Theory and Practice of Science and Technology
2026, VOL. 7, NO. 2, 106-109
DOI: 10.47297/taposatWSP2633-456921.20260702

A Review of Soil Reconstruction Technologies for Mine Dumps

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ABSTRACT
Soil reconstruction in mine dumps is a critical component of mine ecological restoration. Its core objective is to gradually recover soil functions and ecological processes on disturbed surfaces through substrate optimization, nutrient amendment, microbial regulation, and vegetation establishment. Existing studies indicate that foreign research developed earlier technical pathways represented by organic matter amendment, multilayer cover systems, and the resource utilization of industrial by-products, whereas research in China has progressed rapidly in ecological reclamation in loess regions, gradient amendment in arid areas, biochar-microbe combined remediation, and intelligent monitoring. Overall, soil reconstruction in mine dumps has evolved from simple engineering topsoiling toward coordinated regulation integrating materials, structure, biology, and monitoring. However, major bottlenecks remain, including strong spatial heterogeneity of dump substrates, scarcity of high-quality topsoil resources, and insufficient understanding of long-term soil evolution and ecosystem self-sustainability. This review systematically summarizes recent domestic and international advances, major technical pathways, prevailing trends, and key scientific issues, with the aim of providing a reference for the optimization and engineering application of soil reconstruction technologies for mine dumps.

KEYWORDS
Mine dump; Soil reconstruction; Mine ecological restoration; Biochar; Intelligent monitoring

1 Introduction

Mine dumps are artificial geomorphic units formed by the accumulation of stripped overburden during open-pit mining and some underground mining operations. They commonly exhibit coexisting loose and compacted structures, poor nutrient status, weak water retention and regulation capacity, and deficient microbial communities, making it difficult for vegetation and ecological functions to recover rapidly through natural processes alone[1]. The resulting soil erosion, landscape fragmentation, habitat degradation, and geotechnical risks have become major concerns in ecological governance in mining areas [2].

The goal of soil reconstruction is not merely to apply topsoil and re-green disturbed land. Rather, on the basis of engineering reshaping, it aims to rebuild soil structure, improve physicochemical properties, and restore biological activity so that mine dumps can gradually support vegetation growth, promote material cycling, and maintain ecological stability. Research in this field has evolved from early experience-based topsoiling to an integrated technical system that combines material selection, profile configuration, microbial regulation, vegetation allocation, and digital monitoring [3-4].

Nevertheless, soil reconstruction in mine dumps still faces evident bottlenecks. First, the strong spatial heterogeneity of dump substrates makes it difficult to develop unified technical standards. Second, high-quality topsoil resources are limited, and the safety and long-term stability of substitute materials still require verification. Third, most existing studies emphasize short-term re-vegetation performance, while insufficient attention has been paid to long-term soil evolution, carbon sequestration capacity, and the mechanisms of ecosystem self-maintenance. Therefore, a systematic review of this field is needed to clarify the major technical pathways, research hotspots, and future directions.

2 Research Progress in China and Abroad

2.1 International Research Progress

Research on soil reconstruction in mine dumps started relatively early in other countries and has formed a comparatively complete technical framework. One line of work improves substrate fertility, aggregate structure, and water-holding capacity by adding organic materials, compost, and microbial inoculants, thereby promoting the succession of reconstructed substrates toward soil-like states [5]. In recent years, carbon-rich materials such as biochar, spent mushroom substrate, and composted straw have attracted widespread attention because they not only improve soil quality but also offer carbon sequestration potential [6].

A second line of work focuses on multilayer cover systems. Studies represented by Canadian oil-sands reclamation emphasize the simulation of natural soil profiles through the layered placement of materials with different particle sizes

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and functions, thereby balancing water conservation, aeration, nutrient supply, and resistance to freeze-thaw disturbance [7]. This approach has promoted a shift in mine-dump reclamation from single-layer topsoiling to profile reconstruction [8].

A third line of work concerns the resource utilization of industrial by-products. Some European studies have explored the use of fly ash, steel slag, flue-gas desulfurization gypsum, and related materials for pH regulation, structural improvement, and stabilization, thereby reducing reclamation costs while enabling waste recycling. In general, international studies place greater emphasis on the coupling relationships among material functions, profile design, and long-term ecological processes [9-10].

2.2 Research Progress in China

Although research in China started somewhat later, it has developed rapidly and has gradually formed technical pathways adapted to different regions. In typical mining areas such as the loess region and the Pingshuo mining area, studies have shown that the pathway of loess parent-material cover, surface fertility enhancement, and vegetation reconstruction can significantly improve soil conditions and promote ecosystem succession toward a relatively stable stage. These studies have provided important demonstrations for the ecological reclamation of open-pit coal-mine dumps in China [11].

In the arid and semi-arid regions of northern China, research has mainly focused on water conservation and profile optimization, for example through the layered application of organic materials and inorganic amendments to improve soil water and nutrient retention, together with drought-tolerant pioneer plants to increase survival rates. In cold and high-altitude mining areas, greater emphasis has been placed on integrating soil reconstruction with the restoration of local plant germplasm resources so as to enhance vegetation adaptability and community stability [12].

In the hot and humid regions of southern China, researchers have paid greater attention to soil compaction, nutrient leaching, and insufficient microbial activity, and have proposed technologies such as biochar-microbe combined remediation to improve pore structure and nutrient cycling. Meanwhile, remote sensing, the Internet of Things, and unmanned aerial vehicles have begun to be incorporated into mine-dump monitoring, promoting a transition from experience-based management to data-driven management in soil reconstruction [13-15].

3 Major Technical Pathways and Their Characteristics

The table 1 systematically summarizes five main technical routes for soil reconstruction in dumping sites, outlining their core practices, advantages, and limitations. It offers a clear comparative reference for relevant engineering practices and decision-making in soil restoration strategies.

Table 1 Overview of Major Technical Pathways for Soil Reconstruction in Mine Dumps

Technical pathway	Core approach	Major advantages	Limitations
Organic matter/biochar amendment	Addition of compost, straw, biochar, and related materials to increase organic matter content and porosity	Improves water and nutrient retention and also provides carbon sequestration benefits	Material sources and quality stability are constrained
Combined microbial remediation	Inoculation with functional microbial agents used synergistically with organic amendments	Promotes nutrient cycling and rhizosphere ecological recovery	Long-term field colonization remains uncertain
Multilayer cover and profile reconstruction	Layered placement of different substrates to simulate a natural soil profile	Balances drainage, water conservation, and disturbance resistance	Construction is complex and costs are relatively high
Utilization of industrial by-products	Use of fly ash, steel slag, and similar materials to replace part of the reconstruction materials	High degree of resource utilization and potential cost reduction	Environmental risks and suitability boundaries require strict assessment
Intelligent monitoring and precision management	Integration of sensors, remote sensing, and UAVs for dynamic monitoring	Improves regulation efficiency and evaluation accuracy	High initial investment and insufficient standardization

4 Research Trends and Key Issues

First, the research paradigm is shifting from single engineering restoration to multidisciplinary collaboration. At present, soil science, ecology, microbiology, hydrology, and remote sensing are increasingly integrated, and research no longer focuses only on topsoil thickness or vegetation cover; instead, it pays greater attention to the construction and long-term stability of coupled soil-vegetation-microbe systems [16-17] .

Second, green and low-carbon materials have become an important direction. Materials such as biochar, agricultural wastes, and industrial by-products can improve soil quality while also potentially generating benefits in pollution reduction, carbon mitigation, and resource recycling [9]. However, the environmental safety boundaries, regional suitability, and long-term ecological effects of such materials still require systematic verification [18-19].

Third, intelligent monitoring is changing restoration management. By obtaining multi-scale data through sensor networks, satellite remote sensing, and UAV surveys, it is possible to dynamically perceive soil moisture, temperature, vegetation growth, and surface stability, thereby supporting precision irrigation, supplementary amendment application, and risk warning [20-22].

Fourth, region-specific solutions will become the norm. Limiting factors differ markedly among arid regions, alpine regions, hot-humid regions, and dumps associated with different mineral types [23]. Future technical design must therefore rely on differentiated combinations based on climate, hydrology, parent material properties, and target vegetation types, rather than applying a uniform model [24].

At present, the most prominent common problems include the simultaneous shortage of topsoil resources and the difficulty of screening substitute materials; evaluation periods that are too short to reflect long-term successional effects; insufficient linkage between ecological-function indicators and engineering indicators; and the fact that some techniques perform well at the experimental scale but still require verification of their economic feasibility and stability for large-scale application [25-27].

5 Future Research Directions

First, low-cost and scalable materials should be further developed. Research should focus on agricultural and industrial wastes available around mining areas, including studies on modification, formulation compatibility, and risk control, so as to establish material inventories and combined application schemes suitable for mine dumps in different regions [9].

Second, long-term monitoring and evaluation systems should be improved. On the basis of existing indicators such as vegetation cover, pH, and organic matter, indicators including microbial community structure, carbon sequestration potential, hydrological regulation, and ecosystem stability should be incorporated to establish a multi-scale, long-term evaluation framewor [20].

Third, mechanism-oriented research should be deepened. Future studies should prioritize elucidating the interactive mechanisms among substrate structure optimization, root development, microbial succession, and nutrient cycling, so as to provide theoretical support for technology integration and parameter optimization [12].

Fourth, stronger coordination with overall mine planning is needed. Soil reconstruction in mine dumps should be considered in conjunction with slope stabilization, water-resource allocation, landscape reshaping, and subsequent land use, thereby promoting the integration of ecological restoration with mine transformation and land reutilization [28].

6 Conclusions

Soil reconstruction in mine dumps is a key link in moving mine ecological restoration from engineering reshaping toward ecological rebuilding[29]. Studies in China and abroad show that single-layer topsoiling can no longer satisfy the requirements of high-quality restoration, and that the coordinated advancement of material amendment, profile construction, biological regulation, and intelligent monitoring is becoming the principal direction in this field [22].

Looking ahead, soil reconstruction in mine dumps must achieve a balance among scientific soundness, economic feasibility, and practical applicability [30]. Only by establishing regionally adapted, long-term effective, and widely transferable technical systems can the unity of ecological recovery and sustainable land use in mining areas truly be realized [4].

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