# Research Progress and Challenges in Coal Gangue Resource Utilization Technologies

**Abstract:** Coal gangue is the largest mining solid waste with an annual output of more than 720 million tons and a cumulative stockpiling of more than 7 billion tons in China, and the environmental pressure is huge. Under the impetus of the " double carbon " strategy, its resource utilization has become a national priority. At present, in terms of power generation, circulating fluidized bed ( CFB ) boiler technology has achieved an annual consumption of 3.5 million tons of coal gangue ; in the field of building materials, the amount of spontaneous combustion coal gangue replacing cement in the preparation of ultra-high performance concrete ( UHPC ) by coal gangue can reach 40 %. In terms of underground filling, the overburden bed separation grouting and intelligent filling system achieve large-scale application ; in road engineering, multi-source solid waste collaborative utilization technology significantly improves roadbed performance. Nevertheless, it still faces challenges such as complex composition, high cost and secondary pollution. In the future, it is necessary to further rely on the two-wheel drive of policy and technology to promote the transformation of coal gangue from ' waste treatment ' to ' resources ', so as to achieve high-quality development of environmental protection and resource recycling.

**Keywords:** coal gangue ; resource utilization ; solid waste ; environmental governance technology

1. **Introduction**

“As the main solid waste produced in the process of coal mining and washing, coal gangue is one of the mining solid wastes with the largest emission and the largest stock in China” [1]. “Due to the significant difference between the mining area and the coal seam, its occurrence characteristics generally show the characteristics of " two low and one high " with low carbon content, low calorific value and high hardness” [2]. At present, China 's coal gangue is still mainly stored and disposed. The historical cumulative stock of coal gangue has exceeded 7 billion tons, and it continues to increase by about 720 million tons per year. These huge stockpiles of coal gangue account for more than 70 square kilometers of land, and are accompanied by multiple environmental stresses, including the release of harmful gases by spontaneous combustion, the formation of acid rain and groundwater pollution by rainwater leaching, and the occupation of river channels leading to siltation, and may even induce major geological disasters such as landslides and debris flows. In recent years, incidents such as the illegal dumping of tens of thousands of mu of forest and grassland by coal gangue and the direct discharge of rural waterways by black ditch in some areas have further highlighted the severe ecological and environmental challenges brought about by its disorderly storage.

Under the background of " double carbon " target strategy, the resource utilization of coal gangue has been promoted to the national strategic level. Ten departments, including the National Development and Reform Commission, have clearly stated that by 2025, the comprehensive utilization capacity of coal gangue, fly ash and other bulk solid waste will be significantly improved, and the comprehensive utilization rate of new bulk solid waste will reach 60 %, and the stock storage will be reduced in an orderly manner. Many provinces have also set more specific goals. For example, Yunnan Province plans to reach about 78 % of the comprehensive utilization rate of coal gangue by 2025, and Shanxi Province 's goal is 85 %. In August 2024, the Ministry of Natural Resources further clearly stated that ' encourage the use of coal gangue and other mining solid waste for coal mining subsidence area management ', and allow the land to be converted to agricultural or construction land after restoration. These policies provide a strong institutional guarantee and market orientation for the resource utilization of coal gangue, and promote its transformation from simple ' reduction ' treatment to efficient ' resource utilization ', which is in line with the strategic needs of national ecological civilization construction and circular economy development.

**2. Analysis on utilization status of coal gangue at home and abroad**

The resource utilization of coal gangue is an important problem faced by China and even the international community. In order to promote its rational utilization, China has introduced the " Management Measures for Comprehensive Utilization of Coal Gangue " in the early years, and has gradually established a standardized system to guide the utilization of coal gangue resources after many revisions. The " Key Points of Coal Gangue Comprehensive Utilization Technology Policy " issued subsequently further clarified the application direction of coal gangue in roadbed construction, power generation, cement admixture, building materials, backfilling and harmless treatment. In 2021, the " Guiding Opinions on the Comprehensive Utilization of Bulk Solid Wastes in the 14th Five-Year Plan " has pointed out the implementation path for the large-scale and high-value utilization of coal gangue.

China 's research on the utilization of coal gangue resources started relatively late, but in recent years, technological progress has been remarkable. At present, coal gangue is mainly used in landfill, underground backfilling, roadbed laying, power generation and building materials production and other fields [3]. In terms of large-scale underground disposal, China Coal Research has developed a full coal-based solid waste paste material and intelligent filling system. In terms of high-value utilization, China has developed processes such as suspension calcination and high-temperature balling, which can prepare high-value-added products such as metakaolin and white carbon black. Inner Mongolia Hui Neng Company plans to invest in the construction of an annual treatment of 6 million tons of coal gangue project, the production of aluminum silicon alloy and other products, showing good prospects. Ecological application has also made progress. By converting coal gangue into ecological functional soil for mining area reclamation and soil improvement, Yulin City has built 50,000 tons of annual pilot production line, and 35,000 tons of ecological functional soil are produced annually.

A number of advances have been made in the resource utilization technology of coal gangue abroad, and the overall utilization rate is high, but it also faces challenges such as high treatment cost and technical economy. In the field of building materials, the application of coal gangue is not limited to traditional fired bricks or cement admixtures. The research team in Russia 's Rostov region used spontaneous combustion coal gangue to treat under specific concentration of phosphoric acid and microwave power conditions, and successfully prepared lightweight foam materials with uniform porous structure. Its excellent performance, far more than the traditional alkali-activated geopolymer, provides a high-performance and environmentally friendly solution for the field of building insulation [4]. In addition, the use of coal gangue for the production of geopolymers and related alkali-activated materials is also a research hotspot. The high silicon and aluminum content of coal gangue makes it have the potential of alkali activation. By compounding with slag and fly ash, and optimizing the alkali activator and process, green building materials with improved compressive strength and significantly reduced carbon emissions can be prepared, which can be used in grouting materials and roadbed construction [5]. The energy utilization of coal gangue continues to advance. A number of coal gangue power plants have been built in Russia, Ukraine and other places. Circulating fluidized bed combustion technology is mainly used to treat gangue with calorific value of 1200-2500 kcal / kg.The application technology of coal gangue in ecological restoration and backfilling is also developing and standardizing. In developed countries such as the United States and Australia, coal gangue backfilling technology is widely used to treat mining subsidence areas.

**3. Development status of comprehensive utilization technology of coal gangue**

**3.1** **Coal gangue is used as fuel for power generation:**

At present, coal gangue is mainly used for power generation through circulating fluidized bed ( CFB ) boiler combustion technology. This is because coal gangue has low heat and complex composition, and traditional boilers are difficult to deal with it efficiently. CFB boiler achieves low-temperature stable combustion through high-rate circulation of materials in the furnace [6], which can effectively reduce the volatilization of alkali metals and the formation of nitrogen oxides in coal gangue [7]. It has wide adaptability to fuel, can ' eat coarse grain ', and is very suitable for coal gangue with low calorific value and large fluctuation of composition. Luan Group has built a 4 × 135,000 kW coal gangue power plant, with an annual utilization of coal gangue of up to 3.5 million tons. In addition, China 's coal gangue power generation technology has been applied in many places, and a large amount of coal gangue has been consumed (Xu et al., 2024). Successful coal gangue power generation projects can bring both environmental and economic benefits, and the ash and fly ash produced after combustion can also be used to produce building materials, chemical and other industries. Materials are a green cycle of resource utilization. Of course, this technology also continues to face challenges in improving efficiency, stable operation, and cost control [8]. In the future, through the continuous iteration of technology and the continuous support of policies, coal gangue power generation is expected to play a more important role in the green transformation of the coal industry.

**3.2** **Coal gangue is used to make building materials:**

The technological development of coal gangue in building materials manufacturing is very active. Its core goal is to consume this solid waste on a large scale and with high value, and to reduce the environmental impact of traditional building materials production. Coal gangue contains a certain amount of silicon and aluminum, which can exhibit pozzolanic activity after mechanical grinding or thermal activation [9]. This means that it can react with calcium hydroxide produced by cement hydration to form a gel material with strength. Li et al. [10] proposed a composite mechanical-hydrothermal activation ( CMHTA ) process to achieve efficient resource utilization of coal gangue and provide a technical solution for its high content application in cement-based materials. Compared with the coal gangue T activated by TMTA technology and the untreated raw coal gangue, the mechanical properties of the coal gangue-based mixed cement prepared by are better than those of the coal gangue C activated by CMHTA technology.At the same time, coal gangue can be used as recycled aggregate for concrete after crushing, screening and shaping. Or through sintering, non-burning process made of artificial lightweight aggregate [11]. Bricks and blocks are also one of the most traditional and extensive ways of coal gangue resource utilization, and the technology is relatively mature. At present, more attention is paid to improving product quality, production efficiency and product added value. Using coal gangue to prepare lightweight and porous thermal insulation materials is another high-value utilization path. These technological advances are of great significance for saving natural resources, reducing environmental load and developing circular economy.

**3.3** **Gangue used for underground filling:**

The underground filling technology of coal gangue, especially the technology of overburden separation grouting and intelligent goaf filling, has achieved large-scale application and achieved remarkable environmental, economic and social benefits. It is not only an important means to deal with coal gangue, but also one of the key technologies to promote the transformation of coal mining to green, safe and efficient [12]. However, this method also has problems such as large investment in the early stage, low efficiency, affecting the speed of underground coal mining, and increasing the complexity of the process . Although it still needs to continue to explore in terms of cost control, geological universality and long-term monitoring, the prospect of this technology is very broad with the continuous iteration of technology, the improvement of intelligence level and the possible new value of carbon sink.

**3.4** **Coal gangue used in road engineering:**

The application technology of coal gangue in road engineering is not only an effective way to absorb solid waste, but also an alternative to traditional sand and gravel materials. It is of great significance for saving resources, protecting the environment and reducing engineering costs. In recent years, it has been commonly used in highway subgrade filling [13]. Wang Chuan et al. [14] used coal gangue to cooperate with mineral powder to prepare roadbed filling materials. Considering its rheological properties, setting time, compressive strength and other properties, it is considered that when the content of coal gangue is 30 % ~ 40 %, the performance of coal gangue-mineral powder combination is the best. The 28 d compressive strength is higher than that of P.O 32.5 cement, and the water absorption rate is less than 30 %, which can be used as a filling material with good performance. The application technology of coal gangue in road engineering is developing towards the direction of refinement, intelligence and high performance [15] . In terms of roadbed filling, particle size control and uniform water content are the key. In terms of pavement base materials, the core is to stimulate the activity of coal gangue and improve its stability. Through hundreds of tests, the technical team developed a multi-source solid waste phase reconstruction technology, which mixed 8 kinds of industrial solid wastes such as coal gangue and slag in a specific proportion, supplemented by green cementitious materials to form a new road construction material. This material is even stable in extreme temperature environment, and the crack rate is significantly lower than that of traditional materials.Intelligent construction and environmental protection control are gradually implemented.

**4. Coal mine waste environmental protection treatment technology**

**4.1 Stacking treatment technology:**

At present, China 's coal gangue stock is huge and continues to increase every year. In the process of resource utilization, the stacking treatment technology is indispensable, mainly because it plays an important transition and basic role in dealing with huge stockpiling, achieving the primary goal of ' reduction, stabilization and harmlessness ', and creating conditions for subsequent resource utilization. At present, the cumulative stock of coal gangue in China has exceeded 7 billion tons, and it is increasing at a rate of about 700 million tons per year. Such a huge volume is far beyond the immediate consumption capacity of the current resource utilization technology. A large amount of coal gangue not only occupies land resources, but also may cause potential safety hazards such as spontaneous combustion and landslides, as well as environmental problems such as dust and water pollution. Although the resource utilization technology of coal gangue is developing, many high-value and large-scale utilization technologies still need time and conditions to mature, and all coal gangue cannot be consumed immediately. In addition, the resource utilization itself also needs to pre-treat the coal gangue. In this process, temporary standardized stacking is necessary.

The traditional stacking method is gradually being replaced by more scientific and environmentally friendly standardized stacking and sealing technology. These technologies are designed to minimize environmental risks and provide possibilities for subsequent use. Layered compaction and loess coverage adopt the process of ' from inside to outside, from bottom to top, reducing the ice, layered compaction '. The gangue is compacted by covering a layer of loess with a certain thickness according to a certain height. The bottom of the yard will also lay an anti-seepage layer. It can effectively prevent spontaneous combustion, inhibit dust, reduce leaching water pollution and lay the foundation for subsequent greening. After the stockpiling reaches the design elevation or the end of the stockpiling, the final thick soil coverage and vegetation restoration will select plant species with strong adaptability and barren tolerance. Before or during the stacking process, the coal gangue is preliminarily sorted, classified according to its composition, calorific value and rock phase characteristics, and stacked or simply processed respectively. After crushing and grinding, coal gangue is mixed with cementitious materials such as cement to make slurry, which is injected into goaf or abandoned roadway by high-pressure pumping equipment.In the disposal of solid waste in coal mines, stacking treatment technology is more commonly used. The use of stacking treatment technology can reduce the surface water load, do not need to deal with a large number of dissolved solids, the load of mud sand is small, and avoid the risk of surface water pollution [16].Because the discharge of solid waste will have a direct leaching effect and influence on the water body, the use of stacking treatment technology can effectively prevent such problems. However, the selection of the site for stacking waste is also high. It is necessary for geological survey personnel to collect information on nearby hydrology, topography, atmosphere, earthquakes, etc., conduct comprehensive research, and select accurate stacking sites. There are more stringent requirements for the location of the tailings. For example, the tailings stacking site requires the basic materials to have sufficient strength and strong impermeability [17].

**4.2** **Resource utilization technology:**

The development of coal gangue resource utilization technology is particularly urgent, which is mainly due to the huge stock and amazing annual increment of coal gangue in China, as well as the environmental pressure it brings. At the same time, under the strategic background of " double carbon " goal and green development, the traditional stacking and landfill methods are unsustainable. Promoting the resource utilization of coal gangue and realizing " turning waste into treasure " is an inevitable choice for both economic development and environmental protection. Replacing traditional building materials production, reducing resource consumption and carbon emissions ; the study of Xu et al. [18] showed that the use of spontaneous combustion coal gangue ( SSG ) instead of cement to prepare ultra-high performance concrete ( UHPC ) can significantly optimize its pore structure, reduce the formation of harmful pores and capillary pores, and thus greatly improve the impermeability of UHPC. This study points out that the maximum substitution amount of SSG can reach 40 %, which provides important theoretical support for further promoting the application of coal gangue in UHPC. Underground filling and other technologies also help to reduce surface subsidence and ecological damage.Xie et al. [19] pointed out that by constructing a " ground centralized pulping + high-level grouting " system, the coal gangue was broken to a particle size of ≤ 5mm and mixed with 20 % fly ash to prepare a filling slurry with a slump of 220mm ( good fluidity ). The engineering measurement shows that the technology reduces the surface subsidence rate from 12 mm / month of traditional mining to 2.3 mm / month through the supporting effect of the filling body on the overburden rock, and at the same time reduces the surface stock of 470,000 tons of coal gangue every year and reduces the solid waste stacking pressure.On the one hand, resource utilization saves the cost of coal gangue disposal and the cost of traditional raw material procurement ; on the other hand, high value-added products have created new economic growth points and formed a new industrial chain. The recycling of solid waste is realized, and the concept of ' eating dry and squeezing ' improves the efficiency of resource utilization, which is in line with the development direction of circular economy. Underground filling and goaf management are helpful to reduce the risk of geological disasters and ensure the safety of mining production and surrounding residents. The development of resource utilization projects and the extension of the industrial chain have created new jobs. In the future, the resource utilization technology of coal gangue may develop in the direction of intelligence and precision, technology coupling and system integration, high value and product diversification, and policy and standard improvement.

**4.3** **Ecological environment restoration technology:**

The resource utilization of coal gangue is facing multiple difficulties. Although China has developed a variety of utilization ways such as power generation, building materials and backfilling, the overall utilization rate is still not ideal, and the regional differences are significant. Some coal gangue is rich in heavy metals and sulfur elements, and there is a risk of acid production and heavy metal release, which restricts its large-scale ecological restoration and utilization. Although traditional resource utilization methods such as power generation and brick making consume a certain amount of coal gangue, they often face problems such as large investment scale, high cost, high energy consumption and possible secondary pollution, which are difficult to meet the huge demand for coal gangue treatment. In the context of the ' double carbon ' target strategy, the state and many provinces have formulated more specific targets, which require coal enterprises to seek more efficient and environmentally friendly coal gangue treatment methods.

It is often difficult to completely absorb huge amounts of coal gangue by simple resource utilization. Some coal gangue has high content of heavy metals and sulfur, and there is a risk of acid production and heavy metal release, which restricts the large-scale ecological restoration and utilization. It is necessary to combine resource utilization with ecological restoration to realize the large-scale disposal of coal gangue. Coal gangue is rich in nutrients and substances such as nitrogen, phosphorus, potassium and organic matter, and the minerals are mainly quartz and clay minerals, which can provide the necessary material basis for the ecological restoration and utilization of coal gangue. Through ecological restoration technology, coal gangue can be transformed into ecologically functional soil with good moisture conservation, fertilizer conservation, water permeability and air permeability, so as to maximize the value of resources. Fan et al [20] successfully used coal gangue and plant ash to prepare silicon-potassium-based modifiers, which successfully promoted the growth of maize plants. Ecological restoration technology effectively controls the environmental risk of coal gangue. Through microbial technology, oxidation bacteria inhibition technology and heavy metal passivation technology, the release of heavy metals in coal gangue can be effectively controlled. In view of the risk of acid production and heavy metal release from coal gangue, physical, chemical and microbial multi-channel combined technology can inhibit acid production and heavy metal release, and realize the safe utilization of coal gangue ecological restoration [21].Ecological restoration technology has effectively restored the damaged ecosystem, and the land function has been restored and improved, which has brought significant economic benefits and promoted industrial transformation and upgrading.

**5. Conclusion**

Coal gangue is the largest mining solid waste in China, with huge annual production and significant environmental pressure. Its resource utilization has become a key task at the national level under the background of " double carbon " strategy. At present, there are various ways of comprehensive utilization of coal gangue, including power generation, building materials production, underground filling and road engineering. In terms of power generation, circulating fluidized bed boiler technology can effectively deal with low calorific value coal gangue and realize energy utilization ; in the field of building materials, coal gangue after activation treatment can be used as cementitious materials or lightweight aggregate, used in the manufacture of bricks, blocks and high performance concrete ; the underground filling technology not only absorbs gangue, but also helps to control the settlement of goaf. Coal gangue has good technical and economic potential to replace natural aggregate in road engineering. In addition, stacking treatment, as a transitional means, still plays an important basic role in achieving ' reduction, stabilization and harmlessness '. However, the resource utilization of coal gangue still faces technical and management challenges such as complex composition, high utilization cost and secondary pollution risk. In the future, it is necessary to further promote technological innovation and policy support, promote the high-value, large-scale and intelligent utilization of coal gangue, and achieve the dual goals of environmental protection and resource recycling.

Disclaimer (Artificial intelligence)

Option 1:

I hereby declare that no generative AI techniques such as large language models ( ChatGPT, COPILOT, etc. ) and text-to-image generators were used during the writing or editing of this manuscript.

# 6.References

[1] Xu Peijie, Zhu Yifei, Cao Yongdan, et al. Research progress on high-value utilization of coal gangue resources [ J ].Environmental Engineering Journal, 2023,17 ( 10 ) : 3137-3147.

[2] Li Y. Review of coal gangue characteristics and ecological restoration management technology[C]//IOP Conference Series: Earth and Environmental Science. IOP Publishing, 2021, 781(3): 032033.

[3] ZHU T, WU X, XING C, et al. Current situation and progress of coal gangue resource utilization[J]. Coal Science and Technology, 2024, 52(1): 380-390.

[4] Lazorenko G, Kasprzhitskii A, Chaudhary S. One-step microwave preparation of phosphoric acid activated foams from spontaneous combustion coal gangue[J]. Journal of Industrial and Engineering Chemistry, 2025.

[5] Lazorenko G, Kasprzhitskii A, Yatsenko E A, et al. Towards coal mining waste valorization: Gangue as resource for the production of geopolymer and related alkali-activated materials[J]. Green Technologies and Sustainability, 2025: 100205.

[6] Xu, Y., Wu, H., Dong, Z., Wang, Q., & Chen, X. (2024). Life cycle energy use efficiency and greenhouse gas emissions of circulating fluidized bed coal-fired plant with coal gangue and coal co-combustion. Environment, Development and Sustainability, 26(8), 20049-20071.

[7] Snehasree N, Nuruddin M, Moghal A A B. Critical Appraisal of Coal Gangue and Activated Coal Gangue for Sustainable Engineering Applications[J]. Applied Sciences, 2025, 15(17): 9649.

[8] Zhang L, Wu Y, Liu M, et al. Dual NO/SO2 mitigation in coal gangue-high-alkali-coal co-combustion: Synergistic reactivity enhancement and mechanistic insights[J]. Sustainable Materials and Technologies, 2025: e01581.

[9] Wang C, Wang Y, Sun W, et al. An acid-free short-flow process for high-quality separation of kaolinite in coal waste rock: Based on mineralogical determinations[J]. Applied Clay Science, 2025, 271: 107792.

[10] Li C, Wan J, Sun H, et al. Investigation on the activation of coal gangue by a new compound method[J]. Journal of Hazardous Materials, 2010, 179(1-3): 515-520.

[11] Jia X, Li W, Dong X, et al. Mechanical and Durability Properties of Concrete Prepared with Coal Gangue: A Review[J]. Buildings, 2025, 15(17): 3048.

[12]Zhang J, Li B, Xie Y, et al. Carbon negative backfill mining in coal mines for carbon neutralization: Chemical carbon fixation performances with mineralized gangue[J]. International Journal of Rock Mechanics and Mining Sciences, 2025, 186: 106016.

[13] Li Z,Guo Tengteng,Chen Yuanzhao,et al.Road performance analysis of cement stabilized coal gangue mixture[J].Materials Research Express,2021,8(12):125502.

[14] Wang Chuan, Liu Chao, Fei Wenjing, et al. [ J ]. Discussion on the preparation of roadbed filling materials by activating coal gangue tvv stone [ J ]. Acta Scientia Sinica Sinica, 2022,40 ( 1 ) : 97-103.

[15] Jiang Z, He K, Zhang D. A review of intelligent coal gangue separation technology and equipment development[J]. International Journal of Coal Preparation and Utilization, 2024, 44(9): 1308-1324.

[16] Zhu L, Yao Q, Xu Q, et al. Experimental study on the purification mechanism of mine water by coal gangue[J]. Water, 2023, 15(4): 697.

[17] Wang H, Chen D, Guo R, et al. A preliminary study on the improvement of gangue/tailing cemented fill by bentonite: Flow properties, mechanical properties and permeability[J]. Materials, 2023, 16(20): 6802.

[18]XU Y, WU Q, ZHANG Y, et al. Preparation of ultra-high performance concrete using spontaneous combustion gangue as a substitute for cement [J]. Materials Today Communications, 2024, 41: 110856.

[19]Xie S, Pan H, Gu W, et al. Technology and engineering test of filling goaf with coal gangue slurry[J]. Scientific Reports, 2023, 13(1): 20536.

[20]FAN Y, JIA H, PINO V, et al. A Si-K-Based Amendment Prepared by Coal Gangue and Plant Ash Could Improve the Growth of Maize Plants in Saline Soils[J]. Journal of Soil Science and Plant Nutrition, 2024, 24(1): 761-74.

[21]Kebe M. Biorecovery of rare earth elements from hard rock, extraction and analysis[M]. University of Alaska Fairbanks, 2023.