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Research and Application of Plant Configuration Models for Ecological Restoration of Green Mines in Huizhou City

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Abstract Through on-site investigations and case analyses of green mines in Huizhou City, and by integrating technical measures including soil improvement, plant configuration, and community construction, this study proposes a plant configuration model tailored for ecological restoration in the mining areas of Huizhou. The implementation of a multi-level configuration model that predominantly employs native plant species, combined with a "soil-vegetation-microorganism" collaborative restoration strategy, can significantly enhance vegetation coverage in mining areas, increase soil organic matter content, and reduce the bioavailability of heavy metals in the soil. Based on field research and case study analyses, several optimization recommendations are proposed from the perspectives of slope stability and soil and water conservation. Ultimately, it summarizes plant configuration models and their application effects in the ecological restoration of green mines in Huizhou City. These findings may serve as valuable references for the ecological restoration of mines in South China.

Key words Huizhou, Green mine, Ecological restoration, Plant configuration

1 Introduction

The development of mineral resources constitutes a fundamental pillar of Huizhou's economic growth. Nevertheless, prolonged mining activities have resulted in significant ecological and environmental challenges, such as vegetation destruction, soil erosion, heavy metal contamination, and biodiversity loss[1]. Currently, Huizhou City hosts numerous licensed mining areas. Additionally, historical abandoned mining sites are extensively distributed across Huicheng, Boluo, Huidong, and other areas, resulting in numerous exposed slopes and mine pits that continuously threaten the regional ecosystem. In recent years, guided by the national principle that "lucid waters and lush mountains constitute invaluable assets", Huizhou City has actively advanced ecological restoration projects for mining areas. To date, six green mine demonstration projects have been completed, including the first phase of Boluo Shenshan, Hengli Quarry in Huicheng, Xinwei Quarry in Huiyang, Lianghua Quarry in Huidong, Gepu Quarry in Longmen, and Yangguang Quarry in Zhongkai[2].

Ecological restoration in mining areas continues to encounter challenges related to adverse site conditions, including soil degradation, acidification, and heavy metal contamination[3]. Additionally, Huizhou, situated in a subtropical climate characterized by frequent heavy rainfall, experiences a heightened risk of soil erosion on slopes. This study addresses these issues by examining the case of green mine restoration in Huizhou City. It integrates standards such as the *Technical Code for Ecological Restoration Construction of Open-pit Mine Slopes* to analyze the effectiveness of plant selection, configuration models, and management and maintenance techniques. The objective is to develop a "low-maintenance, high-efficiency, and sustainable" plant configuration model for green mines, thereby providing a scientific foundation for the ecological restoration of mines in Huizhou City and the broader South China region.

2 Overview and ecological status of mining areas in Huizhou City

2.1 Distribution of mining areas and ecological background

Huizhou City possesses abundant mineral resources, primarily located in Boluo County, Huidong County, Longmen County, and surrounding areas. The region experiences a subtropical monsoon climate, characterized by an average annual temperature of 21.7 ℃ and an annual precipitation of approximately 1 900 mm. The native vegetation predominantly consists of subtropical evergreen broad-leaved forests, with representative tree species including *Cinnamomum camphora*, *Schima superba*, and *Elaeocarpus sylvestris*. According to the investigation, six green quarries have been fully operational, with a total designed annual production capacity of 31 million m^3. The abandoned mines from historical activities primarily consist of ceramic clay mines and metal slag dumps, resulting in degraded landforms characterized by exposed slopes, mine pits, and tailings accumulation.

2.2 Major ecological and environmental issues Open-pit mining operations often result in extensive removal of surface vegetation, which subsequently leads to a decrease in vegetation coverage within the mining area. This disturbance contributes to soil erosion, habitat fragmentation, a reduction in plant species diversity, and a contraction of the habitat range for protozoan communities. Mining activities can substantially affect soil structure, soil organic matter content, and contribute to heavy metal contamination. These issues directly impede the normal growth and development of plants[4], thereby adversely influencing the effectiveness of subsequent greening and reclamation efforts.

2.3 Restoration policy and practical foundation In the eco-

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logical restoration efforts of mining sites in Huizhou City, the principle of "concurrent mining and remediation" has been explicitly emphasized. Large-scale surface clearance in mining areas should be avoided unless absolutely necessary. For exposed loess surfaces, prompt greening and re-vegetation measures should be implemented. Concurrently, the "ecology + industry" model has been employed to progressively channel social capital into ecological restoration efforts, aiming to realize a synergistic benefit for both ecological and economic systems. From a technical perspective, an ecological restoration approach encompassing "slope re-greening, water interception and diversion, and microbial regulation" has been preliminarily developed, but the precision and rationality of plant configuration require further refinement.

3 Plant configuration technology for green mine ecological restoration

3.1 Soil improvement and micro-environment regulation technology To address the prevalent issue of soil degradation in mining areas, stratified improvement strategies are typically implemented. The substrate layer is enhanced by applying a mixed substrate composed of sand, soil, and organic fertilizer at a ratio of 1 : 1 : 0.5, which serves to reduce soil salinity and elevate microbial biomass carbon levels. During the ecological restoration of the ceramic mine at Dunzi Forest Farm, Huicheng, the application of organic fertilizer substantially increased the soil organic matter content, thereby effectively mitigating soil compaction. In areas contaminated with heavy metals, passivation restoration techniques, including the use of biochar or humic acid, were employed to reduce the bioavailable concentrations of copper and lead[5]. At the Xinwei Quarry in Huiyang, the implementation of "waste-to-waste" restoration techniques enabled the conversion of mud cakes generated by the machine-made sand production line into ecological bricks. These bricks were subsequently utilized for slope protection and restoration, thereby facilitating resource recycling.

3.2 Plant screening and configuration models In accordance with the principle of selecting appropriate tree species for specific locations, Huizhou City has developed a multi-tiered species screening system. Hyperaccumulative and tolerant plant species have been chosen for areas contaminated with heavy metals. Research indicates that *Cynodon dactylon* exhibits a copper enrichment coefficient of 0.71. Its well-developed rhizomes facilitate the translocation of heavy metals to the root system, enhance the abundance of rhizosphere microorganisms, and significantly improve the soil's detoxification capacity. In areas characterized by high and steep slopes, a vegetation model combining shrubs, grasses, and vines is employed. The resilient shrub *Bougainvillea spectabilis* is planted in the upper layer, *Parthenocissus tricuspidata* is arranged in the middle layer, and the bottom layer is covered with *C. dactylon* or *Paspalum notatum*. Following the implementation of this model in the Dayawan mining area, dust suppression was effectively achieved. "Economic-ecological" communities were established on gentle slopes and plateau regions. At the Dunzi Forest Farm in Huicheng, *Castanopsis fissa* was planted in an abandoned ceramic clay mine and integrated with native tree species such as *C. camphora* and *E. sylvestris* to create a mixed forest. The drought tolerance and rapid growth characteristics of *C. fissa* have contributed to increased income for the forest farm.

3.3 Microbial-plant synergistic restoration technology Microorganisms play a crucial role in the ecological restoration of mining areas. Research indicates that the rhizosphere microbial community associated with *C. dactylon* is relatively diverse and abundant. These microorganisms primarily contribute to processes such as organic matter metabolism and nitrogen cycling, thereby facilitating the accelerated degradation of pollutants[6]. In ecological restoration practices, inoculation with arbuscular mycorrhizal fungi and nitrogen-fixing agents has been shown to enhance seedling survival and preservation rates, as well as significantly increase plant growth[7]. Furthermore, the addition of microbial agents to the spray seeding substrate in the Dayawan mining area resulted in a significant optimization of the soil microbial biomass carbon/nitrogen ratio and a marked improvement in the microbial nutritional structure.

3.4 Coordinated restoration of water ecology and slopes In addressing water environmental challenges in mining areas, Huizhou has innovatively implemented the concept of West Lake governance, thereby facilitating the self-purification capacity of aquatic ecosystems through the establishment of aquatic plant communities. Drawing upon the successful experiences of West Lake and Nanfeng Lake in Huizhou, submerged plants such as *Vallisneria natans* and *Myriophyllum verticillatum* were introduced, alongside the floating-leaved plant *Nymphaea tetragona*. Additionally, field snails and filter-feeding fish were released to establish a functional ecological chain[8]. Following the implementation of the project, the transparency of the water body improved significantly, and the dissolved oxygen levels increased markedly. At the Shenshan Quarry in Boluo, a "flexible protective net combined with vegetation bag" technology was employed. A water interception ditch was constructed at the top of the slope, and honeycomb compartments were installed on the slope surface. These compartments were filled with an improved substrate, into which seeds of *C. dactylon* and *P. notatum* were planted. In conjunction with a drip irrigation system, the vegetation coverage rate reached 90% during the maintenance period.

4 Innovation and application of plant configuration models in typical green mines

4.1 Open-pit quarry The Boluo Shenshan Quarry, a flagship project of Huizhou Jiaotou Mining, has innovatively implemented a "three-dimensional re-greening approach combined with an intelligent management and protection" model, employing a zoned configuration strategy for each area. The mining platform established a mixed forest predominantly composed of *C. fissa* and *Cinnamomum burmannii*, with interplanted shrubs such as *Ixora* *chinensis* beneath the canopy to promote biodiversity. Additionally, *Ficus benjamina* and *Allamanda schottii* were planted along both sides of the transportation road to create a green isolation belt, complemented by an automatic sprinkler dust suppression system. At the final pit slope, a combination of "floating channel greening and vegetation bag" technology was employed. *P. tricuspidata* and *Hibiscus rosa-sinensis* were planted within the channel, while vegetation bags containing *C. dactylon* seeds were placed at the base of the slope. Within 6 months, vegetation coverage improved significantly. Following the implementation of this project, the vegetation coverage rate increased by 50% compared to pre-restoration levels, and soil erosion was reduced by 90%.

4.2 Metal slag dumps A novel model combining "enrichment plants and microorganisms" was developed for the copper slag dump in Longmen County. The core species, *C. dactylon*, was selected as the pioneer species, and copper-tolerant microbial strains were inoculated into the soil at the restoration site to enhance the diversity of rhizosphere microorganisms and to accelerate the transformation of copper from its acid-soluble form to a residual state. Following the restoration process, the available copper content in the soil decreased by 16%, while vegetation coverage increased from 15% to 75%, thereby successfully achieving the objectives of "both restoration and control".

4.3 Abandoned ceramic mine The Hengli Quarry in Huicheng has successfully converted abandoned mining pits into valuable green spaces through an "ecological reserve forest and industrial integration" model. In regions characterized by exposed loess, priority should be given to the cultivation of *C. fissa* due to its tolerance to poor soil conditions and rapid growth. This species can be effectively combined with broad-leaved trees such as *C. camphora* and *Liquidambar formosana* to establish a significant ecological barrier. Furthermore, the *C. fissa* plantations will be utilized to promote under-forest economic activities and ecotourism, thereby enhancing the income of local villagers.

5 Conclusions and discussion

This study summarizes the principal technologies and application models related to plant configuration in the ecological restoration of green mines in Huizhou City. The scientificity of plant configuration constitutes a fundamental element for the successful ecological restoration of mining areas. Based on the "soil-vegetation-microorganism" synergistic restoration strategy[9], appropriate pioneer species, including *C. dactylon* and *C. fissa*, were selected. Through a multi-level configuration approach, restoration efficiency was markedly enhanced. Furthermore, the application of *C. dactylon* in copper-contaminated sites significantly increased the abundance of rhizosphere microorganisms. The zoned governance model effectively addresses the heterogeneous conditions present in mining areas. On the slopes of open-pit quarry, the "drift channel greening combined with vegetation bag" technology has been implemented. Additionally, the ecological chain comprising "submerged plants and benthic animals" has been introduced into mine pit lakes. Furthermore, a "mixed forest of *C. fissa* alongside under-forest economic industries" has been developed in historically legacy mines. These approaches have collectively yielded positive outcomes[10].

Although the plant configuration model for green mine restoration in Huizhou City has demonstrated preliminary success, challenges related to the long-term stability of the restoration outcomes and the migration of heavy metals warrant further comprehensive investigation. During the restoration process, certain slopes still require continuous artificial irrigation to support greening efforts. Under conditions of extreme drought, the effectiveness of greening may deteriorate. In the ecological restoration of mining areas contaminated with heavy metals, the harvested biomass from plants that accumulate high or excessive levels of heavy metals must be disposed of safely. Improper handling of these materials can lead to secondary pollution issues[11]. The existing "ecological and industrial" restoration model predominantly depends on government funding. In the advanced stages of ecological restoration, it is recommended to enhance the ecological compensation mechanisms and carbon sink trading systems to further encourage the involvement of private capital in restoration efforts. By primarily utilizing native plants supplemented with engineering measures, the practice in Huizhou has demonstrated that "lucid waters and lush mountains constitute invaluable assets". The current ecological restoration technology model exhibits a degree of universality applicable to mining areas within the southern subtropical zone of China and can serve as a reference for mine restoration efforts under comparable climatic conditions. However, it is important to note that further advancements are necessary in developing technologies to ensure the long-term stability of restored vegetation communities.

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6.1.3 Quantitative analysis of the economic benefits of silicon fertilizer application. To more effectively illustrate the economic benefits of silicon fertilizer application, a quantitative analysis was performed. The data indicated that the cost of spraying silicon fertilizer was 750 yuan/hm^2. After accounting for this expense, the Si group exhibited a significant increase in net income at all monitoring points compared to the CK group. For example, in Longtang Village, Ma'an Town, the net income increase from the Yexiangyoulisi variety reached 2 918.4 yuan/hm^2. In Pengling Village, Shuikou Subdistrict, the Zhenguiai variety yielded a net income increase of 1 314.0 yuan/hm^2. Additionally, the Xuanzhimi variety cultivated in Lanpai Village, Luzhou Town, demonstrated a net income increase as high as 3 328.5 yuan/hm^2. These data clearly indicate that the spraying of silicon fertilizer not only offsets its cost but also generates substantial economic benefits for farmers.

6.1.4 Comprehensive benefits and promotion prospects of silicon fertilizer application. From the perspective of comprehensive benefits, the application of silicon fertilizer not only directly enhances the yield and quality of rice but also indirectly increases farmers' income by improving market value. Furthermore, the use of silicon fertilizer contributes to the improvement of soil structure and the enhancement of crop stress resistance, thereby providing long-term ecological benefits and supporting the potential for sustainable agricultural development. Therefore, taking into account both economic and ecological advantages, the promotion and utilization of silicon fertilizer in rice cultivation hold significant potential. Particularly in the context of ongoing agricultural transformation, upgrading, and the pursuit of high-quality development, the application of silicon fertilizer is poised to become a crucial strategy for enhancing agricultural competitiveness and increasing farmers' incomes.

In conclusion, the application of silicon fertilizer on rice has demonstrated remarkable effectiveness in enhancing economic benefits. By various mechanisms, including directly increasing yield, improving quality, and elevating market value, silicon fertilizer has generated substantial economic advantages for farmers. Future efforts should focus on expanding the promotion and application of silicon fertilizer to fully exert its potential in supporting the sustainable development of agriculture.

6.2 Ecological and social benefits Silicon fertilizer exhibits a significant ecological-social synergy in rice cultivation. Ecologically, it enhances yield, improves soil quality, increases stress resistance, and reduces pesticide usage. Socially, it boosts economic benefits and fosters sustainable development.

Silicon fertilizer has facilitated the integrated advancement of ecological and economic objectives in rice cultivation. Its primary contributions include economic benefits through enhanced planting income achieved by simultaneous improvements in yield and quality; ecological benefits by promoting sustainable agricultural development via reduced chemical inputs and improved soil conditions; and social benefits by ensuring food security through increased production capacity per unit area and fostering rural economic stability by raising farmers' incomes. This synergy generates a positive feedback loop among "economic benefits, ecological protection, and social stability", ultimately resulting in a mutually beneficial outcome for both ecological and economic benefits.

Therefore, the application of silicon fertilizer spraying technology in rice cultivation should be explicitly recognized as an efficient, environmentally sustainable, and green agricultural practice. It represents a crucial approach to advancing agricultural modernization and achieving sustainable agricultural development. Future efforts should focus on intensifying research and promoting the adoption of silicon fertilizer technology. Additionally, application strategies should be optimized according to varying soil types and crop characteristics to improve its efficacy and widespread acceptance, thereby contributing more significantly to sustainable agricultural development and comprehensive societal progress.

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