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Research on ecological restoration and green reclamation technology of goaf in phosphorus mines

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The subsidiary of Yunnan Phosphate Group Co., Ltd., Kunyang Phosphate Mine's mining area is the subject of study. The mining of open-pit phosphate mines has caused significant damage to the ecological environment. Therefore, carrying out ecological restoration and green reclamation of the ecosystem in the mining area has become the top priority for current development. This article establishes an evaluation system for ecological restoration indicators, selecting four indicators including vegetation coverage, soil and water conservation, restoration of native plants, and Plant Species Diversity Index to assess the effects of ecological restoration and green reclamation of phosphate mines. The techniques of reconstructing soil ecological structure using phosphate tailings substrate and improving acidic soil with soil conditioner and calcium-magnesium phosphate compound fertilizer were applied. A series of other measures were taken, including: drafting scientific ecological restoration plans; employing physical, chemical, and biological methods for ecological restoration and green reclamation; selecting suitable plant species for planting; enhancing planting techniques; and strengthening post-restoration ecological monitoring and regulation. After ecological restoration and green reclamation, the Ecological Remediation Effect Index (EREI) for the years 2020, 2021, and 2022 were 48.40, 87.38, and 93.23 respectively, indicating significant improvement in the ecological environment. Furthermore, the difficulties encountered during the ecological system restoration process of the mine and the future development directions were summarized, providing practical and guiding significance for ecological restoration and green reclamation of abandoned mining areas both domestically and internationally.

KEYWORDS

phosphate mine, green-land reclamation, ecological restoration, measures, ecological remediation effect index

1 Introduction

Since the initiation of reform and opening up, China has vigorously pursued economic development, leading to an increased demand for both economic and natural resources. Substantial progress has been achieved in the economy, accompanied by rapid growth in the mining industry. However, due to a lack of awareness regarding environmental protection and large-scale and disorderly mining practices, as well as improper disposal of waste, significant damage has been inflicted upon China's hydrological systems, ecological environment, and land. As a result, the overall functionality of the ecosystem has deteriorated (Li et al., 2014; Yichang City Vigorously, 2017; Jia H. et al., 2021). In recent years, China has dramatically emphasized environmental protection and has prioritized ecosystem restoration in mining areas. Therefore, there is a growing need to develop reclamation technologies for Goaf areas. To achieve coordinated development between mineral resource development and ecological environment protection, increase the efficiency of mineral resource development and utilization, and minimize harm to the ecological environment of mining areas, required by relevant laws, regulations, and policy documents such as the "Law of the People's Republic of China on the Prevention and Control of Solid Waste Pollution Environment" that as of 2015, the land reclamation rate of historical mining sites should be over 45%, and the rate for newly built mines should exceed 85%.

As an important component of human production and life, mineral resources have promoted the rapid development of the social economy. However, many mining methods have not been implemented according to national standards, causing serious environmental damage and altering traditional mining methods (Xu et al., 2019; Hou et al., 2023; Li et al., 2023). To eliminate the phenomenon of sacrificing the environment for mineral resources and achieve the rational development and utilization of mineral resources and the long-term development of the environment has become an inevitable choice for enterprise development (Jin and Zhou, 2016; Du et al., 2019; Zhao et al., 2021).

Yunnan Phosphorus Chemical Group Co., Ltd. is one of the largest open-pit phosphate mining enterprises in China. After decades of open-pit phosphate mining, it has accumulated some experience in mining technology, mining processes, flotation of phosphate rock, land reclamation, ecological restoration, and green reclamation. It has the conditions for ecological restoration and green reclamation. In addition, the Kunyang Phosphate Mine is adjacent to the national-level tourist attraction, Dianchi Lake. The local government attaches great importance to the restoration of the ecological environment. The ecological restoration and green reclamation of the phosphate mine have become pressing issues for the enterprise to address.

This paper takes the abandoned mining area of Kunyang Phosphate Rock as the research object, with the ecological restoration and green reclamation of the open-pit phosphate mine's abandoned mining area as the starting point. A series of ecological restoration technologies are adopted, and an evaluation system for ecological system restoration indicators is established to assess the abandoned mining area after ecological restoration and green reclamation. The relevant research results have important practical and guiding opinions for promoting the construction of green mines.

2 Overview of mining area environment

2.1 Geographical environment of mining area

The Kunyang phosphate rock is one of the main mines of Yunnan Phosphate Group Co., Ltd., belonging to a large state-owned open-pit mine. It is located in Sanjia Village, Kunyang Town, Jinning County, Kunming City, with convenient transportation as roads and railways connect to the mine. The Kunyang phosphate rock deposit type is sedimentary phosphate rock deposit. The mining area is located in a water ridge gentle slope zone with deep groundwater burial. The geological occurrence of the mining area is gentle, with an inclination angle of 4°–17°. Water for mining in the area comes from atmospheric precipitation. During the dry season, the dust generated by tailings blankets the entire mine. The whole mining area has caused significant impacts on the residents and the ecological environment. The three-dimensional image of Kunyang phosphate rock's geographical location is shown in Figure 1.

During the early open-pit mining process, the ecological environment was severely damaged, with hidden dangers such as landslides, soil erosion, and rocky desertification. The on-site situation of the mining pit area is shown in Figure 2.

After a long period of weathering, the mining area contains a large amount of gangue and waste, producing metal salts and sulfides, among other harmful substances, which have polluted the groundwater and affected the hydrological environment of the mining area. Particularly, the erosion of soil and water rich in elements such as fluorine and phosphorus has intensified the eutrophication of Dianchi Lake, polluting its water (Liu and Yang, 2015). After decades of continuous mining, the phosphate mine environment has been severely damaged. Although the ecological environment of the mine has been restored, the previous mining still has a very adverse impact on the ecological environment of the mine.Figure 2.

2.2 The difficulties faced by the mining environment

After conducting on-site surveys of the Kunyang phosphate mine, it was found that the soil elements within the mining area's depleted zones were severely imbalanced, resulting in a sensitive and fragile ecological environment. The landscape has suffered significant damage, with a loss of soil carbon sequestration capacity and poor water retention in the mine. Soil and rock desertification are severe, with significant geological hazards and poor climatic conditions in the mining area, among a series of issues. During the mining process of the Kunyang phosphate rock, attention has been paid to the importance of the ecological environment and land reclamation. Although certain measures have been taken, after decades of large-scale investment in ecological environment management, the improvement effect of goaf work in the mine is relatively average. With the increasing emphasis on ecological environment construction by the country in recent years, Ecological restoration of mined-out areas has become

FIGURE 1
Geographic location of the Kunyang phosphate rock.

FIGURE 2
On-site of the mining pit area.

an important step in promoting the construction of national green mines.

2.2.1 The soil elements are severely imbalanced

The Kunyang phosphate rock is rich in phosphorus resources, but large-scale mining activities have caused certain damage to the surrounding ecological environment and have led to significant changes in the original geological and soil conditions after mining. The proportion of soil element allocation has become imbalanced, resulting in poor natural vegetation restoration ability and weak self-regulation and adaptability of the natural ecological environment. The vegetation (Jin and Wei, 2020; Gao et al., 2021; Sun et al., 2022) and soil reconstruction in the goaf of mines (Wang et al., 2022; Yan et al., 2022; Wang et al., 2023; Zhou et al., 2023) have become one of the urgent problems to be solved.

2.2.2 Ecological environment around the mining area is relatively sensitive and fragile

During open-pit phosphate mining, the green vegetation resources within the mining area are excessively cut down and damaged, resulting in a significant reduction of native plants in the mining area. Only a portion of secondary forests and young forests survive, or there are very few native forests left, making the ecological environment sensitive and fragile.

2.2.3 Loss of soil carbon sequestration capacity

The primary cause of carbon sequestration capacity loss lies in the disturbance to the relatively balanced ecosystem carbon cycle within the mining area prior to mining activities. The cultivated land, forest land, and grassland served as significant biomass carbon pools, dead organic matter carbon pools, and soil carbon pools. However, the extraction and mining operations have caused the destruction of the original land cover, leading to a decline in the mining area's ability to sequester biomass carbon. Additionally, it has accelerated the decomposition rate of dead organic matter and soil carbon pools, resulting in carbon emissions. Consequently, this disturbance has had a severe impact on the carbon cycling process within the surrounding atmosphere, soil, and vegetation.

2.2.4 The degree of landscape environmental damage is significant

Mining activities have damaged the original natural landscape and altered the topography of the mining area. At the same time, mining activities have reduced biodiversity, resulting in the survival of only a small number of trees in the area, with a single species surviving, uneven distribution, and irregular tree growth. This has increased the difficulty of protecting ecological diversity.

2.2.5 Soil and rock desertification is severe

Extensive mining activities have significantly damaged the original vegetation and soil structure. This destruction of the soil structure has led to poor water retention and less atmospheric precipitation, resulting in severe rock desertification that is detrimental to plant growth. As a result, the preconditions for landscape restoration are inadequate.

2.2.6 Significant hidden dangers of geological disasters

The open-pit mining has resulted in significant alterations to the original geological environment, causing the local geological environment to become loose and the consolidation force to decrease. This makes it more susceptible to triggering geological disasters such as landslides and mudslides, posing a significant threat to the production and livelihoods of residents in the surrounding mining area (Jia L. et al., 2021; Liang, 2022).

2.2.7 Poor climatic conditions

The Kunyang phosphate rock is located near the Dianchi Lake Ecological Environment Protection Zone. Large-scale mining activities have caused significant damage to the ecological environment and soil around Dianchi Lake. Moreover, in recent years, Yunnan has experienced frequent droughts, with reduced rainfall and dry climates, leading to a gradual decrease in the self-regulation ability of the ecological environment. Therefore, it is urgent to implement ecological restoration and soil reconstruction plans.

3 The establishment of content and evaluation system for ecological restoration in the mining area's depleted areas

3.1 Content of ecological restoration and green reclamation

Ecological restoration and green reclamation are important conditions for constructing green mines. They are essential for enhancing the economic viability of mining areas, improving environmental structures, achieving coordinated development between mining activities and the environment, and optimizing the industrial structure of mining areas (Hu et al., 2023).

Mine land reclamation (Du and Zhao, 2022; Zhai, 2022; Fu, 2023; Li and Chu, 2023) and ecological restoration (Zhang B. C. et al., 2023; Hu and Xu, 2023; Yan et al., 2023) in mine void areas require careful consideration of the extent of ecological damage caused by mining activities. Specific ecological restoration techniques should be employed based on the degree of damage to restore the disturbed void areas to their original state. Ecosystem restoration should include at least three aspects:

(1) Soil nutrient accumulation and biogeochemistry cycle recovery;
(2) Restoration of biodiversity;
(3) The direction of vegetation succession and the restoration of the self-sustaining ability of the ecosystem.

3.2 Ecological restoration index evaluation system

After the restoration of the ecosystem, the effectiveness of ecological restoration is determined through the evaluation system of ecological restoration indicators. The ecological restoration index evaluation system is mainly determined by four indicators: vegetation coverage, soil and water conservation, native vegetation restoration, and vegetation species diversity. Four of these indicators are positive factors, where larger values indicate better ecological restoration outcomes.

3.2.1 Vegetation coverage

The Vegetation Coverage Rate denotes the proportion of the vertical projected area occupied by vegetation, including leaves, stems, and branches, on the ground in relation to the total area of the designated region. It serves as an indicator that reflects the level of greening within a particular area. The dynamics of plant cover can be effectively captured using the Normalized Difference Vegetation Index (NDVI) (Wang et al., 2003). However, it is important to note that NDVI may experience saturation in the red light channels when dealing with regions characterized by dense vegetation. In such cases, the MODIS EVI provides a viable alternative as it effectively mitigates saturation issues in vegetation indices. Furthermore, the MODIS EVI also incorporates comprehensive corrections for essential atmospheric variables such as molecules, aerosols, thin clouds, water vapor, ozone, and other factors that affect the accuracy of the basic data (Wang et al., 2003).

$$EVI = \frac{G \times (\rho_{NIR} - \rho_{red})}{\rho_{NIR} + C_1 \times \rho_{red} - C_2 \times \rho_{blue} + L} \tag{1}$$

In formula (1), ρ_{NIR}、 ρ_{red}、 ρ_{blue} represents the reflectance of near-infrared light, red light, and blue light, respectively; G is the gain adjustment factor; C_1 and C_2 is the atmospheric regulation parameter; L is the vegetation canopy background adjustment factor.

The quantification of plant coverage can be achieved through the use of EVI. By grading the EVI images acquired from MODIS during different time periods and employing image interpolation to generate the different images between them, it becomes possible to assess the trend of EVI variations (Wang and Hu, 2020), specifically focusing on the affected pixel 0. When the pixel value exceeds 0, it signifies an upward trend in EVI, indicating an increase in plant coverage and a positive development toward the intended ecological restoration outcomes. Conversely, when the pixel value is negative, it suggests a contrary direction of ecological restoration efforts.

3.2.2 Soil and water conservation degree

The Soil Erosion Impact Index is frequently utilized to assess soil and water conservation plans and can also be applied to evaluate the extent of soil and water conservation in the ecological restoration and green reclamation efforts across several mines operated by the Kunyang Phosphate rock. Following the open-pit mining activities at the original site, extensive vegetation was disrupted, leading to a substantial reduction in the natural soil and water conservation capacity. A weighted summation of the key impact indicators is conducted to analyze the gains and losses in soil and water conservation, thereby yielding a dimensionless value that reflects the magnitude of soil erosion impact. The calculation formula for the Soil Erosion Impact Index is outlined as follows (Jiang, 2010):

$$\mathrm{SWII} = \sum\nolimits_{i=1}^{n} \alpha_i x_i \tag{2}$$

In formulas (2) and (3), α_i is the weight of the ith factor, which can include rainfall erosivity, soil invasiveness, slope and length, plant cover, soil and water conservation measures, impact time limit, research mining area, impact area, etc. The value of i ranges from 1 to 8; x_i is the normalized value of the ith factor data, obtained from the original value x_i Standardize it after i.

$$x_i = \frac{x_0 - \min(x)}{\max(x) - \min(x)} \tag{3}$$

The smaller the SWII value, the shorter the impact time of the project, the smaller the amount of soil erosion, and the better the degree of soil and water conservation. The higher the SWII value, the greater the amount of soil erosion and the worse the soil and water conservation.

(1) Rainfall erosivity x_1. The Richardson daily rainfall erosivity model can be utilized for calculation, and the formula for estimating half-month erosivity based on daily rainfall is as follows:

$$t_i = \alpha \sum\nolimits_{j=1}^{k} P_j^{\beta} \tag{4}$$

In formula (4): t_i represents the erosion value of the i half-month period ($\mathrm{MJ} \cdot \mathrm{mm} \cdot \mathrm{hm}^{-2}$); k denotes the number of days with erosive rainfall during the half-month period (d); P_j stands for the daily rainfall of ≥12 mm on the j day of the half-month period (mm). The parameters α and β are calculated using the following formulas (5) and (6):

$$\alpha = 21.586\beta^{-7.1981} \tag{5}$$

$$\beta = 0.8363 + \frac{18.144}{P_{d12}} + \frac{24.455}{P_{y12}} \tag{6}$$

In formula: P_{d12} represents the daily rainfall with an intensity of ≥12 mm (mm); P_{y12} is the annual average rainfall with a daily intensity of ≥12 mm. The annual rainfall erosivity is obtained by summing up the rainfall erosivity for each half-month period within a year, resulting in formula (7):

$$x_1 = \sum\nolimits_{i=1}^{24} t_i \tag{7}$$

(2) Soil erodibility factor x_2. Because of the high demand for direct determination of the x_2 value, soil properties are commonly employed to calculate the x_2 value. This article utilizes the formula developed by Williams et al. to compute the x_2 value in the EPIC model and estimates the x_2 value using data on soil organic carbon and soil particle composition (Williams et al., 1996).

$$x_2 = \left\{0.2 + 0.3\exp\left[-0.0256S_d\left(1 - \frac{S_i}{100}\right)\right]\right\} \cdot \left(\frac{S_i}{Cl + S_i}\right)^{0.3} \cdot \left[1 - \frac{0.25C}{C + \exp(3.72 - 2.95C)}\right] \cdot \left[1 - \frac{0.7\delta}{\delta + \exp(-5.51 + 22.9\delta)}\right] \tag{8}$$

$$\delta = 1 - \frac{S_d}{100} \tag{9}$$

In formulas (8) and (9): S_d represents the sand content (%); S_i denotes the silt particle content (%); Cl signifies the clay content (%); and C indicates the organic carbon content (%).

(3) The impact of terrain on soil erosion can be assessed using slope and slope length factors represented by x_3. The specific calculation formula is as follows (Yi et al., 2015):

$$x_3 = \left(\frac{\lambda}{72.6}\right)^m (65.41\sin^2\beta + 4.56\sin\beta + 0.065) \tag{10}$$

In formula (10): λ represents the slope length (m); m is the variable related to the slope; β denotes the slope in degrees. When β is greater than or equal to 2.86°, $m = 0.5$; When β is between 1.72° and 2.86°, $m = 0.4$; When β is between 0.57° and 1.72°, $m = 0.3$; When β is less than 0.57°, $m = 0.2$.

(4) Plant coverage factor x_4: The EVI (Enhanced Vegetation Index) value, calculated from the plant coverage index, serves as a positive factor. A higher EVI value indicates greater plant coverage.
(5) Soil and water conservation measures factor x_5: This factor represents the ratio of soil loss after implementing soil and water conservation measures to the amount of soil loss during slope planting. Its values range between 0 and 1, with 0 indicating no occurrence of soil erosion and 1 indicating the absence of soil and water conservation measures. While all other factors in SWII are negative, the plant coverage factor and soil and water conservation measures factor are exceptions. Negative values are assigned to these two factors to align with the objective of achieving better soil and water conservation with a smaller SWII value.
(6) Impact time limit x_6, the area of the mining area being studied x_7, and the area of the affected area x_8, The three factors are determined by referring to the general information of mining engineering.

3.2.3 Restoration degree of native plants

The recovery degree of native plants refers to the local plant species that can still grow in mines after various natural disasters, such as changes in times, soil erosion, and climate, despite long-term growth in mines (Gao et al., 2020).

Field investigations and visits were conducted while the mine was not being mined, and local historical data was consulted to determine the native plant species of the local mine. Then, based on the characteristics and growth status of the species, maintenance, and management were selected from aspects such as soil and water conservation, carbon sequestration, pollutant adsorption, landscape fragmentation, reproduction and cultivation, and maintenance. The types of native plants for local restoration were determined. The native plant type can be characterized by the Native Plant Remediation Index (NPRI) to assess the degree of Native Plant Remediation Index (Gao and Meng, 2019).

$$\mathrm{NPRI} = \frac{\sum_{i=1}^{n} \beta_i S_i}{S_0} \tag{11}$$

In formula (11), n represents the total number of selected native plant types; β_i denotes the weight assigned to the i type of native plants; S_0 signifies the total area of the restoration site; and S_i represents the coverage area of the i type of native plants post-

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restoration. A larger value of NPRI indicates a greater coverage of native plants in the restoration area, thereby reflecting a more favorable ecological restoration outcome.

3.2.4 Plant Species Diversity Index

Plant Species Diversity Index serves as the bedrock for safeguarding animal diversity and stands as the fundamental requirement for upholding a healthy ecological environment (Zhang H. W. et al., 2023). Indicators of Plant Species Diversity Index are capable of depicting the abundance and uniformity of plant species within the restoration area. The Plant Species Diversity Index (PSDI) facilitates a quantitative characterization of Plant Species Diversity Index. Additionally, the Patrick richness index (R), Shannon Wiener diversity index (H), and Pielou evenness index (E) can be employed to analyze the plant diversity index (Liu et al., 2020).

$$R = M \tag{12}$$

$$H = -\sum_{i=0}^{M} P_i \ln P_i \tag{13}$$

$$E = \frac{H}{\ln(M)} \tag{14}$$

$$\mathrm{PSDI} = k_1 R + k_2 E \tag{15}$$

In formulas (11)–(14), M represents the total number of plant species in the mining survey area; P_i denotes the importance value of the ith species, which is calculated as the average of its relative abundance, relative coverage, and relative density; k_1 and k_2 represent the weights assigned to the Patrick richness index and the Pielou evenness index, respectively.

A higher PSDI value indicates a richer and more evenly distributed range of plant species in the mining area, thus facilitating the restoration of the original ecosystem and ultimately advancing the objective of ecological restoration.

4 Analysis and research on ecological restoration technology in mining areas

4.1 Green reclamation technology for phosphorus tailings base soil

4.1.1 Technology for reconstructing soil ecological structure of phosphorite tailings base soil

The goal is to emulate the chemical composition, physical structure, biological communities, and ecosystem of natural, healthy soil by constructing an artificial matrix soil based on phosphorus tailings. This involves primarily adding exogenous biological organic matter, soil functional microorganisms, and soil animals in order to simulate the structure and function of both the soil surface and profile, thereby maximizing the restoration of the soil ecosystem.

4.1.2 Technology for amending acidic soil with soil conditioners and calcium-magnesium-phosphate compound fertilizers in phosphorite tailings base soil

By harnessing the vital nutrients present in tailings, such as calcium, magnesium, and phosphorus, and incorporating diverse exogenous substances like functional microbial agents, bio-organic fertilizers, and trace elements, it becomes possible to prepare agricultural soil conditioners and composite fertilizers tailored to specific soil types and crops. This enables the provision of essential nutrients to plants and supports optimal soil conditions. The comparison between phosphorus tailings matrix soil products and existing products is shown in Table 1.

Using the solid waste from the Kunyang phosphate rock as the experimental object, soil was modified, nutrient balance was adjusted, and soilization was carried out to make it suitable for planting seedlings for ecological restoration in mine areas. Through continuous monitoring and environmental risk assessment for more than 2 years, a soil reconstruction technology with soil functions and environmental safety was ultimately developed. A plant ecological system suitable for mining environments was established, providing theoretical and technical support for the utilization of solid waste resources in phosphate mines and ecological reconstruction of mines. A demonstration base for ecological restoration soil with an annual capacity of 400,000 tons was established in the Kunyang phosphate rock area, as shown in Figure 3. In addition, this technology was applied to slope ecological restoration in the abandoned areas of the Kunyang phosphate rock, as shown in Figure 4.

4.2 Specific restoration measures for phosphorus mines

(1) Formulate the implementation plan for ecological restoration of the mine, providing scientific basis for the restoration of mine vegetation, and ensuring the smooth implementation of ecological restoration. Yunnan Phosphorus Chemical Group Co., Ltd. has formulated key experimental research and engineering projects such as “Restoration and Management of Geological Environment in Yunnan Phosphate Mines,” “Comprehensive Control Technology Research and Demonstration of Ecological Restoration in Abandoned Mining Areas,” and “Engineering Technology for Controlling Phosphate Mine Area Source Pollution. Simultaneously compiled two enterprise standards: “Matrix Soil for Ecological Restoration of Phosphorite Tailings Base” and Technical Specifications for the Application of Ecological Restoration Materials in Phosphorite Tailings Base. The production process of mining and stripping was improved, with mining and stripping materials being discharged into the goaf, and land reclamation projects were implemented.

(2) To address environmental issues such as soil and water resource pollution in goaf areas of mines, it is crucial to establish a new mining area reclamation model. This includes accelerating the restoration of the surrounding geological environment and water source pollution issues, resolving unfavorable conditions for plant and biological survival, expediting the evolution of natural ecosystems, creating prerequisites for ecological restoration, and improving the sustainable development of ecological restoration. To address soil and water pollution in the goaf of the five mines belonging to Yunnan Phosphate Group, three approaches were employed for ecological restoration and green reclamation: physical methods, chemical methods, and biological methods.

TABLE 1 Comparison of phosphorus tailings matrix soil products with existing products.

Product		Production costs	Technical parameter	Advantages and disadvantages
Mining ecological restoration matrix soil	Ecological restoration of phosphorus tailings-based matrix soil	70 yuan/m^3	Composed of phosphorus tailings, agricultural and forestry waste, municipal sludge, coagulants, and other materials, and added with plant seeds	Large in size, capable of manually adjusting nutrients and structural composition according to demand
	Restoration Technology for Hakka Soil Mines	90 yuan/m^3	Diversification of materials	Mostly raw soil, lacking in nutrients
Soil conditioner	Calcium magnesium phosphorus soil conditioner	200 yuan/ton	$P_2O_5 \geq 6\%$, pH value 8.0–11.0, moisture $\leq 10\%$, CaO + MgO $\geq 40\%$, effective calcium (calculated as CaO) $\geq 23\%$, effective magnesium (calculated as MgO) $\geq 13\%$	Rich in Ca, Mg, and P elements required by plants; Improves acidic soil
	Traditional soil conditioner	There are many types, and prices are uneven	Varied	Diverse functions

FIGURE 3
Demonstration base of phosphorite tailings base soil.

FIGURE 4
Slope after restoration with base soil.

Physical methods: Soil restoration techniques encompass processes such as tillage, grading, leveling, and topsoil replacement. The first step is to remove the previously damaged topsoil from the mine area, followed by backfilling with stripped topsoil to effectively restore the original soil structure. The thickness of the soil cover is determined by the plants planted. To maximize the enrichment of soil structure and reduce the impact on the original stripped land during surface soil replacement processes, a dedicated natural soil cultivation base has been established. Soil is stripped from this base when needed.

Chemical method: Incorporate chemical compound fertilizers such as urea, ammonium nitrate, and soluble phosphate, along with essential trace elements like zinc, copper, lime, and chelates. This helps in the remediation of heavy metals, asbestos, metalloids, and other soil pollutants. Alternatively, the addition of inorganic compound limestone can be employed to regulate the soil's pH levels.

Biological methods: Soil bioremediation, commonly referred to as phytoremediation, employs the cultivation of herbaceous green vegetation and the introduction of microorganisms to enhance the efficiency and stability of vegetation restoration (Chunqiao et al., 2021; Zheng et al., 2024). Simultaneously, microorganisms are utilized to holistically manage and enhance soil structure, nutrient content, and enzyme activity within the reclaimed area, thereby maximizing the effectiveness of land reclamation efforts (Yue and Bi, 2017).

(3) The mining vegetation planting techniques have been improved to ensure that the planted vegetation in the mine can maximize its value with the highest efficiency. During the process of mine vegetation greening, there are several factors contributing to the low survival rate of trees and economic fruit trees. These factors include insufficient expertise in planting techniques for greening tree species and economic fruit trees, as well as unprofessional and immature methods for seedling transplantation and planting. To address this issue, it is crucial to enhance the proficiency in planting techniques for mine vegetation.

During the mine restoration process, the vegetation trench technique was adopted to plant a certain amount of 1 × 1 m trench plates in areas with relatively harsh soil conditions. The spacing between each trench plate is 1 m, arranged in a cross-shaped pattern. These slot plates were positioned at 1 m intervals in a pattern resembling the shape of a font. Subsequently, phosphorus

TABLE 2 Selection of vegetation species.

Vegetation types	Species name	Specifications
Tree	Dry winter melon, Yunnan cherry blossom, Yunnan pine	Annual container seedlings
Shrub	Red leaf pomegranate, Rose, Hawthorn	30–50 cm
Vine	Hedera helix, Ground pomegranate, Ivy	Annual container seedlings
Grass	Paradise grass, Peacock grass, Early bluegrass	3:1:1

TABLE 3 Ecological effect level.

Grade	Excellent	Good	General	Inferior
Ecological index (EREI)	90–100	80–90	70–80	<70

tailings-based soil conditioner and calcium magnesium phosphorus composite fertilizer were incorporated into the trough plates to ameliorate the acidic soil and serve as the substrate soil. Local mining plants were then transplanted into these trough plates. This vegetation planting technique integrates both engineering and biological measures, effectively contributing to the restoration of the mine ecology.

(4) Strengthening the efforts of replanting and management after vegetation restoration in mines. In order to improve the survival rate of mining vegetation, the selection of vegetation species is shown in Table 2. A combination of trees, shrubs, and grasses is employed in the industrial, residential, and office zones. The chosen tree species include Dry Winter Melon, Yunnan Cherry Blossom, and Yunnan Pine, with annual container seedlings as per the specified specifications. Shrubs such as Red Leaf Heather, Rose, and Hawthorn are carefully chosen, with a recommended height range of 30–50 cm. As for vine species, Hedera helix, Ground Pomegranate, and Ivy are selected. For the lawns, a ratio of 3:1:1 is advised, with Paradise Grass, Peacock Grass, and Early Bluegrass being the preferred choices.

Implementing and completing the environmental greening transformation of industrial, living, and office areas is necessary. Through unified planning, centralized investment, and standardized governance, the greening, tree planting, and evergreen tree planting rates of industrial, living, and office areas have reached the standard requirement of 80%. At the same time, timely maintenance is required for the green goaf to prevent the low survival rate of planted trees and a decrease in the yield of economic fruit trees due to inadequate maintenance.

(5) To ensure the sustainability of ecosystem restoration, the main measures taken include: intensifying publicity efforts on mining ecological restoration and afforestation, raising public awareness of the importance of environmental protection. Additionally, special management is implemented for the reclamation areas of the mining voids, with arrangements made for relevant personnel to conduct inspections, preventing areas that have already undergone ecological restoration from being damaged again. Regular sampling and testing of soil and water samples from the ecological restoration areas are conducted to assess the content of organic matter and the survival of microorganisms.

Conduct public lectures on the importance of environmental protection, so that local community residents can realize the importance of protecting the environment and fulfill their obligations. Establish tourist attractions in areas where ecological restoration has been completed, increase the income of local residents, make local residents aware that a good mining ecological environment can promote local production efficiency, and establish friendly relations between local communities and enterprises.

4.3 Analysis of the results of the ecological restoration index evaluation system

4.3.1 Data source and processing

The remote sensing data is downloaded from the Level-1 and Atmosphere Archive and Distribution System Distributed Active Archive Center (LAADS DAAC) website, with a spatial resolution of 200 m and a time series from 2020 to 2022. The MODIS Reprojection Tool is used to transform the Enhanced Vegetation Index (EVI) data into the WGS 1984 projection, and the EVI band images are extracted for further processing using ArcGIS.

The rainfall data is obtained from the daily rainfall records of the Kunming Meteorological Station of Yunnan Provincial Meteorological Bureau (http://yn.cma.gov.cn). Soil types, plant species, and other data are sourced from the Dianchi National Ecological Protection Area in Yunnan Province (Xie et al., 2000).

4.3.2 Indicator Processing and Result analysis

Utilizing the Ecological Remediation Effect Index (EREI) system, key indicators such as vegetation coverage, soil and water conservation, Native Plant Remediation Index, and Plant Species Diversity Index have been identified to assess the efficacy of ecological restoration and green reclamation in open-pit phosphorus mines. These indicators play a crucial role in evaluating the overall effectiveness of the restoration efforts in these mining areas (Liao et al., 2021; Liao et al., 2022).

$$\mathrm{EREI} = \mathrm{X_1Y_{EVI}} + \mathrm{X_2Y_{SWII}} + \mathrm{X_3Y_{NPRI}} + \mathrm{X_4Y_{PSDI}} \tag{16}$$

In formula (16), $\mathrm{Y_{EVI}}$, $\mathrm{Y_{SWII}}$, $\mathrm{Y_{NPRI}}$, and $\mathrm{Y_{PSDI}}$ are the corresponding scores for the four indicators; X_1, X_2, X_3 and X_4 are the weights of the four indicators, respectively.

TABLE 4 Specific values and corresponding scores of indicators.

Importance level	Indicator name	Level I	Level II	Level III	Level IV	Weight
Main indicators	EVI	>0.17	0.16–0.17	0.15–0.16	<0.15	0.325
	SWII	<0.10	0.10–0.20	0.2–0.3	>0.30	0.271
	NPRI	>0.40	0.30–0.40	0.2–0.3	<0.20	0.234
	PSDI	>2.20	2.10–2.20	2.00–2.10	<2.00	0.170
Natural endowments		100	75	50	25	

The ecological restoration effect is primarily assessed through the ecological index interval value (EREI), which serves as the basis for evaluating the ecological impact. The grade evaluation outcomes offer insights into the effectiveness of ecological restoration and green reclamation in mining areas. A higher ecological index EREI signifies a more favorable ecological restoration outcome. The ecosystem-level evaluation is presented in Table 3.

When calculating the Ecological Remediation Effect Index, experts assigned scores to various indicators based on the characteristics and requirements of the restoration project. Following an assessment of the actual restoration situation at the mine, the optimal value range for each indicator was established during the scoring process. Subsequently, the interval level difference between each level was defined, and the scoring intervals for levels I, II, III, and IV were sequentially determined. In accordance with the Analytic Hierarchy Process theory, the weight values for each indicator were set at 0.325, 0.271, 0.234, and 0.170, respectively, with the total weight of the four indicators amounting to 100%. The specific values and corresponding scores of the indicators are detailed in Table 4.

After ecological restoration and green reclamation of a phosphate mine, it is necessary to conduct tracking investigations on vegetation coverage, soil and water conservation, Native Plant Remediation Index, and Native Plant Remediation Index. We have omitted the company's internal proprietary data, and specific calculation methods can be referred to in the evaluation index system formula.The study obtained the Enhanced Vegetation Index (EVI), Soil Erosion Impact Index (SWII), Native Plant Remediation Index (NPRI), and Plant Species Diversity Index (PSDI) for 2020, 2021, and 2022 using the calculation formula of the evaluation index system. The Ecological Index (EREI) before and after ecological restoration was calculated according to formula (16), as shown in Table 5.

According to formula (16), the EREI values for 2020, 2021, and 2022 were calculated as 48.40, 87.38, and 93.23, respectively. The EREI gradually increased, with the largest increase in 2021, reaching a growth rate of 80.54%; compared to 2021, the growth rate slowed down in 2022, increasing by 6.69%; compared to 2020, it increased by 92.62%. As indicated in Table 1 of the ecological effect level, the initiation of the second phase of ecological restoration construction in 2020 resulted in relatively poor ecological effects. However, the extensive implementation of ecological restoration projects in 2021 markedly improved the ecological effects compared to 2020, achieving a positive outcome. By the completion of the ecological restoration and green reclamation project in 2022, the ecological effect level is anticipated to reach excellence. This process underscores the gradual nature of ecological restoration and green reclamation. During the initial stages of ecological restoration, changes in ecological effects tend to progress at a relatively slow pace. However, as ecological restoration projects advance, the ecological restoration effect demonstrates continuous improvement, closely linked to the project construction cycle, plant planting progress, and the status of plant growth and survival.

TABLE 5 Ecological restoration index (EREI) from 2020 to 2022.

Year	Content	EVI	SWII	NPRI	PSDI	EREI
2020	Result	0.156	0.215	0.180	2.181	48.40
	Y_i	50	50	25	75	
2021	Result	0.174	0.125	0.331	2.23	87.38
	Y_i	100	75	75	100	
2022	Result	0.177	0.115	0.484	2.260	93.23
	Y_i	100	75	100	100	

The Kunyang Phosphate Mine has applied phosphate tailings substrate soil technology and implemented a series of restoration measures, achieving significant results. As of 2022, the company has invested a total of 1.002 billion yuan in land reclamation and vegetation, with afforestation covering an area of nearly 49,100 acres (Le, 2019). The land reclamation and vegetation rate reached 94%. Within the reclaimed areas, ecological forests, economic forests, and landscape forests have been established, including the "Forest Lake Ecological Park" and the "Zhen Dan Geological Ecological Park" (Xie et al., 2000). After ecological restoration and green reclamation, not only has the environment significantly improved, but the reclamation area has also contributed to local socioeconomic benefits. After the ecological restoration of the mine, it has attracted a large number of domestic and foreign tourists to come and visit, promoting local tourism revenue. In addition, during the ecological restoration process, a large number of economically viable fruit trees were planted, increasing the company's income. The on-site situation after ecological restoration and green reclamation is shown in Figure 5.

5 Difficulties encountered during the mine restoration process and future research directions

Through field investigations of an open-pit phosphate mine in Yunnan Province and based on the practical experience of ecological

FIGURE 5
Mining pit area after ecological restoration and green reclamation.

restoration and green reclamation from 2020 to 2022, several key challenges have been identified regarding the ecological restoration of the mine.

(1) Implementation of restoration projects is challenging. The area where the mining goaf is located has various characteristics, such as steep slopes, a high density of erosion ditches, poor soil fertility, a thin soil layer, poor water retention, high soil gravel content, and loose geology. These factors make it difficult to prepare and repair soil in the mining area, resulting in a low survival rate of artificial ecological trees.
(2) Simultaneous vegetation restoration and mining activities in the mining area cause secondary disturbance to the restored goaf during the mining process of ore resources, making it difficult to manage and protect the restored goaf.
(3) The processes of soil replacement and plant cultivation are rather complex. For example, soil sources are limited, so soil replacement relies solely on stripping the local soil layer, which can also lead to the disruption of the original soil structure. Additionally, planting sites are far from water sources, and the plant species may not be well-adapted to the local climatic conditions. Further research is needed to address these issues.
(4) In terms of land reclamation in mined-out areas, the management of land reclamation remains at the level of land leveling and surface soil filling. The focus is only on restoring the mined-out areas to a usable state. However, there are few high-level studies on soil optimization and reconstruction. Ecosystem restoration is particularly important for restoring environmental bacterial communities, the balance of soil elements, and the balance of soil acidity and alkalinity.
(5) The artificial vegetation optimization technology and ecological restoration model of open-pit phosphorus mines are still in the exploratory stage. The quality of ecological restoration in Goaf areas is mainly determined by soil quality and climate characteristics. However, the soil for mining reclamation has significant spatial differences, and existing research is limited to a single small-scale range. Therefore, realizing ecological restoration on a large scale in mining areas has significant limitations.
(6) The ecosystem is relatively weak after vegetation restoration in the mining area. The thickness of the overburden layer after land reclamation is thin, and the soil is relatively barren, which makes it difficult for vegetation to thrive. Strengthening conservation and daily management practices in the restoration area is essential. Additionally, the current ecological restoration mode for the goaf in the mining area is relatively simplistic, with an unreasonable allocation of land structures and an incomplete technical system for artificial vegetation optimization and ecosystem restoration.

6 Conclusion

This article takes the goaf of a phosphate mine in Yunnan as the research object. Following an extensive on-site investigation of the mine, it was evident that the Goaf area suffered from significant ecosystem instability, low biodiversity, severe landscape fragmentation, and frequent geological disasters. Based on a comprehensive study of ecological restoration and green reclamation technologies in phosphorus mines, the following conclusions have been reached.

(1) A thorough investigation and analysis were conducted on the five major mining goaves, and an ecological restoration index evaluation system was introduced. Four of the most important indicators in the ecological restoration process of mines, including vegetation coverage (NDVI), soil and water conservation (SWII), Native Plant Remediation Index (NPRI), and Plant Species Diversity Index (PSDI), were selected to evaluate the effectiveness of ecological restoration and green reclamation in mines.
(2) This utilizes the technology of reconstructing soil ecological structure with phosphate tailings matrix soil and improving acidified soil with soil conditioner and calcium-magnesium-phosphorus compound fertilizer made from phosphate

tailings matrix soil. This proposes physical, chemical, and biological methods for ecological restoration and green reclamation of soil and water pollution in mine void areas. Meanwhile, a series of measures have been taken, including the drafting of ecological restoration plans, improvement of vegetation planting techniques, and strengthening of replanting and management efforts after vegetation restoration.

(3) According to the Ecological Remediation Effect Index (EREI) system, the EREI for 2020, 2021, and 2022 were calculated to be 48.4, 87.38, and 93.23, respectively. After evaluating the level of ecological restoration effect, it was found that the ecological restoration effect in 2022 was rated as excellent (Grade I), and there has been significant improvement in the ecological environment. In addition, difficulties encountered during the mine restoration process and future research directions were summarized, providing valuable reference for ecological restoration and green reclamation of other mines.

This technology is not only applicable to phosphate mines but also to ecological restoration and green reclamation of various large and medium-sized metal and non-metal open-pit mine voids, underground mines, coal mines, and saline-alkali land both domestically and internationally. It can also be applied to areas affected by natural disasters or human factors, such as areas affected by natural disasters, damaged forests and woodlands, urban vacant lots, and abandoned land. It can provide technical support and practical guidance for ecological restoration and green reclamation at home and abroad, and promote the construction and development of green mines worldwide.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

DH: Formal Analysis, Methodology, Supervision, Writing–original draft, Writing–review and editing. MX: Validation, Writing–original draft, Writing–review and editing. MW: Conceptualization, Validation, Writing–review and editing. XL: Supervision, Writing–original draft, Writing–review and editing. SL: Formal Analysis, Investigation, Writing–review and editing. JW: Investigation, Methodology, Supervision, Writing–review and editing. MC: Conceptualization, Investigation, Supervision, Writing–review and editing.

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Conflict of interest

Authors MX, MW, and SL were employed by Ynnan Phosphate Chemical Group Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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