Present situation of comprehensive utilization of coal-based solid waste

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Abstract: At present, the annual discharge of coal-based solid waste in China has exceeded 800 million tons, but the mainstream treatment methods are still simple treatment methods such as goaf backfilling and open-pit stacking. The massive stacking of coal-based solid waste is not only a serious waste of resources itself, but also brings a series of problems such as environmental pollution. Under the “Carbon Peak” and “Carbon Neutrality” strategy in China, it is necessary to solve the problem of coal-based solid waste treatment and achieve green and comprehensive utilization of coal-based solid waste. Taking coal gangue, gasification slag and fly ash as representative coal-based solid waste, the present situation of coal-based solid waste production in China and the basic properties of coal-based solid waste are introduced. The utilization status and application characteristics of coal-based solid waste in cement concrete, roadbed materials, soil improvement and so on are focused on, and the resource utilization potential of coal-based solid waste is analyzed and summarized. Then the application prospect of coal-based solid waste in high-value utilization in the future is analyzed and prospected.

1. Introduction
At present, coal is still the main primary energy in China, and the situation is unlikely to undergo significant alterations in the near future [1]. The extensive use of coal will result in the generation of a large amount of coal-based solid wastes, which will cause serious environmental problems and even endanger personal safety. Coal-based solid waste is mainly a by-product in the process of coal mining, processing, combustion and conversion, including coal gangue, fly ash, coal gasification slag, etc. [2].

Coal gangue is mainly waste formed during coal mining, with annual emissions reaching nearly 800 million tons [3]. It has lower carbon content and higher ash content. At present, the main treatment methods of coal gangue are goaf backfilling and open-air stacking. Many coal gangue mountains will spontaneous combustion in the process of open-air stacking, releasing a large amount of sulfur dioxide and nitrogen oxides, seriously polluting the local air. At the same time, coal gangue contains heavy metal elements such as Mn, Cr, and As [4]. Long-term open-air stacking will cause harmful elements in coal gangue to spread to the surrounding environment, destroying the local ecological equilibrium and affecting the lives of local residents [5].

Coal gasification slag primarily comprises the by-product generated during the coal gasification process. According to statistics, the cumulative yearly discharge of coal gasification slag has surged to 60 million tons in 2021 [6]. The current main treatment method in our country is still open-air stacking. The open-air stacking of large amounts of coal gasification slag will not only cause dust and pollute the atmospheric environment, but also contain heavy metal ions such as Mo, Sr, and Sb that are relatively easy to leach and flow in the gasified slag [7]. It will seriously pollute nearby soil and groundwater resources.

Fly ash is mainly a waste produced during the combustion of coal. In some thermal power plants, pulverized coal is burned as a source of power, and a large amount of fly ash is produced after combustion. As of the end of 2021, the national fly ash emissions in 2021 exceeded 650 million tons [8]. The simple accumulation of large amounts of fly ash will not only waste land resources, but harmful substances such as heavy metal ions will gradually penetrate into the groundwater, contaminating the groundwater and destroying the local ecological environment [9]. Moreover, the fine particles in fly ash will be suspended in the air to form fine particulate matter (PM2.5 and PM10), which will have a negative impact on air quality and seriously endanger the health of local residents.

Under the “Carbon Peak” and “Carbon Neutrality” strategy in China, in order to achieve green and rapid development of the coal industry, addressing the issue of coal-based solid waste management is imperative to attain environmentally sustainable and all-encompassing utilization practices for coal-based solid waste.

Based on this, taking coal gangue, coal gasification slag and fly ash as representative solid wastes, on the basis of summarizing the classification and characteristics of
coal-based solid waste, the ways of comprehensive utilization of coal-based solid wastes are focused on. The prospective development trajectory of coal-based solid waste's comprehensive utilization is forecasted to offer insights for further research in this field.

2. Output of coal-based solid waste

2.1 Output of coal gangue

Coal gangue is a kind of black rock with low carbon content, low heat utilization value and hard texture. Coal gangue output represents 10% to 15% of the total raw coal production, originating from three primary sources: gangue during open-pit mining stripping and roadway construction, gangue extracted from the roof, floor, and interlayers during mining operations, and gangue separated during coal washing processes. The respective proportions of these sources are 45%, 35%, and 20%. In recent years, China's coal output has increased year by year, and coal gangue production has also increased. According to the data calculated in the "2021-2022 China Bulk Industrial Solid Waste Comprehensive Utilization Industry Development Report", the coal gangue production in 2021 will be approximately 743 million tons, an increase of 5.84%, a significant increase.

The production of coal gangue in coal mines varies greatly in different parts of China. The production of coal gangue in Taiyuan, Tangshan and other places is about 30%, while that in the newly built mines in Ordos and other places is about 10%. At the same time, most of the coal gangue production in China is concentrated in Shanxi Province, Shaanxi Province, Inner Mongolia Autonomous region and Xinjiang Uygur Autonomous region, where coal gangue production accounts for more than half of the national coal gangue production.

2.2 Output of coal gasification slag

The application of coal gasification technology is becoming more and more widespread under the domestic energy structure and actual demand, and the amount of coal gasification slag is also increasing. Coal gasification is a technology in the coal chemical industry that converts incomplete combustion of coal into CO and H₂ in an oxygen environment while producing tar at the same time. Gasification slag is a solid waste formed by reacted inorganic matter and residual carbon particles in coal. According to statistics, the annual output of waste residue from the million-ton coal gasification process can reach more than 900,000 tons. Coal gasification slag as the main component of waste residue, it can account for as much as 95%. According to statistics, the annual emission of coal gasification slag in China is more than 33 million tons.

2.3 Output of fly ash

China's current main method of producing electricity is thermal power generation, and the main fuel is still coal. 250~300Kg fly ash is produced for every ton of coal burned. The energy policy of "power transmission from west to east" implemented in China has increased the production of fly ash in Northwest China, and a large amount of fly ash has been stranded in Northwest China due to the limitation of transportation cost. According to the 2019 China Fly Ash Industry Development report, the production of fly ash in China in 2019 is about 655 million tons, and it is expected that subsequent production will continue to grow.

A large number of coal-based solid wastes in China have been treated by simple methods such as open-air stacking and landfill for a long time, which has seriously affected the environment. Hence, there is an urgent need to advance novel technologies to enhance the efficiency of coal-based solid waste utilization.

3 Properties of coal-based solid waste

3.1 Properties of coal gangue

The common coal gangue is grayish black or dark brown. Its shape will be obviously different according to the density of coal gangue and the way of treatment. The density of coal gangue is usually low, which depends on the content of carbon, the proportion of rock and mineral composition, and the water content. The size of particles in coal gangue ranges from powder to bulk. The carbon content of coal gangue is low, generally 20% to 30%. Coal gangue has multi-phase structure such as kaolinite, illite and Muscovite, and its chemical composition is complex and diverse. The main components are SiO₂, Al₂O₃ and C, accounting for more than 80%, as shown in Table 1. There are also some substances such as Fe₂O₃, CaO, MgO and trace heavy metal elements.

It is worth noting that due to the differences in the generation age and mining methods of coal mines in different mining areas, the composition and properties of coal gangue are also quite different. Du Yanzhe analyzed the physical and chemical characteristics of coal gangue in specific regions of Shanxi Province, and found that the contents of Fe, Ca and K in coal gangue are quite different. The main mineral composition is kaolinite and quartz, and some samples also contain hematite, calcite and dolomite. Huang Cheng and other researchers found that after long-term storage or spontaneous combustion of coal gangue, the toxic and harmful elements in coal gangue are more easily leached, and the properties of coal gangue may change.

<table>
<thead>
<tr>
<th>Composition</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>CaO</th>
<th>MgO</th>
<th>K₂O</th>
<th>C</th>
<th>Na₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td>wt/‰</td>
<td>30–60</td>
<td>15–40</td>
<td>2–10</td>
<td>1–4</td>
<td>1–3</td>
<td>1–2</td>
<td>20–30</td>
<td>1–2</td>
</tr>
</tbody>
</table>

Table 1. main composition and content of coal gangue.
3.2 Properties of coal gasification slags

Gasification slag is a byproduct generated during coal gasification, typically classified into coarse slag and fine slag fractions. The gasification slag formed after condensing along the furnace wall in the molten state becomes coarse slag, the general particle size is 1.19mm~4.75mm, and the residual carbon content is about 0~10% [21], which is mainly concentrated in the slag discharge outlet of the gasifier, accounting for 60% and 80% of the total gasification slag. The slag brought out by the gas becomes fine slag, the particle size is generally less than 0.075mm, and the residual carbon content is about 10%~30% [22], which is mainly concentrated in the gas dedusting device, accounting for 20%~40% of the total gasification slag. Because of its formation mode, coal gasification slag is mainly composed of minerals and unburned carbon. SiO2, Al2O3, Fe2O3 and C are the main components of coal gasification slag.

The physical and chemical characteristics of coal gasification slag are influenced by various factors such as coal rank, gasification process, and operating temperature. Li Yu [23] found that the preliminary quality classification of coal gasification slag can be realized only by screening and classification, which can be divided into three types according to its carbon content. The characteristics of high, medium, and low carbon slag exhibit substantial variations. High carbon slag primarily consists of porous, irregular, flocculent particles characterized by a high specific surface area and well-developed pore structure. Medium carbon slag is mainly composed of dense and smooth spherical, irregular massive and flaky particles, as well as some irregular flocculent particles. Low carbon slag almost has no crystal phase and is mainly composed of dense and smooth irregular particles with small specific surface area. Ge Xiaodong [24] found that the surface of coal gasification fine slag is severely oxidized, has many voids, and contains a large amount of water. However, its surface is mainly composed of hydrophobic functional groups, so it has a certain degree of hydrophobicity, and carbon can be recovered through flotation.

3.3 Properties of fly ash

Fly ash is a solid waste produced in the process of coal combustion, and its color is brown to black affected by residual carbon particles. The properties of fly ash are mainly affected by many factors, including the coal type, combustion mode, combustion temperature, boiler type and so on. The clay minerals in coal are in the melting state at high temperature environment in the pulverized coal furnace. After condensation, spherical fly ash with smooth surface is formed due to surface tension [25]. The crystalline minerals are mainly quartz and mullite, and the amorphous minerals are mainly amorphous glass phases composed of SiO2 and Al2O3. However, the combustion temperature of the circulating fluidized bed is low, so most of the fly ash produced is irregular flocs [26]. The crystalline minerals are mainly quartz and the amorphous minerals are mainly clay minerals such as metakaolin.

Fly ash is mainly composed of inorganic substances in coal, mainly SiO2, Al2O3, Fe2O3, CuO and a small amount of MgO, K2O, Na2O and other metal oxides, as well as a small amount of unburned carbon particles [27], in which there is less unburned carbon in pulverized coal furnace and more unburned carbon in circulating fluidized bed fly ash. Due to the addition of calcareous desulfurizer in fluidized bed fly ash, the content of calcium oxide in fly ash is higher [28]. The fly ash of pulverized coal furnace is generally small and hollow because of the high temperature, and the average particle size is less than 10 μm [29]. Because the surface atoms of fly ash are in an unsaturated state, the surface has certain activity. Fly ash has a porous structure inside, so it has a large specific surface area and is adsorbable.

Analysis of the composition and characteristics of coal gangue, coal gasification slag, and fly ash reveals significant variability in the properties of coal-derived solid waste, influenced by factors such as coal rank, mining location, and processing techniques. This variability poses a major challenge in the comprehensive utilization of coal-based solid waste. To achieve truly efficient utilization, different methods must be adopted based on the specific composition and properties of the waste. Presently, China faces a major obstacle in the lack of classified utilization of coal-based solid waste, hindering progress towards comprehensive utilization in the future.

4. Utilization mode of coal-based solid waste

Coal-based solid waste is not only one of the bulk industrial solid waste, but also a valuable resource disposed of. For a long time, the utilization of coal-based solid waste in China mainly adopts the way of direct treatment, including open-pit accumulation, goaf backfilling and incineration treatment. The storage of coal-based solid waste has the advantages of low cost and simple treatment process. However, long-term storage requires a lot of land resources, and there is still a risk of pollution.

Using coal-based solid waste to backfill mined-out areas can effectively reduce waste volume, but poses the risk of soil and groundwater contamination. Direct incineration of coal-based solid waste diminishes the overall waste volume, yet releases hazardous gases like sulfur oxides, leading to environmental pollution. Thus, secondary processing and utilization following classification is recommended. This approach aligns with the green development principles of the modern era. According to statistics, the utilization rate in China of coal gangue, coal gasification slag and fly ash is 20%, 16% and 65% respectively [30]. Due to their unique properties and diverse valuable components, coal-based solid waste finds extensive applications in resource extraction, construction materials, agriculture, environmental protection, and high-value-added sectors. Notably, the cement industry stands as a prominent sector for comprehensive utilization of coal-based solid waste in China, with coal gangue and fly ash commonly utilized in the production of building
materials like bricks, mortar, and concrete blocks. Coal-based solid waste is also widely used as roadbed stabilizer and pavement material in highway, railway and other road engineering. Coal-based solid waste accounts for a relatively small but also of great significance in soil improvement. Therefore, three utilization methods of coal-based solid waste including as cement and concrete, roadbed material, and soil improver are discussed in the present paper.

4.1 Used as cement and concrete

Coal-based solid waste can be used to make cement, since its the main component is SiO$_2$ and Al$_2$O$_3$, which is similar to clay. Sun Daosheng [31] studied the thermal technology and reasonable formula for preparing cement clinker by using coal gangue as silica-alumina raw material, mixed with limestone, iron tailings, and quartz sand. Controlling lime saturation coefficient in 0.89～0.95, aluminum ratio in 1.2～1.6, silicon ratio in 2.1～2.6, the prepared raw meal calcined at 1400 ℃, the safety of the cement clinker is qualified. When the clinker is calcined at 1450 ℃ according to the proportion of lime saturation coefficient 0.95, silicon ratio 2.55 and aluminum ratio 1.55, the 3d static compressive strength of the cement produced is 45.3MPa, and the 28d slurry compressive strength is 95.3 MPa.

Su Wenjun [32] found that adding phosphorus slag and fluorite compound mineralizer to coal gangue raw meal can improve the burnability of raw meal. And phosphorus slag contains CaO, which can save limestone resources. The composite mineralizer can accelerate the solid state reaction when the calcination temperature is in the range of 1300 ℃～1400 ℃.

Bai Guoliang [33] studied the physical and chemical properties of coal gangue, such as calorific value and carbon content, and the mechanical properties of coal gangue concrete. The study found that the surface of coal gangue coarse aggregate is rough and there are many internal pores. Therefore, after the gangue concrete is stressed, the gangue coarse aggregate cannot effectively control the crack extension. In the compression test, the gangue concrete cubes were mostly broken by the gangue coarse aggregate, and the interface bond between gangue and cement exhibited significant strength, indicating a robust connection. Carbon content emerged as the primary factor influencing the mechanical characteristics of coal gangue concrete. Regression analysis was conducted to formulate a predictive equation for the mechanical strength of coal gangue concrete based on the carbon content of the gangue.

Liu Chaoqun [34] studied the effect of activated coal gangue mixed with cement on concrete. The study revealed that the fluidity of cement blended with activated coal gangue surpasses that of standard concrete, with an optimal water-to-binder ratio of 0.36. The enhanced mechanical properties of concrete when incorporating activated coal gangue can be attributed to its robust secondary hydration reaction activity, leading to the effective filling of cement pores with secondary hydration reaction products.

Although the main components of coal gasification slag are SiO$_2$ and Al$_2$O$_3$, according to the national standard of “Fly ash used in cement and concrete” (GB/T 1596Mel 2005), the loss on ignition of fly ash that can be used in cement and concrete should not be more than 15%. However, the loss on ignition of gasification slag is about 20%, so it can’t be directly used to prepare cement and concrete. In view of the precedent of fly ash being used as cement raw material ingredients, Dang Liwen [35] mixed a small amount of coal gasification slag into cement raw material and calcined it. The compressive and flexural strength of the obtained gasification slag cement is higher than that of cement without adding gasification slag.

Hang Meiyuan [36] et al. studied the effect of activators on coal gasification slag powder. The loss on ignition of coal gasification slag was controlled below 6% by grinding and screening. The coal gasification slag powder was treated with an activator and then added with cement. Scanning analysis was carried out through SEM and SED. It was found that the compressive strength of the coal gasification slag cement after activation was greatly improved.

Fly ash is mainly composed of SiO$_2$ and Al$_2$O$_3$, and its particle size is fine and its surface is rough, so it is suitable to be used as cement and concrete. Liu Quan [37] and others studied the physical and chemical properties of fly ash in China, and found that with SiO$_2$+Al$_2$O$_3$+Fe$_2$O$_3$ content and loss on ignition as constraint conditions, fly ash in accordance with mixing mortar and concrete accounted for 53.2%, and fly ash in accordance with cement active mixture accounted for 73.1%. This shows that most of the fly ash in China is suitable for making cement and concrete.

In a study by Bai Jiajia [38], the impact of fly ash content on carbonated cement paste was investigated, revealing that the addition of fly ash can accelerate the carbonation process of cement paste, enhance its pore structure, and promote crack healing. Optimal reduction in crack width occurred at a 30% fly ash content.

Chen Hongfei [39] explored the effects of fly ash substitution for Portland cement clinker on cement's physical properties, noting that fly ash inclusion prolongs setting times and significantly alters the mechanical properties of cement mortar. While compressive strength decreased notably, flexural strength exhibited an initial rise before declining, with peak flexural strength achieved at a 10% fly ash content.

Peng Yufa [40] studied the influence of fly ash on concrete performance, it was established that fly ash content significantly influences concrete's mechanical properties, with compressive strength initially increasing and then decreasing with rising fly ash content. The maximum compressive strength was achieved at a 30% fly ash content. Overall, variations in the source, coal quality, and processing methods of coal-based solid waste can impact the ultimate performance of cement and concrete. Notably, the calcination process of coal-based solid waste may lead to the conversion of elements like S and N into pollutants such as SO$_2$ and NO$_x$, posing environmental concerns. Therefore, it is not only necessary to further ensure the stability of the indicators of products in different regions and explore the mechanical properties of
coal-based solid waste cement and concrete, but also to explore the performance differences caused by differences in product raw materials, as well as potential risks such as environmental pollution risks during utilization.

4.2 Used as subgrade material

Coal gangue physically has a certain compressive strength and stability, can withstand the role of vehicles and traffic load, and coal gasification slag can also be used to build road base or subbase. Coal gangue as a by-product, does not need additional mining costs, so coal gangue as a roadbed material can save construction costs. Although coal gangue may be slightly fragile compared with traditional roadbed materials such as crushed stone, it is easy to break up in the process of practical application, resulting in changes in gradation. Therefore, it is very important to use graded coal gangue as roadbed material.

Zhang Zongtang [41] studied the influence of grading on the compaction and characteristics of coal gangue roadbed filling. It has been found that the compaction characteristics of coal gangue roadbed filling have a significant impact on the grading. When the value limit of good gradation is obtained through the model equation as 1.8867 ≤ D ≤ 2.6309, the gradation is uniform. As the fine particles increase, the compacted dry density of the coal gangue roadbed first increases and then decreases. The optimal grading range is 2.04 ≤ D ≤ 2.55.

Zhang Rui [42] studied the road performance of coal gangue. The physical and chemical properties of coal gangue was analyzed through tests on its chemical composition, loss on ignition, liquid plastic limit and plasticity index, water immersion expansion, resistance to disintegration, and crushing value. The road performance of coal gangue was studied by combining screening tests, compaction tests, and California bearing ratio tests.

Hao Liping [43] studied the settlement of coal gangue roadbed in practical engineering applications using practical engineering as an example. After being subjected to static pressure for 1 time, vibration 2 times, the strength requirements can be met. During the construction process, water can be replenished in a timely manner.

4.3 Used as a soil improver

In some areas of China, the content of organic matter in...
soil is less, and the porosity is small, which is not conducive to plant growth. Coal-based solid waste is rich in various trace elements needed for plant growth, and the content of organic matter is between 15% and 20%. Therefore, coal-based solid waste can be used as soil improver, improve soil porosity, increase soil trace elements, and make soil suitable for plant growth.

Zhang Yuhang \(^{[50]}\) investigated the enhancement impact of coal gangue on the physical and chemical characteristics of saline-alkali soil. Coal gangue was incorporated into the saline-alkali soil based on varying dosages and particle sizes, with improvement assessed through alfalfa pot culture for analysis of the soil's physical and chemical properties. When the amount of coal gangue was 20%, the effect of small particle size and mixed particle size on saline-alkali soil quality and plant growth was the best.

Fan Qiuyun \(^{[51]}\) and others studied the effect of adding fly ash to coal gangue matrix on plant growth. After mixing coal gangue and soil at 1:1, different amounts of fly ash were added respectively. It is found that adding fly ash to coal gangue matrix can greatly improve the properties of coal gangue matrix and promote plant growth.

Li Yilin \(^{[52]}\) studied the effect of coal-based solid waste combined with AM fungi on improving degraded soil in mining area. Weathered coal, coal slime and coal gangue were quantitatively mixed with cow dung and AM fungi respectively. It was found that coal-based solid waste combined with AM fungi could promote plant growth, improve soil nutrients and improve soil microbial community structure.

The utilization of coal gasification slag as a soil conditioning agent following appropriate treatment is a viable approach for incorporating coal gasification slag in ecological agriculture. Zhu Dandan \(^{[53]}\) investigated the utilization of coal gasification slag for soil improvement and observed that gas slag exhibits favorable outcomes in enhancing desertified soil. By adding coal gasification slag, the soil water retention rate increased significantly, pH decreased, carbon content increased, and available silicon content increased significantly. And gas slag can be used as humic acid slow-release agent for organic fertilizer.

Wang Shaoli \(^{[54]}\) studied the effect of coal gasification slag conditioner on the growth and quality of ryegrass. It was found that gas slag conditioner could effectively increase the yield of ryegrass and the content of crude protein in ryegrass. When the application rate was 2.25kg/m\(^2\), the yield and quality of ryegrass were the best. Moreover, gasification slag conditioner can improve soil nutrients, nitrogen and potassium content increased.

Ai Guo \(^{[55]}\) studied the effect of coal gasification slag combined with bacterial bran on soil improvement. With the increase of coal gasification slag dosage, the root activity of alfalfa seedlings increased at first and then decreased. When the gasification slag is 30% and bacterial bran is 15%, the effect of combined application is the best.

Fly ash has rough surface, high porosity and large specific surface area, which can effectively improve soil porosity and water retention. Fly ash contains a variety of trace elements, such as Ca, Mg, K, etc., which can effectively improve soil fertility. Fly ash is weakly alkaline which can neutralize acidic soil, making it more suitable for plant growth.

Wu Lin \(^{[56]}\) studied the nutrient index and risk of fly ash as soil improver, and found that fly ash is rich in available phosphorus, available potassium and organic matter, and most of the heavy metals such as Co, Ni, Cr, Zn, Pb and Cu are stable residue state, which exhibits limited migratory and transformative properties, resulting in a low risk of heavy metal pollution.

Zheng Peng \(^{[57]}\) investigated the impact of fly ash and soft rock on enhancing soil water characteristics in mining areas, revealing that the incorporation of fly ash elevated the fine soil particle content. Optimal soil water retention was achieved at a fly ash to soft rock ratio of 3:1.

Ou Yanjun \(^{[58]}\) explored the mechanisms underlying yield enhancement through fly ash-based soil conditioners, determining their ability to immobilize heavy metal contaminants, enhance soil water retention, and boost corn yield by up to 52.3%. Generally speaking, the current studies are mainly focused on the properties of soil, but there are few studies on the plant properties of reclaimed soil. Although the leaching amount of heavy metal elements is lower than the national standard in the short term, the increase of long-term leaching amount will inevitably affect plant growth. Long-term monitoring of reclaimed soil should be carried out, and the physiological properties of growing plants in reclaimed soil should be further studied.

5. Conclusions

To sum up, coal-based solid waste is a huge bulk industrial solid waste in China. If resources cannot be properly utilized and disposed of randomly, it will not only have a huge impact on the environment, but also waste the utilization value of coal-based solid waste. At present, coal-based solid waste is used as cement and concrete, preparation of roadbed materials, soil improvement and remediation, etc., which has the advantages of abundant raw materials and simple treatment, as well as typical successful cases and economic and environmental protection value. Although the products need to be regularly tested to eliminate related risks, it still provides a green application model for the development of coal-based solid waste. Nevertheless, there remains a significant disparity compared to developed nations. Further advancements in new technologies are essential to enhance the overall utilization rate of coal-based solid waste.

In addition to the aforementioned utilization approaches, numerous scholars have conducted extensive research on extracting useful components from coal-based solid waste and exploring high-value utilization strategies. Despite these efforts, a large-scale and mature application technology for coal-based solid waste resources has yet to be established. Therefore, the comprehensive utilization of coal-based solid waste requires further research and development of high-value utilization methods on the basis of optimizing existing methods, reducing resource waste and accelerating green development.
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