoring and Sustainable Management. *Sustainability* **2020**, *12*, 8209. [CrossRef]
49. Liang, T.; Huo, M.; Yu, L.; Wang, P.; Zheng, J.; Zhang, C.; Wang, D.; Ding, A.; Li, F. Life cycle assessment-based decision-making for thermal remediation of contaminated soil in a regional perspective. *J. Clean. Prod.* **2023**, *392*, 136260. [CrossRef]
50. Lu, L.; Xie, Y.; Yang, Z.; Chen, B. Sustainable decontamination of heavy metal in wastewater and soil with novel rectangular wave asymmetrical alternative current electrochemistry. *J. Hazard. Mater.* **2023**, *442*, 130021. [CrossRef] [PubMed]
51. Emenike, C.; Agamuthu, P.; Fauziah, S. Sustainable remediation of heavy metal polluted soil: A biotechnical interaction with selected bacteria species. *J. Geochem. Explor.* **2017**, *182*, 275–278. [CrossRef]
52. Prosenkov, A.; Cagnon, C.; Gallego, J.L.R.; Pelaez, A.I. The microbiome of a brownfield highly polluted with mercury and arsenic. *Environ. Pollut.* **2023**, *323*, 121305. [CrossRef] [PubMed]
53. Kamdar, B.A.; Solanki, C.H.; Reddy, K.R. Moringa Seed Cake Biochar: A Novel Binder for Sustainable Remediation of Lead-Contaminated Soil. *J. Environ. Eng.* **2023**, *149*, 04023059. [CrossRef]
54. Al-Alam, J.; Harb, M.; Hage, T.G.; Wazne, M. Assessment of *Opuntia ficus*-indica (L.) Mill. extracts for the removal of lead from soil: The role of CAM plant harvest phase and soil properties. *Environ. Sci. Pollut. Res.* **2023**, *30*, 798–810. [CrossRef] [PubMed]
55. Lake, L.M.; Scott, S.B.; Hood, D.B.; Kellis, M.; Gardiner, M.M.; Basta, N.T. Risk management approach using ash-based amendment blends for remediation of lead-contaminated urban soils and protection of public health. *Soil Environ. Health* **2024**, *2*, 100102. [CrossRef]
56. Ma, F.; Zhang, Q.; Xu, D.; Hou, D.; Li, F.; Gu, Q. Mercury removal from contaminated soil by thermal treatment with $FeCl_3$ at reduced temperature. *Chemosphere* **2014**, *117*, 388–393. [CrossRef] [PubMed]
57. Sierra, M.J.; Millán, R.; López, F.A.; Alguacil, F.J.; Cañadas, I. Sustainable remediation of mercury contaminated soils by thermal desorption. *Environ. Sci. Pollut. Res.* **2016**, *23*, 4898–4907. [CrossRef] [PubMed]
58. Zhao, T.; Zhang, K.; Chen, J.; Shi, X.; Li, X.; Ma, Y.; Fang, G.; Xu, S. Changes in heavy metal mobility and availability in contaminated wet-land soil remediated using lignin-based poly(acrylic acid). *J. Hazard. Mater.* **2019**, *368*, 459–467. [CrossRef] [PubMed]
59. Argyraki, A.; Boutsi, Z.; Zotiadis, V. Towards sustainable remediation of contaminated soil by using diasporic bauxite: Laboratory experiments on soil from the sulfide mining village of Stratoni, Greece. *J. Geochem. Explor.* **2017**, *183*, 214–222. [CrossRef]
60. Taneja, S.; Karaca, O.; Haritash, A.K. Electrokinetic remediation: Past experiences and future roadmap for sustainable remediation of metal-contaminated soils. *J. Geochem. Explor.* **2024**, *259*, 107437. [CrossRef]
61. Zhang, H.; Lv, X.; Yang, Z.; Li, Q.; Wang, P.; Zhang, S.; Xu, Y.; Wang, X.; Ali, E.F.; Hooda, P.S.; et al. A field trial for remediation of multi-metal contaminated soils using the combination of fly ash stabilization and *Zanthoxylum bungeanum- Lolium perenne* intercropping system. *J. Environ. Manag.* **2024**, *361*, 121231. [CrossRef] [PubMed]
62. Visentin, C.; Braun, A.B.; Reginatto, C.; Cecchin, I.; Vanzetto, G.V.; Thomé, A. Are contaminated soil and groundwater remediation with nanoscale zero-valent iron sustainable? An analysis of case studies. *Environ. Pollut.* **2024**, *352*, 124167. [CrossRef] [PubMed]
63. Sigmund, G.; Poyntner, C.; Piñar, G.; Kah, M.; Hofmann, T. Influence of compost and biochar on microbial communities and the sorption/degradation of PAHs and NSO-substituted PAHs in contaminated soils. *J. Hazard. Mater.* **2018**, *345*, 107–113. [CrossRef] [PubMed]
64. Rabieian, M.; Qaderi, F. Modeling and optimization of PAHs contaminated soil remediation using green solvent in a continuous flow by response surface methodology. *Environ. Dev. Sustain.* **2024**, *26*, 12109–12132. [CrossRef]
65. Gomes, H.I.; Dias-Ferreira, C.; Ottosen, L.M.; Ribeiro, A.B. Electroremediation of PCB contaminated soil combined with iron nanoparticles: Effect of the soil type. *Chemosphere* **2015**, *131*, 157–163. [CrossRef] [PubMed]
66. Gomes, H.I.; Ottosen, L.M.; Ribeiro, A.B.; Dias-Ferreira, C. Treatment of a suspension of PCB contaminated soil using iron nanoparticles and electric current. *J. Environ. Manag.* **2015**, *151*, 550–555. [CrossRef] [PubMed]
67. Xu, Y.; Dang, C.; Cao, X.E.; Cao, Y.; Huang, J.; Xu, Y.; Shan, M.; Liu, R.; Li, P.; Xu, G.; et al. Artificial phytoremediation solar interface evaporator for efficient heavy metal salt separation and saline soil remediation. *J. Environ. Chem. Eng.* **2024**, *12*, 113114. [CrossRef]
68. Singh, S.K.; Singh, R.K. An overview on remediation technologies for polycyclic aromatic hydrocarbons in contaminated lands: A critical approach. *Environ. Dev. Sustain.* **2025**, *27*, 2753–2787. [CrossRef]
69. Fan, X.; Wu, X.; Wang, X.; Zheng, L.; Liu, Y.; Zhang, D. Eliminating the stabilizer antagonistic effects for efficiently stabilizing Pb and As co-contaminated soil by innovative stepwise steam flash heating. *J. Hazard. Mater.* **2024**, *473*, 134627. [CrossRef] [PubMed]

70. Lee, H.; Sam, K.; Coulon, F.; De Gisi, S.; Notarnicola, M.; Labianca, C. Recent developments and prospects of sustainable remediation treatments for major contaminants in soil: A review. *Sci. Total Environ.* **2024**, *912*, 168769. [CrossRef] [PubMed]
71. Zhang, B.; Wang, X.; Liu, C. Screening and Optimization of Soil Remediation Strategies Assisted by Machine Learning. *Processes* **2024**, *12*, 1157. [CrossRef]