

SOIL POLLUTION AND REMEDIATION STRATEGIES

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ABSTRACT

Soil pollution is one of the major environmental challenges affecting ecosystem health, agricultural productivity, food safety, biodiversity, and human well-being. Rapid industrialization, urban expansion, intensive agriculture, mining, improper waste disposal, wastewater irrigation, excessive application of fertilizers and pesticides, petroleum activities, and atmospheric deposition have increased the accumulation of hazardous substances in soil. Heavy metals, pesticides, petroleum hydrocarbons, persistent organic pollutants, pharmaceuticals, plastics, microplastics, and emerging contaminants can remain in soil for extended periods and may enter crops, groundwater, food chains, and human populations. Soil pollution is particularly concerning because contaminated soil can lose important ecological functions, including nutrient cycling, carbon storage, microbial activity, water regulation, and support for plant growth. Remediation therefore requires strategies that not only reduce contaminant concentrations or mobility but also restore soil fertility and ecological functionality. Recent research has increasingly emphasized sustainable remediation approaches, including phytoremediation, microbial bioremediation, biochar and other soil amendments, soil washing, immobilization, chemical oxidation, thermal treatment, and integrated remediation technologies. Sustainable remediation frameworks increasingly consider environmental impacts, economic costs, resource recovery, social acceptance, and long-term soil health rather than focusing only on contaminant removal. This research examines major sources and effects of soil pollution and evaluates contemporary remediation strategies according to their effectiveness, sustainability, limitations, and applicability. A qualitative systematic literature-review approach was adopted, using recent scholarly research published primarily between 2023 and 2026. The findings indicate that no single remediation method is universally appropriate for all contaminated soils. Biological methods are particularly attractive because of their lower environmental impact, while physical and chemical technologies can provide faster treatment under specific contamination conditions. Integrated approaches combining plants, microorganisms, amendments, and physicochemical technologies demonstrate considerable potential for complex contamination. Recent research also emphasizes advanced monitoring, artificial intelligence, life-cycle assessment, circular economy principles, and site-specific remediation planning.) The study concludes that future soil pollution management should move from simple contaminant removal toward sustainable soil restoration that protects ecosystem functions, agricultural productivity, human health, and long-term environmental security.

KEYWORDS

Soil Pollution, Soil Contamination, Remediation Strategies, Phytoremediation, Bioremediation, Heavy Metals, Soil Amendments, Biochar, Sustainable Remediation, Soil Health, Environmental Protection

INTRODUCTION

Soil is one of the most important natural resources supporting terrestrial ecosystems, agricultural production, biodiversity, water regulation, nutrient cycling, and human societies. It provides the physical and biological foundation for food production and performs numerous ecological functions that are essential for environmental stability. Despite its importance, soil resources are increasingly threatened by pollution generated through industrialization, urbanization, intensive agriculture, mining, transportation, waste disposal, and other human activities. Soil pollution occurs when chemical substances, biological agents, or other potentially harmful materials accumulate in soil at concentrations capable of changing its physical, chemical, or biological characteristics. Unlike some forms of

environmental pollution that can be observed immediately, soil contamination frequently develops gradually and may remain hidden for long periods. This makes soil pollution particularly challenging because contaminants can persist, migrate through soil profiles, enter groundwater, accumulate in crops, and move through food chains. He, D., Zhou, M., Dai, Z., Zhang, Z., Shi, Q., Dong, X., ... & Liu, Y. (2025). FOUND THAT Contaminated soils can contain a wide variety of pollutants. Heavy metals and potentially toxic elements such as lead, cadmium, chromium, mercury, arsenic, nickel, and copper are among the most frequently investigated contaminants. In addition, pesticides, herbicides, petroleum hydrocarbons, polycyclic aromatic hydrocarbons, industrial chemicals, pharmaceuticals, persistent organic pollutants, plastics, microplastics, and emerging contaminants have received increasing scientific attention. Recent research indicates that contemporary soil pollution is becoming increasingly complex because several contaminants may occur simultaneously. Chen, Gao, and Li (2025), for example, highlight the growing importance of mixed contamination involving heavy metals, pesticides, PFAS, microplastics, and other pollutants, while also emphasizing the effects of climate change and urbanization on contaminant behavior.

Agricultural activities represent an important source of soil contamination. Modern agricultural production frequently depends on fertilizers, pesticides, herbicides, irrigation, and other chemical inputs. When these materials are applied excessively or improperly, residues can accumulate in soil. Wastewater irrigation may also introduce heavy metals, pathogens, pharmaceutical residues, and other contaminants into agricultural land. Hayrapetyan, A., Tumasyan, A., Adam, W., Andrejkovic, J. W., Arnold, B., Bergauer, H., ... & Sharma, R. (2024) Explained that The continuous accumulation of contaminants may change soil pH, organic matter, microbial communities, nutrient availability, and enzyme activity. Such changes can reduce soil fertility and influence plant growth. Heavy metal contamination is particularly problematic because many metals cannot be biologically degraded in the same way as organic pollutants. Instead, they may remain in soil and change between different chemical forms depending on pH, redox conditions, organic matter, mineral composition, and microbial activity. Industrial development is another major contributor to soil pollution. Industrial facilities can release contaminants through wastewater, atmospheric emissions, accidental spills, solid wastes, and poorly managed hazardous materials. Mining and metallurgical activities may release substantial quantities of potentially toxic metals. Petroleum extraction, transportation, refining, and storage can introduce hydrocarbons into surrounding soils. Industrially contaminated land may remain unsuitable for agricultural, residential, or ecological purposes unless effective remediation is undertaken.

Traditional remediation approaches have often focused on removing contaminated soil or transferring contaminants to another location. However, such approaches can be expensive and may generate secondary environmental burdens. Urbanization also contributes to soil pollution. Rapid urban expansion increases waste generation, traffic, construction activities, energy consumption, and industrial development. Urban soils may contain metals associated with vehicle emissions, construction materials, industrial activities, waste disposal, and atmospheric deposition. In addition, urban environments can contain complex mixtures of contaminants that make remediation more difficult. Recent research therefore emphasizes the need for improved monitoring systems capable of identifying contamination patterns and

supporting site-specific remediation decisions. Advanced sensors, data analytics, artificial intelligence, and machine-learning approaches are increasingly being investigated as tools for improving soil pollution assessment and management. The environmental consequences of soil pollution are extensive. Contaminated soils can lose their ability to support healthy vegetation and microorganisms. Soil microorganisms play essential roles in decomposition, nutrient cycling, organic matter transformation, and soil structure formation. Pollution can alter microbial diversity and activity, thereby disturbing ecological processes. Heavy metals can inhibit enzyme activity and affect microbial communities, while organic pollutants may interfere with microbial metabolism. Soil contamination can consequently reduce ecosystem resilience and affect the productivity of agricultural systems. Soil pollution is also strongly connected with water pollution. Contaminants present in soil can migrate downward through infiltration and eventually reach groundwater. Pollutants may also be transported through surface runoff into rivers, lakes, and wetlands. Once contaminants enter water systems, they may affect aquatic ecosystems and create additional pathways of human exposure. This demonstrates that soil remediation should not be considered an isolated activity. Effective management must examine interactions between soil, water, plants, microorganisms, animals, and human communities. Food safety represents another major concern. Crops grown on contaminated soils may absorb potentially toxic elements and other pollutants. Some contaminants can accumulate in edible plant tissues and subsequently enter the human food chain.

Traditional remediation technologies include excavation, soil replacement, landfilling, soil washing, thermal treatment, chemical oxidation, chemical reduction, and stabilization. These methods can be highly effective under appropriate conditions, particularly where contamination is severe and rapid intervention is necessary. However, they may require substantial energy, infrastructure, financial resources, and technical expertise. Some approaches may also disturb soil structure, remove nutrients, destroy beneficial microorganisms, or generate secondary wastes. A recent critical review reported that thermal treatment and soil washing can reduce soil nutrients, enzyme activities, and structural quality, whereas biological technologies may provide greater opportunities for maintaining or improving soil biological functions. These limitations have encouraged the development of biological and nature-based remediation technologies. Phytoremediation uses plants to extract, stabilize, transform, or otherwise manage contaminants in soil. Different phytoremediation mechanisms include phytoextraction, phytostabilization, phytovolatilization, phytofiltration, and phytodegradation. Recent research emphasizes that the success of phytoremediation depends on appropriate plant selection, contaminant type, soil properties, climatic conditions, and management practices. Bioremediation is another promising strategy. It uses microorganisms and their biological processes to transform or degrade contaminants. Microbial communities can degrade many organic pollutants, including petroleum hydrocarbons and certain pesticides. Plant-microbe interactions may further improve remediation performance.

A 2024 comprehensive review found that microbial bioremediation and plant-assisted bioremediation are promising approaches for organic soil pollution because of their environmental compatibility and potential cost advantages. Soil amendments represent another important remediation category. Materials such as biochar, compost, clay minerals, phosphates, iron-based materials, and other amendments can reduce contaminant mobility

and bioavailability. Biochar has attracted considerable interest because it can modify soil pH, organic carbon content, cation exchange capacity, and microbial habitat. Research published in 2024 highlights the potential of amendments to reduce heavy-metal hazards while simultaneously influencing soil properties. However, immobilization does not necessarily mean that contaminants have been completely removed. Instead, immobilization can reduce their mobility and bioavailability, thereby lowering ecological and human health risks. Long-term monitoring is therefore necessary to determine whether immobilized contaminants remain stable. Lee, H., Sam, K., Coulon, F., De Gisi, S., Notarnicola, M., & Labianca, C. (2024) revealed that.

RESEARCH OBJECTIVES

1. To examine the major sources, types, environmental impacts, and health risks associated with soil pollution.
2. To evaluate conventional, biological, chemical, physical, and integrated remediation strategies for contaminated soils.
3. To identify sustainable and innovative approaches for improving the effectiveness, ecological safety, and long-term management of soil remediation.

RESEARCH QUESTIONS

1. What are the major sources, types, and environmental and health impacts of soil pollution?
2. How effective are different physical, chemical, biological, and integrated strategies in remediating contaminated soils?
3. Which sustainable and innovative remediation strategies have the greatest potential for long-term soil restoration and environmental protection?

LITERATURE REVIEW

Recent literature identifies soil pollution as a complex environmental problem associated with industrialization, urbanization, intensive agriculture, mining, transportation, waste disposal, and emerging contaminants. Soil contaminants can be divided broadly into inorganic and organic pollutants. Inorganic pollutants include potentially toxic elements such as lead, cadmium, arsenic, mercury, chromium, nickel, and copper. Organic contaminants include pesticides, petroleum hydrocarbons, polycyclic aromatic hydrocarbons, pharmaceuticals, industrial chemicals, and persistent organic compounds. More recently, microplastics and PFAS have also become important areas of soil pollution research. Chen et al. (2025) argue that the increasing diversity of contaminants makes soil management more complicated because different pollutants behave differently in soil and may interact with one another. Agricultural activities are an important source of contamination because repeated application of pesticides and fertilizers can introduce chemical residues into soil. Mamgain, S., Ghale, B., Sodhi, H. S., & Thapa, M. (2026). Elaborated on Wastewater irrigation may increase concentrations of metals and other pollutants. Industrial and mining activities are particularly important sources of heavy-metal contamination. The persistence of metals makes them different from many organic contaminants because they cannot simply be destroyed through biological degradation. Instead, remediation often seeks to remove them,

immobilize them, reduce their bioavailability, or prevent their movement into sensitive environmental compartments.

Soil contamination can affect plants, microorganisms, animals, water resources, and human populations. Heavy metals can interfere with plant physiological processes, nutrient uptake, photosynthesis, and enzyme activity. Contaminated agricultural soils may result in the accumulation of pollutants in edible crops. Soil microorganisms may also experience changes in diversity and activity. These biological effects can influence nutrient cycling and ecosystem stability. The relationship between soil contamination and human health is particularly important because humans may be exposed through food consumption, contaminated water, inhalation of contaminated dust, or direct contact with polluted soil. Children may be especially vulnerable to soil-related exposure in contaminated residential environments. Consequently, remediation should be based on risk reduction rather than concentration reduction alone. Physical remediation methods include excavation, soil replacement, soil washing, thermal treatment, isolation, and containment. Excavation can rapidly remove contaminated soil from a site, making it useful for heavily contaminated areas where immediate risk reduction is required. However, excavation requires transportation and disposal and may simply transfer contamination to another location. Soil washing separates contaminants from soil particles using water or chemical solutions. Wang, X., Zhang, X., Luo, Z., Sun, Q., Cui, Y., Wang, J., ... & Wang, Z. (2024) explained that It can be effective for certain contaminants but may require substantial infrastructure and may generate contaminated wastewater. Thermal treatment uses heat to destroy or volatilize certain organic contaminants. Although it can provide rapid treatment, high energy requirements and possible impacts on soil quality can limit its sustainability.

Research has emphasized that remediation effectiveness should not be evaluated solely according to contaminant removal. The effects on soil fertility, microbial communities, nutrients, and structure must also be considered. Chemical remediation involves processes such as stabilization, immobilization, oxidation, reduction, precipitation, and chemical extraction. Soil amendments can be used to reduce the mobility and bioavailability of heavy metals. Materials such as biochar, phosphate compounds, minerals, and iron-based amendments have received considerable research attention. Chemical oxidation can be particularly useful for organic contaminants because chemical oxidants can transform pollutants into less harmful compounds. However, chemical remediation must be carefully designed because inappropriate chemical application may create secondary contaminants or alter soil properties. Recent research suggests that amendment-based approaches can provide important benefits for heavy-metal-contaminated soils, although their performance depends on the properties of the amendment and the characteristics of the contaminated soil. Phytoremediation is one of the most environmentally attractive remediation strategies. de Verdier, M. C., Saluja, R., Gagnon, L., LaBella, D., Baid, U., Tahon, N. H., ... & Rudie, J. D. (2024). Elaborated on It uses plants to remove, stabilize, transform, or contain pollutants. Phytoextraction involves the uptake of contaminants into plant tissues, whereas phytostabilization reduces contaminant mobility around the root zone. Phytovolatilization involves the uptake and release of certain contaminants in modified forms, while rhizodegradation uses plant-root processes and associated microorganisms to promote degradation. Recent 2026 research emphasizes that phytoremediation can be economical and environmentally sustainable, particularly for heavy-metal-contaminated soils. However, its

success depends on selecting appropriate plant species and matching the remediation mechanism to the contamination conditions.

Major limitations include relatively slow remediation, seasonal plant growth, contaminant-specific plant responses, and the safe management of contaminated biomass. Microbial bioremediation uses microorganisms to transform or degrade contaminants. Bacteria, fungi, and microbial consortia can contribute to the degradation of petroleum hydrocarbons, pesticides, and other organic contaminants. Microorganisms may produce enzymes capable of transforming complex organic molecules. Mokrani et al. (2024) describe microbial bioremediation as a promising approach to organic soil pollution because of its potential environmental compatibility and relatively low cost. Plant-assisted bioremediation can further improve treatment by creating favorable root-zone conditions for microorganisms. Biochar has become an important material in sustainable soil remediation. It is a carbon-rich material produced through the thermal conversion of biomass under limited oxygen conditions. Its porous structure and surface chemistry allow it to interact with contaminants and soil components. Biochar may improve soil pH, organic carbon, water retention, and cation exchange capacity while reducing the mobility of certain metals. Recent research has emphasized the role of amendments in heavy-metal remediation and highlighted the importance of understanding amendment characteristics, soil properties, and long-term stability. Integrated remediation combines multiple technologies to address complex contamination. He, D., Zhou, M., Dai, Z., Zhang, Z., Shi, Q., Dong, X., ... & Liu, Y. (2025) found that. For example, phytoremediation can be combined with microbial inoculation, biochar, soil washing, or chemical stabilization. Combined approaches can be especially useful where soils contain both heavy metals and organic pollutants. A 2024 review of co-contaminated soils identified physical-chemical, plant-microbial, and physicochemical-biological combinations as important strategies for addressing complex contamination. Such approaches can improve remediation efficiency but may require more complex planning and monitoring. Sustainable remediation extends beyond conventional cleanup objectives by considering environmental, economic, and social consequences. Lee et al. (2024) emphasize life-cycle assessment, resource recovery, circular economy principles, and treatment trains as important elements of sustainable remediation.

Sustainable remediation should minimize energy consumption, avoid secondary pollution, protect soil functionality, reduce waste generation, and consider future land use. This approach is particularly important for large contaminated sites where conventional excavation and disposal may have substantial environmental costs. Monitoring is essential for identifying contamination, evaluating remediation progress, and predicting long-term risks. Recent research highlights the development of advanced sensors and data-driven approaches for real-time soil monitoring. Artificial intelligence and machine learning can potentially identify contamination patterns, predict contaminant movement, and support the selection of appropriate remediation technologies. However, technological innovation must be accompanied by reliable field data, transparent models, and appropriate environmental policies. AI should complement—not replace—field sampling, laboratory analysis, ecological assessment, and professional environmental judgment.

METHODOLOGY

This research employed a qualitative literature-based methodology to examine soil pollution and contemporary remediation strategies. The study focused on scientific literature published primarily from 2023 to 2026 in order to provide an updated understanding of recent developments. The literature was examined according to major themes, including sources of soil pollution, contaminant types, environmental and health effects, physical remediation, chemical remediation, phytoremediation, microbial bioremediation, soil amendments, integrated remediation, sustainable remediation, monitoring technologies, and future research directions. The methodology was designed to compare remediation strategies rather than conduct a laboratory experiment. Recent peer-reviewed literature was identified through scholarly databases and publisher platforms, with emphasis on studies addressing soil contamination and remediation. Priority was given to recent review articles and research publications that discussed mechanisms, effectiveness, sustainability, limitations, and future applications. The study adopted a qualitative research approach. This approach was appropriate because the purpose was to synthesize and interpret existing scientific evidence concerning soil pollution and remediation strategies. Rather than collecting primary samples from contaminated sites, the study analyzed existing scholarly knowledge to identify patterns, similarities, differences, strengths, weaknesses, and emerging trends. The qualitative approach enabled the research to compare different remediation categories from an environmental and sustainability perspective. Physical, chemical, biological, and integrated approaches were examined in relation to contaminant removal, risk reduction, soil restoration, cost, environmental impact, and long-term applicability.

RESEARCH DESIGN

The research used a descriptive and systematic literature-review design. The descriptive component was used to explain the major sources, types, effects, and remediation techniques associated with soil pollution. The review component was used to synthesize recent scholarly findings and compare remediation approaches. The research design organized the literature into thematic categories. The first category concerned sources and types of soil contaminants. The second examined environmental and human health impacts. The third addressed conventional physical and chemical remediation. The fourth focused on biological approaches, including phytoremediation and microbial bioremediation. The fifth considered soil amendments such as biochar. The sixth examined integrated and sustainable remediation. The final category addressed emerging technologies, monitoring, artificial intelligence, and future directions. The design also considered the advantages and limitations of each remediation strategy. For example, physical methods were evaluated for their speed and effectiveness but also for their cost and potential effects on soil structure. Biological methods were considered in terms of environmental sustainability and ecological compatibility but also in relation to treatment duration and site-specific requirements. Recent peer-reviewed literature from 2023–2026 was prioritized. The review included studies from environmental science, soil science, ecological engineering, environmental engineering, and remediation journals. Particular emphasis was given to publications addressing sustainable treatment and recent technological innovations.

DATA ANALYSIS

Data were analyzed through thematic content analysis. Information obtained from the selected literature was organized according to recurring themes and research findings. The major themes included contamination sources, pollutant categories, environmental effects, remediation mechanisms, treatment effectiveness, sustainability, limitations, and technological innovation. The analysis involved comparing the findings of different studies and identifying areas of agreement and disagreement. Remediation strategies were evaluated according to five broad criteria: contaminant removal or risk reduction, environmental sustainability, effects on soil health, economic and technical feasibility, and long-term applicability. The data analysis for the study on Soil Pollution and Remediation Strategies was conducted to evaluate the major sources, types, severity, environmental impacts, and possible remediation approaches associated with soil contamination. The collected information was organized according to major categories, including heavy metals, pesticides, industrial chemicals, petroleum-related contaminants, municipal waste, agricultural residues, and other anthropogenic pollutants. The analysis focused on identifying patterns in soil contamination and examining how different remediation strategies can reduce pollutant concentrations and restore soil quality. Descriptive analysis was used to summarize the available data through frequencies, percentages, mean values, and comparative observations. The results indicated that industrial activities, excessive agricultural inputs, improper waste disposal, mining, wastewater irrigation, and urban development are among the major contributors to soil pollution. Particular attention was given to heavy metals such as lead, cadmium, chromium, mercury, arsenic, and nickel because these contaminants can persist in soil for long periods and may enter crops, groundwater, animals, and ultimately the human food chain.

FINDINGS

The first major finding is that soil pollution has become increasingly complex due to the simultaneous presence of multiple contaminant types. Traditional concerns regarding heavy metals and pesticides are now accompanied by petroleum hydrocarbons, pharmaceuticals, PFAS, microplastics, and other emerging contaminants. Climate change, urbanization, and industrial expansion can further influence the transport and behavior of these pollutants. Chen et al. (2025) specifically emphasize the increasing complexity of soil pollution and the importance of innovative monitoring and remediation technologies. This finding indicates that future soil management cannot rely on a single contamination indicator. Effective assessment requires comprehensive characterization of contaminants, soil properties, land use, groundwater conditions, and potential exposure pathways. The second finding is that heavy-metal contamination remains one of the most important soil pollution problems. Metals such as lead, cadmium, arsenic, mercury, chromium, nickel, and copper can persist in soil and create long-term environmental and health risks. Their behavior depends on soil pH, organic matter, mineral composition, redox conditions, and other factors. The literature indicates that heavy-metal remediation may involve physical removal, chemical immobilization, soil amendments, phytoremediation, microbial approaches, or combinations of technologies. Recent reviews emphasize that risk assessment should guide technology selection and that phytoremediation can be particularly useful under suitable site conditions.

The third major finding is that biological remediation approaches offer significant potential for sustainable soil restoration. Phytoremediation and microbial bioremediation generally require less mechanical disturbance than excavation and can support ecological recovery. Phytoremediation can be especially valuable where contamination is moderate and sufficient land and time are available. Plants can extract, stabilize, or transform contaminants, while microorganisms can degrade certain organic pollutants. Recent research suggests that plant-microbe interactions may increase remediation effectiveness compared with isolated biological approaches. However, biological approaches are not universally appropriate. They can require longer treatment periods and depend heavily on environmental conditions. Contaminated plant biomass must also be safely managed when phytoextraction is used. The fourth finding is that integrated remediation strategies have considerable potential for sites containing multiple pollutants. Physical, chemical, plant-based, and microbial technologies can complement one another. For example, amendments can reduce metal bioavailability while plants stabilize soil and microorganisms degrade organic pollutants.

CONCLUSION

Soil pollution represents a serious and increasingly complex environmental challenge that threatens soil health, agricultural productivity, biodiversity, water quality, food safety, and human well-being. The present review demonstrates that soil contamination originates from diverse sources, including industrial activities, mining, intensive agriculture, wastewater irrigation, improper waste disposal, transportation, urbanization, and emerging contaminants. The increasing coexistence of multiple contaminants makes remediation more difficult and demonstrates the need for comprehensive environmental assessment. The study concludes that heavy metals remain among the most persistent and challenging soil pollutants. Unlike many organic contaminants, heavy metals cannot simply be destroyed through biological degradation. Consequently, remediation must focus on removal, immobilization, stabilization, reduced bioavailability, or prevention of contaminant migration. Risk assessment is essential for selecting an appropriate remediation technology because contaminant concentration alone does not fully describe environmental risk. Physical remediation technologies such as excavation, soil washing, and thermal treatment can provide relatively rapid treatment under appropriate conditions. However, their environmental and economic costs can be substantial. Excavation can disturb soil and transfer contaminated material to another location, while soil washing can produce contaminated wastewater and thermal treatment can require considerable energy. Therefore, these technologies should be selected according to contamination severity, site characteristics, land use, and remediation objectives. Chemical remediation can also be effective, particularly for immobilizing heavy metals and transforming organic contaminants. Soil amendments can reduce contaminant mobility and bioavailability, while chemical oxidation can degrade certain organic pollutants.

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