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Soil pollution and remediation: emerging challenges and innovations

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This perspective addresses the critical issue of soil pollution, exacerbated by rapid urbanization, intensive agriculture, and climate change, which introduces a complex mix of contaminants such as heavy metals, pesticides, per- and polyfluoroalkyl substances, and microplastics into the soil. These pollutants pose severe risks to environmental health and agricultural productivity by altering soil functionality and contaminant mobility. This perspective summarizes innovative monitoring and remediation technologies, including advanced sensors and bioremediation strategies, that enable real-time detection and effective management of soil pollutants. The integration of artificial intelligence and machine learning offers significant advancements in predicting and managing soil contamination dynamics. Furthermore, the perspective discusses the challenges and future directions in soil pollution research, particularly the need for robust policy frameworks and international cooperation to effectively manage and mitigate soil contamination. Emphasizing a multidisciplinary approach, this study calls for enhanced global standards, public engagement, and continued scientific research to develop sustainable solutions for soil remediation and to ensure the protection of vital soil resources for future generations.

KEYWORDS

soil pollution, soil remediation, extreme weather, pollution sensor, environment policies

Introduction

Soil pollution, driven by rapid urbanization, intensive agriculture, and industrial expansion, represents a critical environmental concern (Zhang et al., 2023; Roy et al., 2022). The mixed matrix of pollutants in soils, such as heavy metals, pesticides, pharmaceuticals, per- and polyfluoroalkyl substances (PFAS), and microplastics, poses significant risks to soil health and agricultural productivity, complicating remediation efforts (Maddela et al., 2022; Liu et al., 2024). Climate change further affects soil pollution dynamics, altering pollutant behavior, mobility, and environmental fate (Biswas et al., 2018). Concurrently, advances in analytical methods, sensors, and artificial intelligence present opportunities for precise and real-time monitoring and management of soil contamination (Fan et al., 2022; Aniagor et al., 2022). This paper examines recent advances in understanding soil contaminants, the impact of extreme climate-induced changes on pollutant dynamics, and innovative technologies for pollution monitoring, assessment, and remediation. Furthermore, it explores integrated policy frameworks, social-economic initiatives, and education efforts for protecting soil resources, aiming to guide future research, policy development, and global collaboration.

Emerging challenges

Soil co-contamination with inorganic and organic pollutants, along with particle matters is increasingly common due to complex industrial activities and the reuse of waste materials (Bian et al., 2024). Understanding these interactions is challenging since coexisting pollutants can alter each other's physicochemical behavior and toxicity, subsequently affecting the effectiveness of soil remediation strategies (Nie et al., 2024; Zeng et al., 2024). For example, combined metals, organic contaminants (such as petroleum, pesticides, pharmaceuticals, and PFAS), or microplastics can exacerbate toxicity beyond individual effects or enhance each other's mobility and persistence in the soil matrix (Deng et al., 2017; Kastury et al., 2023). Current soil pollution studies primarily focus on a single pollutant or a group of similar pollutants; thus, improving knowledge of pollutant interactions is critical for risk assessments and effective remediation.

Extreme weather conditions, including temperature fluctuations, flooding, and drought, significantly affect the fate and transport of soil contaminants. Elevated temperatures can increase the volatilization of pollutants (e.g., mercury or polycyclic aromatic hydrocarbons), promoting their atmospheric transport and deposition (Chételat et al., 2022; Gbeddy et al., 2020). Flooding alters soil physicochemical conditions, mobilizing contaminants previously bound to soil matrices and significantly increasing pollutant mobility (Ciszewski and Grygar, 2016). Additionally, intense rainfall events accelerate contaminant leaching, potentially altering transport patterns of pollutants (Stuart et al., 2011). Drought concentrates contaminants and enhances soil oxidation, which may shift redox-sensitive species and alter organic pollutant transformation pathways (Zhang and Furman, 2021). Due to the increasing frequency of extreme weather events, future research should integrate climate variables into soil pollution migration models.

Rapid urbanization and intensified agriculture introduce soil to a wide range of contaminants, thereby disrupting soil health and its ecological functions (Chen, 2007; Li et al., 2018). Urban sources like industrial emissions, road dust, construction materials, and waste disposal contribute contaminants such as heavy metals, hydrocarbons, PFAS, and hazardous particles (Goonetilleke et al., 2017; Sager, 2020; Yao et al., 2024). Agricultural practices add significant loads of pesticides, herbicides, synthetic fertilizers, and veterinary pharmaceuticals, which accumulate in soil over time (Yan et al., 2022). These contaminants pose risks to human health through direct exposure, bioaccumulation in food chains, and groundwater contamination (Baweja et al., 2020). Innovative approaches are needed to prevent soil pollution amid sustainable urbanization and agricultural intensification.

Innovative monitoring and remediation technologies

Advanced sensing technologies enable specific, real-time detection of soil contaminants such as molecularly imprinted polymers, aptamers, microbial biosensors, and microelectromechanical systems-based arrays (Shah et al., 2023). Integrated with wireless platforms, these tools support continuous monitoring, timely data delivery, and informed mitigation strategies for stakeholders (Tsakiridis et al., 2023). Recent advances in sensor technology for monitoring soil contaminants are characterized by breakthroughs in microfluidics, miniaturization, and multiplexing techniques. Microfluidics enables precise control of flow and reaction conditions, thus promotes sample processing efficiency (Aryal et al., 2024). Miniaturized sensors allow for portable or field-deployable detection for *in-situ* monitoring with reduced field sampling and laboratory analysis (Satish, 2024). Multiplexed platforms are cost-effective and designed for the simultaneous detection of multiple pollution (Coskun et al., 2019). These innovations are driving the development of next-generation sensors for scalable soil pollution monitoring.

Artificial Intelligence (AI) and advanced statistical methods represent emerging tools for tackling the complexity of soil pollution dynamics (Wani et al., 2024). Deep-learning algorithms, such as convolutional neural networks, analyze high-dimensional sensor data and hyperspectral images for soil pollution identification and spatial mapping (Wang et al., 2024). Machine learning approaches, such as random forests, support vector machines, and gradient-boosting models, have been applied in modeling source attribution or soil contaminant distribution (Wei et al., 2019; Sakizadeh et al., 2017; Wang et al., 2020). Additionally, advanced geostatistical techniques, such as Bayesian hierarchical modeling and kriging interpolation, provide frameworks to quantify uncertainties and predict contaminant transport at large scales (Wang et al., 2023; Boente et al., 2019). Future research should integrate AI-driven analytical workflows for proactive pollution management.

Advances in bioremediation are revolutionizing soil remediation efforts using biological agents to degrade persistent contaminants such as PFAS (Ye et al., 2017; Lee et al., 2025). Recent studies have utilized engineered microbial strains, which can defluorinate PFAS under anaerobic conditions, significantly reducing PFAS toxicity and persistence (Smorada et al., 2024). Phytoremediation research has led to a new direction using genetically engineered plants with enhanced detoxifying enzymes for the degradation of broader organic pollutants (Abhilash et al., 2009). To enhance bioremediation of soil contaminants, future research should explore targeted genetic improvements in plants and microbes, along with the optimization of metabolic pathways for pollutant degradation with emphasis on field-scale validation.

Policy and regulatory developments

Strengthening global regulatory standards is critical for effectively managing soil pollution, particularly for contaminants with transboundary impacts, such as airborne heavy metals, persistent organic pollutants (POPs), or PFAS. International agreements, like the Stockholm Convention on POPs and the United Nations Environment Programme (UNEP)'s guideline for PFAS, emphasize global cooperation for managing traditional and emerging contaminants in soil. (Cheng et al., 2023; Fiedler et al., 2022). However, substantial gaps remain due to a lack of unified guidelines and consistent monitoring protocols for pollutants globally. Future policymaking should enhance global standards and cooperation frameworks to improve the capacity to manage the risks associated with transboundary soil contamination.

Evidence-based policymaking for soil pollution control requires the integration of regulatory decisions with scientific data. Recent examples include the European Union's Soil Strategy for 2030, which incorporates data from large-scale monitoring programs and advanced risk assessment methodologies, and the U.S. EPA's evolving guidelines on PFAS, informed by ongoing toxicological and environmental research (Panagos et al., 2022). Leveraging machine learning and data analytics for predictive scenario modeling, current research data enable risk forecasting to support policy-related decision-making processes. Future research efforts should focus on improving the transparency and accessibility of scientific data, enhancing collaboration, and developing adaptive policy frameworks that can incorporate new scientific insights rapidly.

Public engagement and education are crucial for soil pollution prevention and management. Recent community science projects, such as citizen-led microplastic monitoring campaigns, have demonstrated that informed community participation can enhance data collection capabilities and increase public awareness (Sinha et al., 2024). By combining science with community outreach, "SoilSHOP" initiative led by the U.S. Agency for Toxic Substances and Disease Registry empowers individuals to take action and reduce exposure risks in their own environments (Saikawa et al., 2023). Future outreach efforts should prioritize developing accessible educational resources encouraging community participation for collaborative approaches toward sustainable soil management.

Soil contamination reduces agricultural productivity imposes significant social and economic burdens, exacerbating social inequalities (Martinho, 2020). Economically, soil pollution contributes to substantial losses, land devaluation, and high remediation costs (Graves et al., 2015). Future research should prioritize incorporating socio-economic vulnerability indicators into pollution risk assessment frameworks, that could enhance the equitable pollution control policies, thus better protecting vulnerable communities. Economic modeling quantifies the long-term economic benefits of soil protection and pollution management should also be emphasized to reinforce the soil remediation investment.

Conclusion

Co-contamination, extreme weather events, rapid urbanization, and intensified agriculture pose significant challenges for protecting soil resources. These challenges highlight the importance of integrating advanced monitoring technologies, precise analytical tools, and science-based policies. Embracing sustainable practices combined with enhanced global standards and targeted bioremediation can effectively manage soil contaminants and facilitate restoration. Addressing socioeconomic impacts, actively promoting and engaging local communities, and continuous collaboration among scientists, policymakers, and the public remain essential for protecting soil resources and promoting soil health.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

HC: Writing – original draft. BG: Writing – review and editing, Conceptualization. YL: Validation, Writing – review and editing, Conceptualization, Supervision.

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