WEP Warwick Evans Publishing

International Journal of Natural Resources and Environmental Studies

ISSN: 3006-2012 (Print), ISSN: 3006-0834 (Online) | Volume 7, Number 3, Year 2025
DOI: https://doi.org/10.62051/ijnres.v7n3.01
Journal homepage: https://wepub.org/index.php/IJNRES/index

Discussion on the Improvement Path of Soil Quality in Goaf of Coal Mine

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ABSTRACT

The large-scale exploitation of coal resources not only supports China's economic and social development, but also causes large-scale coal mine goafs, causing serious soil degradation problems. The degradation of soil quality in goaf is manifested as physical structure destruction, chemical property deterioration and biological function failure, which seriously restricts regional land reclamation and ecological reconstruction. This paper systematically analyzed the core crux of soil quality degradation in coal mine goaf, including soil structure disturbance, nutrient loss, heavy metal pollution and microbial community imbalance. On this basis, from the four dimensions of physics, chemistry, biology and comprehensive integration, the specific path of soil quality improvement is discussed in depth. Finally, the future prospects of constructing the integrated technical system of 'diagnosis-planning-technology integration-monitoring' and improving the policy guarantee and market participation mechanism are put forward, in order to provide theoretical basis and technical support for the ecological environment governance and sustainable development of coal mining areas in China.

KEYWORDS

Coal mine goaf; Soil quality improvement; Ecological restoration; Land reclamation; Technical path.

1. INTRODUCTION

As the main energy source in China, long-term large-scale mining of coal has formed a large-scale goaf, resulting in serious land damage and soil degradation. According to statistics, the total amount of land destroyed by mining in the country exceeds 4 million hectares, and it is still increasing by tens of thousands of hectares per year. [1] The mined-out area is not only the source of surface subsidence, ground fissures and other disasters, but also the structural damage to the soil layer, causing systematic soil quality degradation, making it lose its production, ecology and bearing function, which has become a key bottleneck restricting the sustainable development of the mining area.

Soil quality represents the ability of soil to maintain biological productivity, protect the environment and promote ecological health[2]. Soil degradation in the goaf is an overall imbalance of physical, chemical and biological properties. However, traditional reclamation is mostly limited to surface leveling and vegetation coverage, and lacks systematic reconstruction of soil ecosystem functions, resulting in unsustainable remediation effects.

Therefore, it is of great theoretical and practical significance to deeply reveal the internal mechanism of soil degradation and construct a systematic, efficient and sustainable quality improvement path. The purpose of this paper is to clarify the characteristics and causes of soil degradation in mined-out areas, and to systematically explore multi-dimensional restoration paths such as physics, chemistry, biology and collaborative management from a multidisciplinary perspective, so as to promote the qualitative change of land reclamation in mining areas from "surface green" to "system resurrection."

2. THE CORE CRUX OF SOIL QUALITY DEGRADATION IN COAL MINE GOAF

Soil degradation in mined-out areas is the ultimate manifestation of the chain interference of mining activities on soil-rock-groundwater-biological systems. The core crux of the problem can be attributed to the following three aspects.

2.1. Physical structure degradation

(1) Soil structure disorder and compaction: Subsidence leads to uneven surface, cracks or even step-like subsidence, so that the original soil profile is destroyed, mixed or even missing, valuable surface soil is buried or lost. At the same time, the rolling of heavy machinery in the process of reclamation is easy to cause soil compaction, resulting in an increase in soil bulk density and a decrease in porosity.

(2) Water transport dysfunction: Structural damage directly affects the three-phase composition of the soil. Compaction leads to poor soil permeability, and precipitation is difficult to infiltrate, forming surface runoff and aggravating soil erosion. At the same time, the destruction of capillary pores also affects the water holding capacity of the soil, which greatly reduces the available water content of plants and makes the soil prone to drought.

(3)Surface temperature anomaly: Due to the change of soil moisture and pore structure, the heat capacity and thermal conductivity of the soil in the goaf change, which leads to the increase of surface temperature fluctuation and is not conducive to the growth of plant roots and microbial activity.

2.2. Deterioration of chemical properties

(1) Extremely lack of organic matter and nutrients: Mining activities turn the deep barren parent material, coal gangue, etc.to the surface, and the content of organic matter and available nutrients such as nitrogen, phosphorus, and potassium is extremely low. At the same time, the destruction of soil structure accelerated the mineralization and decomposition of residual organic matter, while the lack of vegetation cut off the circulation channel of nutrient return.

(2) Soil acidification or alkalization: The pH value of the soil in the mining area often changes drastically due to the oxidation of associated minerals. For example, coal gangue and pyrite are oxidized to sulfuric acid after exposure to air and water, resulting in strong acidification of the soil. [3] On the contrary, the application of carbonate-rich gangue or fly ash in some areas may lead to soil alkalization.

(3) Pollution of heavy metals and toxic elements: Coal strata and coal gangue often contain a certain amount of cadmium, lead, chromium, arsenic, mercury and other heavy metal elements. Under acidic conditions, these elements are more easily activated and enter the soil solution in the form of ions, which not only poisons plants, but also may migrate through the food chain and endanger human health.

(4) Salinization: In arid and semi-arid mining areas, the change of groundwater level and evaporation are strong, which may cause deep salt to rise with capillary water to accumulate on the surface, resulting in secondary salinization of soil.

2.3. Biological failure

(1) Microbial community structure and function disorder: In degraded soil, the total amount, diversity and activity of microorganisms decreased significantly. The abundance of functional groups such as

mycorrhizal fungi, nitrogen-fixing bacteria, and cellulose-decomposing bacteria that are crucial to ecosystem functions decreased, while stress-tolerant pathogens may be relatively increased. The intensity of soil biochemical processes such as respiration, nitrification and nitrogen fixation decreased.

(2) Simplification of soil fauna : Earthworms, nematodes, arthropods and other soil animals are 'engineers' of soil structure and promoters of organic matter decomposition. These animals are difficult to survive in compacted, polluted and food-deprived mined-out soil, which leads to the simplification of soil food web structure and the decline of ecological function.

(3) The loss of seed bank and the difficulty of plant settlement : surface disturbance and topsoil loss make the soil seed bank completely destroyed. Even if artificial seeding is carried out, poor site conditions (such as hardening, barren, drought) also make it difficult for plant seeds to germinate, seedlings to survive and grow, and the natural restoration process of vegetation is extremely slow or even interrupted.

3. MULTIDIMENSIONAL PATH OF SOIL QUALITY IMPROVEMENT

In view of the above-mentioned degradation crux, the improvement of soil quality must adopt a systematic plan of 'adjusting measures to local conditions, classifying measures and multi-path coordination'.

3.1. Physical structure improvement path

The goal of the physical pathway is to reconstruct a soil skeleton suitable for root growth and water and air flow. (1) Foreign soil and topsoil cover. Before mining, the fertile topsoil layer in the mining area is stripped and preserved. After the subsidence is stable, it is backfilled and covered on the reshaped surface. If there is no such condition, the soil (foreign soil) suitable for farming can be transported from elsewhere to cover, providing an immediate physical and nutritional basis for vegetation restoration. The cost of this method is high, but the effect is fast. (2) Deep tillage and subsoiling and land leveling. For areas with serious compaction, large-scale agricultural machinery is used for deep tillage or subsoiling to break the hard plough bottom and compacted layer and increase soil porosity. Combined with the land leveling project, the surface cracks and subsidence basins are eliminated to create convenient conditions for subsequent farming and management. (3) The application of soil structure improver, the application of natural or synthetic soil structure improver. For example, gypsum and lime can be used to improve the physical structure of alkaline soil ; polymers can significantly promote the formation of soil aggregate structure, improve corrosion resistance and water retention. The use of industrial by-products such as desulfurization gypsum, municipal sludge composting, etc., can not only improve the structure, but also increase nutrients.

3.2. Regulation path of chemical properties

The core of the chemical pathway is to improve the chemical environment of the soil and provide the necessary nutrients and suitable growth conditions for plants and microorganisms. (1) The synergistic supplement of organic matter and nutrients and the application of organic materials are the soul of improving soil quality. A large amount of organic fertilizer, green manure, crop straw, biogas residue, and harmlessly treated municipal sludge and kitchen waste compost were applied. These materials can not only provide comprehensive nutrients, but the humus produced in the decomposition process is the core cementing agent to form a stable aggregate structure, and can significantly improve the buffering capacity and water and fertilizer retention performance of the soil. (2) Balanced fertilization, on the basis of organic fertilizer, according to the results of soil test, precise application of nitrogen, phosphorus, potassium and other chemical fertilizers and trace element fertilizers, in order to meet the needs of early rapid growth of plants. Promote slow and controlled release fertilizers, improve fertilizer utilization, and reduce the risk of non-point source pollution. (3) Acidity and alkalinity regulation and passivation remediation, acid soil improvement, general application of lime ($CaCO_3$), limestone powder, etc., neutralize soil active acid and latent acid, and increase the pH value to the appropriate range of plants (6.0-7.5). At the same time, increasing the pH value can effectively promote the formation of hydroxide or carbonate precipitation of heavy metal ions and reduce their bioavailability.(4) Heavy metal passivation, adding passivation agent to the contaminated soil, such as biochar, zeolite, sepiolite, phosphate, red mud, etc. These materials immobilize heavy metal ions by adsorption, precipitation, and complexation to reduce their mobility and biological toxicity. Among them, biochar has shown great potential in soil improvement and carbon sequestration and emission reduction due to its huge specific surface area, rich functional groups and stability[4].

3.3. Bio-ecological restoration path

The biological pathway is the use of biological life activities to restore soil ecological functions, and is the fundamental way to achieve self-sustaining and sustainable development of soil ecosystems. (1) Phytoremediation. Pioneer plants with barren tolerance, drought tolerance, heavy metal tolerance, fast-growing, nitrogen fixation and other characteristics were selected for planting, such as alfalfa, Astragalus adsurgens, Caragana korshinskii, Amorpha fruticosa and other leguminous plants, as well as eucalyptus, willow and other trees. They can quickly cover the surface, reduce erosion, and improve soil structure through root action. Plant extraction, stabilization and volatilization : for heavy metal pollution, planting hyperaccumulators, absorbing and transporting pollutants to the aboveground parts, and removing them by harvesting; or plant tolerant plants and fix them in the rhizosphere through root exudates to reduce migration to groundwater and food chains. (2) The introduction of functional microorganisms, artificial inoculation from healthy soil screening or commercial production of excellent microbial agents, such as arbuscular mycorrhizal fungi (AMF), rhizobium, phosphate-solubilizing bacteria, potassium-solubilizing bacteria, organic matter degradation bacteria. AMF can form symbionts with most terrestrial plants, greatly expanding the absorption range of plant roots, improving their absorption efficiency of water and nutrients (especially phosphorus), and enhancing plant stress resistance [5].Microbial-plant combined remediation : The combination of specific hyperaccumulators or tolerant plants with rhizosphere microorganisms with the functions of promoting growth and activating / passivating heavy metals to form a remediation complex can significantly improve the remediation efficiency. (3) The introduction of soil animals. After the initial improvement of soil physical and chemical conditions, earthworms (especially Eisenia foetida and other species) were introduced. Earthworms can effectively improve soil structure, promote organic matter decomposition and nutrient cycling through feeding, burrowing, excretion and other activities. Its vermicompost is an excellent soil conditioner.

3.4. Bio-ecological restoration path

Any single technology path has limitations and must move towards technology integration and system management. (1) Constructing an integrated system of ' diagnosis-planning-technology integration-long-term monitoring ' : Accurate diagnosis : Before reclamation, a detailed background survey of the soil in the goaf was conducted to clarify the dominant factors and spatial heterogeneity of degradation. System planning : according to the direction of land use (agriculture, forestry, animal husbandry, landscape), the degree of degradation and cost budget, formulate personalized repair plan, clear priority and combination of physical, chemical and biological technology. Technology integration : For example, the composite mode of 'leveling land+applying biochar and organic fertilizer+inoculating AMF+planting leguminous green manure' can achieve the unity of rapid efficiency and long-term stability. Long-term monitoring and adaptive management: Establish a long-term monitoring network of soil quality and ecosystem succession, and dynamically adjust management measures based on feedback information to ensure the sustainability of remediation effects. (2) Improve policies and regulations and market mechanisms: strengthen corporate responsibility: strictly implement the legal provisions of 'who destroys, who reclamation', and raise soil quality to ecosystem health level as the core standard for reclamation acceptance. Innovative financing model: explore the establishment of mining area ecological restoration fund, the implementation of "mine environmental governance recovery voucher" and other systems, attract social capital participation, solve the bottleneck of funds. Promote the combination of production, teaching and research : Encourage scientific research institutions to cooperate with enterprises to transform the latest research results into practical technologies and products that can be promoted and operated easily.

4. CONCLUSION

The improvement of soil quality in the goaf of coal mine is a complex project aimed at reversing the degradation of soil system and rebuilding healthy ecology. Accurate diagnosis is the premise, and it is necessary to identify the dominant factors and interaction mechanisms of degradation to avoid the blindness of repair. Multi-path synergy is the key. Physical improvement, chemical regulation and bioremediation constitute a progressive relationship of foundation-means-core, and the three promote each other to form a virtuous circle. System management is the guarantee, supporting policies and funds are needed to promote the transformation of governance model from project-based to ecosystem adaptive management. Future development will be deepened along three dimensions: refinement of technology, development of new improved materials, and construction of efficient bioremediation complexes; intelligent decision-making, integration of '3S' technology to achieve the whole process of dynamic simulation and intelligent management ; the goal is diversified, and the soil restoration and carbon sink increase, biodiversity protection and industrial development are integrated to achieve ecological-economic-social benefits. Through interdisciplinary integration, technology integration and multi-governance, the fundamental leap from 'degradation' to 'health' of goaf soil is finally promoted, which lays an ecological foundation for regional sustainable development.

ACKNOWLEDGEMENTS

This research was funded by Shaanxi Agricultural Development Group fund (NFJC2025-33).

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