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Editorial

Innovative Technologies for Soil and Water Remediation

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Soil and water serve a pivotal role in surficial earth processes, such as life support and elemental circulation, which are responsible for sustaining ecological health and perpetuating human civilization. Both soil and water are essential sources that direct or provide the habitats for living organisms, mitigate climate change, and support energy transformation. For example, soil is the largest terrestrial carbon reservoir, with ~55% of the total soil organic carbon (SOC) stock to 1 m (containing ~1505 Pg C), about twice the amount of carbon in the atmosphere [1,2]. The dynamic changes of this carbon pool directly affect greenhouse gas emissions by regulating the carbon/nitrogen cycle, which, in turn, has a profound impact on the global climate. Meanwhile, as a medium of energy conversion, water drives energy flow in the climate system through evaporation, condensation and precipitation. Within terrestrial ecosystems, soil and water are often regarded as dominant sinks, accumulating and retaining a wide range of contaminants [3]. The complexity of pollution sources and cross-media migration pathways, including atmospheric deposition, surface runoff, and groundwater infiltration, pose significant challenges for accurate source identification [4]. These dynamic transport processes not only complicate contamination attribution but also amplify the spatial–temporal variability of pollutant distribution in terrestrial systems, especially the soil. Therefore, establishing a comprehensive monitoring network becomes imperative to (1) track contaminant migration paths, (2) quantify source contributions, and (3) assess system resilience. Such infrastructure forms the foundation for maintaining environmental health, protecting ecosystem services, and ultimately supporting sustainable development.

Pollution control and management is a mode of systematic engineering aimed at using science and technology to reduce the hazards of pollutants to the soil, water, and air. First of all, we identify pollution sources through remote sensing technology or isotope tracing technology. Machine learning models are then used to analyze the vast amount of data obtained to visualize their spatial distribution pattern, recognize the sources, and quantify their contributions. Furthermore, machine learning models were used to further promote the accuracy of models for better presentation of the results [5]. The integration of these advanced methodologies has fundamentally transformed the paradigm of remediation engineering, which has been successfully applied in cases of heavy metal pollution in farmland soil. By analyzing multi-source data, these technologies can identify the main emission sources (such as industrial emissions or atmospheric deposition) and predict pollution trends with high precision. This data-based approach helps select the best remediation methods through hierarchical classification and scenario simulation. For example, for mildly contaminated farmland soil, passivation/stabilization remediation is

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Received: 7 July 2025
Accepted: 17 July 2025
Published: 22 July 2025

Citation: Yang, X.; Li, J.; Wang, F. Innovative Technologies for Soil and Water Remediation. *Water* **2025**, *17*, 2174. https://doi.org/10.3390/w17152174

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often used in conjunction with the application of organic fertilizers [6]. For moderately contaminated farmland soil, a combination of hyperaccumulator plants and microorganisms is preferred [7]. Additionally, to ensure the durability of the remediation effect, long-term tracking and comprehensive evaluation should be carried out through geostatistics, the geographic information system, and life cycle assessment. At the same time, through real-time data fusion and model iterative update technologies, the strategies can be dynamically adjusted, effectively addressing the risk of secondary pollution [8]. Such a comprehensive framework not only enhances decision-making transparency but also provides theoretical support for intelligent environmental governance.

The comprehensive management framework provides a macroscopic strategy for farmland soil remediation. However, to further optimize the remediation efficiency, it is necessary to analyze the interaction between pollutants and remediation materials at the molecular level [9]. From the perspective of basic science, a thorough understanding of microscopic remediation mechanisms is essential for improving existing technologies or developing new ones. Based on synchrotron radiation extended X-ray absorption fine structure (EXAFS), it was revealed that Cd forms more stable inner-sphere complexes with minerals and carboxyl groups (such as Cd-O(Fe/C) and Cd-O(C) bonds). Density functional theory (DFT) calculations quantified the energy of different binding configurations, and it was found that the Cd-O(Fe/C) configuration had the highest binding energy (3.39–4.89 eV). Single-molecule force spectroscopy (SMFS) combined with K-means clustering analysis directly measured the binding force between Cd^{2+} and goethite, confirming that the binding force corresponding to the carboxyl group was the strongest (741.8 pN) [10]. These results elucidate the molecular-level mechanism by which DOM functional groups (especially carboxyl groups) enhance Cd immobilization by optimizing binding configurations and increasing binding energy. These insights directly guide material optimization strategies by using specific modification methods to maximize the formation of these key functional groups (such as carboxyl groups), thereby strengthening the immobilization ability of the modified materials for Cd^{2+}. The integration of microscopic insights into macroscopic management frameworks enables predictive material selection and targeted functionalization, moving soil remediation from a trial-and-error approach to a rationally engineered solution. Future research directions should focus on extending these fundamental principles to complex multi-pollutant systems and field-scale applications, ensuring that molecular insights translate to practical environmental benefits.

As the demand for natural resource conservation and remediation increases, the sustainability of remediation objects is a new and challenging issue for remediation management. This issue requires that not only the immediate environmental intervention effects but also the long-term ecological and socioeconomic benefits be considered in the remediation process. Therefore, a goal-oriented sustainability assessment approach has emerged, which emphasizes the development and implementation of nature-based strategies to strike a balance of remediation effectiveness and environmental receptivity. Sustainability assessment focuses on maintaining and improving soil fertility for agricultural soil, while controlling potential environmental risks for industrial land. This includes an assessment of the soil's carrying capacity, stability, permeability, and chemical properties that may affect the durability of building structures. In summary, goal-oriented sustainable assessment not only emphasizes the scientific evaluation of the current state of the land but also focuses on the prediction of future land use potential and risk. This approach reflects a deep understanding of the characteristics of the remediation target and its environmental, social, and economic context, and is an important tool for addressing the challenges of remediation management.

Overall, this Special Issue of *Water* contains 11 studies on the current progress of innovative technologies in the field of soil and water remediation. These studies have made strides in controlling pollution by exploring novel remediation techniques, such as phytoextraction, soil stabilization, and the use of nanocomposites for pollutant degradation. They also provide insights into the environmental behavior of specific contaminants, such as arsenic and anatoxin-a, and their risks to ecosystems and human health. Nevertheless, future research should focus on the development of interdisciplinary approaches that combine chemistry, biology, materials science, and data science to create more effective and sustainable remediation solutions. Additionally, there is a pressing need for the long-term monitoring and evaluation of remediation efforts to ensure their durability and effectiveness over time. We look forward to more innovative research results to promote the advancement of environmental remediation technologies and the improvement of environmental management.

Author Contributions: Conceptualization, X.Y., J.L. and F.W.; writing—original draft preparation, X.Y.; writing—review and editing, X.Y., J.L. and F.W. All authors have read and agreed to the published version of the manuscript.

Funding: The authors gratefully acknowledge the financial support provided by the National Natural Science Foundation of China (Grant No. 42207456, U21A2023).

Acknowledgments: The authors of this paper, who served as the Guest Editors of this Special Issue, would like to express their gratitude to the journal editors, all authors submitting papers, and the referees who contributed to revising and improving the eleven published papers.

Conflicts of Interest: 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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