Front. Environ. Sci. Eng. 2024, 18(6): 74
https://doi.org/10.1007/s11783-024-1834-1

REVIEW ARTICLE

Paving the way toward soil safety and health: current status, challenges, and potential solutions

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HIGHLIGHTS

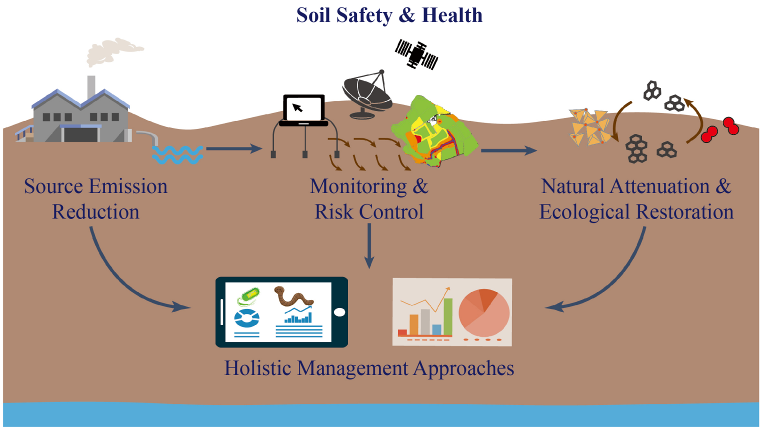
- The safety and health of soil face global threats from widespread contamination.
- Tackling soil pollutions require holistic soil remediation and management.
- Big data can revolutionize contaminated soil management and remediation.

ARTICLE INFO

Article history:
Received 2 February 2024
Revised 6 March 2024
Accepted 6 March 2024
Available online 5 April 2024

Keywords:
Soil safety and health
Source emission reduction
Process monitoring and simulation
Green remediation technology
Soil health management

GRAPHIC ABSTRACT



ABSTRACT

Soil is a non-renewable resource, providing a majority of the world's food and fiber while serving as a vital carbon reservoir. However, the health of soil faces global threats from human activities, particularly widespread contamination by industrial chemicals. Existing physical, chemical, and biological remediation approaches encounter challenges in preserving soil structure and function throughout the remediation process, as well as addressing the complexities of soil contamination on a regional scale. Viable solutions encompass monitoring and simulating soil processes, with a focus on utilizing big data to bridge micro-scale and macro-scale processes. Additionally, reducing pollutant emissions to soil is paramount due to the significant challenges associated with removing contaminants once they have entered the soil, coupled with the high economic costs of remediation. Further, it is imperative to implement advanced remediation technologies, such as monitored natural attenuation, and embrace holistic soil management approaches that involve regulatory frameworks, soil health indicators, and soil safety monitoring platforms. Safeguarding the enduring health and resilience of soils necessitates a blend of interdisciplinary research, technological innovation, and collaborative initiatives.

1 Introduction

Soil stands as an essential natural resource in providing 95% of food and 70% of fiber across the world (Amundson et al., 2015; Marris, 2022). Further, soil plays a vital role in providing numerous ecosystem services, and serves as the largest terrestrial carbon reservoir, therefore fulfilling pivotal functions in regulating carbon cycles and climate change (de Vries et al., 2013; Crowther et al., 2019; Guerra et al., 2022). Despite its vital functions, soil health is increasingly imperiled, particularly by contaminants released through human activities. Globally, soil contamination poses a significant threat, with a myriad of industrial chemical compounds

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compromising soil safety (Rodrigo et al., 2014; Washington et al., 2020). This widespread contamination is a pressing environmental concern, impacting approximately 5 million brownfield sites worldwide (Hou et al., 2023). The remediation of these contaminated soils stands as a formidable environmental challenge, necessitating comprehensive efforts to mitigate the detrimental effects of human-induced soil degradation. Addressing these issues is essential for preserving the integrity and functionality of soils, ensuring sustainable agricultural practices, and mitigating the broader environmental consequences associated with soil contamination.

Soil contaminants encompass a diverse array of substances that, when present in soil at elevated concentrations, pose a threat to environmental and human health (Liu et al., 2023). Two primary categories of soil contaminants are heavy metals and organic pollutants (Table 1) (Atashgahi et al., 2018). Heavy metals like lead, cadmium, and mercury are naturally occurring elements that can become problematic in the environment due to human activities (Table 1) (Larson, 2014; Xu et al., 2019; U.S. Environmental Protection Agency, 2020). In croplands, heavy metals originated from industrial activities, improper waste disposal, or the use of contaminated irrigation water, can persist in soils for extended periods. Their toxicity can disrupt soil microbial communities, hinder plant growth, and, through the food chain, lead to adverse effects on animals and humans (Hou et al., 2015). Organic pollutants, on the other hand, are carbon-based compounds that originate from both natural and anthropogenic sources (Laszakovits et al., 2022). Pesticides, herbicides, industrial chemicals, and petroleum hydrocarbons are common examples of organic pollutants found in soils (Table 1) (Froger et al., 2023). Soil organic contamination in industrial sites stems from the release of contaminants such as petroleum products, solvents, and chemical residues. Furthermore, organic pollutants in soils may permeate into groundwater, spreading across large areas (Ma et al., 2011; Wu et al., 2023). Within cropland, organic pollutants can diminish soil fertility, hinder crop growth, and pose health risks to consumers. Recent studies indicate that these pollutants may influence enzymes and gene expression, impacting carbohydrate metabolism and photosynthetic carbon fixation in crops (Liu and Zhu, 2020; Zhang et al., 2022). Further, emerging

Table 1 Most frequently identified soil contaminants of concern in industrial land of USA and China

Compounds	USA		China	
	Standard a) (mg/kg)	Major concern b)	Standard c) (mg/kg)	Major concern d)
Inorganic				
Arsenic	0.4	√	20	√
Cadmium	78	√	20	√
Chromium (VI)	270	√	3	√
Copper	–	–	2000	√
Lead	400	√	400	√
Mercury	10	√	8	√
Nickel	1600	–	150	√
Zinc	23000	–	–	√
Organic				
Naphthalene	3100	√	25	√
Benz[a]anthracene	0.9	√	5.5	√
Benzo[b]fluoranthene	0.9	√	5.5	√
Benzo[a]pyrene	0.09	√	0.55	√
Dibenz[a,h]anthracene	0.09	√	0.55	√
Indeno[1,2,3-cd] pyrene	0.9	√	5.5	√
DDT	2	–	2	√
γ-HCH(Lindane)	0.5	–	0.62	√
PCBs	1	√	0.14	–
Tetrachloroethylene	11	√	11	–
Trichloroethylene	5	√	0.7	–

Notes: a) Adapted from USA superfund soil screening guidance-generic soil screening levels (SSLs), b) adapted from USA superfund remedy report (17th Edition), c) adapted from China soil environmental quality-risk control standard for soil contamination of development land (SSLs for type I, GB 36600-2018), d) adapted from China national soil contamination survey bulletin.

contaminants, such as pharmaceuticals and microplastics, pose a growing concern for soil ecosystems due to their persistence and potential adverse effects on soil health (Sun et al., 2022). These contaminants can disrupt nutrient cycling, soil structure, and microbial communities, ultimately impacting agricultural productivity and environmental sustainability (de Souza Machado et al., 2018; Senevirathna et al., 2022). Notably, heavy metals and organic pollutants often interact in soils, leading to synergistic or antagonistic effects on overall soil health. The combined impact can result in further decreased soil fertility, impaired microbial activity, and compromised ecosystem functions (Nriagu and Pacyna, 1988).

Current soil remediation technologies encompass a diverse range of approaches that can be broadly classified into physical, chemical, and biological methods (Fig. 1) (Sun et al., 2018). Physical methods involve the mechanical removal or alteration of contaminants in the soil. Techniques such as excavation, dredging, and soil washing physically extract contaminated soil, which is then treated or disposed of appropriately (Song et al., 2022). The physical separation is among the mostly used remediation technolgoes both in China (29%) and USA (28%). *In situ* methods like soil vapor extraction and air sparging involve the injection of air or other gases to volatilize and remove contaminants from the soil matrix (Aelion and Kirtland, 2000). Chemical methods aim to alter the chemical composition of contaminants in the soil, rendering them less toxic or mobile. Soil flushing involves the injection of chemicals, such as surfactants or chelating agents, to enhance the solubility and removal of contaminants (Ruiz et al., 2014). Another approach is solidification/stabilization applied in over 30% sites in China and USA (Fig. 1), where additives are introduced to bind with heavy metals, reducing their bioavailability (Baker et al., 2019). Yet physicalchemical remediation technologies frequently encounter challenges related to elevated energy and reagent inputs, along with potential damage to soil structure and function. For example, the process of removing 1 kg of chlorinated volatile organic compounds through *in situ* thermal desorption requires an average energy consumption of 1716 kWh (Heron et al., 2015). In contrast, bioremediation harness the capabilities of microorganisms, plants, or enzymes to degrade or immobilize contaminants (Simmer and Schnoor, 2022). Microorganisms can break down organic pollutants or transform heavy metals into less harmful forms (Rodríguez-Rodríguez and Rodríguez-Saravia, 2023). Phytoremediation involves using plants to uptake, accumulate, or transform contaminants, making them less harmful to the environment (Hu et al., 2022; Liu et al., 2022b). Nevertheless, biological methods frequently entail extended remediation durations and demonstrate sensitivity to the surrounding environmental conditions. Thus, bioremediation was selected for only 9 out of 86 remediated sites in USA from 2018 to 2020 (U.S. Environmental Protection Agency, 2023).

We note that the soil remediation technologies exhibit distinct adaptability depending on soil type, contamination depth, as well as pollutant species and concentrations (Song et al., 2022; Lee et al., 2024). In sandy soils with high permeability (10^{-3}–10^{-5} cm/s), physical remediation methods such as soil vapor extraction or pump-and-treat systems are effective for removing volatile contaminants. Conversely, clayey soils, with lower permeability (10^{-12}–10^{-15} cm/s), may benefit more from chemical methods like *ex-situ* chemical oxidation to break down pollutants pollutants

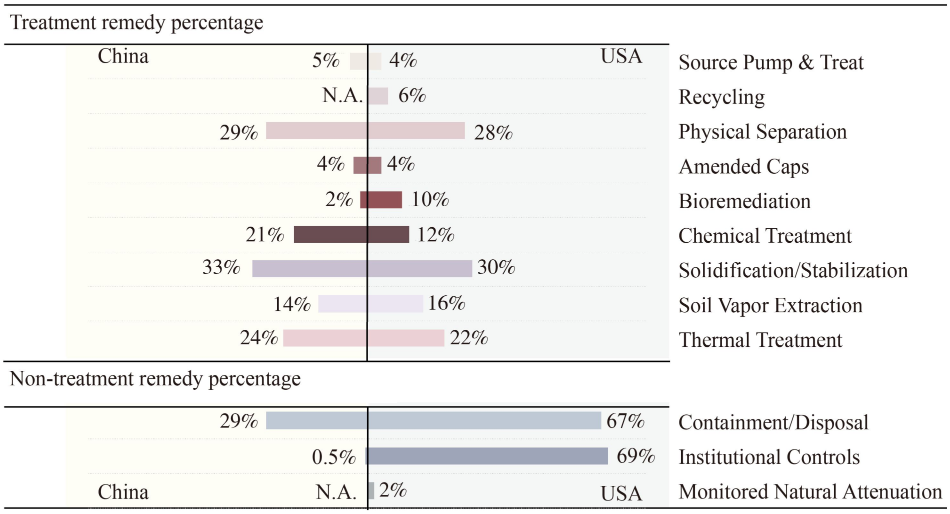

Fig. 1 Most frequently selected soil remediation technologies in China and USA. We note that multiple treatment and non-treatment techonologies may be applied in one remedy site and therefore the sum of remedy technology percent is over 100%. The remedy technology data for USA were apted from U.S. Environmental Protection Agency, 2023; the remedy technology data for China were adapted from Wang et al. (2017); Liang et al. (2021).

(U.S. Environmental Protection Agency, 2019). The depth of contamination also influences the choice of remediation techniques. Shallow contamination may be remediated using physical methods like excavation and land disposal, whereas deep contamination may require more sophisticated approaches such as barrier and landfill (Adelopo et al., 2018). Moreover, the concentration of pollutants plays a pivotal role in selecting appropriate remediation strategies. High concentrations may necessitate aggressive techniques like thermal desorption or electrokinetic remediation, while lower concentrations could be effectively treated through microbial degradtion.

Further, the combined use of physical, chemical, and biological soil remediation technologies can often address the limitations of individual methods, leading to more efficient and sustainable outcomes (Aparicio et al., 2022). For instance, physical methods like excavation may remove contaminants from the surface but could miss deeper pollutants. By integrating this with chemical techniques such as *in situ* chemical oxidation, which can target deep contaminants, a more comprehensive remediation is achieved. Additionally, the introduction of biological methods like bioremediation complements these approaches by promoting the natural degradation of pollutants in mildly contaminated sites. This holistic approach maximizes remediation efficacy, ensuring that diverse soil types, depths, and pollutant concentrations are effectively managed, providing a robust and adaptable solution to soil contamination challenges.

2 Challenges in soil safety and health

2.1 Cross-media migration of pollutants

Soil contamination can result from various sources, including atmospheric deposition, surface water runoff, and groundwater infiltration (Fig. 2). Atmospheric deposition involves the release of pollutants into the air from industrial activities, transportation, and other sources. These pollutants, such as heavy metals and particulate matter, can settle onto the soil through rainfall or air deposition, contributing to soil contamination. Recent studies show that 16.3% of heavy metals in the soil in central Guangdong Province, China originate from atmospheric deposition which is the main source of soil Hg in studied area (Liang et al., 2023). Similarly, surface water runoff from urban areas, agricultural lands, and industrial sites can carry pollutants like pesticides into the soil, compromising its quality. Furthermore, groundwater, often a vital water source for agriculture and communities, can also act as a source of soil contamination. Once these pollutants enter the soil, they can tightly bind to soil particles, leading to persistent and long-lasting effects. The removal of such contaminants from the soil is often challenging, requiring intricate and resource-intensive remediation processes. Therefore, preventing pollutant emissions at the source by implementing sustainable practices and stringent regulations is crucial for safeguarding soil health and minimizing the economic and environmental burdens associated with soil contamination.

2.2 Pollutant transportation and transformation in soils

The limited knowledge surrounding the transport and transformation of pollutants in soils represents a significant hurdle in the quest for sustainable soil remediation (Fig. 3). Understanding the intricate pathways through which contaminants move within the soil matrix and undergo transformations is pivotal for developing targeted and effective remediation strategies. The transport of soil pollutants involves complex interactions between soil particles, water, and air (Moeckel et al., 2008). Factors such as soil structure, porosity, and the presence of organic matter influence the mobility of contaminants (Zheng et al., 2015). Additionally, the transformation of pollutants, whether through

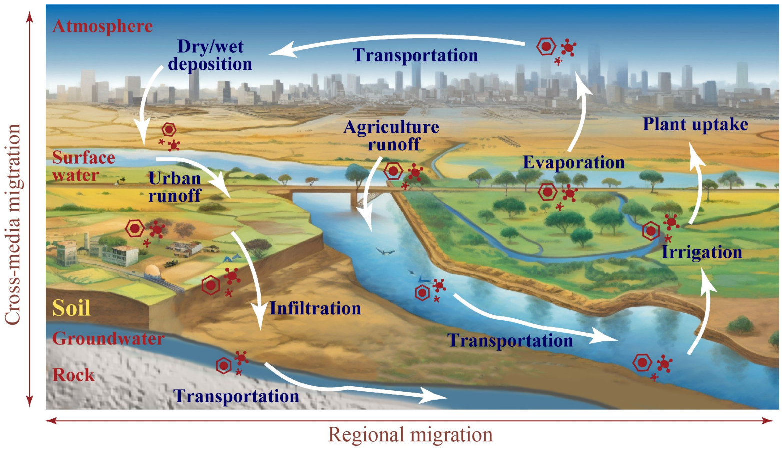

Fig. 2 Cross-media migration of pollutants in soils, atmosphere, surface water, and groundwater.

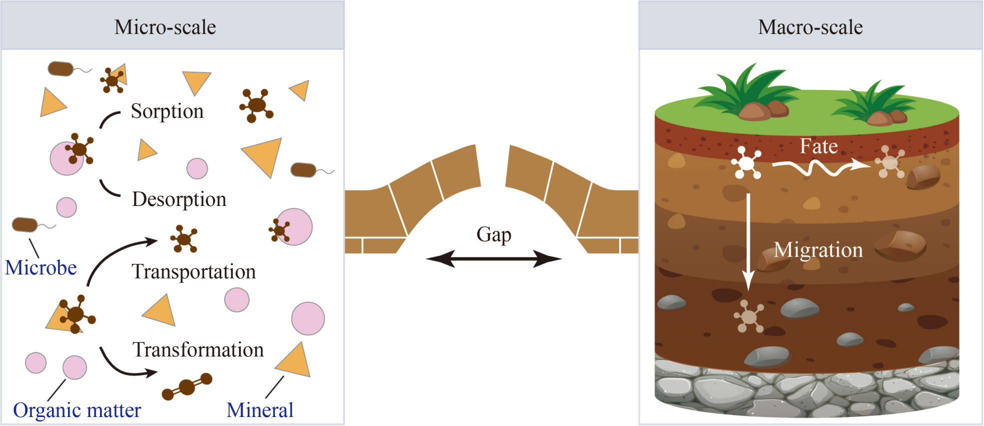

Fig. 3 Knowledge gap between micro-scale and macro-scale soil contamination processes.

chemical, physical, or biological processes, dictates their persistence and potential harm to the environment. However, our comprehension of these processes is often incomplete, hindered by the sheer diversity of contaminants and soil types. Further, the knowledge gap between micro-scale soil processes monitoring and macro-scale soil process simulation is a critical challenge in soil science (Fig. 3). At the micro-scale, detailed observations provide insights into the intricate dynamics of soil processes. However, scaling up this knowledge to larger spatial extents presents a significant challenge, as complex interactions and heterogeneity at the micro-scale may not be accurately represented in macro-scale models. The lack of a comprehensive understanding of the fate and transport mechanisms impedes the development of precise models and predictive tools needed for effective remediation planning.

2.3 Pollutant removal while reserving soil functions

Removing the pollutants while reserving soil structure and function during soil remediation poses a significant hurdle to achieving sustainable soil remediation. Soil structure, characterized by the arrangement of mineral particles, organic matter, water, and air, is vital for supporting essential functions such as water retention, nutrient cycling, and microbial activity (de Souza Machado et al., 2019). Disturbing this delicate balance during remediation processes can have long-lasting consequences on the overall health and productivity of the soil. Various soil remediation techniques, including physical and chemical methods, may inadvertently disrupt soil structure, leading to compaction, erosion, or the loss of essential organic matter. For instance, remediation of a pyrene-polluted site by Fenton oxidation led to decrease of soil organic matter by 20%–24% (Sun and Yan, 2007). Mechanical processes like excavation or soil washing can alter the physical properties of the soil, impacting its ability to provide a supportive environment for plant growth and microbial communities (Longepierre et al., 2021). The interconnectedness of soil components and their roles in supporting biodiversity and ecosystem services demand a nuanced approach to remediation practices, which is crucial for ensuring the resilience and sustainability of ecosystems.

2.4 Risk management of regional soil contamination

Managing the risk of regional soil contamination poses unique challenges compared to single-site remediation efforts, creating hurdles for sustainable soil remediation on a broader scale. While single-site remediation focuses on isolated instances of contamination, regional contamination risk management necessitates a more comprehensive and interconnected approach. One significant challenge lies in the diverse sources and types of contaminants that contribute to regional soil contamination. Unlike a single-site scenario, where the contamination source is often localized and identifiable, regional contamination stems from a myriad of anthropogenic activities, including industrial discharges, agricultural runoff, and atmospheric deposition (Fig. 2) (Lei et al., 2023; Xing et al., 2023). Moreover, in contrast to the application of traditional physicochemical approaches for remediating single sites, addressing soil contamination at a regional scale poses unique challenges. Traditional physicochemical methods, such as excavation or chemical treatment, are often impractical for large-scale soil rehabilitation efforts due to the sheer extent of affected areas. The interconnected nature of ecosystems further complicates regional soil contamination risk management. Contaminants can migrate across landscapes, affecting soil quality, water bodies, and ecosystems beyond the boundaries of a single site. The complexities associated with regional-scale remediation involve the need for innovative and sustainable strategies that go beyond the limitations of conventional techniques applied at smaller scales.

3 Potential solutions toward soil safety and health

3.1 Source emission reduction

3.1.1 Cleaner production

Adopting cleaner technologies across industries is a key route to reducing pollutant emissions (Fig. 4). Sustainable manufacturing processes, green energy alternatives, and advanced waste treatment technologies can significantly minimize the release of harmful substances into the air and water, subsequently preventing soil contamination. For instance, replacement of coal coke with biomass charcoal lead to a reduction of sulfur dioxide emissions by 78% (Heberlein et al., 2022), which could contribute to reducing sulfate entry into soils. In agriculture, promoting sustainable practices is essential. Precision farming, organic farming methods, and integrated pest management help minimize the use of chemical fertilizers and pesticides, reducing the risk of soil contamination (Basso and Antle, 2020). Implementing soil conservation measures, such as cover cropping and agroforestry, can also prevent erosion and sedimentation.

3.1.2 Waste management and recycling

Proper waste management is critical to preventing soil contamination. Recycling programs, waste reduction initiatives, and responsible disposal of hazardous materials are essential components. By minimizing the amount of waste sent to landfills and ensuring safe disposal practices, the risk of soil contamination could be significantly reduced.

3.1.3 Cross-media migration reduction

Preventing the intermedia migration of pollutants from the atmosphere, surface water, and groundwater to soils necessitates a comprehensive, science-based strategy. Employing strategies like vegetative buffers and advanced stormwater management, such as retention ponds, helps mitigate atmospheric and surface water contamination before it infiltrates the soil (You et al., 2019). Integrated environmental planning, backed by interdisciplinary insights, strengthens ecosystem resilience. Robust monitoring systems and educational initiatives aid early detection and informed stewardship, forming a precise defense against cross-media pollutant dissemination, safeguarding soil ecosystems effectively.

3.2 Multi-scale monitoring and simulation of soil processes

3.2.1 *In situ* soil contamination monitoring devices

Deployment of *in situ* monitoring devices allows real-

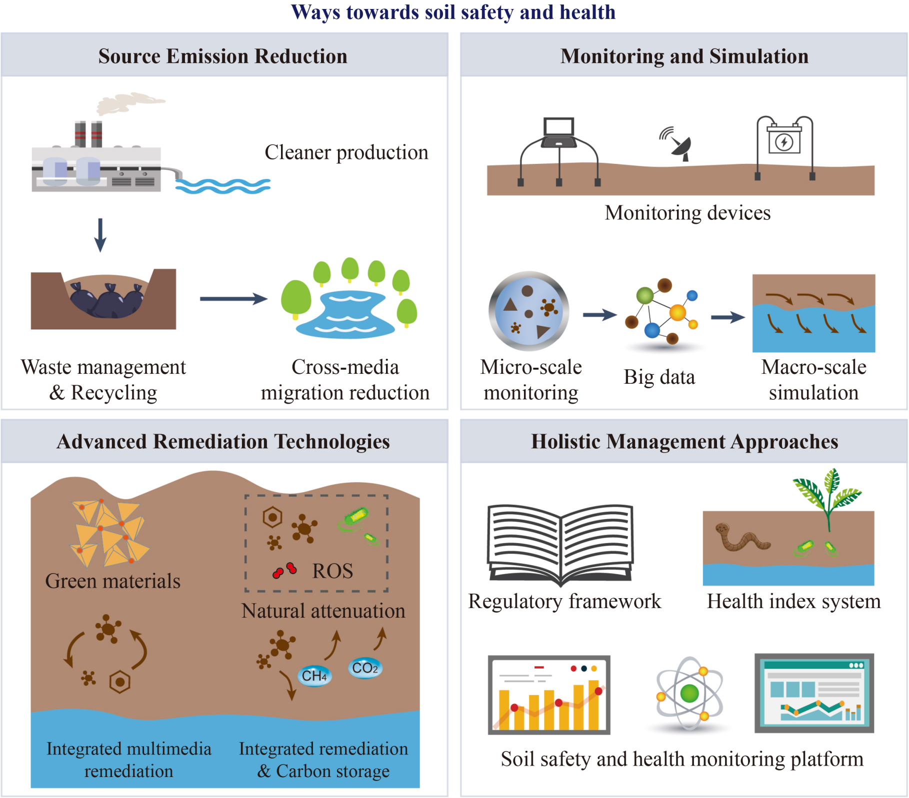

Fig. 4 Framework for the solutions toward soil safety and health.

time, continuous assessment of soil conditions, providing a dynamic understanding of contaminant behaviors (Cao et al., 2023). Technologies such as soil sensors, spectroscopy, and electrochemical sensors offer immediate data on parameters like moisture content, pH, and contaminant concentrations (Fig. 4). These devices facilitate early detection of changes, enabling rapid response strategies and optimized remediation interventions.

3.2.2 Micro-scale pollutant processes monitoring

Understanding pollutant processes at the micro-scale is crucial for targeted remediation efforts. Microbial activity, chemical reactions, and plant–soil interactions can be monitored using advanced techniques such as molecular biology tools and isotopic tracing (Gu et al., 2021). By elucidating the specific mechanisms at play, researchers and practitioners can tailor remediation strategies to address the unique challenges posed by different contaminants and soil types.

3.2.3 Macro-scale spatiotemporal soil processes simulation

Simulation and modeling tools provide a robust method for predicting and comprehending soil processes on a broader spatiotemporal scale. For instance, the utilization of hypergravity devices allows the simulation of deep soil processes. Advanced computational models have the capability to simulate the spatiotemporal dynamics of contaminants, water flow, and nutrient cycling across landscapes. These simulations and models offer valuable insights into the potential long-term impacts of remediation strategies, facilitating the development of sustainable, evidence-based management plans.

3.2.4 Bridging micro-scale and macro-scale processes with big data technologies

The disparity between micro-scale soil processes monitoring and macro-scale soil process simulation is particularly pronounced when addressing soil heterogeneity in the context of pollutant processes. At the micro-scale, the intricate interactions between soil particles, microbial communities, and pollutants are challenging to replicate accurately at broader scales. Regarding this, big data holds immense potential in overcoming this knowledge gap (Fig. 4). By assimilating diverse and extensive data sets from soil sensors, remote sensing technologies, and climate models, big data analytics can capture the multifaceted nature of soil heterogeneity. This wealth of information allows for the development of sophisticated models that integrate micro-scale pollutant processes into macro-scale simulations. Through machine learning algorithms and advanced statistical analyses, big data enables the identification of patterns and relationships within heterogeneous soil environments (Zhang et al., 2023). This, in turn, enhances the accuracy of pollutant dispersion models, providing a more nuanced understanding of how contaminants move and interact with soils at different scales. Consequently, leveraging big data in soil science facilitates more effective decision-making in pollutant management and remediation efforts, bridging the gap between micro-scale intricacies and macro-scale simulations for enhanced environmental protection.

Integration of these solutions creates a comprehensive framework for sustainable soil remediation. *In situ* monitoring devices offer real-time feedback, micro-scale monitoring refines our understanding of localized processes, large-scale simulation provides a holistic view of the landscape, and big data connects the micro- and macro-scale monitoring and simulation. This multidimensional approach enhances our ability to adapt remediation strategies, minimize environmental impact, and promote the long-term health and resilience of soils. As technology continues to advance, the synergy between monitoring and simulation will play a pivotal role in shaping the future of soil health.

3.3 Advanced remediation technologies

3.3.1 Green remediation materials and technologies

Incorporating environmentally friendly and sustainable materials into remediation efforts presents an eco-conscious approach (Fig. 4). Green remediation materials include natural substances and innovative technologies that minimize environmental impact. For instance, the use of bio-based surfactants, biodegradable polymers, and plant-derived materials can enhance the effectiveness of traditional remediation techniques like soil washing and chemical immobilization. Using anionic-nonionic mixed surfactants, the soil flushing of phenanthrene was significantly enhanced (Zhou and Zhu, 2008; Zhang and Zhu, 2009). These materials not only aid in contaminant removal but also contribute to the overall ecological health of the soil. Moreover, their renewable nature reduces the carbon footprint associated with remediation processes.

3.3.2 Monitored natural attenuation (MNA)

MNA is an approach that harnesses natural processes within the soil to attenuate contaminants over time. This method relies on monitoring and managing the conditions favorable for natural degradation, sorption, and dilution of pollutants (U.S. Environmental Protection Agency, 2001). While particularly effective for large-scale contamination scenarios, MNA requires a thorough understanding of site-specific conditions and contaminant behaviors. Integrating MNA into soil remediation strategies minimizes the need for extensive engineering interventions, reducing energy consumption and overall environmental disturbance. By allowing natural processes to take precedence, MNA aligns with the principles of sustainability and offers a cost-effective, long-term solution for large contaminated areas.

3.3.3 Integrated multimedia remediation

Integrated remediation encompassing air, surface water, soil, and groundwater is crucial for comprehensive soil remediation, addressing the interconnected nature of environmental compartments (Fig. 4). A holistic approach is essential to prevent the transfer and cycling of contaminants between these mediums, mitigating the risk of persistent contamination. Achieving integrated remediation involves coordinated efforts, utilizing technologies and strategies that target multiple environmental compartments simultaneously. For instance, phytoremediation techniques involving the use of plants can simultaneously improve air quality, filter surface water runoff, and enhance soil health by extracting and metabolizing contaminants. Additionally, implementing sustainable land management practices and adopting eco-friendly technologies in industrial processes contribute to reducing overall pollutant emissions across air, water, and soil. This approach not only ensures effective soil remediation but also promotes overall environmental sustainability and resilience.

3.3.4 Integrated soil remediation and carbon storage

Contaminants in soil not only pose risks to ecosystems and human health but also affect the soil's ability to sequester carbon, contributing to climate change. Implementing a holistic approach involves addressing pollutant removal, soil structure improvement, and the promotion of microbial activity. Concurrently, adopting practices that enhance carbon storage in soils, such as agroforestry, cover cropping, and organic matter addition, reinforces the soil's resilience. By integrating soil remediation efforts with carbon storage strategies, a synergistic approach emerges that not only mitigates contamination but also contributes to climate change mitigation. The routes for this integration include the promotion of sustainable land management practices, afforestation initiatives, and the use of biochar to enhance soil structure and carbon sequestration. For instance, a two-year field trial suggests that biochar effectively decreased bioavailable Cd content from 0.41 to 0.08 mg/kg and increased soil organic matter from 18.5 to 24.1 g/kg (Liu et al., 2022a). Notably, significant knowledge gap exists in the aforementioned technologies to integrated soil remediation and long-term carbon storage, necessitating further research studies.

3.4 Holistic soil management approaches

3.4.1 Soil regulatory framework

Establishing a comprehensive soil regulatory framework is imperative for promoting sustainable remediation practices. Governments and environmental agencies play a pivotal role in this process by formulating and implementing guidelines and standards that incentivize the adoption of environmentally friendly soil management practices. These regulations can encompass a range of aspects, including permissible levels of contaminants in soil, guidelines for responsible waste disposal, and protocols for sustainable land use. Additionally, these frameworks can encourage the development and implementation of innovative technologies and methodologies that align with sustainable practices, fostering a continuous improvement cycle in soil management strategies. Moreover, a robust regulatory framework provides a legal foundation for holding entities accountable for soil contamination, deterring improper disposal practices, and facilitating a systematic approach to remediation efforts. In essence, a well-crafted soil regulatory framework serves as a cornerstone for steering soil management toward sustainability, balancing the needs of human development with environmental preservation.

3.4.2 Soil health index system

A key component of holistic soil management is the establishment of a comprehensive soil health indicator system. This system should incorporate a range of physical, chemical, and biological parameters to assess the overall health and functionality of the soil. Monitoring indicators such as microbial diversity, organic matter content, and nutrient levels provides insights into the soil's capacity for self-regeneration. An effective indicator system enables practitioners to tailor remediation strategies based on the specific needs of the soil, ensuring sustainable outcomes (Kim et al., 2020). Notably, biological indicators, encompassing animals, plants, and microbes, are crucial for assessing soil functions and largely missing in existing index system. However, the adaptability of these indicators may vary based on local soil types and geological conditions. Therefore, it is essential to consider regional differences when developing biological indicators, ensuring their relevance and effectiveness in diverse environmental contexts.

3.4.3 Soil safety and health monitoring platform

Collecting and analyzing vast amounts of data from diverse sources, including satellite imagery, sensor networks, and historical records, allows for a more nuanced understanding of soil conditions and contaminant distributions. Leveraging big data technologies can revolutionize soil management and remediation efforts (Cheng et al., 2023). Machine learning algorithms can identify patterns, predict outcomes, and optimize remediation strategies (Liu et al., 2022c). By harnessing the power of big data, stakeholders can make informed decisions, streamline remediation processes, and adapt strategies in real-time, fostering a data-driven and sustainable approach to soil management. Additionally, creating centralized platforms for sharing information, data, and best practices facilitates collaboration among stakeholders. These platforms can serve as hubs for regulatory updates, case studies, and advancements in soil management, promoting transparency and knowledge exchange.

The integration of these holistic soil management approaches aligns with the principles of sustainability, balancing environmental protection with human development needs. By combining a supportive regulatory framework, a comprehensive indicator system, and monitoring platform, soil safety practices can be tailored to address the unique challenges of each site, promoting the long-term health and resilience of our soils.

4 Conclusions

Soil is a non-renewable resource that take 100–1000 years for 1 cm of soil to form. Soil contamination, fueled by industrial activities, poses a formidable threat to ecosystems and human health. The imperative for soil safety and health is underscored by the critical role soil plays in global food production, fiber supply, and carbon regulation. While numerous remediation technologies have been developed, maintaining the structure and ecological functions of soil during remediation remains challenging. Further, managing regional soil contamination poses unique challenges compared to single-site remediation efforts. Tackling these challenges require comprehensive understanding of complex pollutant transportation and transformation in soils, where innovation in soil contamination monitoring devices, models, and big data bridging micro- and macro-scale processes could offer new opportunities. In addition, advanced green remediation technologies and holistic soil management approaches could collectively provide a comprehensive framework for sustainable soil remediation. As we strive for effective and environmentally conscious solutions, a harmonized effort among scientists, engineers, policymakers, and communities is essential to ensure the long-term health and resilience of our soils.

Acknowledgements This study was supported by the National Key Research and Development Program of China (No. 2021YFC1809204).

Conflict of Interests Lizhong Zhu is an editorial board member of *Frontiers of Environmental Science & Engineering*. The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Author Biography

Lizhong Zhu is a professor in the College of Environmental & Resource Sciences at Zhejiang University, a member of Chinese Academy of Engineering, and a fellow of the Royal Society of Chemistry. He has achieved a series of innovative outcomes in the field of interfacial behavior and regulation technologies for organic pollutants between soil and water. Through his work, the molecular mechanisms of non-linear behavior at the multi-media interface of organic pollutants and the associated principles of regulation and control technologies have been illuminated. The application of organic bentonite for wastewater treatment has been developed. A series of new technologies have been established to mitigate soil organic pollution in farmland, and ensure the safe production of agricultural products. The technical systems and engineering schemes for collaborative remediation of various complex organic contaminated sites have been constructed. He has published 6 books and 355 papers journals papers, with a total citation of > 19000. He has received 25 national invention patents. Seven achievements won the first prize of Zhejiang Province and the Ministry of Education, and two achievements won the second prize of the National Science and Technology Progress Award and second prize of the National Natural Science Award.