Research on Comparison and Optimization Strategy of Carbon Fixing Capacity of Mine Ecological Restoration Technology under the Target of Carbon Neutralization

JiaHui Wu*

College of Landscape Architecture, Nanjing Forestry University, NanJing, China.

wujiahui@njfu.edu.cn

Abstract. Mine ecosystem, as one of the largest carbon “pools” in the world, is of great significance for carbon fixation and sink enhancement. Under the background of the “carbon neutrality” strategy, in order to strengthen the carbon sequestration in mining areas and achieve the goal of “carbon neutrality”, the mechanism, evaluation methods and technical measures of carbon sequestration in mining areas were systematically sorted out, aiming at providing a scientific basis for carbon sequestration and exchange in mining areas. Firstly, this paper analyzes the international situation of mine restoration, summarizes the mechanism of carbon sequestration in mines and the calculation and evaluation methods of carbon sink, and points out the application of four basic measures of carbon sequestration in mining areas, such as mine waste treatment, landform reconstruction, soil reconstruction and vegetation restoration, as well as the application of collaborative restoration technology and intelligent monitoring in enhancing carbon sink in mining areas. At the same time, in view of the shortage of current carbon sink technology, the promotion strategies of multi-technology collaborative repair and intelligent repair is prospected. It is expected to provide reference for perfecting the technical system, promoting the perfection of carbon sink market and interdisciplinary research, realizing negative emissions in mining areas and realizing the transformation from "carbon source" to "carbon sink".

Keywords: carbon neutrality; Mine ecological restoration; Carbon sequestration capacity; Optimization strategy;

With the large-scale utilization of fossil fuels, global greenhouse gas emissions have surged, leading to increasingly prominent climate warming issues. The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) indicates that the global average temperature in 2023 has increased by approximately 1.1° C compared to the pre-industrial period, with frequent extreme weather events posing serious threats to ecosystems and human society [1-2]. To address this challenge, the 2015 Paris Agreement set the goal of limiting the global average temperature rise to within 2° C and striving for 1.5° C [3].

China proposed the "double carbon" goal in 2020 and elevated climate change response to a national strategy. To achieve energy conservation and emission reduction targets, carbon fixation and sink enhancement represent important approaches. Carbon fixation and sink enhancement primarily involve a series of activities or mechanisms that absorb atmospheric carbon dioxide through measures such as reforestation, forest management, and deforestation reduction, combined with carbon sink trading [4].

The mine ecological system, as one of the largest global carbon "pools", serves as a crucial carrier for carbon fixation and sink enhancement. Mine ecological restoration holds a special position in the carbon neutrality strategy. While the development of mineral resources has promoted socioeconomic and technological progress, unreasonable mining activities have caused a series of ecological and environmental issues in mining areas, including land degradation, vegetation loss, and biodiversity decline, ultimately leading to the reduction or even loss of carbon sequestration capacity in mining areas [5]. More notably, such damage significantly disrupts the stability of the carbon pool in mining areas, transforming them into carbon sources [6].

Current research on the carbon sequestration potential of ecological restoration in mining areas has focused on carbon sequestration methods, measures, and the application of collaborative restoration technologies to enhance carbon sinks. However, the field of carbon sequestration in mine ecological restoration still faces numerous challenges: for instance, the lack of standards for calculating carbon sequestration capacity makes it difficult to accurately compare the carbon sequestration effects of different restoration methods; advanced technologies exhibit significant errors in carbon sequestration calculations; from a temporal perspective, the general absence of long-term monitoring mechanisms and maintenance measures hinders the establishment of a long-term data monitoring system, thus affecting the durability and stability of mine ecological restoration effects.

Therefore, this paper aims to deeply analyze the internal connection between mine ecological restoration and carbon neutrality, systematically evaluate the carbon sequestration capacities of various current restoration technologies, identify the shortcomings of existing restoration methods, and propose targeted optimized restoration strategies. This endeavour aims to provide references for the transformation and upgrading of mine ecological restoration within the context of China's carbon neutrality, holding significant theoretical and practical implications for promoting mine ecological restoration.

1. Research Progress of Mine Restoration

Foreign research on mine development and restoration started early. The promulgation of the *Surface Mining Control and Reclamation Act* in the United States in 1977 marked the entry of mine restoration into the legislative stage, promoting standardized restoration practices such as landform reconstruction, topsoil restoration, and vegetation planting, and gradually forming a sound legislative framework [7]. In contrast, mine ecological restoration in China has developed rapidly after the 18th National Congress of the Communist Party of China, with significantly enhanced policy support. Documents such as the *Technical Specifications for Mine Ecological Environment Protection and Restoration* have provided institutional guarantees for restoration work [8]. At the technical level, foreign countries have actively explored diversified carbon sink technologies, including vegetation restoration, microbial restoration, biochar improvement, and carbon sequestration technologies, with a relatively mature research system. China initially drew on foreign experience but has gradually formed a localized restoration system focusing on waste treatment, terrain reshaping, vegetation restoration, etc., in recent years. It has explored the application of environmental materials like biochar in improvement, though systematic restoration concepts and long-term monitoring still need improvement.

Scholars at home and abroad have conducted a series of studies on the carbon sequestration potential of ecological restoration in mining areas. Chinese scholars have pointed out that globally distributed mines, if their ecological systems are effectively restored, could significantly increase carbon sequestration [9]. Extensive research has also been conducted on carbon sequestration technologies and methods in mining areas. As early as 1990, foreign researcher Seifritz first published studies on carbon dioxide mineralization and sequestration in *Nature*. The relevant legislative system is relatively complete, and restoration technologies are mature, with active exploration and application of advanced technologies such as geological sequestration and biochar improvement.

After the 18th National Congress of the Communist Party of China in 2012, with the introduction of policies like the *Technical Specifications for Mine Ecological Environment Protection and Restoration*, restoration work in mining areas has gradually attracted more scholarly attention. However, at that time, restoration technologies and methods mainly borrowed from foreign cases, and a systematic restoration concept and technical system had not yet been formed. Through recent development, methods for mine ecological restoration in China have increasingly focused on landform reconstruction, mine waste treatment, vegetation restoration, and microbial promotion [4]. Domestic scholars have also begun to explore CO_2 storage technologies [10] and the use of biochar for soil improvement [11], aiming to find more economical, feasible, and eco-friendly technical means to achieve long-term and stable carbon dioxide storage in mine carbon pools.

2. Carbon Sequestration Mechanisms

Currently, carbon sinks in mining areas mainly derive from carbon sequestration via vegetation photosynthesis, soil carbon sequestration, and microbial carbon sequestration [12].

2.1 Carbon Sequestration via Photosynthesis

Plants first generate carbohydrates through photosynthesis and transport them to various tissues and organs to maintain plant growth and development, as well as the increase of aboveground and underground biomass (Figure 1). Huang Lin et al. [13] found that artificially induced "young forests" exhibit a higher capacity to absorb CO_2 than natural forests, indicating that implementing vegetation restoration measures in mining areas holds great potential for improving carbon sinks in these areas.

2.2 Soil Carbon Sequestration

Root exudates and plant litter are decomposed by microorganisms to form carbon-containing organic matter (humus) [14], which improves soil fertility and facilitates nutrient cycling and the maintenance of soil microaggregate structures. Soil organic carbon remains stable in the soil under the protection of soil aggregates, achieving long-term storage of organic carbon [15]. The content of soil organic carbon fluctuates significantly due to soil physical-chemical properties, geographical factors, and microbial activities, and is prone to loss through rainwater erosion and soil respiration [9] (Figure 1).

2.3 Microbial Carbon Sequestration

Some autotrophic microorganisms in the soil can directly fix atmospheric carbon dioxide through pathways such as the Calvin cycle [16]. Additionally, microorganisms act as key links connecting plants and soil, regulating processes including nutrient turnover, litter degradation, and humus formation, thereby driving various links of the carbon cycle [17] (Figure 1). After microbial death, their residues directly contribute to soil organic carbon content [18].

The mine ecological system is essentially a natural ecological system disturbed by human activities. Its carbon cycle process has changed due to alterations in terrain, soil structure, and vegetation types, leading to a decrease in carbon sequestration benefits. Therefore, to fundamentally improve the carbon sequestration capacity of mining areas, it is necessary to integrate ecological restoration principles and deeply evaluate the carbon sequestration potential of restoration measures [9].

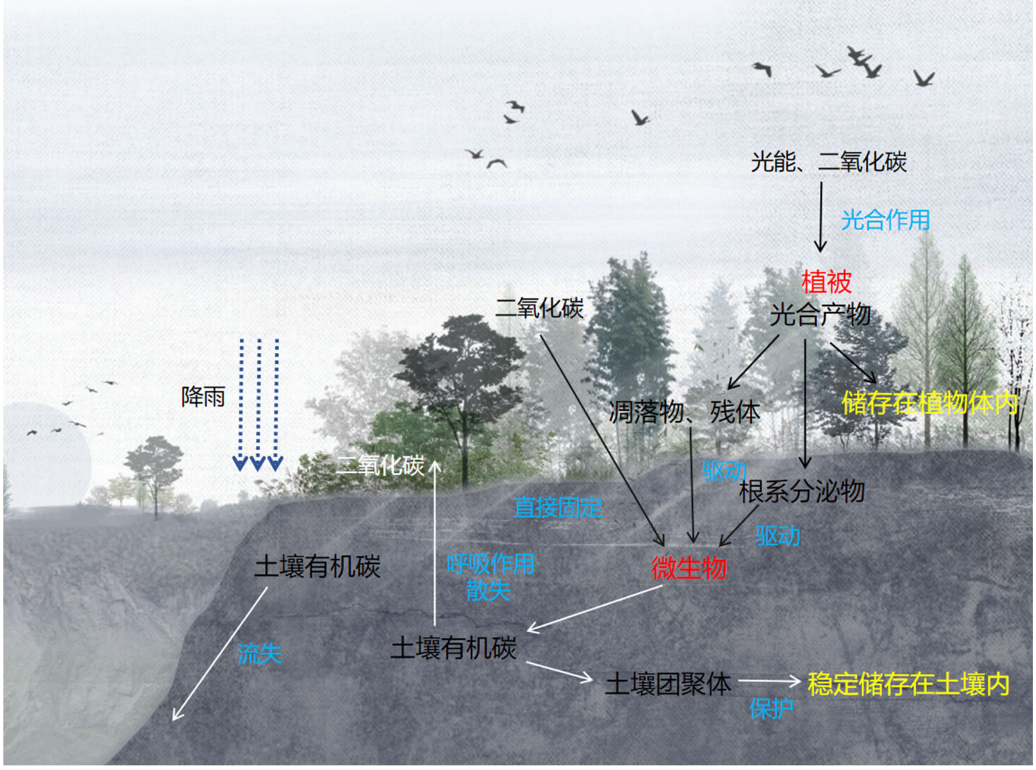

Fig.1 Carbon sequestration mechanism of carbon sink in mining area

3. Monitoring and Calculation Methods for Carbon Sinks

Establishing accurate and reliable measurement methods for carbon sinks in mining areas is crucial for calculating and comparing the carbon sink amounts brought by restoration measures, as well as scientifically evaluating the carbon sequestration effects of ecological restoration projects. Reliable carbon sink measurement methods can not only optimize restoration design schemes and enhance carbon storage per unit area but also support the implementation of the national “double carbon” strategy.

Currently, research on calculation methods for carbon storage in mining areas is relatively limited. Most studies directly adopt calculation methods from forest ecosystems when estimating carbon storage in mining areas. However, due to significant differences in slope height, gradient, lithology, soil thickness, and other factors between mine ecosystems and forest ecosystems, existing methods have notable limitations in calculating carbon sequestration in mining areas.

Aiming at the particularity of the mining area environment, Li Xiaokai et al. [19] proposed a calculation method for carbon sink amounts in mines that combines sample plot surveys and remote sensing technology. This method considers the impact of topographic factors on carbon sink amounts, fully leveraging the high precision of sample plot surveys and the extensive coverage of remote sensing technology to correct terrain-induced errors, significantly improving the accuracy of carbon sink amount calculations in mining areas and providing a reference for future calculations.

Scholars have also used technical methods to monitor and evaluate carbon storage in mining areas. For example, Li Fan et al. [20] used multi-period Landsat remote sensing images to accurately classify and extract land use and cover information of the Yimin Mining Area from 1984 to 2016, systematically analyzing land use changes and monitoring dynamic carbon storage changes based on this. Wu Guowei et al. [21] effectively estimated vegetation carbon storage in coal mining areas using an improved CASA model and proposed that since various estimation models have different parameter requirements for climatic characteristics and tree species compositions in restoration areas, establishing a reliable dataset through long-term dynamic monitoring and using multi-model cross-validation can enhance the scientificity of results. Tang Jiajia et al. [22] combined UAV remote sensing technology, LiDAR technology, hyperspectral remote sensing technology, and stepwise multiple regression analysis to develop a comprehensive technical system for inverting aboveground vegetation carbon storage in mine ecological restoration areas.

4. Mine Carbon Sequestration Technologies

The technical system for carbon sequestration in mining areas has now basically taken shape, comprising four basic measures: “waste treatment-landform reshaping-soil reconstruction-vegetation restoration”. Under this basic framework, collaborative restoration technologies serve as efficiency-enhancing means, and intelligent restoration technologies act as auxiliary measures to jointly improve overall carbon sequestration efficiency. Based on this, a path and model diagram of how mining area technologies facilitate carbon neutrality can be drawn (Figure 2).

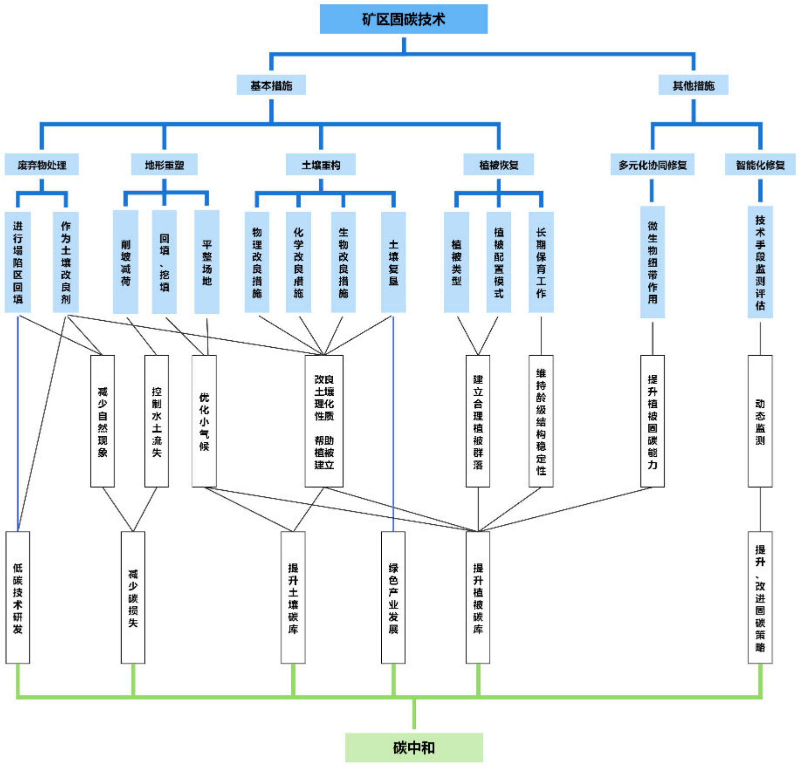

Fig.2 Path and mode of carbon fixation technology in mining areas to help carbon neutralization

4.1 Mine Waste Treatment

The scientific treatment of mine waste is a key link in mine ecological restoration. Long-term open-air stacking of mine waste, represented by coal gangue, not only occupies large areas of land but also causes spontaneous combustion. Studies have shown that carbon dioxide emissions from the spontaneous combustion of coal gangue can reach500-3000 kg CO^2-e y^{-1} m^{-2}, constituting one of the main carbon losses in mining areas [23]. Meanwhile, under the action of rainwater leaching and percolation, toxic and harmful elements in coal gangue pollute soil and groundwater, damage the ecological environment, and affect the carbon sequestration efficiency of mine ecosystems. Therefore, proper treatment of mine waste is an important measure to improve carbon sink capacity.

Fan Xiaoping et al. [24] took coal gangue as an example to systematically discuss the application of mine waste in restoring mine ecological systems and enhancing carbon sinks. On the one hand, through the collapse area backfilling technology, coal gangue can be utilised for backfilling underground goafs and surface collapse areas, thereby preventing ground subsidence and geological disasters, reducing carbon losses from the spontaneous combustion of open-air stacked coal gangue, and protecting the achievements of mine ecological restoration research. On the other hand, coal gangue can serve as a high-quality soil conditioner to improve the physical and chemical properties of mine soil, promote vegetation restoration, and enhance the carbon sink functions of vegetation and soil. It is important to note that during this process, vigilance against heavy metal pollution caused by coal gangue is necessary to ensure no secondary pollution while improving carbon sinks.

4.2 Landform Reconstruction

As the foundation of mine ecological restoration, landform reconstruction not only lays the groundwork for subsequent ecological restoration but also serves as the key to ensuring long-term restoration effects and maintaining carbon sink functions [25].

Landform reconstruction alters surface morphology through measures such as slope cutting and load reduction, backfilling, excavation and filling, and site leveling, influencing carbon sink benefits in mining areas from three aspects: controlling soil organic carbon loss, adjusting soil respiration, and optimizing vegetation growth environments.

Studies have shown that excessively steep slopes lead to a significant decrease in soil carbon dioxide flux and exacerbate soil organic carbon loss during rainfall [26]. Landforms can significantly affect regional microclimates, changing key climatic factors such as temperature and precipitation, which in turn influence microbial activities in the soil. Generally, at low temperatures, microbial metabolism rates are slow, the decomposition rate of organic carbon decreases, and soil organic carbon accumulation increases [27]. Additionally, landforms can affect vegetation coverage, indirectly influencing vegetation growth by adjusting meteorological conditions [28]. Lu Chunjiang et al. [29] found that when implementing terrain regulation projects, constructing terrace structures on slopes can effectively reduce gradients, mitigate soil erosion, expand cultivated land or vegetation coverage areas, and create favorable conditions for increasing carbon sinks.

4.3 Soil Reconstruction

Open-pit mining activities in mining areas cause severe damage to land resources, forming exposed artificial mining pits on the soil surface, damaging the original soil structure, altering soil physical properties, and reducing the overall carbon sequestration benefits of mining areas [30]. Soil reconstruction refers to the comprehensive use of engineering measures and physical, chemical, biological, and soil reclamation measures to restore damaged soil systems, construct suitable soil profiles, restore soil fertility, and provide a good and long-term stable growth environment for plants [31].

Physical improvement methods mainly include covering a suitable depth of new soil on the basis of landform reconstruction, adding materials such as sand and clay, and implementing water conservancy project construction.

On the basis of landform reconstruction, soil covering is an important measure to improve damaged areas such as subsidence areas. By covering a suitable thickness of soil, soil structure is optimized, and a growth matrix for plants is provided. The covering depth of the soil should be determined according to the growth requirements of different plants to assist in the restoration of vegetation communities [32]. To improve restoration efficiency, fertile topsoil can be stripped and properly stored during mining and then re-covered during soil reconstruction to effectively maintain soil fertility [33].

Adding improvement materials regulates soil texture by incorporating materials like sand and clay into mine soil, improving air permeability and water permeability to create more favorable conditions for plant growth. Ojeda et al. [32] mixed municipal sewage sludge with mine soil and used the organic matter in the sludge to promote soil aggregate formation, significantly improving soil physical-chemical properties and anti-erosion capabilities.

Water conservancy project construction effectively controls the accumulation of surface water and groundwater, prevents soil salinization, and reduces soil erosion by constructing drainage ditches, pipes, and other facilities, thereby improving soil quality. In mine restoration projects in ecologically fragile and arid western regions, the construction of irrigation systems provides necessary water conditions for vegetation restoration, promoting an increase in carbon sinks [33].

Chemical improvement methods focus on soil pH, heavy metal content, and soil fertility, representing the most effective means of soil improvement. Common methods include adding acid-base regulators, structure improvers, nutrient regulators, pollution repair agents, and other chemical agents. In practical applications, multiple chemical agents are often used to achieve better improvement effects. For example, lime is first used to adjust soil pH, followed by phosphate materials to fix heavy metals, and finally organic fertilizers to improve soil fertility. However, the use of chemical agents may lead to environmental issues such as chemical residue and secondary pollution, necessitating careful evaluation and selection in practical applications [34].

Due to the limitations of traditional chemical agents, a series of functional, environmentally compatible, and economical environmental materials, represented by biochar, have received widespread attention and application in recent years. Studies have found that biochar can stably store carbon in soil for hundreds of years, possessing potential long-term carbon sink capabilities and directly increasing soil carbon storage [35]. Whether used alone [36, 37] or combined with organic amendments like red mud and bamboo charcoal [11, 38], biochar can effectively reduce heavy metal and toxic substance concentrations, increase soil nutrient content, promote plant growth, and thereby enhance the carbon sink capacity of mine ecosystems. Furthermore, Zhang Yafu [12] further discovered that the application of biochar can increase the capacity of the soil carbon pool, enhance the soil's water retention capacity and the soil water content that plants can effectively utilize. When the soil quality is low, it is also beneficial for plant growth and the improvement of the soil carbon pool, contributing to the increase of carbon sinks in mining areas. Biological improvement methods mainly employ the combined actions of soil animals, plants, microorganisms, and plant-microorganisms to restore the soil in damaged mining areas [34]. It is worth noting that in the practical application of biochar, there is a lack of systematic observation and research on whether the use of biochar has an impact on animal growth. In this regard, a long-term research plan should be established to enrich and improve the application database of biochar, providing solid support for its scientific and rational utilization [37].

Biological improvement methods mainly utilize soil animals, plants, microorganisms, and plant-microbe joint actions to repair damaged mine soil [34]. Soil animals, as important components of ecosystems, play a crucial role in accelerating the ecological restoration process in mining areas. Take earthworms as an example: studies have shown that earthworms can increase topsoil fertility, improve soil structure, and promote plant growth through burrowing and digestive activities, thus playing a key role in promoting ecological restoration [39]. Plant-microbe interactions enhance restoration efficiency—research has proven that inoculating arbuscular mycorrhizal fungi (AMF) can secrete glomalin-related soil protein (GRSP) to promote soil humification, significantly increasing soil organic carbon content [40]. Microbial improvement can enhance soil quality by improving soil physical-chemical properties and optimizing microbial community structures, offering advantages such as low cost and environmental friendliness [4].

This collaborative soil reconstruction shows potential for repairing damaged mine soil, but biological improvement still has limitations in soil reconstruction due to factors like slow growth of hyperaccumulator plants, limited biological utilization efficiency of heavy metals, and long restoration cycles.

Soil reclamation refers to improving the physical and chemical properties of soil substrates through agricultural practices in areas with favorable hydrological conditions and potential soil productivity, creating suitable conditions for soil organic matter accumulation and promoting vegetation establishment. Wu Guowei et al. [21] tracked the carbon storage after converting mining subsidence areas into cultivated land and found that soil reclamation can restore 4.731% of the carbon loss caused by mining activities, effectively alleviating the damage of coal mining to ecosystem carbon storage. Studies have shown that before planting fast-growing trees, reclaiming mining areas by sowing grass seeds and appropriate grazing can achieve a carbon storage of 9.03 Mg C ha^{-1} after five years, which is five times higher than that of unreclaimed areas, significantly increasing soil organic matter content [41]. Similarly, Čížková et al. [42] found that grasslands reclaimed with topsoil have high carbon sequestration potential, with measured carbon sequestration reaching 1.6 Mg $ha^{-1}y^{-1}$. Marcin Pietrzykowski et al. [43] suggested planting annual yellow lupine (Lupinus luteus L.) in abandoned mining areas, as it can significantly increase soil organic carbon content, improve soil quality, and promote plant growth, making it a preferred crop for reclamation.

In summary, soil reconstruction can effectively improve soil physical-chemical properties, creating favorable conditions for soil organic carbon storage [44]. Soil organic carbon, an important indicator of soil fertility, can promote plant growth and enhance plant carbon sequestration efficiency as its content increases. Studies have shown that the interaction between soil and plants forms a positive feedback mechanism over time: the extension of the restoration cycle significantly increases soil organic carbon content, and the prolonged survival of vegetation further enhances soil carbon sequestration capacity [9], ultimately achieving the improvement of the overall carbon sequestration capacity of mine ecosystems.

4.4 Vegetation Restoration

Vegetation restoration achieves maximum carbon sink benefits through multi-type zonal combined planting of trees, shrubs, and herbaceous plants, ensuring species diversity and ecosystem stability. This method has multiple ecological functions such as climate regulation, water and soil conservation, and carbon fixation and sink enhancement, making it the main approach to achieve carbon sinks in mine ecological restoration [9]. The selection of vegetation types, configuration patterns, and post-restoration conservation measures in the vegetation restoration process jointly determine the carbon sequestration efficiency of mine ecosystems [45].

4.4.1 Selection of Vegetation Types

The selection of vegetation types should follow the principle of adapting to local conditions, prioritizing multi-vegetation combinations with strong stress resistance and outstanding carbon sink capabilities.

From a macro-climatic adaptability perspective, the selected vegetation types need to match regional climatic characteristics. Studies have shown that afforestation tree species with excellent carbon sink effects have significant climatic zonal characteristics [46]. Vindušková et al. [47] confirmed this point in their research: they found that herbaceous plants are more conducive to soil organic carbon (SOC) accumulation in warm regions, coniferous forests are suitable for cold regions, and deciduous broad-leaved forests are appropriate for temperate transition zones. This climate-responsive configuration can effectively enhance SOC storage.

At the specific species selection level, species adaptability and stress resistance should be considered first. Studies have shown that pioneer plants such as sea buckthorn and bermudagrass, as well as nitrogen-fixing plants like Caragana and Amorpha fruticosa that can symbiose with rhizobia, exhibit superior growth characteristics under various site conditions due to their outstanding stress resistance and adaptability [48]. On the premise of ensuring ecological safety and species survival rates, introducing high-carbon-sequestering tree species such as black locust and Amorpha fruticosa (leguminous plants) is beneficial. Studies have shown that leguminous plants can symbiose with rhizobia, providing high leaf litter to the soil, promoting microbial activities, and facilitating organic matter decomposition and soil organic carbon accumulation [49]. Sangeeta Mukhopadhyay et al. [50] found that the exotic tree species Cassia siamea is superior to the native tree species Albizia lebbeck in increasing soil carbon storage, showing important application value for ecological restoration of post-mining land. Sangeeta Mukhopadhyay et al. also established a Reclaimed Mine Soil Index (RMSI) by analyzing the improvement effects of different tree species on soil quality in reclaimed mining areas, screening tree species suitable for reclamation of coal mine-degraded land and providing a scientific basis for tree species selection and reclamation measure formulation in mining area restoration [51].

Reasonable vegetation combinations can not only significantly increase soil organic carbon content [41] but also promote a virtuous circle in the soil-vegetation system. Adopting mixed planting of multiple plants can enhance the ecosystem's adaptability to climate change and enrich soil microbial communities through differences in litter composition and timing, maintaining soil carbon sequestration efficiency. Finally, multi-species mixed forests should be selected. Studies have shown that diversified species mixed sowing has stronger adaptability to climate change and anti-disturbance capabilities, and different litter compositions and falling times can enrich soil microbial community diversity, maintain long-term carbon sequestration efficiency, and thus construct a soil-vegetation virtuous circle system with climate resilience [9].

4.4.2 Vegetation Configuration Patterns

The carbon sequestration capacities of different vegetation types vary significantly. Numerous studies have confirmed that the carbon sequestration benefit of arbor-shrub-herb composite configuration is significantly better than that of single vegetation patterns [45]. Research shows that carbon density and storage of trees, shrubs, and herbs present obvious gradient changes, among which trees have the most prominent carbon sequestration capacity and are the main body of carbon sinks. Therefore, in vegetation reconstruction, trees should be the main component, supplemented by appropriate shrubs and herbs, which can not only optimize carbon sink effects but also balance water and soil conservation and cost control [9].

In specific implementation, differentiated plant configuration strategies should be adopted according to topographic features. For stable areas such as dump platforms, it is recommended to use a three-layer structure dominated by trees, with shrubs and herbs. For special terrains like slopes, studies have shown that due to soil erosion issues, the carbon sequestration rate of grasslands is 2.2 times that of forests, so slope vegetation reconstruction should focus on grasslands, followed by shrubs [52]. Shrubs should preferably be species with deep root characteristics such as Amorpha fruticosa and Lespedeza, which can ensure vegetation restoration effects and effectively reduce slope load [45].

In addition, during plant configuration, a model of natural restoration as the mainstay and artificial nurturing as the supplement should be adopted—prioritizing the preservation of the site's original vegetation, strictly controlling the density and types of newly planted plants to ensure they do not exceed the ecosystem's carrying capacity, reducing unnecessary human intervention, and giving full play to the natural ecosystem's self-repair ability. Meanwhile, moderate artificial intervention can make up for the shortcomings of natural restoration to achieve better vegetation community reconstruction effects. This is actually a nature-based solution that conforms to ecological laws and can effectively improve restoration efficiency [45].

Post-restoration conservation management is also a key link affecting vegetation carbon sequestration efficiency. The material and energy transfer of different vegetation-soil systems has obvious spatial-temporal differences, and the carbon sequestration capacity of forests does not remain unchanged but gradually declines with forest age. Optimizing the age structure through phased harvesting and other measures can effectively reverse this downward trend in carbon sequestration capacity [9].

Based on the above, in the later stage of vegetation restoration, a full-cycle nurturing management mechanism must be established. Regular dynamic monitoring of vegetation succession status should be carried out to promptly grasp vegetation growth changes, implement scientific thinning and renewal measures, maintain a reasonable community age structure, and ensure the continuous and stable operation of the ecosystem's carbon sink function.

4.5 Diversified Collaborative Restoration (Mycorrhizal Inoculation Technology)

In the process of enhancing carbon sinks in mining areas, extensive research has focused on constructing soil-vegetation systems to improve the carbon sequestration efficiency of mine ecosystems, while microorganisms, as the key link connecting soil and plants, show huge research potential. Studies have shown that the collaborative effect of microorganisms and plants plays a key role in improving soil carbon sequestration capacity during mine ecological restoration.

In the early stage of mine ecological restoration, the lack of viable mycorrhizal fungal populations in the soil often leads to delayed vegetation establishment. Through mycorrhizal inoculation technology, the symbiotic relationship formed between mycorrhizal fungi and plants can effectively enhance the productivity of degraded land, promote plant growth, and increase carbon sinks in mining areas. In addition, mycorrhizal fungi have multiple positive impacts on plant growth. They can significantly enhance plant drought resistance, salt tolerance, heavy metal tolerance, and disease resistance, which is particularly important for mine vegetation growing in harsh environments. Experiments have proven that in the reclamation of coal mine dumps, VA mycorrhizal fungi can significantly increase plant growth rate and survival rate, accelerate the ecological restoration process, and improve carbon sinks in mining areas [53].

With the in-depth study of the symbiotic mechanism between mycorrhizal fungi and plants and the continuous optimization of inoculation technology, the application prospect of mycorrhizal fungi in carbon sinks of mining areas will be more broad.

4.6 Intelligent Restoration

In recent years, with the continuous advancement of remote sensing technology and geographic information system technology, as well as the emergence of emerging technologies such as machine learning, artificial intelligence, and mixed reality, intelligent restoration has played an increasingly critical role in enhancing carbon sinks in mining areas.

O'Donnell et al. [54] used remote sensing technology to monitor vegetation types and growth conditions and evaluate vegetation restoration in mine lands. By combining field data with remote sensing data and using advanced algorithms such as machine learning and deep learning to establish prediction models, key indicators such as vegetation coverage, biomass, and vegetation indices were accurately evaluated to measure the progress and effectiveness of restoration work, helping mine ecosystems restore to expected goals. Studies have also shown that combining UAV (unmanned aerial vehicle) technology with geographic information system (GIS) has verified the viability of black locust in mine restoration and its applicability in carbon sequestration in mining areas, while exploring how to improve the scientificity of vegetation layout [55].

Masoud Samaei et al. [56] studied and verified the collaborative application of UAV technology, sensor networks, artificial intelligence (AI), and mixed reality (MR) technology. The research shows that this technology can effectively support the full-life-cycle monitoring and management of mine ecological restoration, helping to adjust and optimize mine restoration strategies. In this collaborative working system, UAV and sensor technology can collect high-spatiotemporal resolution environmental data, AI algorithms realize real-time data processing and restoration effect prediction, and MR technology converts complex environmental data into spatial models through 3D visualization modeling, facilitating multi-dimensional analysis and decision-making by researchers. At present, the core functional modules of this system have been tested and optimized in multiple independent studies and are expected to be applied in practice in the near future.

5. Optimization Strategies for Carbon Sequestration Capacity

5.1 Technical Collaboration

Factors in the ecosystem are interwoven and influence each other, jointly maintaining ecological balance and stability. The improvement of carbon sinks in mining areas cannot rely on isolated application of a single technology to a single link but requires comprehensive consideration of the collaborative effects among restoration technologies to construct a multi-level collaborative restoration system, thereby better enhancing carbon sink capacity in mining areas.

5.1.1 "Vegetation-Soil-Microorganism" Collaborative Restoration

The current insufficient carbon sink benefits in many mining areas may be caused by the failure to form "vegetation-soil" collaborative restoration and the unexploited driving potential of microorganisms [57]. In response, "vegetation-soil-microorganism" collaborative restoration can be promoted (Figure 3). According to the principle of "suitable trees for suitable land", plant communities should be scientifically configured to create a vegetation system with excellent carbon sequestration efficiency, providing a good living environment and nutrient sources for microorganisms; in turn, microorganisms feed back to plants, promoting their growth and nutrient absorption, while degrading pollutants, giving full play to the key role of microorganisms in the carbon cycle and enhancing the overall restoration effect [58].

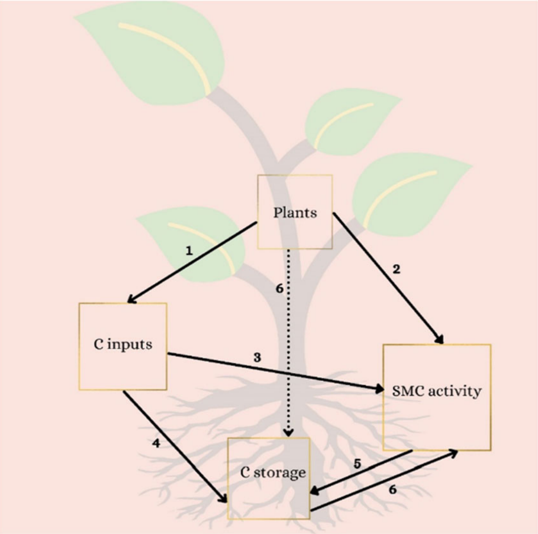

Fig.3 Relationships between plant, microorganisms and C storage in soil[59]

5.1.2 Application of New Materials for Auxiliary Restoration

Paying attention to the application of new materials in the construction of carbon sinks in mining areas is a key consideration for the application of mine restoration technologies. New environment-friendly materials such as biochar and its derivatives, and activated carbon have unique advantages. They can directly serve as exogenous carbon to increase the carbon content of carbon pools in mining areas, while enhancing microbial metabolic activity, improving soil environment, optimizing soil aggregate structure, reducing carbon loss, promoting plant growth, and improving carbon sinks in mining areas in a cleaner and more economical way [6].

5.1.3 Exploration of Diverse Carbon Sink Models

Different mining areas have distinct original environmental conditions and advantages, so strategies for enhancing carbon sinks should also vary. Based on the actual situation of mining areas, it is necessary to explore diverse carbon sink models to meet the needs of strategy optimization.

In mine ecological restoration, wetland carbon sinks have huge carbon sequestration potential, but limited by the terrain and ecological conditions of mining areas, not all mining areas are suitable for transformation into wetlands, resulting in relatively insufficient related research and practice. Taking the Xuzhou coal mine subsidence area as an example, during its transformation, the wetland ecosystem was reasonably laid out by fully considering the terrain and ecological conditions of the mining area to maximize the carbon sequestration potential of wetlands and increase carbon sinks in mining areas. Scholars have calculated that the soil organic carbon storage of Pan'an Lake Wetland is approximately 18,792.39 Mt, the total vegetation carbon storage is approximately 24,570 Mt, the aquatic vegetation carbon storage is 90.2 Mt, and the water sediment carbon storage is 15,986.4 Mt. If incorporated into the carbon trading market, calculated at a carbon trading price of 56 yuan/ton, the carbon sink value of Pan'an Lake Wetland can be further converted into economic benefits. Through policy guidance, financial support, and technical optimization, the carbon sink capacity of this ecosystem can be further stimulated [60].

Constructing photovoltaic power stations in coal mining subsidence areas is an effective measure to utilize renewable energy such as solar energy to govern coal mining subsidence areas and optimize the local energy industry structure. In arid and semi-arid areas such as Inner Mongolia, the ecosystem is relatively fragile, but studies have shown that large-scale photovoltaic facilities help improve local vegetation population density and carbon sequestration capacity. Therefore, scholars have proposed promoting a "photovoltaic+" model for mine ecological restoration in the grassland area of eastern Inner Mongolia, developing diversified models such as "photovoltaic+tourism", "photovoltaic+agriculture", and "photovoltaic+grassland animal husbandry" according to local conditions. This new restoration model can not only reduce thermal power generation and promote the optimization and adjustment of the energy structure but also increase local residents' income, achieving a win-win situation for ecology and economy.

5.2 Intelligent Monitoring

Carrying out real-time intelligent monitoring of carbon sinks in mining areas can help researchers deeply understand the status of carbon sinks in mining areas and improve research strategies for carbon fixation and sink enhancement. To achieve this goal, the optimization of intelligent monitoring can be promoted from three key aspects.

First, construct a comprehensive data collection system. Comprehensive use of advanced technical means such as remote sensing technology, UAV technology, and sensor networks to form a comprehensive, multi-level monitoring network. Remote sensing technology can achieve large-scale and rapid information acquisition in mining areas, UAV technology can flexibly obtain local high-precision data, and sensor networks can real-time and continuously monitor key indicators such as vegetation growth status and soil carbon content changes in mining areas. Through the collaborative application of these multi-technologies, the progress of mine ecological restoration and the dynamic changes of carbon sinks can be comprehensively grasped.

Second, carry out data processing and analysis. With the help of advanced algorithms such as machine learning and artificial intelligence, the collected massive data can be processed and analyzed in real time, and accurate prediction models can be established to precisely evaluate key indicators such as vegetation coverage, biomass, and vegetation indices, providing a scientific basis for the adjustment and optimization of restoration strategies.

Finally, introduce mixed reality technology to achieve visual display, converting complex monitoring data into intuitive spatial models, enabling researchers to conduct in-depth analysis of mine ecological restoration and carbon sink conditions from multiple dimensions, intuitively observe the changes in mine ecosystems, promptly identify potential problems, and formulate targeted solutions, so as to improve the accuracy and effectiveness of restoration work and promote the continuous improvement of carbon sink capacity in mining areas.

6. Summary and Prospect

At the 75th United Nations General Assembly, China formally made a "double carbon" commitment to the world, addressing the severe challenge of global warming. As one of the largest global carbon "pools", the mine ecological system's carbon sequestration capacity has become a key means to respond to climate change and achieve the "double carbon" goal. However, current mine ecological restoration still faces challenges: insufficient development of carbon sink functions, limited efficiency of traditional carbon sequestration technologies despite significant basic effects, high costs and insufficient stability of new technologies, and large errors in carbon sink measurement relying on forest models, which requires integrating remote sensing and AI to improve accuracy. To achieve the carbon neutrality goal, it is crucial to enhance carbon sequestration efficiency by constructing a "vegetation-soil-microorganism" system through multi-technology collaboration and realize dynamic evaluation and intelligent monitoring using UAV and AI.

Therefore, this paper systematically combs the existing research achievements in this field, focusing on the carbon sequestration capacity of mine ecological restoration technologies under the carbon neutrality goal, hoping to provide practical optimization strategies for mine ecological restoration.

The current mine carbon sequestration technical system is complete, covering core links such as waste treatment, landform reconstruction, soil reconstruction, and vegetation restoration, supplemented by diversified collaborative restoration, intelligent restoration, and carbon sequestration technologies.

For optimizing carbon sequestration capacity, two strategies are proposed: technical collaboration and intelligent monitoring. Technical collaboration emphasizes "vegetation-soil-microorganism" collaborative restoration to enhance overall carbon sequestration efficiency. Intelligent monitoring constructs a comprehensive data collection system through technologies such as remote sensing, sensor networks, artificial intelligence, and mixed reality to achieve precise dynamic evaluation of carbon sequestration amounts.

In the future, mine carbon sinks should comprehensively apply ecological carbon sinks and technologies such as carbon dioxide capture, storage, utilization, and conversion to ultimately achieve negative emissions in mining areas and realize the transformation of mining areas from "carbon sources" to "carbon sinks". The breakthrough and application of negative emission technologies are the key to realizing the transformation of mining areas from "carbon sources" to "carbon sinks".

In terms of ecological carbon sinks, the potential of microorganisms, biochar, and its derivatives should be deeply explored. Efficient degradation microbial communities or biochar can be used to improve polluted soil in a low-cost and high-benefit manner to enhance the carbon fixation efficiency of mining areas. At the same time, attention should be paid to the long-term conservation of mine ecosystems and the risk of soil organic carbon saturation, and scientific soil management measures should be adopted to maintain its maximum carbon sequestration potential. As the core means of sink enhancement, the breakthrough of carbon sequestration technology is crucial. For example, using natural soil bacteria to induce carbon mineralization of carbon dioxide and mineral waste provides new ideas for traditional carbon sequestration technologies, which is expected to reduce dependence on high-temperature and high-pressure equipment and promote the large-scale application of carbon sequestration technologies, thereby providing important support for achieving the carbon neutrality goal.

Strengthening the technical system support is an important way to improve the management level of carbon sinks in mining areas. Mine carbon sink detection needs to comprehensively use cutting-edge technologies such as remote sensing, UAV, sensor networks, machine learning, and artificial intelligence. By constructing a multi-dimensional monitoring network and improving the mine carbon sink measurement model, precise dynamic evaluation of carbon sequestration amounts can be realized, providing real-time basis for researchers and helping to carry out multi-dimensional analysis of mine carbon sink conditions, so as to optimize carbon sequestration improvement measures. This technical integration can not only improve monitoring efficiency but also provide a scientific basis for policy formulation and implementation, promoting the refinement and intelligence of mine carbon sink management.

The institutional innovation of carbon sink marketization is a long-term means to stimulate mine ecological restoration. In the future, it is necessary to continuously improve the carbon sink accounting methods and mine carbon trading policies and market mechanisms, and establish carbon sink accounting standards and trading rules in line with the characteristics of mining areas. At the same time, differentiated carbon trading policies should be formulated for different types of mining areas and different restoration stages to precisely stimulate mine ecological restoration and carbon sink improvement. In addition, the linkage mechanism between carbon sink trading and ecological compensation should be actively explored, so that the income from carbon trading can effectively feedback the improvement and implementation of carbon sink technologies in mining areas, further enhance the carbon sequestration potential of mining areas, and provide economic guarantee for the sustainable development of mining areas.

The deepening and expansion of interdisciplinary research are important driving forces for technological innovation in mine carbon sinks. In the process of improving carbon sink measures in mining areas, it is crucial to break disciplinary barriers and integrate research achievements in multiple disciplines such as soil science, microbiology, and ecological engineering. Through interdisciplinary collaborative innovation, a targeted mine carbon sequestration technical system can be developed. In the future, with the continuous development of artificial intelligence technology and ecological modelling technology, it is expected to accurately predict the development of the "vegetation-soil-microorganism" carbon sequestration system, providing reliable theoretical support for mine carbon sequestration research and promoting mine carbon sink research to a higher level.

Against the backdrop of the "double carbon" goal, the importance of mine ecological restoration and carbon sink capacity improvement has become increasingly prominent. In the future, efforts should be further made to promote the innovation and development of mine carbon sequestration technologies and potential evaluation methods to enhance mine carbon sequestration efficiency. This requires not only technological breakthroughs and policy support but also the joint participation and collaborative efforts of the whole society. By integrating multi-disciplinary forces and leveraging the incentive role of market mechanisms, technological innovation and management optimization can be promoted, which is expected to facilitate the transformation of mines from "carbon sources" to "carbon sinks", provide Chinese wisdom and solutions for global climate change governance, and help achieve the ultimate goal of sustainable development.

References

[1] Liu Z, Deng Z, Davis S J, Ciais P. Global carbon emissions in 2023. Nature Reviews Earth and Environment, 2024, 5(4): 253-254.

[2] IPCC. 2023: Sections. In: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp.35-115. DOI: 10.59327/PCC/AR6-9789291691647.

[3] Adoption of the Paris Agreement.

[4] Ji C, Zhang H, Zhang C, Shi H B, Liu H. Exploration and research on mine ecological restoration engineering and safety production effects based on the concept of carbon fixation and sink enhancement—taking southern Jiangxi as an example [J]. Jiangxi Building Materials, 2024(11): 244-247, 259.

[5] Yan Z K, Cao Y G, Li Z T, Liu X Y. Research on mine ecological restoration in the grassland area of eastern Inner Mongolia: key technologies and carbon reduction paths. Journal of Agricultural Resources and Environment, 2023, 40(3): 570-582.

[6] Chen F, Zhu Y F, Ma J, Dong W X, You Y N, Yang Y J. Carbon sequestration mechanism, sink enhancement potential and regulation of ecological restoration in loess plateau mining areas. Coal Science and Technology, 2023, 51(1): 502-513.

[7] McKenna P B, Lechner A M, Phinn S, Erskine P D. Remote sensing of mine site rehabilitation for ecological outcomes: A global systematic review. Remote Sensing, 2020, 12(21): 3535.

[8] Yu W J, Sun M L, Du J Y, Chen G L, Wang C. Research progress on mine ecological restoration and emission reduction and sink enhancement approaches under the 'double carbon' target. Mining Safety and Environmental Protection, 2025, 52(1): 38-46.

[9] Chen H, Cui Y H, Wang H M, Lin J Q, Wu H L, Peng J L, Zhang J J, Zhai Y Z. Research progress on mine ecological restoration and its carbon sequestration potential. Earth Science—Journal of China University of Geosciences, 2024, 49(12): 4594.

[10] Li Y, Wu Z, Dong X, Xu Z, Zhang Q, Su H, Jia Z, Sun Q. Pyrite oxidization accelerates bacterial carbon sequestration in copper mine tailings. Biogeosciences, 2019, 16(2): 573-583.

[11] Qin J, Wang X, Deng M, Li H, Lin C. Red mud-biochar composites (co-pyrolyzed red mud-plant materials): Characteristics and improved efficacy on the treatment of acidic mine water and trace element-contaminated soils. Science of the Total Environment, 2022, 844: 157062.

[12] Zhang Y F. Study on the influence of biochar addition on the characteristics of compacted soil in mining areas and its carbon sequestration effect. China University of Geosciences (Beijing), 2023.

[13] Huang L. Research progress on the climate regulation effect of afforestation and its influence mechanism. Acta Ecologica Sinica, 2021, 41(2): 469-478.

[14] De Deyn G B, Cornelissen J H C, Bardgett R D. Plant functional traits and soil carbon sequestration in contrasting biomes. Ecology Letters, 2008, 11(5): 516-531.

[15] Liu Y L, Wang P, Wang J K. Formation and stability mechanisms of soil aggregates: research progress and prospects. Acta Pedologica Sinica, 2023, 60(3): 627-643.

[16] Ma J, Dong W X, Zhu Y F, Hao C, Xiao D, Chen F. Effects of reclamation in eastern plain mining areas on soil microbial carbon sequestration potential. Journal of China Coal Society, 2022, 47(3): 1306-1317.

[17] Zhu Y, Ge X, Wang L, You Y, Cheng Y, Ma J, Chen F. Biochar rebuilds the network complexity of rare and abundant microbial taxa in reclaimed soil of mining areas to cooperatively avert cadmium stress. Frontiers in Microbiology, 2022, 13: 972300.

[18] Cai Y, Zheng Y, Bodelier P L E, Conrad R, Jia Z. Conventional methanotrophs are responsible for atmospheric methane oxidation in paddy soils. Nature Communications, 2016, 7(1): 11728.

[19] Li X K, Zhang P C, Sun M Y, Zhang X, Zhou S L. Research on carbon sink investigation and calculation method after ecological restoration of open-pit mines. Environmental Science and Management, 2024, 49(8): 16-21.

[20] Li F, Bao N S, He J H. Remote sensing change monitoring of land use/cover and carbon storage in grassland open-pit coal mining areas for 32 years. Geomatics and Spatial Information Technology, 2019, 42(1): 83-87.

[21] Wu G W, Zhao Y L, Fu Y H, Ni W, Zhang Y, Yu J X. Effects of land use type changes in reclaimed mining areas on vegetation carbon storage. Chinese Journal of Eco-Agriculture, 2015, 23(11): 1437-1444.

[22] Tang J J, Dong J, Yang Y J, Xu M S, Lei S G, Hua X. Inversion of aboveground vegetation carbon storage in mine ecological restoration areas by combining LiDAR and hyperspectral data. Metal Mine, 2023(1): 65-72.

[23] Day S J, Carras J N, Fry R, Williams D J. Greenhouse gas emissions from Australian open-cut coal mines: Contribution from spontaneous combustion and low-temperature oxidation. Environmental Monitoring and Assessment, 2010, 166(1-4): 529-541.

[24] Fan X P, Liu J, Kang Z, Dong X G. Strategic thinking on comprehensive utilization of coal gangue and mine ecological restoration. Environmental Sanitation Engineering, 2023, 31(1): 8-15.

[25] Hancock G R, Duque J F M, Willgoose G R. Mining rehabilitation—Using geomorphology to engineer ecologically sustainable landscapes for highly disturbed lands. Ecological Engineering, 2020, 155: 105836.

[26] Ru Jian L, Yan Jun Z, Man Z, Lan Lan D, Zhi Qi W, Sheng Li G. Simulation on the effects of slope and rainfall on soil CO_2 flux and SOC loss. Acta Scientiae Circumstantiae, 2016, 36(4): 1336-1342.

[27] Liu X R, Cui Y Y, Wang Z W, Sun H L, Han G D, Hou D J, Wang J, Li Z G, Liu Z T. Effects of grazing and simulated precipitation on the diversity of plant functional groups in Stipa breviflora desert steppe. Acta Agrestia Sinica, 2023, 31(3): 868-875.

[28] Wang N N, Liu Y L, Yin F, Shi Y G, Liu Y F. Estimation and analysis of ecosystem carbon sink considering topographic correction. Journal of Wuhan University (Information Science Edition), 2024: 1-24.

[29] Lu C J. Study on ecological environment restoration and management of mines in Zhangzhou. Fuzhou: Fujian Agriculture and Forestry University, 2018.

[30] Kai X, Chen H C, Yue Q Q, Xin Z, Peng Y L, Xi Neng Y. Study on the destruction of land resources caused by open-pit mining in coal mines and its countermeasures—taking Heidaigou as an example. Open Journal of Natural Science, 2023, 11(1): 1-8.

[31] Hu Z Q. Theory and method of soil reconstruction for mine reclamation. Journal of China Coal Society, 2022, 47(7): 2499-2515.

[32] Ojeda G, Ortiz O, Medina C R, Perera I, Alcaniz J M. Carbon sequestration in a limestone quarry mine soil amended with sewage sludge. Soil Use and Management, 2015, 31(2): 270-278.

[33] Zhenqi H, Peijun W, Jing L. Ecological restoration of abandoned mine land in China. Journal of Resources and Ecology, 2012, 3(4): 289-296.

[34] Zhao P, Shi X P, Shang Q, Tan J, Wang X G, Huang Z B. Research progress on soil improvement in mine reclamation areas. Journal of Agricultural Resources and Environment, 2023, 40(1): 1-14.

[35] Colantoni A, Evic N, Lord R, Retschitzegger S, Proto A R, Gallucci F, Monarca D. Characterization of biochars produced from pyrolysis of pelletized agricultural residues. Renewable and Sustainable Energy Reviews, 2016, 64: 187-194.

[36] Liu Y, Zhu J R, Wu Y C, Shu L Z. Effects of biochar application on the abundance and community structure of ammonia-oxidizing microorganisms in coal mining subsidence area soil. Chinese Journal of Applied Ecology, 2017, 28(10): 3417-3423.

[37] Rodriguez-Franco C, Page-Dumroese D S. Woody biochar potential for abandoned mine land restoration in the U.S.: A review. Biochar, 2021, 3(1): 7-22.

[38] Simiele M, Lebrun M, Del Cioppo G, Scippa S G, Trupiano D, Bourgerie S, Morabito D. Evaluation of different amendment combinations associated with Trifolium repens to stabilize Pb and As in a mine-contaminated soil. Water Air Soil Pollution, 2020, 231(11): 539.

[39] Boyer S, Wratten S D. The potential of earthworms to restore ecosystem services after opencast mining - a review. Basic and Applied Ecology, 2010, 11(3): 196-203.

[40] Wang L P, Zhang H, Qian K M, Li J. Role of arbuscular mycorrhizal fungi in carbon sequestration of mine restoration system. *

[41] Wang L P, Zhang H, Qian K M, Li J. Role of arbuscular mycorrhizal fungi in carbon sequestration of mine restoration system. Journal of China University of Mining and Technology, 2012, 41(4): 635-640.

[42] Misebo A M, Pietrzykowski M, Woś B. Soil carbon sequestration in novel ecosystems at post-mine sites — a new insight into the determination of key factors in the restoration of terrestrial ecosystems. Forests, 2022, 13(1): 63.

[43] Čížková B, Woś B, Pietrzykowski M, Frouz J. Development of soil chemical and microbial properties in reclaimed and unreclaimed grasslands in heaps after opencast lignite mining. Ecological Engineering, 2018, 123: 103-111.

[44] Pietrzykowski M, Gruba P, Sproull G. The effectiveness of yellow lupine (Lupinus luteus L.) green manure cropping in sand mine cast reclamation. Ecological Engineering, 2017, 102: 72-79.

[45] Zhang Z, Wang J, Li B. Determining the influence factors of soil organic carbon stock in opencast coal-mine dumps based on complex network theory. Catena, 2019, 173: 433-444.

[46] Jia M X, Wang J M, Li Y N, Zhang Y F, Gao T Y, Wu D W. Research progress on mine ecological restoration based on nature-based solutions. Coal Science and Technology, 2024, 52(8): 209-221.

[47] Xu H, Yue C, Piao S. Future forestation in China should aim to align the temporal service window of the forest carbon sink with the "carbon neutrality" strategy. Science China Earth Sciences, 2023, 66(12): 2971-2976.

[48] Vindušková O, Frouz J. Soil carbon accumulation after open-cast coal and oil shale mining in northern hemisphere: A quantitative review. Environmental Earth Sciences, 2013, 69(5): 1685-1698.

[49] Wen Y R, Dang T H, Tang J, Li J C. Distribution characteristics of soil organic carbon under different forest restoration patterns in open-pit coal mine dump. Chinese Journal of Applied Ecology, 2016, 27(1): 83-90.

[50] Kumari S, Maiti S K. Reclamation of coalmine spoils with topsoil, grass, and legume: A case study from India. Environmental Earth Sciences, 2019, 78(14): 429.

[51] Mukhopadhyay S, Masto R E. Comparative evaluation of Cassia siamea and Albizia lebbeck for their potential to recover carbon and nutrient stocks in a chronosequence post-mining site. Catena, 2022, 208: 105726.

[52] Mukhopadhyay S, Maiti S K, Masto R E. Use of reclaimed mine soil index (RMSI) for screening of tree species for reclamation of coal mine degraded land. Ecological Engineering, 2013, 57: 133-142.

[53] Li J C, Dang T H, Xue J, Tang J, Guo S L, Jin J J. Changes in soil carbon storage on slopes of open-pit coal mine dumps under vegetation reconstruction. Acta Pedologica Sinica, 2015, 52(2): 453-460.

[54] Mukhopadhyay S, Maiti S K. Biofertiliser: VAM fungi—a future prospect for biological reclamation of mine degraded lands. Indian Journal of Environmental Protection, 2009, 29(9): 801-808.

[55] O'Donnell M S, Whipple A L, Inman R D, Tarbox R D, Monroe A P, Robb B S, Aldridge C L. Remote sensing for monitoring mine lands and recovery efforts. US Geological Survey, 2024.

[56] Popescu G, Popescu C A, Dragomir L O, Herbei M V, Horeblaga A, Maria A, Constantigescu T, Salagean T, Bruma S, Romanszabo M D, Colisar A, Ceuca V, Kader S, Sestras P. Utilizing UAV technology and GIS analysis for ecological restoration: A case study on Robinia pseudoacacia L. in a mine waste dump landscape rehabilitation. Notulae Botanicae Horti Agrobotanici Cluj-Napoca, 2024, 52(4): 13937.

[57] Samaei M, Stothard P, Shirani Faradonbeh R, Topal E, Jang H. Mine closure surveillance and feasibility of UAV-AI-MR technology: A review study. Minerals, 2024, 14(1): 110.

[58] Zhao J, Ma J, Zhu Y F, Yu H C, Zhang Q, Chen F. Effects of vegetation types on soil carbon cycle functional genes in reclaimed opencast mines of the Loess Plateau. Environmental Science, 2023, 44(6): 3386-3395.

[59] Xiang C Y, Luo D Y, Guo L, et al. Research progress on plant-microbe combined remediation of chemically degraded soils [J]. Chinese Journal of Soil Science, 2024, 55(1): 288-300.

[60] Bhattacharyya S S, Ros G H, Furtak K, Iqbal H M N, Parra-Saldívar R. Soil carbon sequestration—an interplay between soil microbial community and soil organic matter dynamics. Science of the Total Environment, 2022, 815: 152928.

[61] Li R. Evaluation of carbon sink benefits of coal mining subsidence wetlands—taking Pan'an Lake as an example. Xuzhou: China University of Mining and Technology, 2023.