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Construction Practices of Green Mines in China

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Abstract: To maintain high-level economic development, protect the ecological environment, and achieve carbon peaking and carbon neutrality goals, the construction of green mines has become a critical issue in China. In this study, the importance of mineral resources to human society is discussed, and the construction experiences and sustainable development directions of green mines are summarized, which can provide valuable references for the global mining industry. The entry and management process in China was introduced to help understand green mines' construction objectives and tasks. Moreover, based on the successful construction cases of green mines, four typical green mine models are concluded: the green technology mining model, operation modernization mining model, stability mining model, and ecological restoration mining model. In addition, the key construction elements of green mines are concluded, for example, the mining environment, mining methods, comprehensive utilization of resources, energy conservation, emission reduction, scientific and technological innovation and intelligence, and enterprise-land stability, which provided the directions and guidance for green mine construction.

Keywords: mineral resource; green mine; directory management; construction model

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1. Introduction

More than 95% of energy, 80% of industrial raw materials, and 70% of agricultural means of production globally come from mineral resources [1]. Thus, mineral resources are important material foundations for the survival and development of human society. The utilization of mineral resources destroys the ecological environment and increases carbon emissions to varying degrees in different countries, leading to a series of environmental problems, e.g., solid waste, exhaust gas, liquid waste, ground collapse, and a decrease in biodiversity. According to the Annual Report of the China Geological Survey in 2016, the coal mines in the Greater Khingan Mountains and Hulunbuir Grassland had destroyed and occupied a total of 2772.77 hectares of grassland due to mining operations. Six waste rock yards with a total area of 19.355 hectares and a total volume of 1.07875 m^3 and five tailing sand dumps with a total area of 25.90 hectares and a stacked volume of 943,000 m^3 of Shizhuyuan multi-metal mine have greatly impacted the environments around the Xiangjiang River [2]. The subsidence area of Yangquan coal mines near the Fenhe River in North China is about 406.73 km^2, accounting for 27.56% of the mining area [3]. Figure 1 illustrates the main geo-environmental problems of the mines. As can be seen from Figure 1, pit drainage is more severe in the central region. The highest cumulative amount of solid waste is mainly located in the provinces of Xinjiang, Inner Mongolia, and Yunnan. Higher wastewater discharges are mainly found in coastal areas. More serious land destruction is mainly in the eastern and western regions. Areas with more serious landslides and mudslides are Yunnan, Sichuan and Chongqing, and Inner Mongolia. Ground subsidence is a more serious problem in Guizhou, Anhui, and other regions. In addition, the transition from shallow mining to deep mining poses a more severe safety production situation,

and the threat of dynamic geological disasters such as water inrush, rock bursts, and high temperatures will continue to increase. From 2001 to 2021, there were 629 mine floods, resulting in 3730 deaths and the highest economic losses among all types of mining accidents [4]. In addition, the environmental problems and carbon emissions caused by mines are particularly prominent. According to the China Carbon Accounting Database (CEADs), China's cumulative carbon emissions in 2022 reached 11 billion tons, accounting for approximately 28.87% of global carbon emissions [5]. Among them, industrial emissions amounted to 4.2 billion tons, accounting for 38.18% of the national emissions, second only to the electricity industry's emissions of 5.1 billion tons, accounting for 46.37% [6]. The main types of energy sources for carbon emissions from China's mining industry are electricity and coal. China's coal-fired power generation accounts for about 50% of the global total [7]. In September 2020, at the 75th United Nations General Assembly, China proposed the "dual carbon" goal of peaking carbon emissions by 2030 and achieving carbon neutrality by 2060, which greatly promoted the green and low-carbon development of mining.

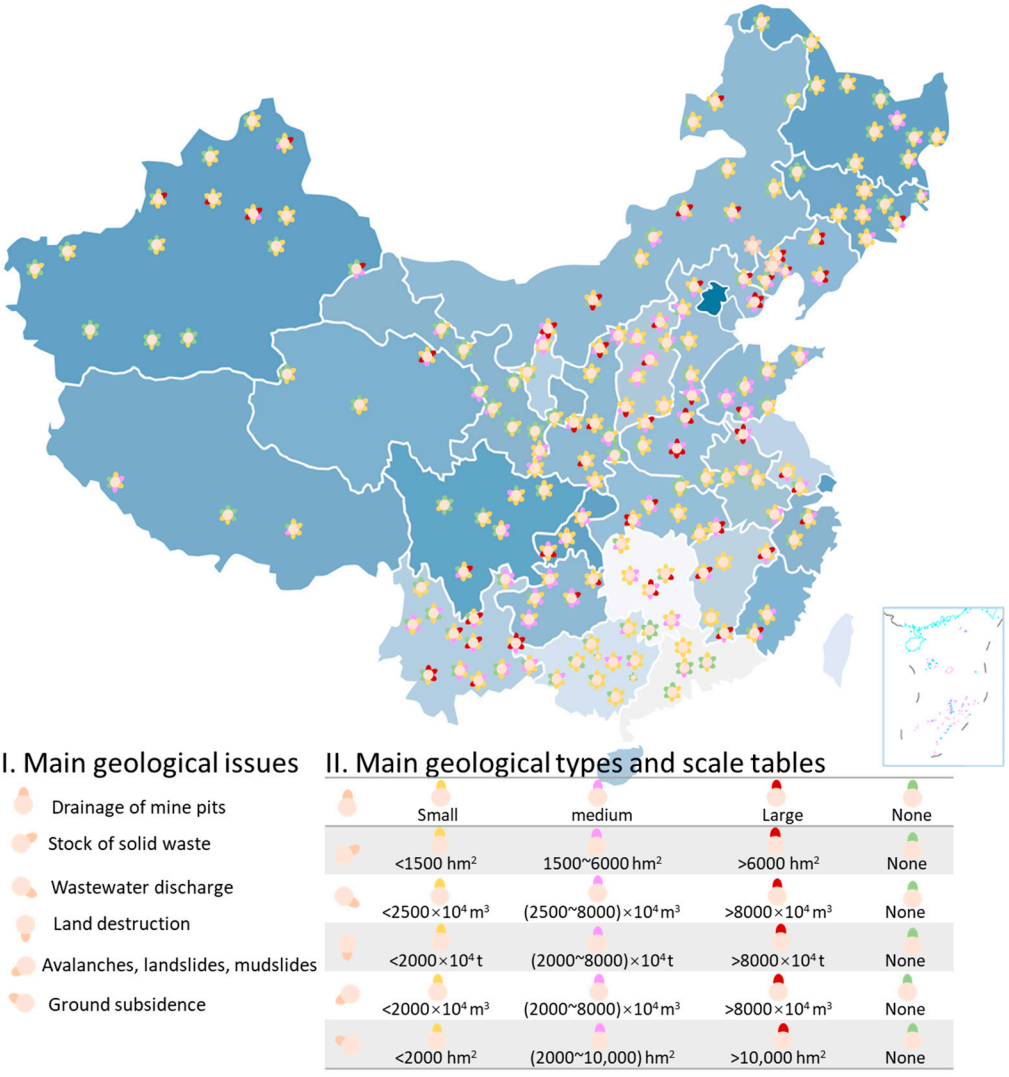

Figure 1. Distribution map of major environmental problems in mines (adapted from [8]).

In response to the challenges of mining, the Chinese government has implemented a national strategy of green mining. The specific connotation of green mining is to implement scientific and regulated mining throughout the life cycle of mines, to control mining disturbances and the surrounding ecological environment within a controllable range, to keep environmental ecology, scientific mining, efficient resource utilization, standardized

enterprise management, standardization of production safety, and stable mining communities harmonious [9,10]. The construction of green mines has become an important issue for the sustainable development of the mining industry in China. The green mine concept was first proposed in 2007 and has since undergone conceptual proposals, road exploration, and pilot demonstrations. Nowadays, it is advancing towards a new stage of standardized construction [11]. China has gained valuable experience and remarkable results in green mine construction over the past decade. To propel the development of the mining industry and support the achievement of dual carbon goals, promote the sustainable development of the mining economy, and promote the green and high-quality development of the mining industry, this paper summarizes the experience of green mine construction. It identifies the problems during green mine construction, providing direction and guidance for mine enterprises building green mines.

2. Mineral Resources and Green Mines

2.1. Global Distribution and Utilization

Figure 2 shows that the distribution of mineral resources globally has distinct regional patterns. The Middle East holds 57% of the world's oil reserves, while Eastern Europe, Russia, and the Middle East contain 72% of the global natural gas reserves [12]. Regarding coal reserves, 53% are concentrated in the United States, China, and Australia [13]. Among non-ferrous metals, 56% of copper reserves are in Chile, Peru, Mexico, the United States, and Canada. Regarding lead reserves, 57.5% are concentrated in Australia, China, the United States, and Kazakhstan. Finally, 48% of zinc reserves are distributed in Australia, China, and the United States [14].

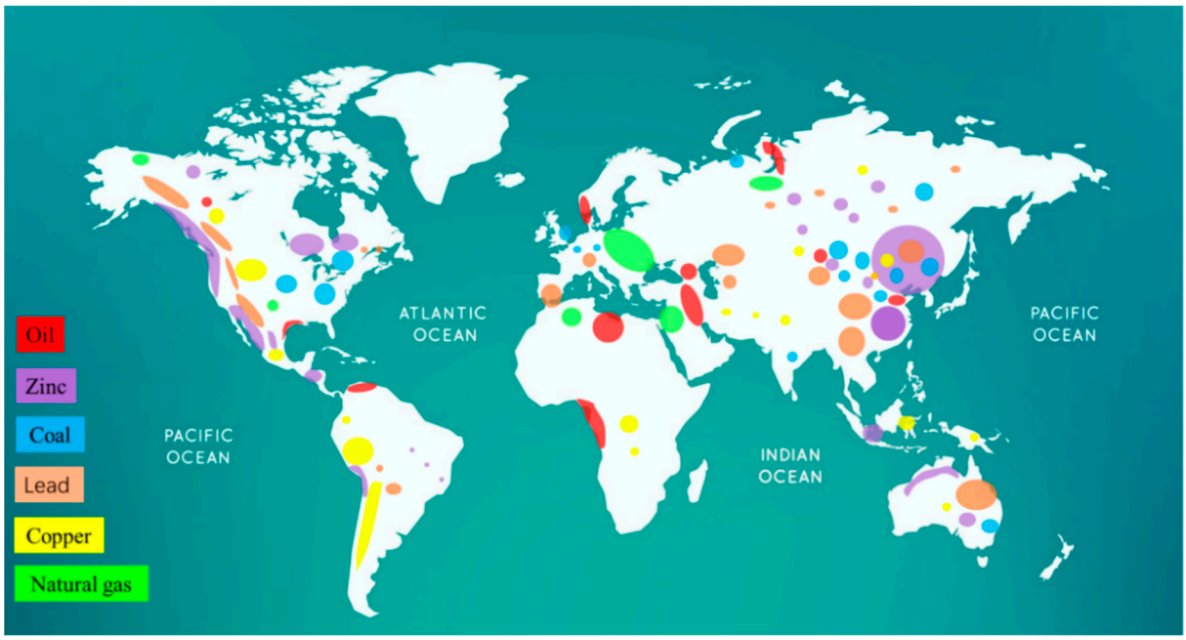

Figure 2. Global distribution map of mineral resources (adapted from [15]).

Mineral resources are essential materials for all industries, significantly impacting socioeconomic development and national security. Figure 3 presents the change in total global production of mineral resources from 2009 to 2022. Figure 4 shows the share of energy, metal, and non-metal production in 2022. In 2022, 1/3 of countries were mining countries, and their ratio of mining output value to GDP was larger than the global average [16]. The mining industry provided 22.7 billion tons of energy, metals, and important non-metallic minerals, with a total output value of USD 5.9 trillion, equivalent to 6.9% of the global GDP [17]. Chinese mining companies account for approximately 12% of the global top 50 mining companies in terms of market value [18]. More than 80% of the natural resources

consumed by humans are mineral resources, with an average of three tons of mineral resources consumed per year per capita [19]. China's energy and mineral consumption accounts for approximately 30% globally [18]. Currently, developing countries, such as those in Asia, Africa, and Latin America, are focusing on the construction in the mining industry to support industrialization, while developed countries, such as those in Europe and North America, are increasing their support for the mining industry to develop the high-end manufacturing industry, further increasing the mining industry's contribution to global economic development [16].

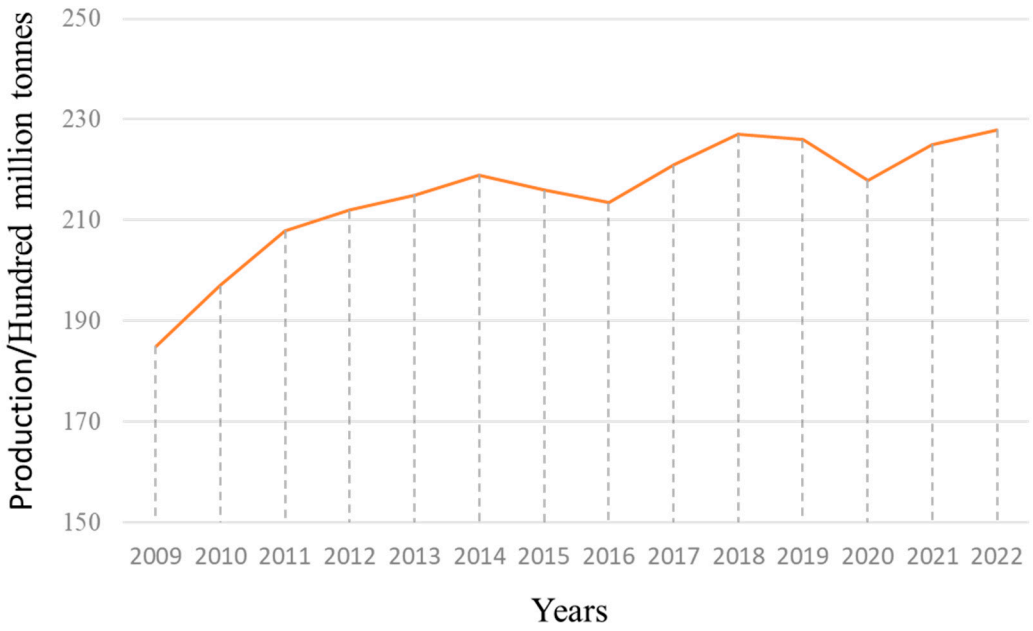

Figure 3. Global production of mineral resources, 2009–2022 (data from [17,18]).

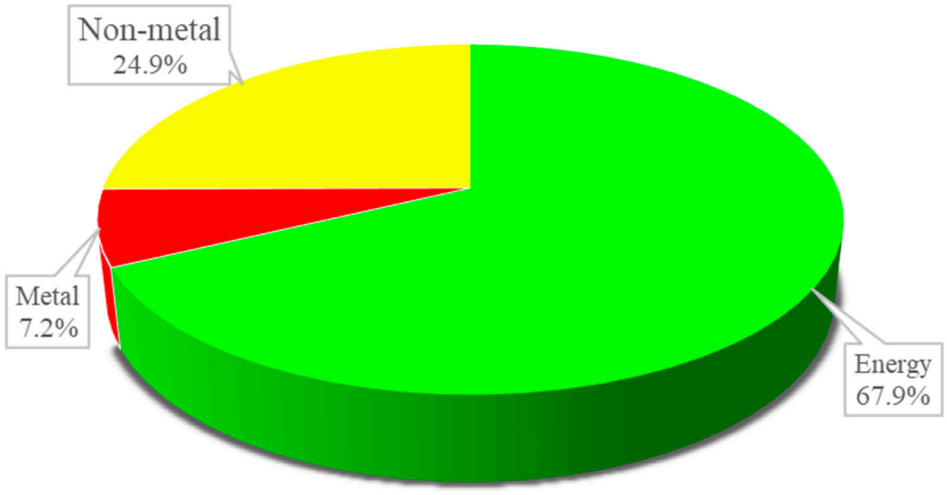

Figure 4. Global proportion of different mineral productions in 2022 (data from [18]).

2.2. Mineral Resource Exploitation and Utilization in China

China is one of the largest countries in terms of resource production, consumption, and trade. Field mining is the main method for obtaining mineral resources, and mineral resources are primarily divided into energy mineral, metal mineral, and non-metallic mineral resources in China. The revenue, income, and the proportion of the mining industry in GDP in China are reflected in Figures 5 and 6.

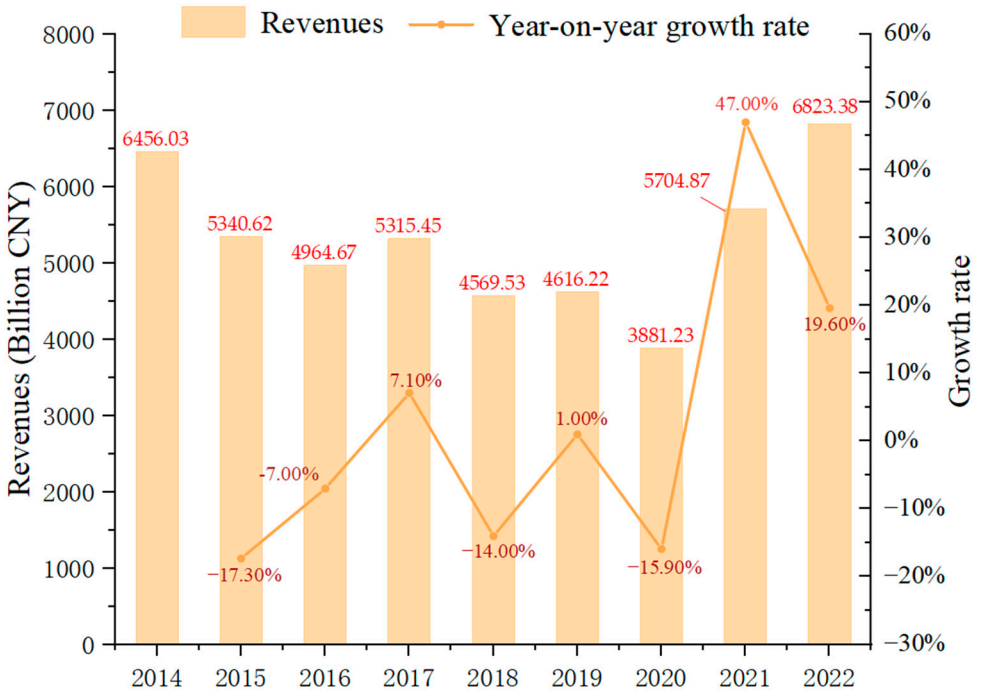

Figure 5. Revenue statistics and revenue growth ratio of China's mining industry from 2014 to 2022 (adapted from [20,21]).

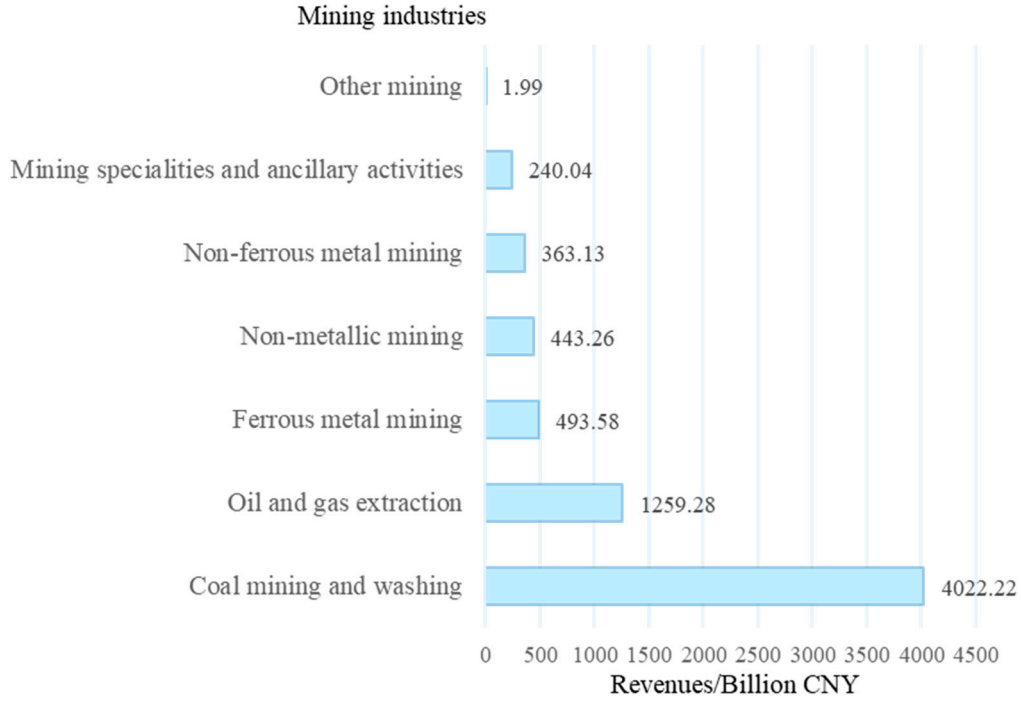

Figure 6. Operating incomes of mining enterprises in different industries above the designated size in 2022 (adapted from [20,21]).

Compared to 2020, China's consumption of 28 mineral resources increased in 2021, while the consumption of 15 mineral resources decreased. The total consumption of 36 mineral resources in China, including coal, paste, manganese, chromium, vanadium, titanium, and copper, ranked first in the world. Figure 7 displays the ratio between China's mineral consumption and that of the world in 2021.

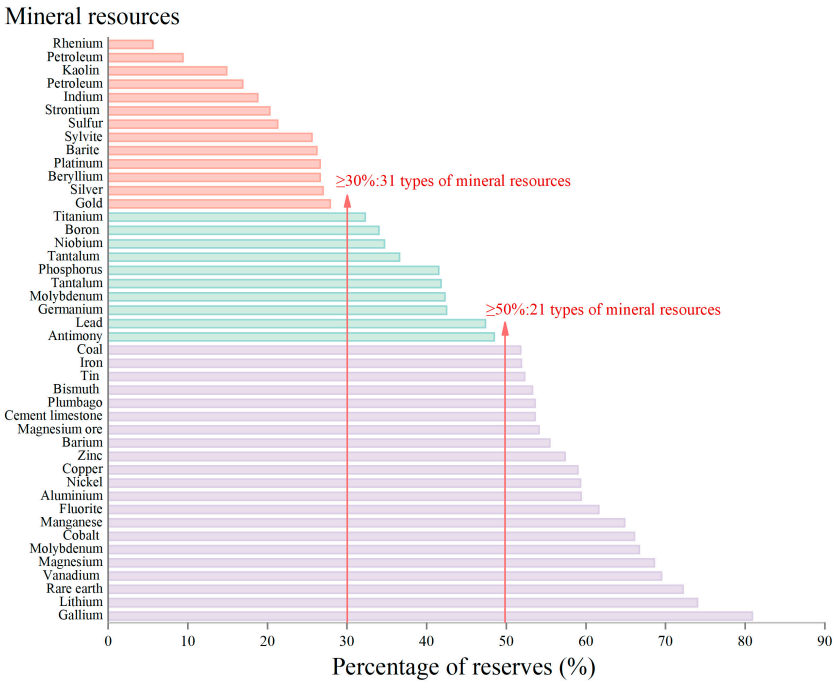

Figure 7. Global proportions of mineral resource consumption for China in 2021 (data from [22]).

Long-term, high-intensity, and large-scale development of mineral resource exploitation has created enormous pressure on the ecological environment. The National Mining Geo-Environmental Survey Report (2016) shows that from 2002 to 2015, mineral resource mining damaged more than 3.03 million hectares of land, and only about 810,000 hectares have been repaired and treated [23]. The accumulated volume of solid waste generated by mining activities is 48.31 billion tons, e.g., 38.69 billion tons of waste rock (soil), 5.48 billion tons of tailings, and 4.09 billion tons of coal gangue. Solid waste has caused several ecological and environmental problems, such as encroaching on cultivated land [24], causing geological disasters, soil and water environmental pollution, etc. In addition, the total output of mining wastewater has been 11.48 billion cubic meters, and mining pit drainage has led to a drop in regional groundwater levels, a reduction in spring flow, and even dryness in many areas [25].

2.3. Construction Mechanisms of Green Mines

Protecting the ecological environment, addressing climate change, and maintaining energy and resource security simultaneously are common global challenges. Promoting mining transformation and realizing green development are the construction goals of green mines. Since 2007, great efforts have been made, and significant progress has been achieved in constructing green mines in China. Figure 8 lists the key nodes for the development of green mines in China [26–28].

In 2007, the initiative was proposed to fundamentally transform the development mode and economic growth mode, truly realizing the coordinated development of rational resource utilization and environmental protection, which has become an inevitable choice for the development of mining enterprises. This is also the first time that China has proposed the concept of "green mining". In 2008, the China Mining Circular Economy Forum was held in Nanning, Guangxi. The China Mining Federation and 11 large mining enterprises advocated for the signing of the "Green Mining Convention", which received recognition and a positive response from many mining enterprises. In 2009, "The National Miner-al Resources Plan (2008–2015)" jointly released by the National Development and Reform Commission and the former Ministry of Land and Resources, put forward clear requirements for the development of "green mining" for the first time, and set the strategic

goal of "basically establishing a green mining pattern by 2020". This also marked the beginning of the comprehensive promotion of green mining construction at the government level. In 2010, the former Ministry of Land and Resources issued the Guiding Opinions on Implementing "The National Mineral Resources Planning, Developing Green Mines, and Building Green Mines". This was the first time that clear requirements for building "green mines" had been put forward in the form of official documents, and the basic conditions for national-level green mines had been listed. In 2011, the former Ministry of Land and Resources announced the first batch of pilot units for "green mines", marking the official launch of China's national green mine pilot work. In 2015, "The Opinions of the Central Committee of the Communist Party of China and the State Council on Accelerating the Construction of Ecological Civilization" officially included green mines in the document. This marks the shift of this work from corporate self-discipline to departmental advocacy, elevating it to a national strategy. In 2016, the Ministry of Land and Natural Resources issued "The National Mineral Resources Plan (2016–2020)", which proposed improving the quality and efficiency of mining development and accelerating the green transformation and up-grading of mining. In 2017, the former Ministry of Land and Resources, in conjunction with the Ministry of Finance and six other ministries, issued "The Implementation Opinions on Accelerating the Construction of Green Mines (Land and Resources Regulations (2017) No. 4)", marking the transition of China's green mining construction from the "pilot exploration" stage to the "comprehensive promotion" stage. In 2020, the Ministry of Natural Resources issued the "Green Mine Evaluation Indicators", which clarified the prerequisites for selecting green mines and unified the evaluation indicator standards.

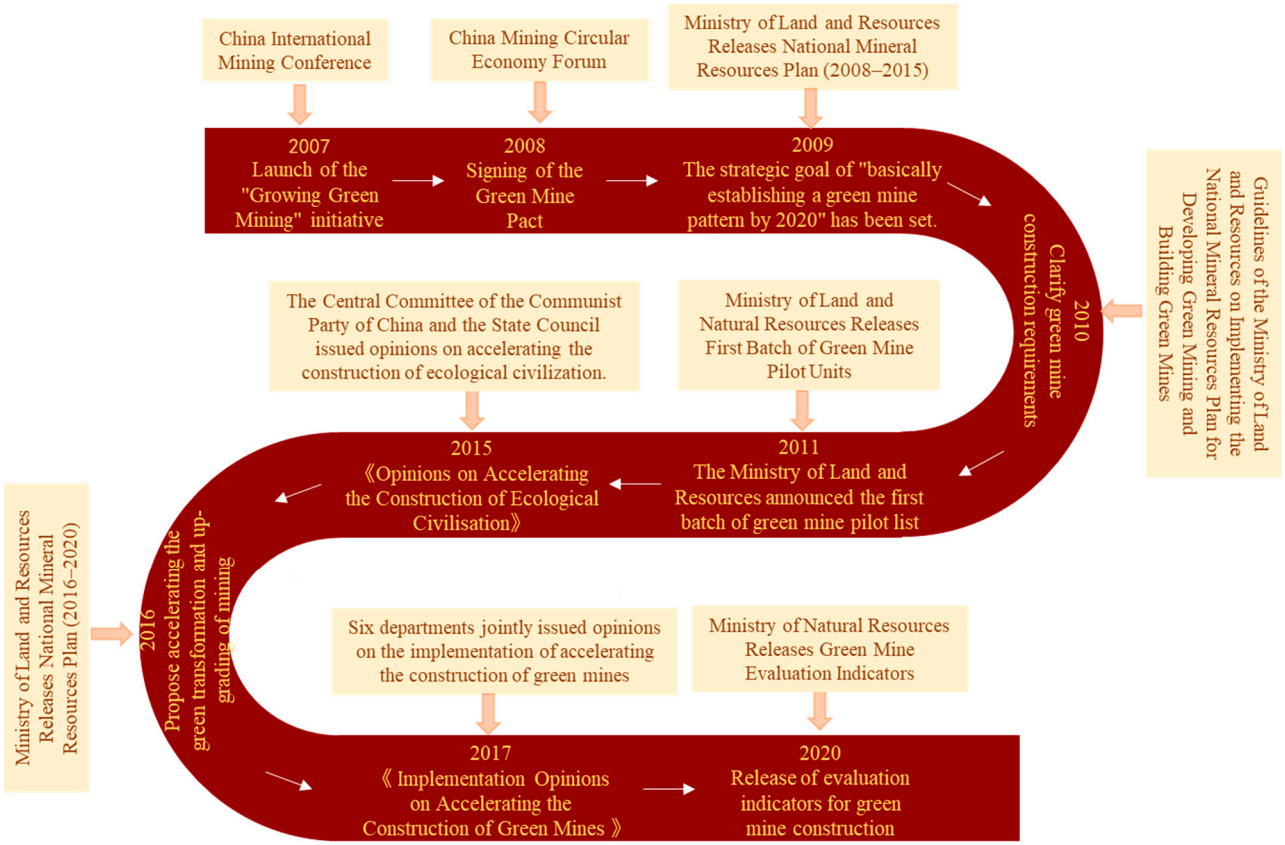

Figure 8. Development history of green mine construction in China.

2.3.1. Theoretical Basis of Green Mines

The creation of green mines is interdisciplinary and influenced by multiple factors. It is necessary to consider not only the efficient utilization of resources but also the safety of

mining and resource utilization, as well as environmental damage and ground stability in mining areas. Therefore, the creation of green mines should be informed by the theories shown in Figure 9.

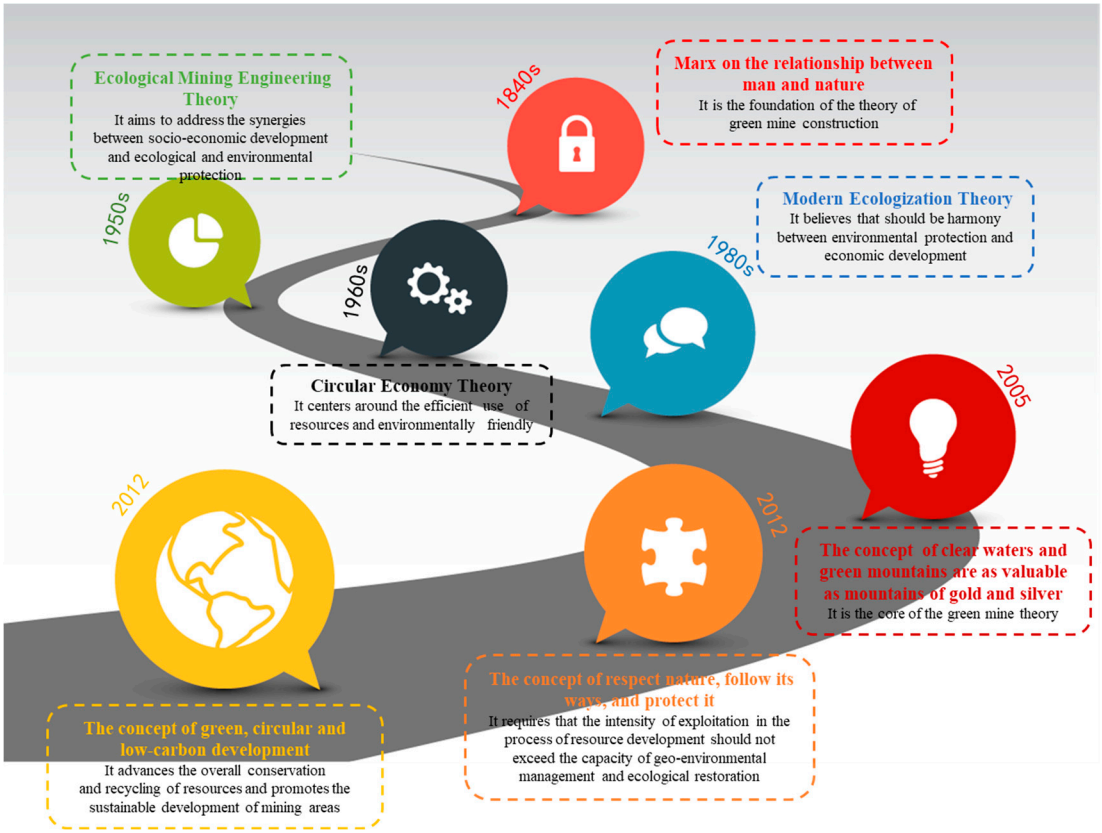

Figure 9. Basic theories for the construction of green mines.

2.3.2. Policy Support for Green Mines

To accelerate the construction process of green mines, the relevant departments and provinces (autonomous regions and municipalities) have put forward a series of policies related to green mines. In 2009, the Ministry of Land and Natural Resources issued Regulations of Geological Environment Protection in Mines, which stipulated the responsibilities, rights, and interests of protecting the geological environment in mines. It also provided for the prevention and restoration of damage to the terrain and landscape caused by mineral resource exploration and other activities [29]. In 2010, to speed up the construction of green mines, the Ministry of Land and Resources in China released the Guiding Opinions on Implementing the National Mineral Resource Planning for the Development of Green Mining and Construction of Green Mines [30]. In 2017, six ministries of China, including the Ministry of Land and Resources, issued the Guidance on Accelerating Green Mine Construction, which implemented incentive policies in four aspects: land use, mine use, finance, and funding [31]. In 2021, the National Development and Reform Commission, the Ministry of Finance, and the Ministry of Natural Resources issued the 14th Five-Year Plan for Promoting the High-Quality Development of Resource-Based Regions, which suggested that we should strongly promote green mine construction and all new and expanded mines should meet the requirements [32]. In addition, the provinces answered the call and introduced relevant policies. In 2020, Shandong Province issued the Shandong Province Green Mine Construction Management Approach [33]. In 2022, Shanxi Province released a notice titled the Guiding Opinions on the Comprehensive Promotion of Green Mine Construction [34].

2.3.3. Green Mine Selection Process and Directory Management

The mines with construction levels meeting the green mine standards can be included in the National Green Mine List of China. The incentive policies on the list have been implemented for the green mines, which can urge them to fulfill their obligations better [35]. The selection process and list management of green mines are shown in Figure 10.

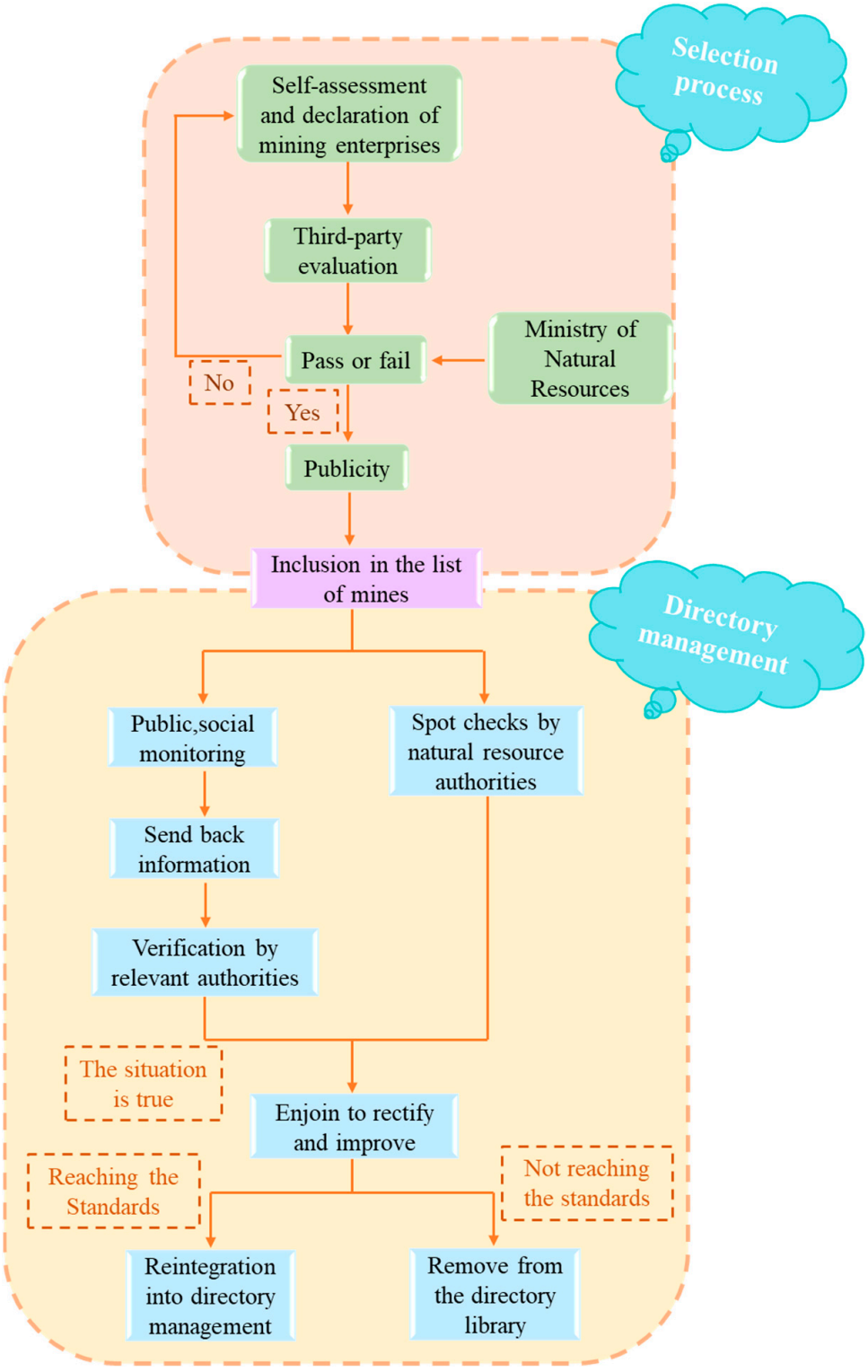

Figure 10. Entry process and list management of green mines in China.

(1) Selection process [35,36]

According to the selection notice of green mines in 2020 issued by the General Office of the Ministry of Natural Resources in China, the main creation procedures are as follows.

i. Application online. The mining enterprises log into the National Green Mine Directory Management Information System and fill out the relevant application information.
ii. Self-assessment of mining enterprises. The mining enterprises conduct self-assessments and create self-assessment reports according to green mines' construction requirements and industry standards. Then, the mining enterprises fill out the self-assessment report through the directory system.
iii. Third-party assessment. In the form of government-purchased services, third-party assessment agencies are commissioned to conduct the on-site green mine construction level assessments. The third-party assessment report is created according to the requirements of unified evaluation indicators. The department in charge of natural resources selects mines and performs field verification.
iv. Publicity. The green mine candidates are publicly announced online, in newspapers, and through other channels. After publicity, and should there be no objection or dissent, the candidates are included on the national list of green mines.

(2) Directory management

To reward mines included on the green mine list and urge them to sequentially fulfill their obligations, the management of the green mine list is implemented by the Land and Resource Management Departments. It mainly includes supervision mechanisms, incentive policies, and degradation mechanisms [14].

i. Supervision mechanisms. The green mines on the national list are open to the public and subject to supervision. The Natural Resource Regulatory Department conducts on-site inspections of the green mines. If the construction levels of mines do not meet the green mine standards, the mines will be ordered to rectify the matter and excluded from the list. Meanwhile, each province's natural resource management departments conduct spot checks on green mines per the requirements of "double random and one disclosed inspection" [37].
ii. Incentive policy. The green mines on the list can enjoy corresponding incentive policy support, and the green mines ordered to rectify cease to enjoy incentive policies.
iii. Degradation mechanisms. The relevant departments will re-include the mines that passed the rectification process on the green mine list. The mines with unqualified rectification are removed from the list and no longer enjoy incentive policies.

2.3.4. Evaluation and Certification of Green Mine Levels

In general, the green mines on the national list have experienced self-assessment and third-party evaluations during the declaration process. Self-assessment refers to the preparation of self-assessment reports by mining enterprises or relevant evaluation institutions entrusted by mines to meet the related construction standards for green mines. Units recognized by the commission can also be invited to certify the construction levels of mining enterprises [35]. Once certified, the mine continues to implement green mine construction based on its deficiencies. After submitting the green mine application, the government department will purchase a third-party assessment service to rate whether the mine meets the green mine construction specifications in accordance with the "Implementing Opinions on Accelerating the Construction of Green Mines", "nine industry standards", "The Green Evaluation Indicator System", and other specifications [38]. The assessment process is shown in Figure 11.

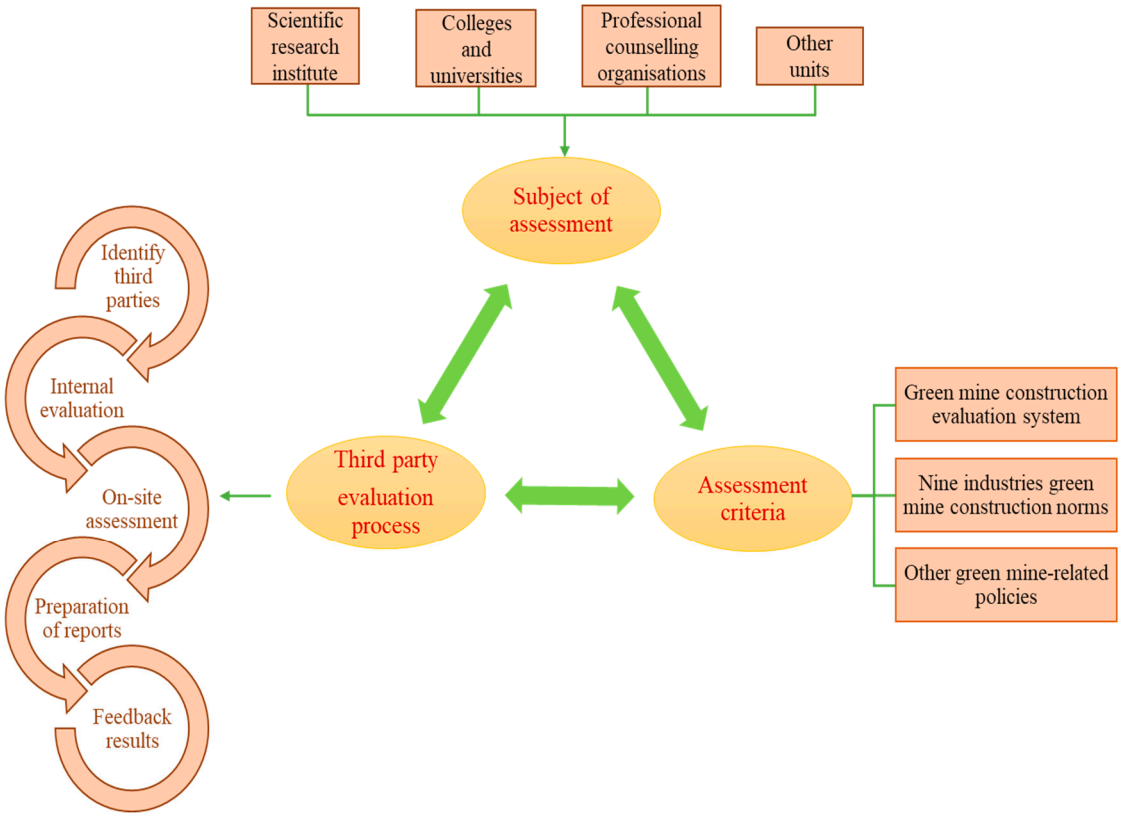

Figure 11. Third-party evaluation flow chart.

3. Parameters of Green Mines

To improve the level of comprehensive utilization of mine resources, reduce energy consumption and emissions, increase scientific and technological innovation and intelligent mine construction, and explore the stability of the mining area, the concept of green development and safety in production exists throughout the whole construction process of green mines to create safe, efficient, economical, and environmentally-friendly mines. The key points for the construction of green mines [39] are shown in Figure 12.

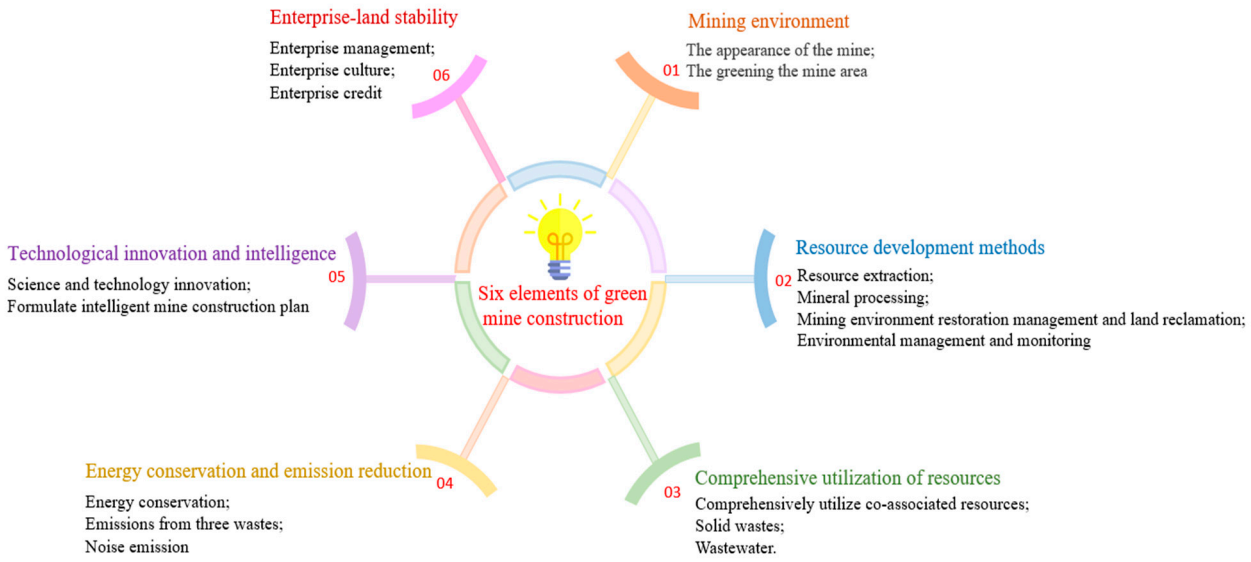

Figure 12. Key points of construction of green mines.

3.1. Mining Environment

Nearly 53,000 square kilometers of geological environment have been damaged in China, of which the seriously damaged areas account for 50% to 60% of the total area [40]. In addition, the types of mines in China are complex, and the mining methods are diverse, with different degrees of damage to the environment. Therefore, it is necessary to reasonably choose the governance measures according to the actual situation, which will not only improve the quality of mining but also promote the restoration of the mining environment. The main starting point is the appearance of the mine and the greening of the mine area.

For the appearance of the mine, combined with safety, environmental protection, practicality, and other factors, the function of the mine is a standardized layout. For example, the living area and production area are arranged in the safety zone, not less than 300 m away from the mine; the production area has set up the corresponding signboards, and the management of materials, equipment, and wastes is standardized [41]. The facilities in the mining area, such as water, roads, sanitation, etc., are fully equipped to ensure an orderly life. In addition, the living garbage is properly treated and utilized. And there are no private buildings on the mine site. The greening of the mining area should be in harmony with the original ecological environment and not affect the overall harmony of the natural environment of the surrounding area. The greening of the mine area is fully covered, a greening guarantee mechanism has been established, and the mine area is beautified based on local conditions [42]. More importantly, a systematic assessment and monitoring of geological hazards, terrain and landscape impacts, aquifer damage, soil and water environmental pollution, and land damage caused by mining should be conducted. Based on the evaluation and monitoring, corresponding land reclamation measures should be taken, and the mining area environment should be coordinated with the local natural landscape after treatment.

3.2. Resource Development Methods

The detailed demands for the construction of green mines in four aspects. i.e., resource extraction, mineral processing, mining environment restoration and management, land reclamation, and environmental management and monitoring, are described as follows [27].

(1) Resource extraction

To meet the quality requirements of the mining face for green mining construction, a reasonable mining scale, mining sequence, mining technology, and equipment are selected based on the geological conditions of the ore body and the characteristics of the ecological environment. During the mining process, solid, liquid, and gas waste is disposed of in a timely and standardized manner [43]. Adopting mining methods can effectively reduce large-scale surface subsidence or uniform subsidence, such as backfill mining, water conservation mining, and other mining processes. To achieve intelligent production and control of various production links and the entire production process indicators, mechanized mining equipment with low energy consumption, low noise, low dust generation, and complete and effective safety protection devices is used. By adopting advanced technology and equipment such as unmanned mining vehicles and intelligent coal mining machines, mines are gradually realizing the mechanization of mining transportation systems, greening mining methods, and improving safety in mining operations.

(2) Mineral processing

To minimize pollution to the environment, efficient, low energy consumption and low pollution equipment and processes should be selected. In addition, according to the characteristics of water quality, mining enterprises should design the wastewater treatment system, and mine water and domestic sewage treatment stations should have complete treatment functions. The appropriate dust removal and dust reduction equipment should be installed.

(3) Mining environment restoration management and land reclamation

The designated areas should be treated and reclaimed to achieve the restoration of ecosystem functions and coordination with the surrounding environment according to the mining geological environment restoration and land reclamation project.

(4) Environmental management and monitoring

Mining enterprises should obtain environmental management system certification, ensure that environmental protection facilities are complete, and establish emergency response mechanisms. In addition, it is necessary to establish an environmental monitoring mechanism in accordance with the relevant regulations of environmental monitoring to dynamically monitor the geological environment, reclamation area, noise, and pollutants in the mining area so as to have a comprehensive understanding of the situation of environmental pollution in mines and take timely measures.

3.3. Comprehensive Utilization of Resources

The comprehensive utilization of resources varies across different industries. Referring to the Mineral Resources Development and Utilization Program or other standards, the mines choose appropriate processing technology to comprehensively utilize co-associated resources, solid wastes, and wastewater. Low-grade ores that are complex and difficult to process are utilized to improve technical and economic indexes by adopting combined processing and metallurgical processes. Enterprises should practically dispose of topsoil and recover valuable elements or useful minerals from solid waste. The solid waste that cannot be recycled is fully utilized through backfilling, paving, and other ways, striving to achieve zero resource discharge [44]. In addition, tailings containing mainly calcite and quartz can be used as raw materials for cement [45]; tailings containing mainly quartz or feldspar can be used as raw materials for ceramics [46]; tailings containing Fe, Zn, Cu, Mo, B, and other trace elements can be used as soil conditioner [47]; tailings that cannot be recovered can be used as underground filling material. Wastewater disposal and comprehensive utilization need to be equipped with corresponding wastewater treatment facilities and recycling systems [48]. Currently, the treatment of acidic wastewater from mines can be categorized into chemical, physicochemical, microbiological, and wetland methods. According to the nature and output characteristics of different mine wastewater, its treatment process and reuse methods are also different.

3.4. Energy Conservation and Emission Reduction

It mainly includes energy conservation, emissions from three wastes, and noise emissions.

(1) Energy conservation

The enterprise establishes a whole-process energy consumption management system and obtains energy management system certification. The energy consumption of each process should be analyzed according to the actual situation of the extraction process. Mining enterprises can optimize the equipment and simplify the process line of those processes whose energy consumption does not meet the standard. In terms of energy consumption in mines, carbon emissions from electricity and transportation consumption account for a large proportion. Therefore, mines should rationally utilize clean energy and adopt unmanned driving to reduce carbon emissions. It is necessary to increase scientific research investment in mining technology and equipment to reduce energy loss through new equipment and technologies [49].

(2) Emissions from three wastes

A list of major dust-producing points is created, and drainage pipes and drains are properly installed. The dust generated in the mining process is processed through appropriate dust removal measures, and wastewater from the extraction process is discharged after treatment. For solid wastes that cannot be completely utilized, they are graded and classified or disposed of according to the corresponding regulations.

(3) Noise emission

Noise emissions should be sorted and analyzed according to the process to form a noise control list. The noise generated in the extraction process is treated with noise reduction and discharged after meeting the standards.

3.5. Technological Innovation and Intelligence

It mainly includes technological innovation and intelligent mining.

(1) Science and technology innovation

The enterprise establishes a research and development team of full-time technical personnel and formulates a technology research and development management system. A collaborative innovation system between the industry, academia, research, and utilization is established, and workers are encouraged to participate in their enterprise's scientific and technological innovation. It is imperative to summarize the scientific and technological achievements, support technological transformation, and select the mining processes, technologies, and equipment that the country encourages, supports, and promotes.

(2) Formulate an intelligent mine construction plan

Build a centralized automation control platform. Implement the processes of three-dimensional reserve management. Develop a production automation system, remote video monitoring system, intelligent working face or unmanned mining vehicle system, and online monitoring system for the mining environment [50].

With the arrival of the 5G era, a number of mining enterprises have introduced the Internet of Things, big data, artificial intelligence, and other advanced technologies to build a dynamic visual three-dimensional geological model, intelligent truck scheduling, all-round video surveillance, real-time monitoring of dust, automation and intelligent distribution of six systems, so that the enterprise production is safer, more efficient use of resources, more environmentally friendly mining methods. For example, loaders, excavators, and other parts of the product line have been mechanized and electrified with a 5G remote control, which improves mining efficiency, reduces carbon emissions, and lowers noise [51].

3.6. Enterprise-Land Stability

The establishment of a practical green mine management system is an indispensable guarantee to maintain order at a mine. At the same time, mining enterprises should improve the production safety responsibility system and establish all production safety management procedures and safety operation procedures to guarantee the safety standardization of the production process. For slope disasters caused by open-pit mining, surface displacement monitoring, internal rock displacement monitoring, and water pressure monitoring are used to control the internal structure of the rock mass and groundwater permeability and increase slope stability. Retaining walls, anchors, anti-slip piles, grouting, and reinforcement methods are adopted to prevent landslides, minimize damage to the surrounding land, and improve the stability of the slopes [52]. The underground mining goaf is mainly treated by setting up isolation walls and observation points, filling them with waste rocks, and collapsing surrounding rocks to reduce disturbance and damage to the land [53]. Among them, waste rock filling can also reduce the occupation of land by waste rock. Enterprises should establish a mining equipment management system, functional area management system, occupational health management system, and environmental protection system. In accordance with the green mine training system and plan, regular training is organized for mine personnel. The dress code for those who enter the site must meet safety requirements. The enterprise must care for its employees, organize regular medical checkups for them, and conduct cultural activities to promote the construction of a green mine culture for the mining enterprise. In addition, the mine pays taxes according to the law, fulfills relevant obligations, cooperates with neighboring residents, and participates in public welfare activities.

4. Discussions

4.1. Construction Achievements

Over the past decade, various regions have promoted policies and regulations, gradually improving upon them, which has led to significant achievements in green mine construction and the overall image of the mining industry. In 2017, six ministries, including the former Ministry of Land and Resources, promulgated the Implementation Opinions on Accelerating Green Mine Construction, officially marking the beginning of China's journey into green mine construction. It symbolizes the transformation of green mine construction with Chinese characteristics from point to surface [54]. Concurrently, a preliminary framework of policies and regulations related to green mines has been established, such as the Regulations on the Protection of Geological Environment in Mines [55], the National Green Mine Construction Standards, and the Green Mine Construction Standards for Nine Major Industries [56]. In accordance with the China Mineral Resources Report (2022) issued by the Ministry of Natural Resources, more than 1100 national-level green mines and 50 green mining development demonstration areas will be constructed by the end of 2021. In 2020, 301 mines were included in the National List of Green Mines [57]. These 301 mines were determined based on their locations and mine types. Xinjiang had the highest number of selected mines, totaling 20. The western region had the highest number of mines on the list. Non-metallic mineral resources account for the largest proportion. Figure 13 displays the number of national green mines by province. Figure 14 analyzes the national green mines in 2020 by mine type and location.

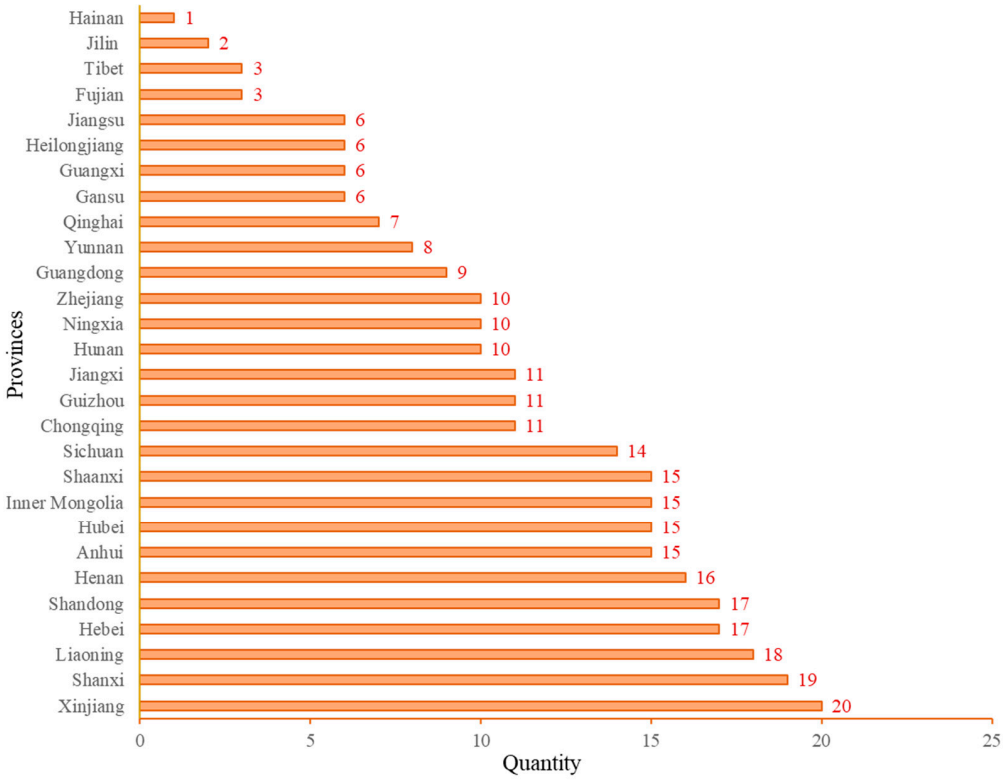

Figure 13. Number of mines included in the National List of Green Mines in 2020 by province (data from [57]).

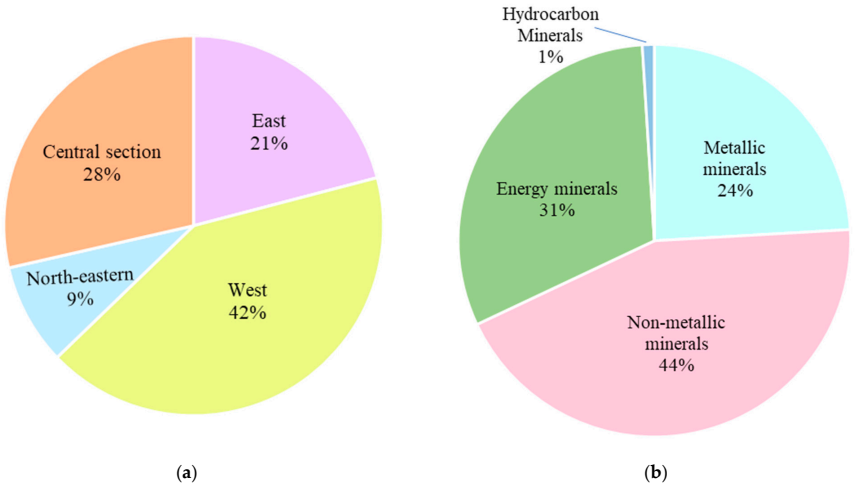

Figure 14. Structural analysis of the 2020 National List of Green Mines (data from [57]). (**a**) Regional analysis; (**b**) Mineral analysis.

4.2. Developing Directions of Green Mines

Since the creation of green mines, green mine models have emerged in China, mainly including green technology mining, modern mining operations, stable mining areas, and the ecological restoration of mines [58,59].

(1) Green technology mining

The core of the green mining model is to realize efficient and intensive mining of resources and the maximum protection of the ecological environment with green technology so that resource extraction and the environment can achieve a unified green mining development mode. Green mining technologies include fill mining, water retention mining, clean mining, etc. [60]. Figure 15 shows the tailings filling system of the green mining.

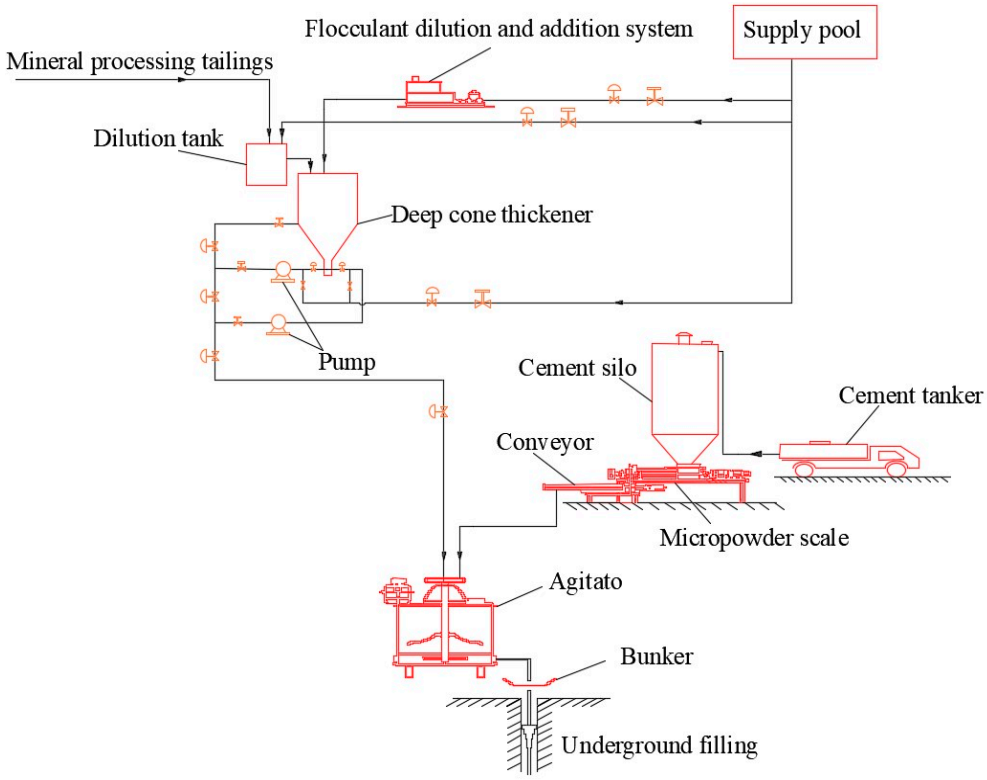

Figure 15. Flow diagram of the filling process (adapted from [61]).

(2) Modernization of mining operations

Among the 661 pilot units, over 90% of them integrate modern network technology and automatic control technology throughout the entire production and operation process, achieving a beneficial situation for both the economy and the environment. For example, building a smart mine platform allows for equipment to be automated remotely to create smart mines and smart mining areas [62–64].

(3) Stability in mining areas

Stability in a mining area means that mining enterprises should fulfill their social responsibilities in the pursuit of development, realizing the coexistence between the mining enterprises and surrounding communities, the promotion of mining development and regional economic development, the coordination of mineral extraction and environmental protection [65]. The paradigm is the Yunnan Phosphatization Hanying model. Figure 16 shows the stable development of economic, environmental, and cultural construction between the Yunnan Phosphorus Chemical Group and Hanying Village through the "321" working mechanism [66].

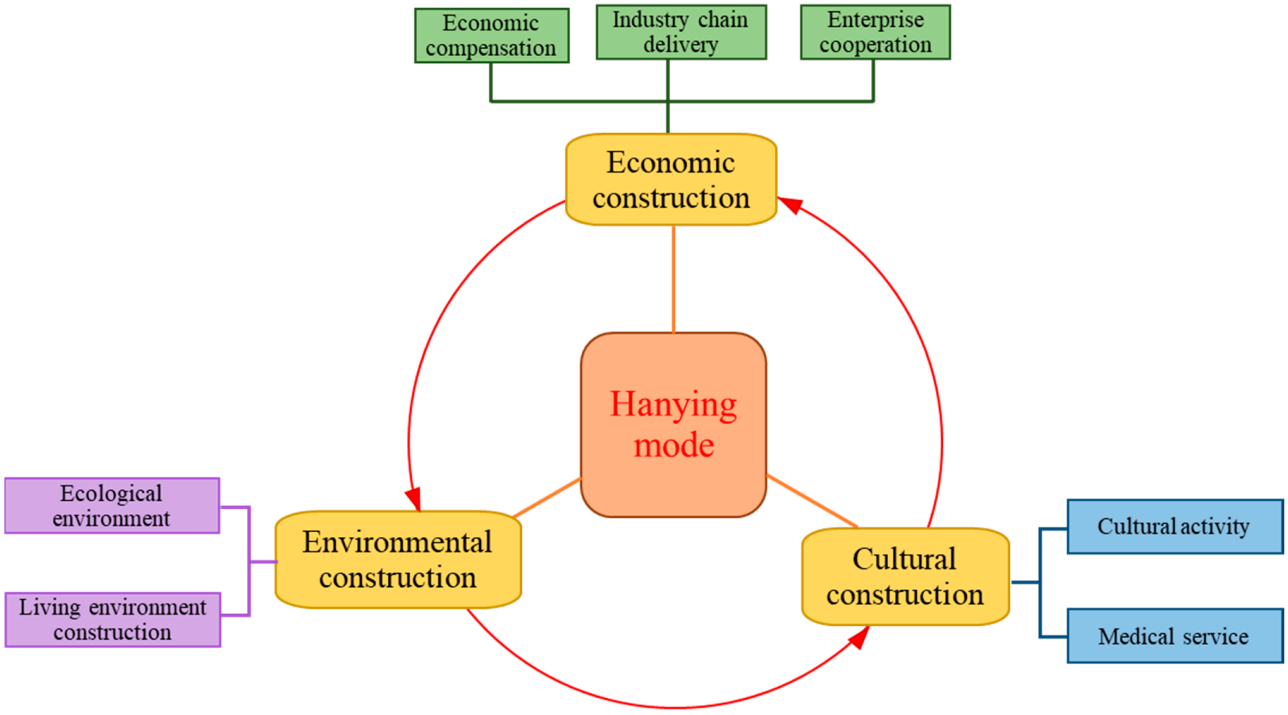

Figure 16. Schematic diagram of Hanying "321" model (adapted from [66]).

(4) Ecological restoration of mines

Mine ecological restoration refers to the optimal restoration of the original appearance or value of the damaged land and environment around the mining area through a series of restoration technologies. The ecological restoration models of mining areas include the re-greening model, the mine park model, and the tourism landscape model [67,68].

4.3. Future Goals for Green Mine Construction

(1) High-quality development contributes to green mining

Currently, problems exist in green mine construction in China, e.g., insufficient enthusiasm for some mines, inadequate evaluation criteria systems, and a low proportion of small-scale mines [14]. Therefore, the mines that are close to profitability should optimize the industrial structure and take the road of intensification. Small mines are intensive into medium-sized mines, while medium-sized mines should be concentrated into large mines.

It is necessary to vigorously promote technological innovation, transform the development model of mining, and breakthrough key technologies that present bottlenecks [69]. Advanced mining and beneficiation processes should be adopted, novel equipment should be used to improve the utilization rate of resources, energy consumption during mining operations should be reduced, and a beneficial relationship between the mine and nature should be achieved.

(2) Promoting green mine construction overall with a focus on points and areas

The green mine construction is the "point", and green mine demonstration areas are the "surface". Mines with remarkable results in green mine construction are selected as demonstration sites. The government actively guides and promotes institutional innovation, management innovation, institutional innovation, point driven areas and achieves centralized integration through the process, thus promoting the development of green mines across the entire region [70].

4.4. Main Measures for Green Mine Development and Construction

(1) Mining enterprises

The mining enterprises should fully recognize the necessity of developing green mines, take active measures to establish green mines, and practice the concept of green development. Mines should try their best to increase scientific and technological innovation to promote the transformation and upgrading of the mining industry. In addition, according to existing policy norms, the enterprises design the green mine construction plans and conduct self-assessments according to green mine standards [14]. Then, the mining enterprises make timely corrections to improve their deficiencies.

(2) Government

i. Improve the policies and formulate the standards for green mines. The nine industry standards and specifications of green mines released in 2018 do not cover aquatic minerals, radioactive minerals, and other types of minerals [71]. Meanwhile, the issued standards are not applicable to different mines; therefore, it is indispensable for the government to improve the standard construction policies of green mines. Differentiated standards and detailed requirements should be formulated for mines with different scales, stages, and locations [38].

ii. Improve the guarantee system for the execution of green mine policies. The government should implement incentive policies for green mining enterprises in terms of land usage, mining, finance, and funding [70]. The mines that meet the relevant green mine requirements should be exempted from taxes.

iii. Strengthen publicity and implement regulatory responsibilities. Enterprises actively convene green mine construction exchanges and training sessions to promote mutual learning and progress in various places. Relevant departments implement regulatory responsibilities, conduct random spot checks, guide, and urge mines to rectify problems on time. The mines that do not meet the requirements are promptly removed from the list of green mines.

5. Conclusions

With the environmental impacts of mining, including three-waste emissions, ground deformation, geological disasters. Occupation and destruction of land, pollution of groundwater resources. It is important to note that, at the same time, as a traditional high-energy consuming industry, mining consumes a large amount of energy. It emits greenhouse gases, so the construction of green mines has become an inevitable trend in the development of the mining industry under the impetus of the dual-carbon target. Over the decade of pushing forward, from pilot exploration to comprehensive promotion, from demonstration sites to demonstration zones, more than 1250 national green mines have been constructed, and four typical green mine models have been developed, achieving significant achievements in

the construction of green mines. However, there are still some problems, e.g., unbalanced regional development, insufficient understanding of green mine construction by some enterprises, imperfect policies and standard systems, etc. Therefore, the construction of green mines in the future requires the joint efforts of enterprises, governments, and society, in accordance with the development model of "government-led, enterprise-oriented, association support, policy guarantee, and market operation", to promote the continuous exploration and innovation of technologies and methods for green mine construction. The government should perfect the policies and standard system, increase the financial support, and strengthen the supervision and management of existing green mines. Enterprises should formulate the construction plan of "one policy for one place and one policy for one mine", provide positivity and initiative, speed up the upgrading and transformation in line with local conditions, and gradually meet the standards of green mine construction. In addition, to achieve breakthroughs in low-carbon technology and efficient resource utilization, promote green and low-carbon development of mines, and reduce carbon emissions, enterprises should carry out research and development of "energy-saving, low-carbon key technologies" and ecological restoration of mines and implement the "two mountains" theory throughout the entire process of mining development, so that sustainable development of China's mines can be promoted. With the joint efforts of the government, enterprises, and others, we will promote the high-quality development of the mining industry and realize a new situation in the development of the mining industry.

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