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Review

Coal Gangue Utilization: Applications, Challenges, and Sustainable Development Strategies

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Abstract: Coal gangue is a kind of typical by-product emitted during the coal mining and washing process. With the increase in coal resource utilization, a large amount of coal gangue was not reasonably utilized, causing environmental pollution and resource waste. The main purpose of this article is to introduce the surface structural features and compositional characteristics of coal gangue and to summarize the utilization of coal gangue in the fields of building materials, energy production, agricultural utilization, and high-value-added areas such as catalysts and adsorbents. Secondly, this review discussed the environmental challenges and technical difficulties derived from the process of coal gangue utilization and how to solve these problems through innovative methods and technological improvements. Finally, the article proposed the development direction and strategies for the future resource utilization of coal gangue, emphasizing the importance of coal gangue as a sustainable resource and its significant role in achieving a circular economy for reducing environmental pollution. By analyzing the potentiality of coal gangue for resource utilization systematically, this article aims to provide valuable references and insights for researchers and decision-makers in related fields.

Keywords: coal gangue; environmental impact; energy applications; high-value products

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1. Introduction

As one of the main energy sources in China, in 2024, the country produced 4.76 billion tons of raw coal, an increase of 1.06% compared to the previous year [1,2]. Coal gangue, as a major by-product associated with coal, accounts for 40% of the total volume of industrial solid waste. Its comprehensive utilization and supply side structural reform have become focal points of concern for both the coal industry and society [3,4]. Figures 1 and 2 show the coal gangue production and percentage across various provinces and cities in China from 2017 to 2023.

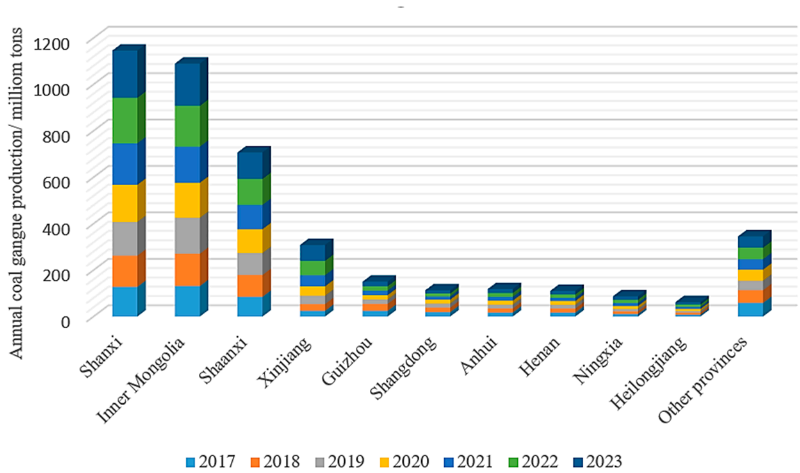

Figure 1. The annual coal gangue production in different provinces of China from 2017 to 2023 [5].

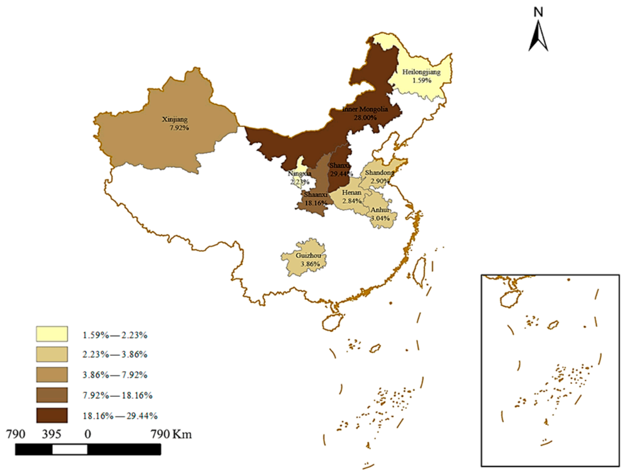

Figure 2. The percentages of coal gangue production in different provinces of China from 2017 to 2023 [5].

Coal gangue is generated during the coal mining and washing process, accounting for 10–15% of the total coal output, making it one of the largest industrial solid wastes in China [6,7]. Additionally, the production of coal gangue mainly comes from several sources: the process of roadway excavation; the roof, floor, and interlayer during the mining process [8,9]. According to the standards of the China Coal Industry Association for gangue classification. It is classified into four categories based on total sulfur content: low, medium, medium-high, and high, as shown in Table 1. This standard specifies the classification categories and naming conventions for coal gangue, applicable to its output and resource utilization. In the traditional coal gangue pre-selection process, the intensity of manual labor is high, efficiency is low, and there are potential safety risks. The improved ResNet18-YOLO algorithm can detect coal gangue at a speed of 45.5 ms per frame, with the model size only about 65.34 MB, and the mAP of coal gangue detection is 96.27%, offering better real-time performance and a smaller model size [10].

Table 1. Classification of coal gangue based on total sulfur content.

Category	Low Sulfur	Medium Sulfur	Medium High Sulfur	Sulfur High Sulfur
W (Std)	W (Std) $\leq$ 1%	1% < W (Std) < 3%	3% < W (Std) < 6%	W (Std) > 6%

Note: Std refers to total sulfur on a dry basis.

Coal gangue, as a commonly encountered industrial solid waste, has a multidimensional and profound environmental impact [11,12]. Firstly, the massive accumulation of coal gangue occupies a significant amount of land resources, especially near mining areas. Extensive stacking can lead to the ineffective use of land resources and may trigger soil erosion and desertification, thereby negatively affecting the local ecosystem [13,14]. Additionally, the toxic elements in coal gangue can penetrate the soil through leaching, altering the soil's chemical composition, and consequently affecting soil fertility and agricultural production [15,16]. The dissolved heavy metals and other harmful substances in coal gangue can also enter groundwater and surface water bodies through leaching, posing potential threats to aquatic life and even human health [17,18]. The organic materials in coal gangue can release harmful gases, such as hydrogen sulfide and nitrogen oxides, under natural conditions or during incineration, further exacerbating air pollution [19]. In terms of social and public health, the harmful substances in coal gangue can enter the human body through the food chain, air, and water sources, increasing the risk of respiratory diseases and skin conditions [20,21]. The spontaneous combustion of coal gangue heaps is a non-negligible issue. According to related research statistics, among approximately 1900 coal gangue heaps in China, more than 600 have experienced or are experiencing spontaneous combustion [22]. This combustion releases harmful gases such as sulfur dioxide (SO_2), carbon monoxide (CO), and nitrogen oxides (NO_X), causing damage to the surrounding environment and vegetation [23,24].

Therefore, the implementation of effective coal gangue management strategies, particularly through resource utilization measures, has become a critical issue in environmental protection and sustainable development strategies. The resource utilization of coal gangue not only effectively reduces its negative environmental impact but also transforms waste into valuable resources, promoting the development of a circular economy. Currently, the main avenues for coal gangue resource utilization include its application in construction materials, soil conditioners, and energy resources. For instance, coal gangue can be used as raw material for cement and bricks after high-temperature sintering. Additionally, with specific treatments, it can serve as a soil conditioner to improve the fertility of degraded lands. Furthermore, the combustion of coal gangue or its co-combustion with biomass can realize its reuse as an energy source. In summary, the resource utilization of coal gangue not only helps mitigate environmental pollution but also creates new development opportunities for related industries, driving the realization of a green and low-carbon economy.

2. Physical and Chemical Features of Coal Gangue

The chemical composition of coal gangue determines its various potential industrial applications. For instance, coal gangue with high silicon and aluminum content can be used as raw materials in the construction materials industry for the production of cement, bricks, and tiles. Additionally, due to the high content of silicon and aluminum in coal gangue, it can also be utilized in the preparation of silicate and aluminate chemical products. Furthermore, some components of coal gangue can be used in the production of adsorption materials, ceramics, and more [25,26].

2.1. Main Chemical Components

Coal gangue contains a large amount of inorganic substances, such as silicates, aluminates, calcium salts, and iron-manganese salts [27]. Specifically, the primary chemical components in coal gangue are silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3) [19], with the mass fractions of SiO_2 and Al_2O_3 in most regions ranging from 37% to 72% and 4.5% to 42%, respectively [28]. In addition, coal gangue may also contain other minerals such as iron oxide (Fe_2O_3), calcium oxide (CaO), magnesium oxide (MgO), and sulfates [29].

The main mineral composition and elemental analysis of coal gangue are shown in Figure 3 and Table 2, respectively. About Figure 3 Gangue samples from the open pit coal mine in Hequ County, Xinzhou City, Shanxi Province, China. The coal gangue samples in Table 2 were obtained from Dazhe Coal Mine, Yulin City, Shaanxi Province, China.

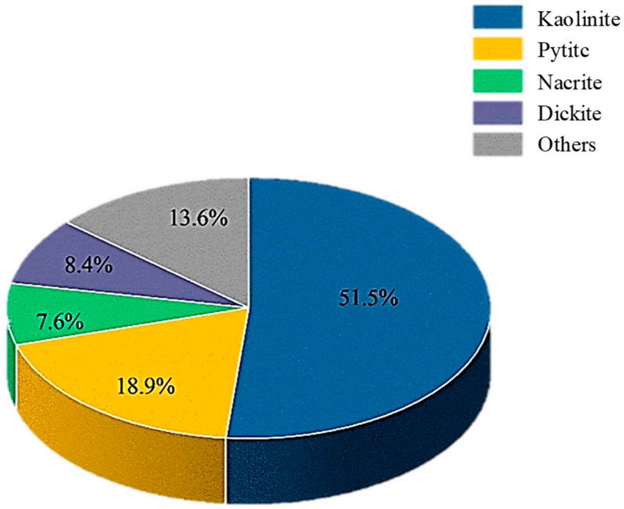

Figure 3. Distribution of main mineral components in coal gangue [30].

Table 2. Elemental analysis of coal gangue [31].

Serial Number	Element	Content (wt%)
1	O	47.549
2	Si	24.686
3	Al	10.601
4	Ca	6.06
5	Fe	3.176
6	S	2.689
7	K	2.134
8	Ti	1.297
9	Na	0.811
10	Mg	0.770
11	Mn	0.075
12	Dy	0.053
13	P	0.037
14	Cr	0.018
15	Sr	0.016
16	Zr	0.08
17	Cu	0.07
18	Rb	0.07
19	Zn	0.06

In recent years, research on the resource utilization of coal gangue has deepened, and the technology has gradually matured. For example, technologies for preparing lightweight aggregates, adsorbents, and ceramic materials from coal gangue have gradually become commercialized [32,33]. In summary, the resource utilization of coal gangue is a complex system engineering project involving environmental science, material science, chemical engineering, and other fields [34]. With the continuous deepening of related research and technological progress, the future pathways for coal gangue resource utilization will become more diversified, and its role in environmental protection and resource conservation will become even more significant.

2.2. Physical Properties

The physical properties of coal gangue include particle size, shape, density, hardness, and porosity, as well as thermal and electrical conductivity [35,36]. Particle size and shape: The particle size of coal gangue varies widely, from dust-like microparticles to large rocks, and the particles are usually irregular in shape, which affects their bulk density and flowability [37,38]. Understanding the particle size and shape helps optimize the processing technology and equipment design when using coal gangue as a raw material. Density and hardness: the density of coal gangue is relatively low, typically between 1.2 and 2.4 g/cm^3, while its hardness varies with its composition. These characteristics affect the load-bearing capacity of coal gangue when it is used as a building material or for roadbeds [39,40]. Porosity: coal gangue has a high porosity, allowing it to absorb and retain moisture [41]. A high porosity also means a higher surface area, which is an important factor when using coal gangue as an adsorbent material or catalyst carrier. The porosity of naturally piled broken gangue is about 47.5%, with micro-pores (less than 0.075 mm) dominating [42]. Thermal and electrical conductivity: the thermal conductivity and electrical conductivity of coal gangue are generally low, making them suitable for use as insulating materials or insulation materials. Understanding these properties facilitates the application of coal gangue in the construction and electric power industries.

As shown in Table 3, the physical properties of coal gangue not only affect their processing and management methods but also determine their potential applications and impact in resource utilization. For instance, small particles of coal gangue can be used as fillers or made into bricks, while large chunks of coal gangue can be utilized in building materials. The low density and high porosity of coal gangue make it an ideal choice for the preparation of lightweight aggregates, adsorbent materials, or filtration materials.

Table 3. Physical properties of coal gangue.

Physical Property	Impact of Resource Utilization
Particle size morphology	Different uses for small and large particles
Density and hardness	Load-bearing capacity when used as a building material
Porosity	Important factors for use as adsorbent materials or catalysts
Thermal and electrical conductivity	Important factors for insulation or insulating materials

3. Coal Gangue Applications

As environmental regulations become increasingly stringent, society has set higher standards for the efficient use of coal gangue. Coal gangue has shown a wide range of uses in emerging fields such as construction, energy, and agriculture, as illustrated in Figure 4. Its recycling and utilization not only solve the disposal problem but also help reduce material costs, promoting the sustainable development of resources. Table 4 shows the source, role, and application of gangue.

Table 4. The source, application, and role of coal gangue.

Source	Application	Functions	References
Coal mining and washing processes	Construction materials (e.g., cement, bricks), soil conditioners, energy recovery	Produces building materials through high-temperature sintering, improves soil quality, provides energy	[43,44]
Coal gangue stockpiles	Soil remediation, environmental pollution control (e.g., heavy metal pollution remediation)	Acts as a soil conditioner, reduces soil pollution, restores ecosystems	[45,46]
Coal gangue stockpiles	Heavy metal pollution control, ecological restoration, solid waste treatment	Adsorbs heavy metals, promotes plant growth, reduces secondary pollution	[47]
Coal mining by-products	Energy recovery (combustion, gasification)	Provides energy, reduces reliance on other energy resources	[48]

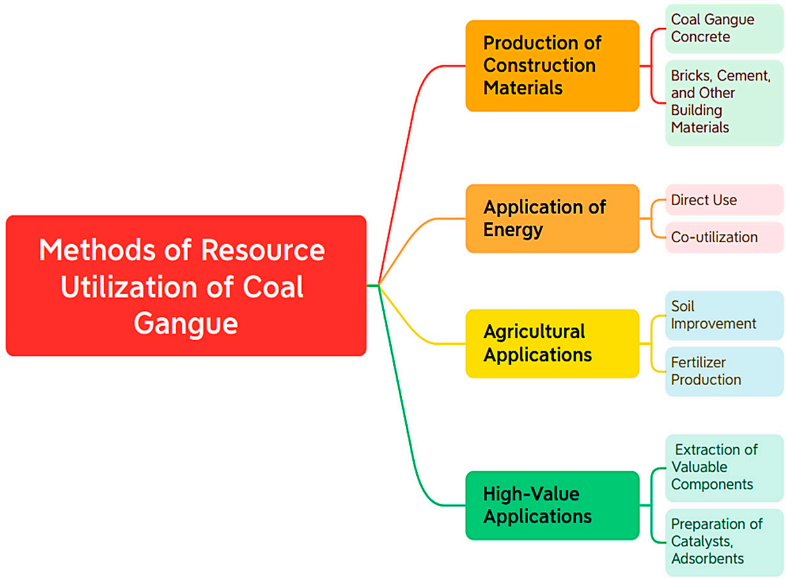

Figure 4. Methods of resource utilization of coal gangue.

3.1. Production of Construction Materials

Using coal gangue as a construction material, especially as coarse aggregate for concrete, aligns with environmental protection concepts and conserves natural resources like sand and gravel [44]. In recent years, significant achievements have been made in the resource utilization of coal gangue in the field of construction materials, mainly in the following aspects: lightweight aggregate: After processes such as crushing and screening, coal gangue can be utilized as lightweight aggregate [11,49]. This type of aggregate can reduce the unit weight of concrete, applicable in the production of lightweight concrete, thereby decreasing the structural weight and enhancing the seismic performance of buildings. Cement material: coal gangue contains silicates and aluminates, essential ingredients for cement production [50,51]. With appropriate processing, coal gangue can partially replace traditional cement production materials, reducing production costs while also decreasing resource consumption [43,52]. Wall material: coal gangue can serve as a raw material for producing sintered bricks, hollow blocks, and other wall materials [53,54]. Sintered bricks made from coal gangue exhibit good thermal insulation properties and adequate mechanical strength, suitable for constructing various building walls. Road Base material: due to its satisfactory compaction properties, coal gangue can also be used as a material for road bases [55,56]. Ceramic material: the silicates and aluminates in coal gangue can form vitreous bodies at high temperatures, thus suitable for manufacturing various ceramic materials [43,57]. These ceramic products can be utilized in areas such as architectural decoration and sanitary ware.

3.1.1. Coal Gangue Concrete

Compared to ordinary concrete, the fluidity of coal gangue concrete decreases by 20% to 53% under different water-cement ratios [58]. The incorporation of coal gangue reduces the early strength of concrete and increases its porosity and water absorption but also enhances its resistance to chloride ion or gas permeability [52,59]. An increase in porosity typically leads to a decrease in the density of concrete, which in turn affects its compressive strength, permeability, and durability. Higher porosity may cause concrete to perform poorly in structures that require long-term load-bearing capacity, especially in fields such as hydraulic engineering and road construction. An increase in water absorption means that concrete is more likely to absorb moisture, leading to internal expansion and reduced strength, which further impacts its durability, especially under humid conditions or extreme climates. Compressive strength is a key indicator of concrete's load-bearing capacity; higher strength enhances its structural stability and durability, which is crucial for seismic and heavy-load applications. Therefore, in the design of coal gangue concrete, it is necessary to control porosity and water absorption effectively to ensure high compressive strength and durability, meeting the requirements of various engineering applications. The strength of coal gangue concrete, constrained by external layers of Carbon Fiber-Reinforced Polymer (CFRP) or Alkali-resistant Fiber-Reinforced Polymer (BFRP), increases by 16.9% to 145.8%, and its axial ultimate strain is 4.787 to 8.812 times that of ordinary coal gangue concrete [60]. Figure 5 shows the lateral strain-axial strain curve of BFRP/CFRP-constrained coal gangue concrete specimens. For CFRP-constrained coal gangue concrete specimens, the lateral strain-axial strain relationship and the slope of the second stage of volumetric expansion have smaller absolute values. Compared to BFRP-constrained specimens, CFRP-constrained specimens have a lower final expansion rate due to their relatively higher constraining stiffness. The mechanical properties of coal gangue concrete differ from those of ordinary concrete due to the substitution of fine and coarse aggregates with coal gangue [61,62]. Using artificial coal gangue sand in concrete fine aggregates can mitigate the environmental negative effects of coal gangue stockpiling and promote the conservation of natural resources [63]. The utilization of coal gangue sand provides an ecological solution to the shortage of natural sand and landfill of mineral tailings. The use of coal gangue sand yields positive social and environmental benefits when the transportation distance exceeds a certain threshold [63]. With the increase in stress level, the frost resistance of coal gangue concrete deteriorates, and the degradation rates of four macro-performance indicators, namely compressive strength, relative dynamic modulus of elasticity, mass loss, and damage layer thickness, significantly accelerate [64].

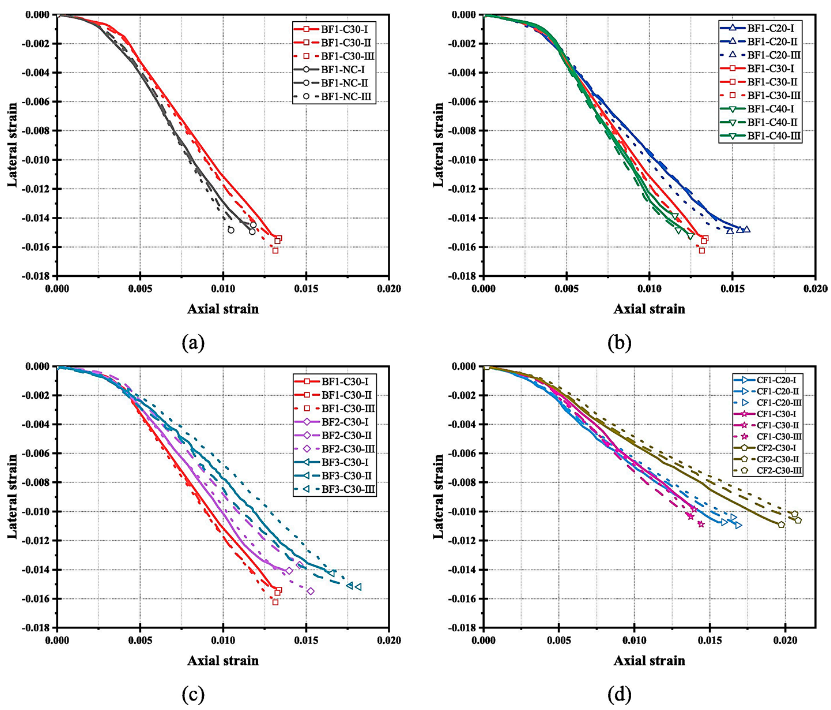

Figure 5. Lateral strain-axial strain curves of BFRP/CFRP-confined coal gangue concrete specimens. (**a**) Comparison between normal concrete and coal gangue concrete; (**b**) Comparison of coal gangue concrete under different pressures; (**c**) Comparison of coal gangue concrete with different number of BF laminations applied; (**d**) Comparison of coal gangue concrete with different number of CF liner applied [60].

Adding nanosilica and coarse coal gangue aggregate to concrete significantly affects a range of concrete properties. Studies have shown that the optimal mix ratio is 25% coarse coal gangue aggregate and 2% nanosilica [65]. This ratio not only improves the mechanical properties of concrete but also realizes the effective utilization of coarse coal gangue aggregate. Municipal solid waste incineration fly ash (MSWI FA) was used as a supplement to compensate for the lack of calcium elements in coal gangue (CG) to synthesize geopolymer materials [27,42]. To further study the impact of replacing coarse aggregate with coal gangue aggregate on its performance, a model was developed to predict the shrinkage behavior of concrete combined with coal gangue coarse and fine aggregates (CGCA and CGFA). Both CGCA and CGFA significantly increased the concrete shrinkage strain, which increased by 145% when both were used at 100%; compared to CGFA, CGCA had a more significant impact on shrinkage; the addition of CGCA led to faster development of concrete shrinkage, while CGFA had no significant effect on the development of shrinkage [66]. By replacing coarse aggregate with coal gangue aggregate (CGA) and using a machine learning model, it was found that the back-propagation neural network (BPNN) exhibited high correlation coefficients in predicting compressive strength and density [67].

3.1.2. Bricks, Cement, and Other Building Materials

Coal gangue, rich in SiO_2, Al_2O_3, Fe_2O_3, and CaO, serves as an appropriate raw material for brick production. The main mineral phases in coal gangue from different mining areas include quartz, kaolinite, and muscovite. The reactivity of the product obtained varies with different temperatures and calcination times [68]. Figure 6 shows the microstructure of sintered bricks at different temperatures. Figure 6a reveals that the cross-section of an unsintered brick is mostly composed of discrete particles of varying sizes and random arrangement. Figure 6b demonstrates the initial formation of small silicate layers and crystalline mineral particles in the brick's cross-section when the sintering temperature reaches 1000 °C, as shown in Figure 6c. The molten glass phase envelops and binds the tiny crystalline mineral particles, filling the gaps and pores between materials, bringing them closer together, leading to an increase in BD (bulk density) and CS (compressive strength), as shown in Figure 6d for the sintered brick at the optimal sintering temperature of 1100 °C, where the brick's melting and solidification degree is very high, resulting in a flat cross-section and a dense structure. The results indicate that the sintered bricks have fine and evenly distributed pores, and the liquid phase bonding action increases the BD and CS of the sintered bricks while decreasing the porosity and WA (water absorption rate) [69]. By adding an appropriate amount of activated coal gangue powder, the performance of coal gangue-based green cement fillers can be significantly enhanced. From an economic perspective, it is recommended that the substitution rate of activated coal gangue powder should be between 50 and 75% [70,71]. Activated calcined coal gangue can produce metakaolin with higher pozzolanic activity, which, when added as a supplementary cementitious material to cement, can not only replace part of the cement but also improve the later performance of cement materials [72,73]. Calcining coal gangue at 600–800 °C can transform the kaolinite phase into metakaolin [74]. Replacing 30% of standard cement with coal gangue reduces the early strength significantly at 3 days but increases the later strength substantially at 28 days, achieving an activity level of over 85%, meeting the basic requirements for the calcination activity of coal gangue [75]. Additionally, coal gangue can be categorized into reactive and non-reactive types, with reactive coal gangue being broadly applicable in various cement productions, while non-reactive coal gangue is limited to specific types of cement production [50]. Appropriate activation methods can significantly enhance the pozzolanic reactivity and hydration characteristics of coal gangue, thereby improving the mechanical and durability properties of cement-based materials [76,77].

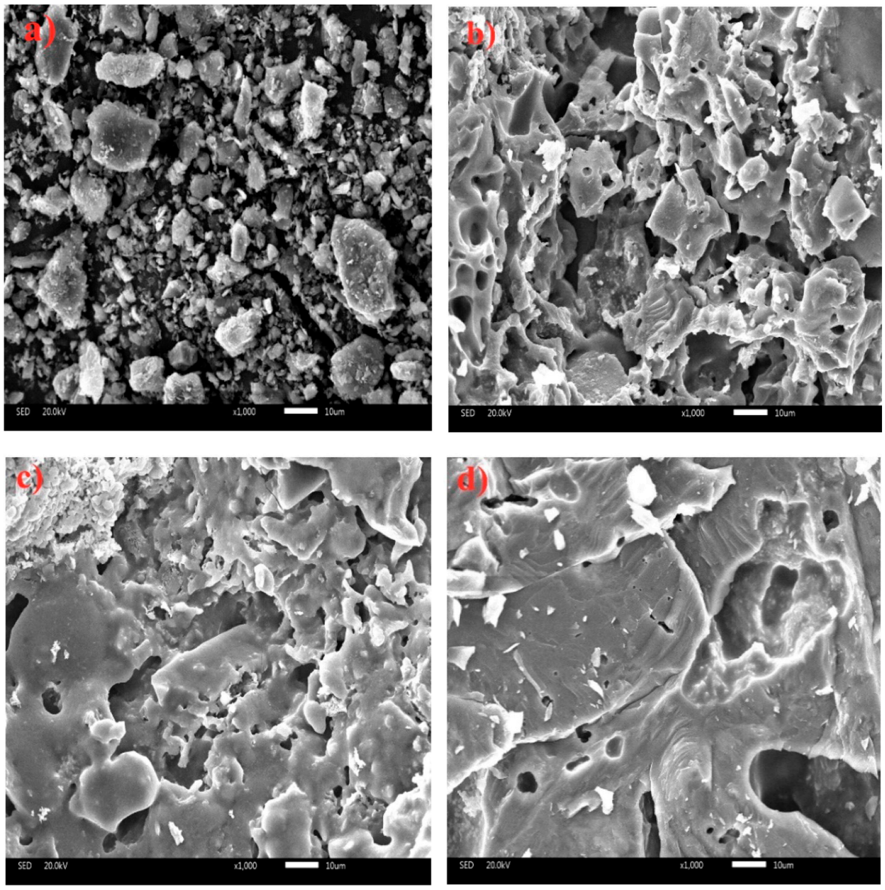

Figure 6. Microstructures of the sections of sintered bricks at different temperatures. (**a**)—raw materials; (**b**)—1000 °C; (**c**)—1050 °C; (**d**)—1100 °C [69].

Thermal activation of coal gangue is key in cement applications, with Figure 7 illustrating the dual benefits achieved by introducing steel slag [78]. The mechanism for achieving can be attributed to the introduction of steel slag, which provides a rich supply of calcium. On one hand, it promotes the fixation of sulfur by forming $CaSO_4$. On the other hand, it aids in the effectiveness of CaO in cement-based materials, accelerating the formation of C-S-H gel. When coal gangue and fly ash replace part of the cement and coarse aggregate, an increase in their proportion significantly improves the permeability coefficient but reduces the mechanical properties [79,80]. Up to 20% of coal gangue can replace portland cement without sacrificing strength [81]. Adding 4–6% of low-sulfur coal gangue with a calorific value of less than 6000 J/g to cement raw meal for producing cement clinker can reduce the unit energy consumption of cement clinker [82]. On the other hand, studies have adjusted the ratio of coal gangue to sludge, adding clay and foaming agents as auxiliary materials, to produce ceramsite with physical properties, including bulk density and cylindrical compressive strength, meet the Chinese standard "Lightweight Aggregates and their Test Methods" [83]. Research on modifying coal gangue powder through chemical intercalation and high-temperature activation treatment improved its microstructural characteristics, applying it to the matrix asphalt, and preparing modified asphalt by the melt blending method. The results showed that the treated coal gangue powder has a larger specific surface area and physical adsorption capacity, which can improve the high-temperature deformation resistance and anti-aging properties of asphalt by enhancing the interaction between coal gangue powder and the asphalt matrix [84].

A proper ratio of coal gangue lime and coal gangue powder can enhance the microwave healing capability of asphalt mixtures [85].

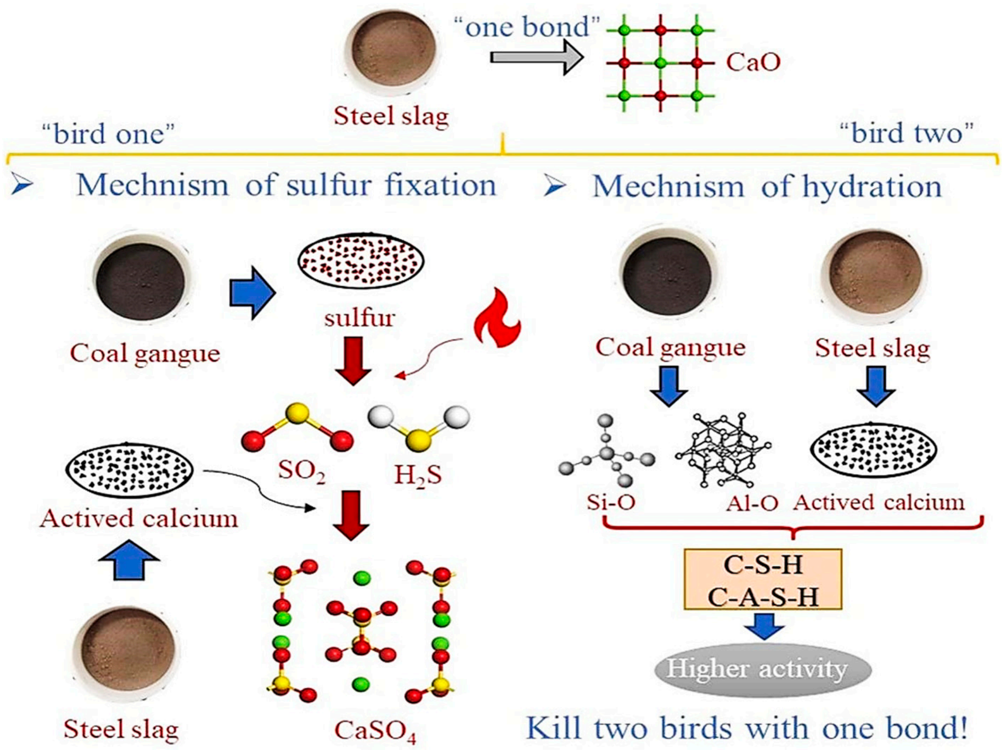

Figure 7. The mechanism of "kill two birds with one stone" [78].

3.1.3. Environmental Impact of Coal Gangue in the Production of Building Materials

When considering the resource utilization of coal gangue, its potential environmental impacts must also be considered. Coal gangue may contain harmful elements such as arsenic, lead, cadmium, and other heavy metals, as well as sulfides. If used directly without proper treatment, it could pose threats to the environment and human health [86]. As shown in Figure 8, this is a schematic diagram of gangue discharge into the environment and its eventual entry into the human body. Therefore, in the process of resource utilization of coal gangue, appropriate treatment measures, such as stabilization and physical and chemical separation, must be taken to ensure its safe use. The economic benefits of different coal gangue utilization methods are ranked as follows: extraction of chemical products > power generation > cement calcination > brick making > mineral admixture and road base material. The environmental effects of various utilization methods, from best to worst, are ranked as follows: brick making and cement calcination > road base and mineral admixture > power generation > extraction of chemical products [87]. Different resource utilization methods have varying impacts on the environment; considering benefits should also account for environmental impacts to avoid secondary pollution. Environmental pollution management strategies need to be developed for each stage of coal gangue utilization, including production, transportation, and comprehensive use, to minimize its impact on the environment [88].

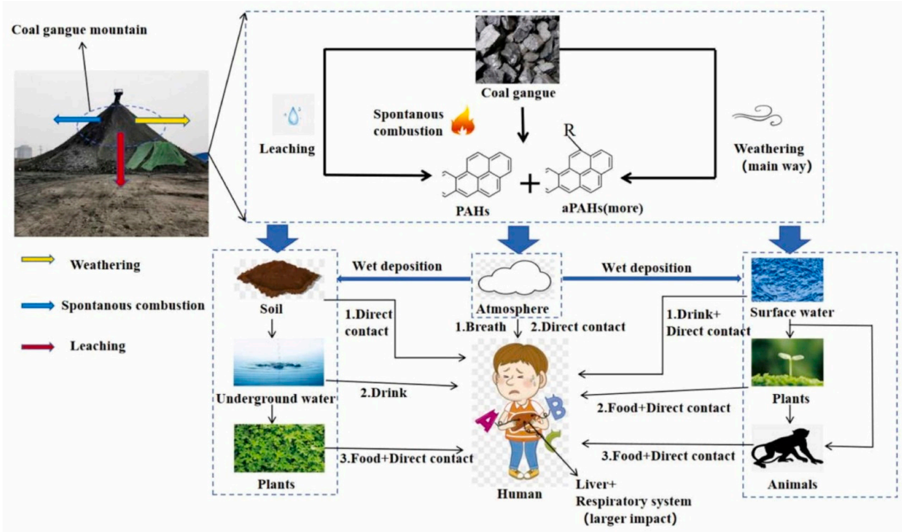

Figure 8. Schematic diagram of the discharge of PACs from coal gangue into the environment and finally entering the human body [89].

When coal gangue is used as a raw material for building materials or other applications, the long-term stability of the products depends on the composition of the coal gangue itself and its interactions with other materials. Coal gangue contains certain amounts of heavy metals and harmful substances, which may leach, weather, or otherwise enter the environment over time, affecting the durability and environmental performance of the products. The measures to ensure long-term stability and safety are as follows: (1) Composition Control and Pretreatment: Pretreating coal gangue to reduce the content of harmful substances. For example, using physical or chemical methods to remove heavy metals, sulfides, and other harmful components, thereby reducing their potential environmental impact. (2) Leaching Tests: Conducting leaching tests (such as the American Standard Leaching Test, European Leaching Test, etc.) to assess the release of heavy metals from coal gangue under specific environmental conditions, ensuring compliance with environmental protection standards. (3) Blending and Stabilization Technologies: Mixing coal gangue with other stabilizing materials (such as cement, lime, etc.) and using solidification or encapsulation techniques to reduce the migration of harmful substances. For example, using cement solidification methods, where coal gangue reacts with cement to form more stable compounds, thereby reducing its leaching potential. (4) Use of Additives: Adding appropriate additives, such as chemical stabilizers, to enhance the chemical stability of coal gangue and reduce its reactivity with the environment. (5) Long-term Monitoring and Assessment: Establishing a long-term environmental monitoring system to regularly test leachates during the product's use, ensuring that they do not cause long-term harm to the environment.

The heavy metal elements abundant in coal gangue, such as lead (Pb), cadmium (Cd), chromium (Cr), and mercury (Hg), may be released into the environment during the production process, causing pollution to soil and water sources. In the preparation of building materials using coal gangue, the high content of some heavy metals is an important consideration for its application and environmental risk management. The production of building materials often requires high-temperature calcination. During the calcination of coal gangue, pollutants such as nitrogen oxides (NOx), sulfur dioxide (SO_2), and heavy metals are released [90]. When firing bricks, dust is generated during raw material crushing; during the baking process, the temperature in the tunnel kiln reaches about 980 °C to 1100 °C. The combustion of coal and spontaneous combustion of coal gangue in tunnel kilns produce gases such as HF, smoke, and SO_2 [91,92]. During the sintering process, trace elements are released and redistributed in bricks, fly ash, and flue gases. Cadmium, copper, mercury, lead, selenium, and tin have high volatility, mainly emitted in the form of flue gases, potentially impacting the atmosphere and soil of the surrounding areas [93]. To reduce environmental impacts, efficient desulfurization and dust removal equipment and optimized production processes can be used.

Due to its relatively stable chemical structure, the reactivity of coal gangue in cement materials needs to be activated to improve its pozzolanic reactivity. This activation could affect the environmental burden and impact of cement-based materials [94]. Microwave-activated coal gangue powder, used as an auxiliary cement material, changes the mineral composition, potentially impacting the environmental and economic aspects of cement production [75]. Adding coal gangue reduces most environmental impacts of cement clinker, such as potential for human toxicity and potential for depletion of abiotic resources. However, the potential for global warming and acidification slightly increases [95]. Although the use of coal gangue in the production of building materials can bring certain environmental benefits, such as waste reduction and carbon footprint reduction, it also raises concerns about increased global warming potential, acidification, and heavy metal pollution. Balancing these factors to ensure environmental sustainability is crucial.

3.2. In the Energy Sector

In recent years, with the increasing awareness of sustainable energy and environmental protection, the application of coal gangue in the energy sector has received greater attention and development. With the changes in national energy and environmental policies as well as adjustments in the coal industry structure, the comprehensive utilization of coal resources for power generation faces a new development situation [96]. Especially, technological advancements have significantly improved the utilization efficiency of resources such as coal gangue and coal slime, which not only helps in conserving resources but also reduces environmental pollution.

3.2.1. Direct Use

Coal gangue is commonly regarded as a low-calorific-value material. However, for those with a higher carbon content, such as between 20% and 30%, its calorific value significantly increases, making it a potential resource for energy recovery and power generation [97]. The high carbon content of this type of coal gangue provides sufficient thermal energy, making it feasible for use in energy conversion processes such as combined heat and power generation. Compared to conventional coal-fired boilers, circulating fluidized bed technology offers significant environmental advantages, including reduced pollutant emissions and improved waste utilization efficiency [98,99]. Moreover, the application of coal gangue in power generation also helps reduce dependence on traditional fossil fuels, thereby alleviating the issue of fossil fuel scarcity to some extent and providing a viable solution for the environmentally friendly disposal of coal gangue. Although direct combustion of coal gangue for power generation is theoretically feasible, it presents a series of technical complexities in maintaining stability during the power generation process, especially for those with high ash content and low calorific value. These challenges highlight the necessity for in-depth research into coal gangue as a fuel for power generation, particularly in optimizing combustion technology, improving energy efficiency, and reducing environmental pollution [100]. Therefore, research in this field is far from mature and requires continuous exploration and innovation.

For coal gangue with ultra-low calorific value, the Aspen Plus 11.0 software can be used for the design and optimization of coal gangue pyrolysis and carbonization processes, with the optimal pyrolysis temperature being about 600 °C [101]. For spontaneously combusting waste coal gangue, energy recovery can be achieved by constructing a novel artificial heat reservoir system. The concept diagram of the coal gangue artificial heat reservoir system is shown in Figure 9 [102].

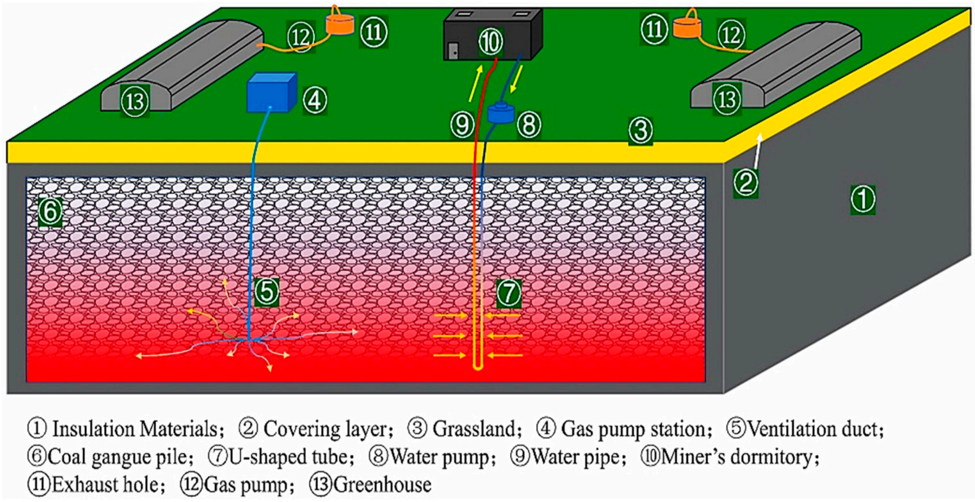

Figure 9. Concept diagram of CGAHR system [102].

Direct calcination of coal gangue is a method of resource utilization. Mainly through high-temperature treatment, coal gangue is transformed into useful products. During the calcination process, usually above 800 degrees Celsius, its organic matter is decomposed and transformed into gas and ash [103]. As the combustion temperature increases, coal gangue minerals decompose at certain temperatures; at 1200 °C, the mineral phases of combustion ash are mullite, quartz, magnetite, hematite, lime, and anhydrite [104]. Figure 10 shows the morphological characteristics during the combustion process of coal gangue; uncalcined fine particles of coal gangue with a diameter of 1.0 micrometer (Figure 10A) form needle-like shapes and cluster together. The coal gangue is in a molten phase, and its surface gradually becomes viscous as the combustion temperature increases (Figure 10B–F). The volatility of trace elements in coal gangue increases with the combustion temperature and can be divided into two categories: the highly volatile first category (Ni, Cu, Zn, Cd, Sn, Pb, and As), and the low volatility second category (Co, Cr, V) [104]. Figure 11 shows the volatility of trace elements at different temperatures. The decomposition of organic matter and pyrite can lead to an increase in the volatility of trace elements at 500 °C. As the combustion temperature increases, carbonate minerals, sulfides, and other minerals decompose, increasing the volatiles [104]. However, combustion of coal gangue can lead to significant emissions of sulfur, arsenic, mercury, and fluorine, which may exceed the emissions from traditional coal combustion [105].

Reducing the emission of pollutants during the combustion process of coal gangue is currently one of the important issues. Moreover, the direct combustion utilization of coal gangue requires specific combustion techniques and equipment. Overall, the direct use of coal gangue is a potential method of energy recovery, which can reduce the environmental impact of waste while providing some energy value. However, to achieve its widespread application, technical, economic, and environmental challenges need to be addressed.

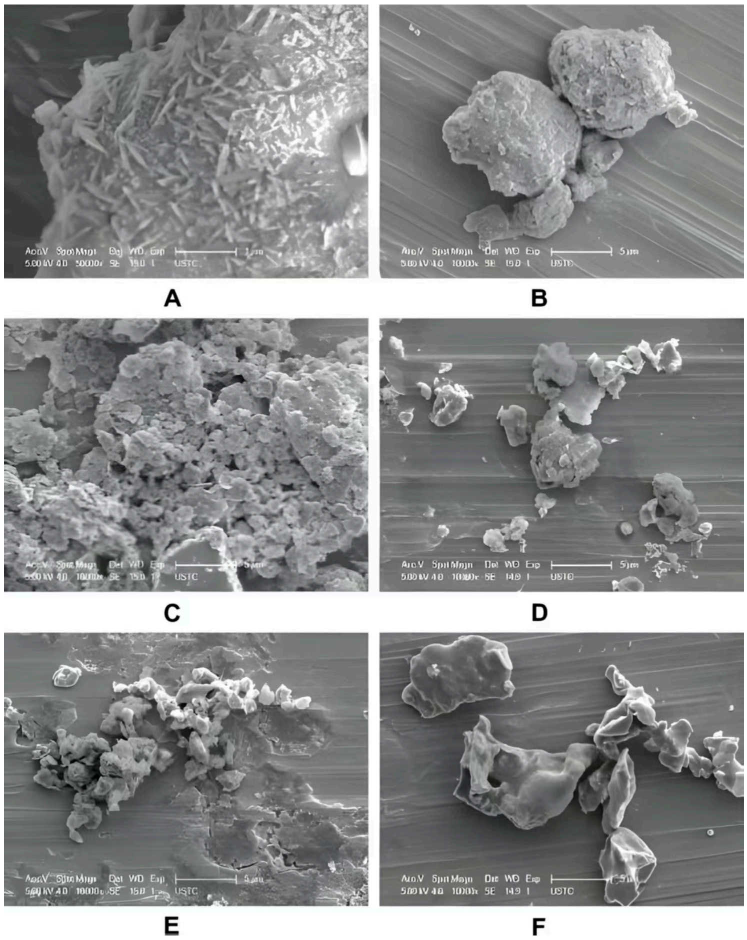

Figure 10. The morphological characterization of coal gangue during combustion. (**A**) uncalcined coal gangue, (**B**) uncalcined coal gangue, (**C**) 500 °C, (**D**) 700 °C, (**E**) 900 °C, and (**F**) 1200 °C [104].

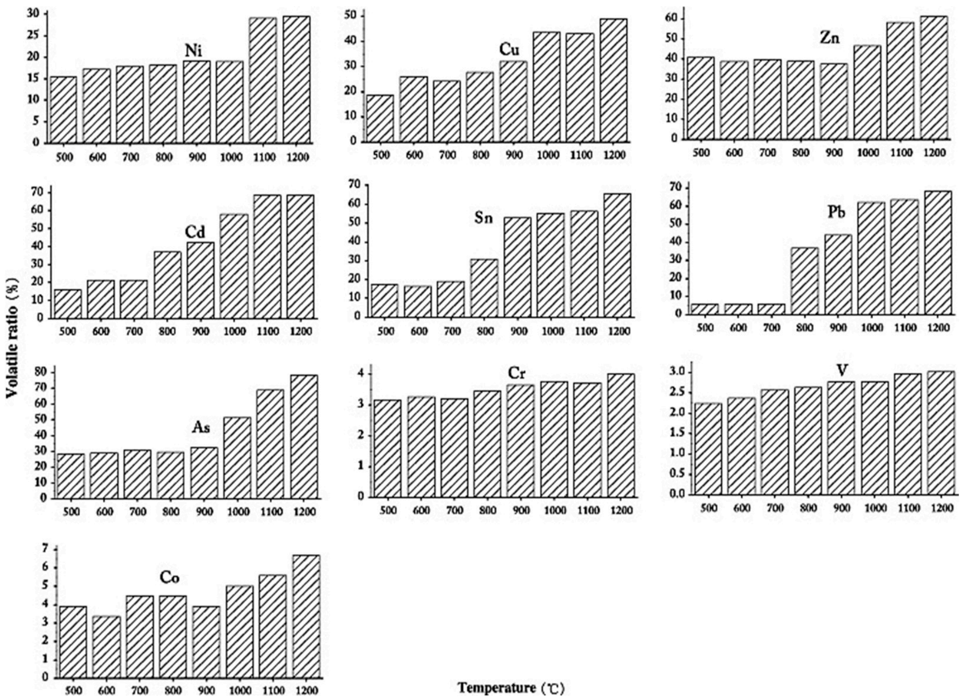

Figure 11. The volatilize of trace elements at various temperatures [104].

3.2.2. Co-Utilization

Adding an appropriate amount of biomass can not only improve the combustion performance of coal gangue but also reduce the emissions of trace elements, thereby contributing to environmental protection. A biomass addition ratio of 20–30% is considered the optimal proportion [48]. In exploring the retention mechanism of trace elements (TEs) during the co-combustion of coal gangue (CG) and soybean straw (SS), it was found that the retention of gaseous TEs increased during co-combustion, which might be due to reactions with active mineral surfaces, chemical adsorption, and interactions with ash components and elements [106]. When sludge (SS) and coal gangue (CG) are co-combusted, it has been found that co-combustion helps improve ignition performance and has a synergistic effect on desulfurization and denitrification. Enhanced retention of trace elements (especially Pb and Zn) was observed during co-combustion [107]. By adding coal gangue as an additive to other biomass fuels (willow branches, wheat straw), not only can the combustion effect of coal gangue be improved, but also the emission of NO can be reduced, with the best proportion being 80% biomass + 20% coal gangue [108]. The real-time NO release curve, as shown in Figure 12, indicates that when 20% coal gangue is added to the composite fuel, the NO emission temperature of the composite fuel increases, and NO emissions decrease. This is because the alkali metals in coal gangue react with the biomass, with the reaction mechanism shown in Figure 13, and possible reactions are as follows [108].

$$Al_2Si_2O_5(OH)_4 \rightarrow Al_2O_3{\cdot}2SiO_2{+}2H_2O\ \# \quad (1)$$

$$Al_2O_3{\cdot}2SiO_2{+}2MCl + H_2O \rightarrow 2MAlSiO_4{+}2HCl \quad (2)$$

$$2MAlSiO_4{+}H_2O \quad (3)$$

$$Al_2O_3{\cdot}2SiO_2{+}2MOH + 2SiO_2 \rightarrow 2MAlSi_2O_6{+}H_2O \quad (4)$$

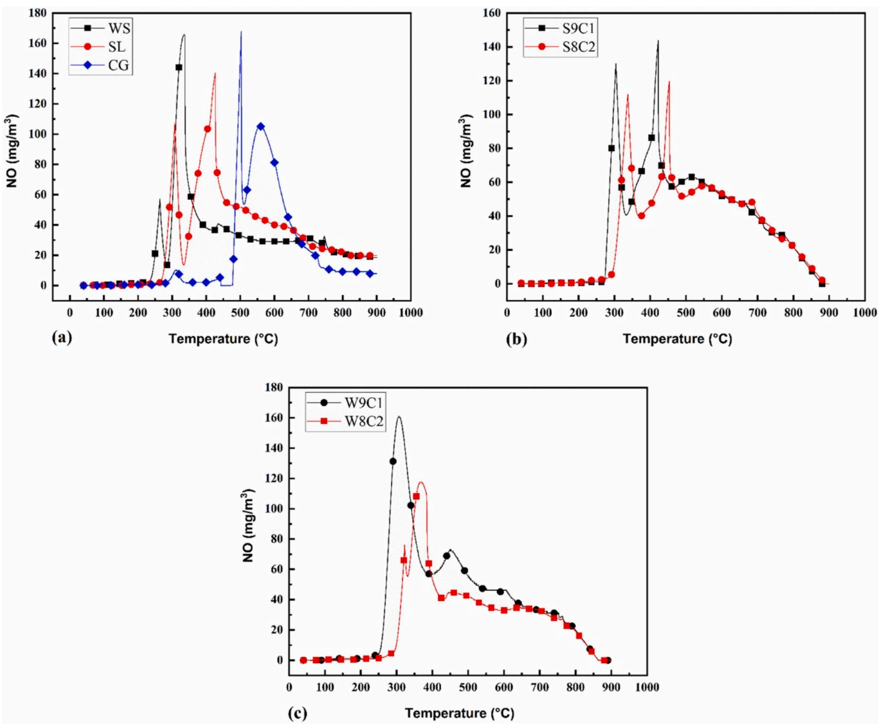

Figure 12. NO real-time emission curve: (**a**) The mono-combustion of WS (Wheat straw), SL (Salix limb) and CG. (**b**) The composite fuel of SL and CG. (**c**) The composite fuel of WS and CG [108].

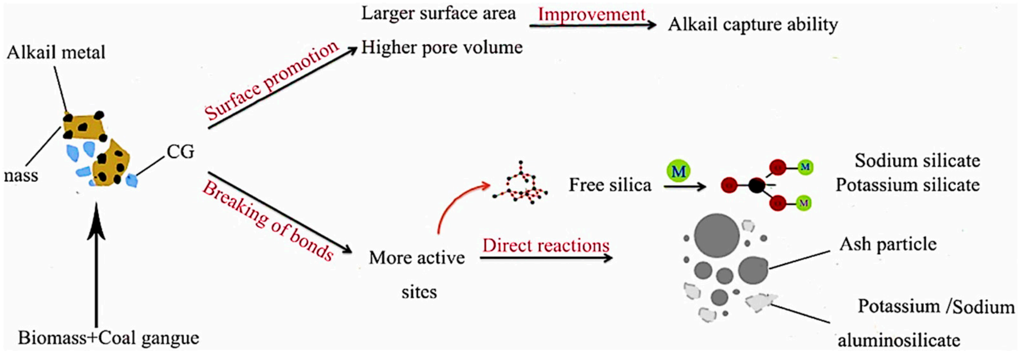

Figure 13. The mechanisms of biomass slagging abatements by coal gangue [108].

During the co-combustion process of straw and coal gangue, when the mixing ratio of coal gangue is 30%, it is expected to reduce sulfur dioxide emissions by 18.19% [109]. In the co-combustion process of low-calorific-value coal mixtures in a fluidized bed, a mixture ratio of raw coal, coal gangue, and coal slime at 20:60:20 may be a suitable choice for co-combustion in a fluidized bed reactor [110].

In the co-firing of coal gangue and peanut shells, an optimal predictive model for the co-combustion of coal gangue and peanut shells was established using the artificial neural network (ANN) method, and ANN20 was determined to be the best model through comparison [111,112]. Figure 14 shows the ANN20 model used to predict the combustion behavior of coal gangue and peanut shells. The ANN20 model is divided into an input layer, hidden layers, and an output layer. The input parameters for the input layer are combustion experimental conditions: heating rate, temperature, and mixing ratio. There are two hidden layers. The number of neurons in the first hidden layer is 5, and in the second hidden layer is 17. The parameters for the output layer are the residual mass percentage from the thermogravimetric experiments. The activation function for the hidden layers is nonlinear, while the activation function for the output layer is linear [111]. Interactions also exist between coal gangue and sawdust, and the addition of sawdust can enhance the oxidative combustion reactivity of coal gangue [113,114]. A study on the synergistic effects of the co-gasification of coal gangue and sawdust was conducted on a homemade two-stage gasification fixed bed experimental setup. The best synergistic effect, with a synergy coefficient of 0.22, was observed under conditions of a gasification temperature of 850 °C, catalytic reforming temperature of 900 °C, steam flow rate of 2 mL/min, and a mixing ratio of coal gangue to sawdust of 1:1. The synergistic effect of coal gangue and sawdust is due to the cracking of -OH functional groups, enhanced by the catalytic action of alkali and alkaline earth metals in the co-gasified char [115]. The effect of different mixing ratios of coal gangue and sawdust on the composition of co-gasification gas is shown in Figure 15. As seen in Figure 15a, with the increase in the sawdust mixing ratio, the volume fraction of H_2 initially increases, then decreases, and finally increases [115]. A significant interaction between coal gangue and weathered coal was observed under oxygen-enriched combustion conditions, likely related to thermal effects [116]. Further research found that a mixture of 70% coal and 30% coal gangue exhibited the strongest synergistic effect, while a mixture of 30% coal and 70% coal gangue showed the strongest inhibitory effect [117]. For coal gangue and polypropylene (PP), when the polypropylene content was 20%, the maximum weight loss rate at the first peak temperature of the mixed fuel increased, and the average thermal coupling degree at 50% and 80% was 1.64 and 2.30 times, respectively [118].

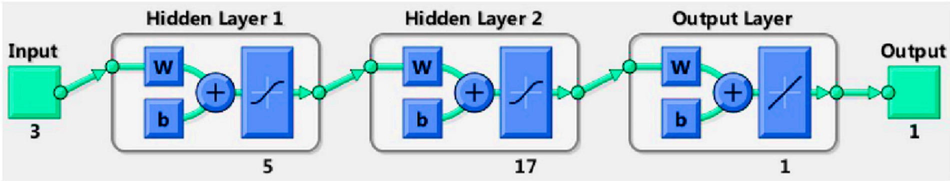

Figure 14. ANN20 structure diagram used for predicting combustion behavior of CG and PS [111].

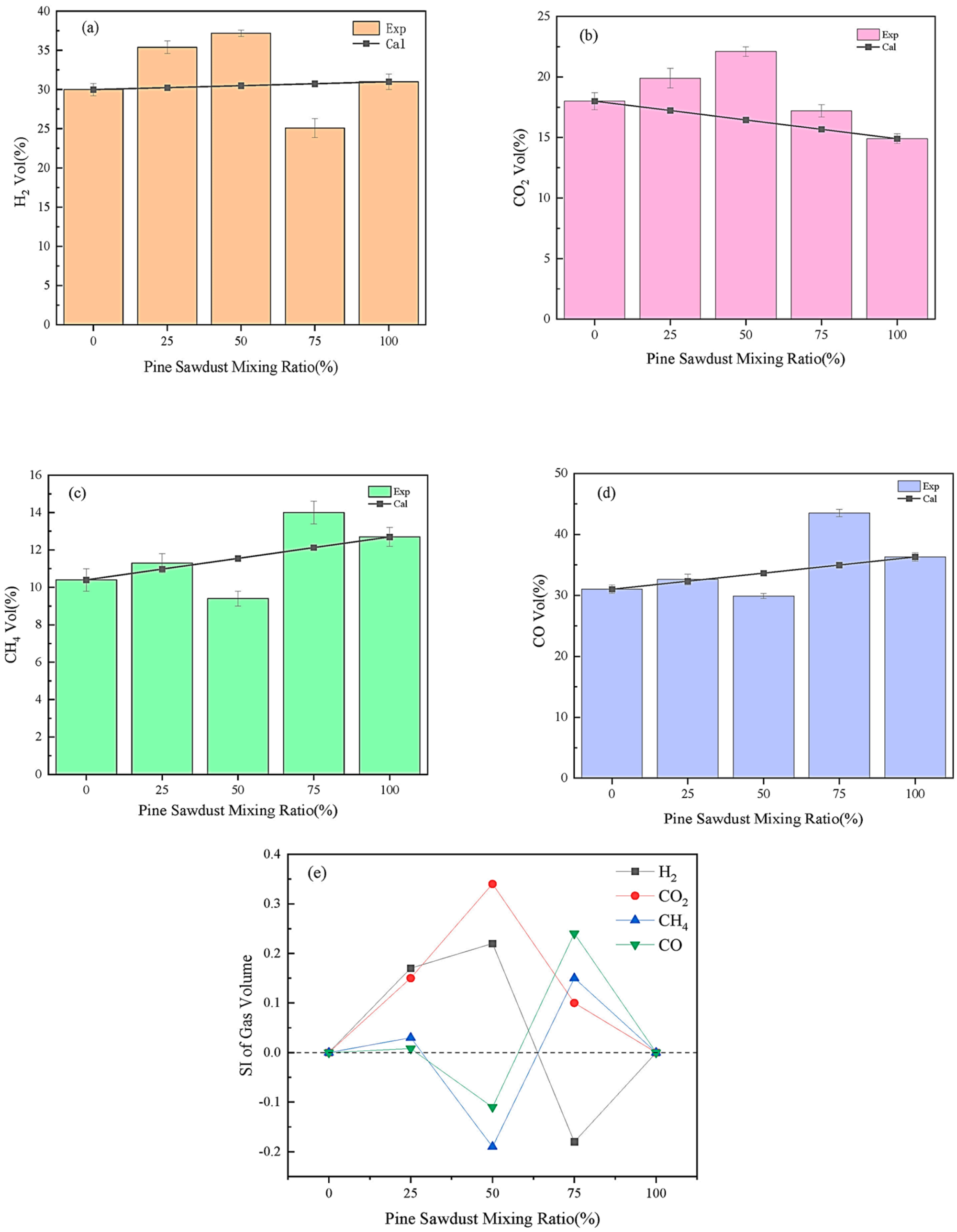

Figure 15. Effect of mixing ratio on gas composition of co-gasification. (**a**) The volume fraction of H_2 as a percentage for different mixing ratios; (**b**) The volume fraction of CO_2 as a percentage for different mixing ratios; (**c**) The volume fraction of CH_4 as a percentage for different mixing ratios; (**d**) The volume fraction of CO as a percentage for different mixing ratios; (**e**) SI values for each gas at different mixing ratios [115].

Pyrolysis is an effective method for transforming coal gangue into high-value materials, offering advantages such as low cost, continuity in the production process, and product diversity. However, the pyrolysis of coal gangue has drawbacks, including low efficiency, high cost, and the emission of harmful gases [104]. Biomass materials are potential feedstocks to enhance the pyrolysis process of coal gangue, compensating for its shortcomings as the volatile substances within biomass can lower the ignition temperature and shorten the reaction time [119,120]. The addition of cellulosic biomass not only significantly affects the pyrolysis characteristics and gas emission patterns of coal gangue but also increases the release of volatiles during pyrolysis [121]. Adding biomass to coal gangue can promote the release of gaseous organic compounds during pyrolysis and has a suppressing effect on the formation of carbon dioxide, which is significant for reducing greenhouse gas emissions [122]. In the co-pyrolysis experiments of coal gangue and peanut shells, mixing ratios of 3:1 and 1:3 are considered suitable for the co-pyrolysis of coal gangue and peanut shells [123]. Research on the co-pyrolysis of coal gangue and coffee grounds shows that adding 30% coffee grounds can increase the CPI value of the sample by 148.56 times, significantly improving the pyrolysis performance of the sample [124]. There is also an interaction in the co-pyrolysis of coal gangue and lignin, with the optimal mixing ratio being 1:3, where the synergistic effect is most evident [125].

3.2.3. Environmental Impact of Coal Gangue in Energy Applications

With the continuous increase in energy demand, coal gangue has been widely applied as a raw material for energy. For coal gangue with high calorific value, the presence of non-mineral impurities in the coal and gangue mixture may affect the combustion efficiency and emissions of power plants [126]. Fly ash and bottom slag produced by the combustion of coal gangue may be enriched in toxic metal elements such as mercury (Hg), arsenic (As), beryllium (Be), and cadmium (Cd). The volatilization characteristics of these elements during the combustion process can cause secondary pollution to the environment [127]. Additionally, workers in coal gangue power plants are exposed to occupational hazards such as silica dust, coal dust, and noise [128,129]. The addition of semi-coke in an oxygen-rich environment with coal gangue can reduce NO emissions under certain conditions. The increase in O_2 concentration significantly affects CO and NO emissions, but the impact on SO_2 emissions depends on the specific value of O_2 concentration [130]. The calcination of coal gangue leads to the migration and diffusion of heavy metals and other harmful substances, which may cause serious impacts on the surrounding ecological environment [131]. Heavy metals in coal gangue may enter the soil and water bodies through weathering and leaching after calcination, thereby polluting these environmental media [132].

The resource utilization of coal gangue in the energy sector holds significant potential, but several key considerations must be addressed during implementation. First, coal gangue exhibits considerable compositional variability, especially in terms of harmful elements such as heavy metals and sulfides, which could impact the safety and environmental effects of the energy production process. Therefore, before using coal gangue as an energy feedstock, comprehensive compositional analysis must be conducted to identify potential pollutants. Appropriate treatment technologies, such as high-temperature roasting and chemical treatments, should be employed to remove harmful components and prevent secondary pollution of the environment. Second, coal gangue has a relatively low calorific value and complex composition, which may affect its combustion efficiency as a fuel. To improve the combustion performance of coal gangue, it is often mixed with other high-calorific-value materials or pre-treated. For example, methods such as crushing and drying can optimize the particle size and moisture content of coal gangue, enhancing its combustibility and combustion stability. Furthermore, during the combustion process, temperature and atmospheric conditions must be strictly controlled to prevent the harmful emissions of gases containing sulfur, nitrogen, and other elements present in coal gangue. Additionally, the use of coal gangue as an energy feedstock should consider its impact on equipment and systems. During combustion, coal gangue may produce by-products such as ash and soot, which can cause corrosion, blockages, or wear on equipment such as boilers and flue gas treatment systems. Therefore, the design of combustion systems must account for the unique physicochemical properties of coal gangue, and careful preparation should be made in equipment selection and maintenance to ensure long-term, stable operation.

In summary, the application of coal gangue resource utilization in the energy sector should focus on multiple aspects, including compositional analysis, combustion performance, equipment compatibility, environmental emissions, and economic feasibility, to ensure its safe, efficient, and sustainable conversion into an energy resource.

3.3. Agricultural Applications

Coal gangue contains a high proportion of organic matter, making it an ideal substrate for carrying nitrogen, phosphorus, and potassium. Appropriately adding coal gangue can improve the soil environment [133]. As a soil amendment material, coal gangue not only helps improve problematic soils such as sandy soil and saline soil but can also be used to prepare fertilizers [134]. In terms of land conservation, direct filling technology can significantly reduce land subsidence and also reduce the environmental impact of coal gangue accumulation [135].

3.3.1. Soil Improvement

The long-term use of chemical fertilizers leads to the gradual depletion of organic matter and humus in the soil, which in turn causes soil compaction and salinization, among other land degradation issues [136]. The addition of coal gangue can significantly improve the physicochemical properties of saline-alkali soil, reducing soil PH, salt concentration, and bulk density, while increasing the content of organic matter, total nitrogen, total phosphorus, total potassium, hydrolyzed nitrogen, and available potassium in the soil [137,138]. Moreover, coal gangue has certain porosity and permeability, which, when added to the soil, can improve its aeration and water retention, especially for problematic soils such as sandy soil and saline soil, significantly improving their physical properties [54]. Through activation treatment, coal gangue's ability to fix and release available phosphorus in reclaimed mine soils has been significantly enhanced, with small particle size alkali-modified activated coal gangue showing the best activation effects, its maximum phosphate adsorption capacity being 11.796 mg/g [45]. AS-FCG is a cost-effective, durable, and environmentally friendly material that can be used for phosphorus fixation as well as for the slow release of phosphorus as a fertilizer, with its phosphorus adsorption mechanism and specific reaction equations illustrated in Figure 16 [45].

$$Ca^{2+} + 2H_2PO^- \rightarrow \text{Ca-P} \downarrow \tag{5}$$

$$Al^{3+} + 3H_2PO_4^- \rightarrow \text{Al-P} \downarrow \tag{6}$$

The preparation of coal gangue soil amendments can help increase available land resources and facilitate the reuse of solid waste. However, current issues with coal gangue amendments include high sulfur content, nutrient deficiencies, and heavy metal pollution, necessitating the addition of other substances to optimize their nutrient content [31].

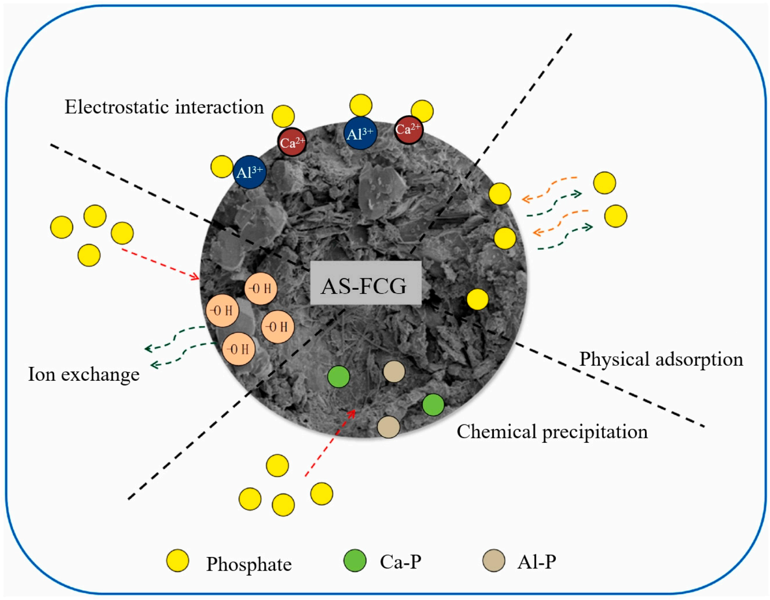

Figure 16. The mechanisms of phosphate adsorption of AS-FCG [45].

Coal gangue has shown significant effects in improving the condition of medium- and low-yield fields [39]. Using coal gangue to construct sand barriers for sand fixation can also increase the content of organic matter, total nitrogen, available phosphorus, and available potassium in the soil by 2.65, 2.66, 1.30, and 1.24 times, respectively [87]. The reactive silicates and aluminates in fly ash and coal gangue undergo hydration in alkaline conditions, lowering the soil's pH value, which is beneficial for the amelioration of saline-alkali soil. A novel compound made from phosphoric acid-modified cauliflower leaf biochar (CLH) and coal gangue-based Na-X zeolite (ZL), mixed together, acts as a soil stabilizer to immobilize heavy metals in polluted alkaline soils [139]. Modified coal gangue (MGE) prepared by a low-temperature alkali fusion method and applied to the immobilization of cadmium (Cd^{2+}) polluted soil resulted in a significant increase in active groups on the surface of the modified coal gangue, aiding the removal of Cd^{2+}. The content of available Cd^{2+} in the treated soil was reduced by 14.2% to 29.8% [46]. Bacterial treatment can significantly improve the availability of nutrients in coal gangue. Research found that using the Stenotrophomonas maltophilia YZ1 bacteria to activate coal gangue, the content of soluble phosphorus, potassium, and silicon significantly increased after treatment with the YZ1 bacterial strain [140].

3.3.2. Fertilizer Production

Research on coal gangue as a fertilizer shows that it can reduce air pollution and nitrogen pollution in groundwater, bringing significant economic, social, and environmental protection benefits. Compared with the background values of soil elements in the Loess Plateau and the national standards for harmful substances control, coal gangue from the Weibei coalfield has tremendous potential as a clay fertilizer [141]. Therefore, coal gangue has significant advantages as a raw material for producing agricultural fertilizers. Coal gangue can be used as a silicon fertilizer, and high-efficiency coal gangue-based silicon fertilizer has been produced through high-temperature activation technology, achieving significant available silicon content and meeting agricultural needs [142]. Studies have found that the maximum phosphate adsorption capacity of rapeseed straw coal gangue-modified biochar (CG-OR700) prepared at 700 °C is 7.9 mg/g at pH4.0, which is 4.6 times that of the original biochar [143]. This can not only be used to remove phosphates from wastewater but also serve as a slow-release fertilizer for agricultural production. After activation and modification, coal gangue can significantly improve its reactivity and soil improvement capabilities. Activation methods include thermal activation, chemical activation, microwave activation, mechanical activation, and composite activation [144].

3.3.3. Environmental Impact of Coal Gangue in Agricultural Applications

The application of coal gangue in agriculture, especially as a raw material for fertilizers and a soil amendment, poses certain potential risks. Experiments on phytostabilization using coal gangue in copper mine tailings have shown that the application of coal gangue not only increased the pH value, organic matter content, and nutrient components of the amended tailings but also reduced the DTPA-extractable concentrations of Zn, Pb, Cd, and Cu [145]. In soils reclaimed with coal gangue, the concentrations of copper, lead, and zinc were enriched by 1.51 times, 1.48 times, and 2.05 times, respectively, compared to original agricultural soil, indicating that these heavy metals could migrate from the coal gangue into the soil [146]. When coal gangue is directly applied to soil as fertilizer, it may contain harmful elements, which could negatively impact the soil and crops. There are potential risks associated with the agricultural application of coal gangue, especially concerning the presence of harmful elements and the health of soil and crops. Therefore, when considering the use of coal gangue as a raw material for fertilizers or a soil amendment, it is necessary to carefully assess its potential impact on the environment and crops.

When applying coal gangue in agriculture, particular attention must be paid to its compositional analysis and treatment. Coal gangue may contain harmful substances such as heavy metals and sulfides, which, if used untreated, could harm the soil and crops. Therefore, coal gangue must undergo purification and modification processes, such as high-temperature roasting or acid-base washing, to remove these harmful components. As a soil amendment, coal gangue can improve soil aeration and drainage, but due to its alkalinity, excessive use may lead to soil alkalization. Thus, it is essential to control the application rate appropriately. The minerals in coal gangue, such as silicon and calcium, can promote crop growth; however, it should be applied in conjunction with other fertilizers to avoid nutrient imbalances. Long-term use of coal gangue may have adverse effects on the soil, potentially contaminating groundwater or compromising crop safety. Therefore, regular monitoring of soil and crop conditions is necessary to assess its long-term impacts. To improve the utilization efficiency of coal gangue, it can be integrated with other agricultural waste materials to increase soil organic matter content and promote resource recycling. In conclusion, the application of coal gangue in agriculture should be scientifically and rationally managed, with strict control over its usage and treatment methods, ensuring its safe and sustainable improvement of soil quality and promotion of crop growth.

3.4. High-Value Applications

Coal gangue contains rare earth elements such as scandium and gallium, which play a crucial role in advanced technologies [147]. Additionally, coal gangue is rich in kaolinite and other clay minerals, constituting a vast potential resource of aluminum and lithium. Therefore, coal gangue can provide essential raw materials for industries such as solar energy and new energy vehicles.

3.4.1. Extraction of Valuable Components

Currently, extraction methods primarily focus on extracting alumina, which is the most feasible and economically valuable. Using hydrochloric acid to extract alumina from coal gangue is a simple and convenient method. Under optimal conditions of calcination temperature at 700 °C, leaching temperature at 150 °C, reaction time of 2 h, hydrochloric acid concentration of 20%, and a liquid-to-solid ratio of 3:1, the extraction efficiency of alumina can reach 91.56% [148]. In the presence of alkali metals Na_2CO_3 and Na_2SO_4, the extraction rate of aluminum from coal gangue is enhanced, reaching a peak value of 91.39% at 850 °C [149]. Various methods of extracting Al from gangue are shown in Table 5. The optimal calcination temperature for converting and separating coal gangue components is 1050 °C ± 50 °C. For the leaching process, the optimal temperature is about 85 °C with a leaching time of 60 to 80 min, under which conditions valuable components of coal gangue, alumina, and silica can be efficiently extracted [150]. At pH values of 2.6, 4.2, 6.5, and 8.1, the leaching rates of chloride after 105 h are 57.21%, 35.97%, 26.65%, and 18.98%, respectively [151]. Coal gangue calcination for desilication, with the addition of 6% secondary aluminum slag, can increase the Al/Si ratio of the desilication product from 0.91 to 1.94 and the desilication rate from 42.99% to 56.16% [152]. Figure 17 shows a schematic diagram of the catalytic behavior of $Al(OH)_3$ and secondary aluminum oxide slag. The active alumina produced by the dehydration of $Al(OH)_3$ can combine with metakaolin in coal gangue to form mullite, releasing active silica in the process. Active silica can be dissolved and separated through a caustic desilication process, and regenerated aluminum slag also has this function, with a stronger catalytic effect. Recovering iron from coal gangue can be performed using magnetic separation methods, calcining coal gangue at temperatures ranging from 300 °C to 1000 °C for 30 to 180 min. After calcination, the magnetization rate of coal gangue significantly increases to 17 times that of the original ore [153].

Table 5. Methods for extracting aluminum from coal gangue—efficiency and drawbacks.

Extraction Method	Efficiency	Drawbacks	References
Acid Leaching	Above 90% (high efficiency)	May cause environmental pollution, difficult waste liquid treatment, and the use of corrosive acidic solutions.	[148,154]
Alkaline Leaching	80–90% (relatively high)	Requires large amounts of alkaline solutions, complex treatment process, and the corrosive nature of alkaline solutions.	[155]
High-Temperature Sintering	70–80% (lower efficiency)	High energy consumption during heating, lower aluminum recovery efficiency, and high equipment investment.	[156]
Gasification	60–70% (lower efficiency)	Requires high temperatures, high equipment investment, and relatively low aluminum recovery efficiency.	[157]

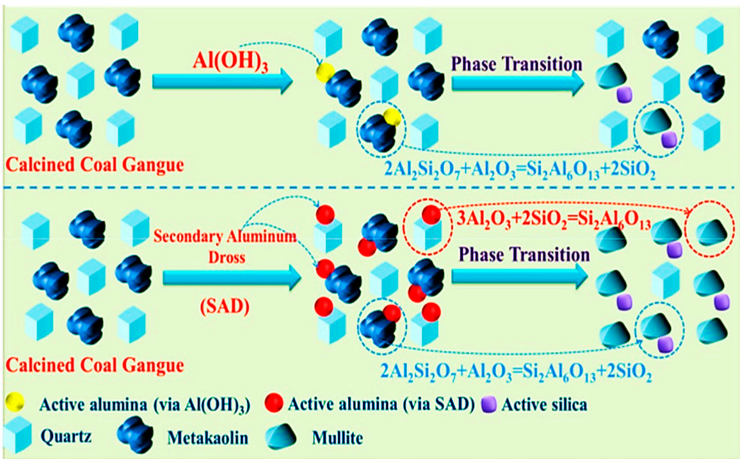

Figure 17. Schematic diagram of the catalytic behavior of $Al(OH)_3$ and secondary alumina dross [152].

Pretreatment and cyclic sintering can effectively promote the green extraction and utilization of key metals in coal gangue. Pretreatment significantly reduces the particle size of coal gangue, effectively strips away the layered silicate structure of the gangue, and improves leaching efficiency [158]. Ga and Li in coal gangue mainly exist in the form of silicates, so enriching and extracting Ga and Li is an effective method [158]. In the process of calcification and desilication of coal gangue, with the addition of 6% secondary aluminum slag and a calcification temperature of 1000–1050 °C, the desilication rate can be increased to 56.16%. The sodium silicate solution after desilication can be used as a silicon source, and the high-aluminum-content desilication slag can be used to extract and produce sodium aluminate solution as an aluminum source [152]. The stenotrophomonas maltophilia (YZ-1) strain can promote the release of soluble phosphorus in coal gangue; its produced organic acids can accelerate the leaching of phosphorus and lead, forming phosphate precipitates with lead ions; thus coal gangue has a synergistic effect on the stabilization of lead [159]. The stabilization mechanism is illustrated in Figure 18.

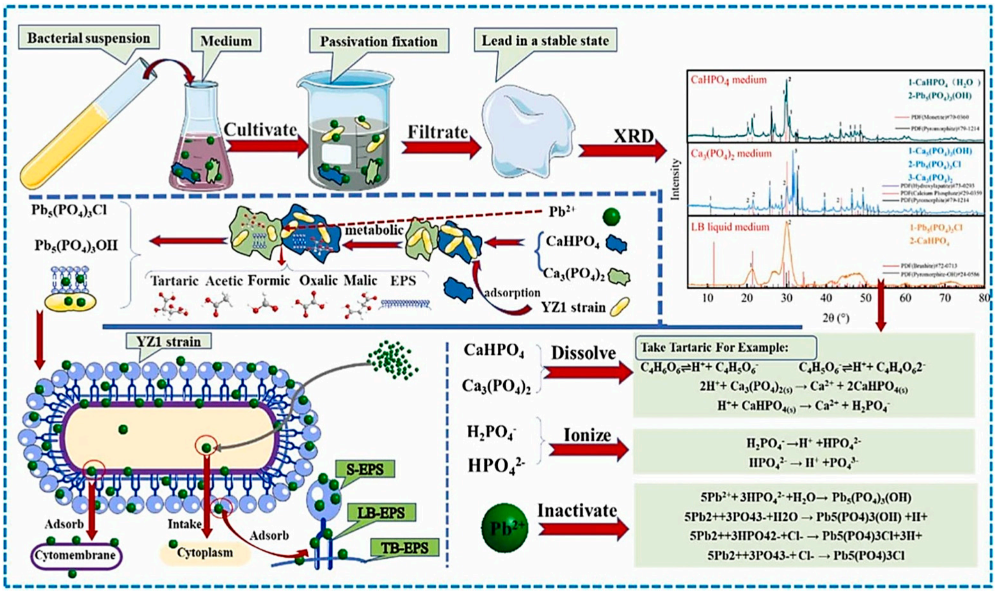

Figure 18. The fixation mechanism of Pb ions with YZ-1 strain [159].

3.4.2. Preparation of Catalysts and Adsorbents

Metal-enriched coal gangue can be directly prepared into carbon-supported catalysts for the in situ catalytic pyrolysis of biomass and the cracking of secondary tar [160]. Through a dual activation method of air calcination and hydrothermal alkali treatment, coal gangue is transformed into a high-performance, low-cost Ni-based catalyst for the hydrogenation of dioctyl phthalate, achieving a conversion rate of 99.9% and can be recycled multiple times without significant loss of activity [161]. The copper-modified ZSM-5 catalyst synthesized from coal gangue (Cu/ZSM-5) effectively decomposes phenol, with 7% Cu/ZSM-5 being able to completely degrade phenol within 30 min, and the total organic carbon (TOC) removal efficiency can reach 92% in 8 h [162]. The copper-silver (Cu-Ag) catalyst system based on coal gangue activates persulfate under visible light radiation to efficiently degrade tetracycline hydrochloride (TC), with the 15% copper and 5% silver ZSM-5 (15%Cu–5%Ag/ZSM-5) catalyst showing a high degradation rate of 75% for TC within 60 min. After five cycles, the degradation rate of TC decreased from 74% to 63%, demonstrating good stability and potential application prospects [163]. Coal gangue activated persulfate degradation of tetracycline hydrochloride follows the mechanism shown in Figure 19, providing three pathways, with the final degradation products being CO_2 and H_2O, in line with the concept of no pollutant release [164]. The catalytic material based on coal gangue (CG-Ca-N) activates peroxymonosulfate (PMS) and can completely degrade Bap within 20 min, and the degradation rate reaches 72.06% in soil slurry medium within 60 min [165]. The main advantages of various catalysts are shown in Table 6.

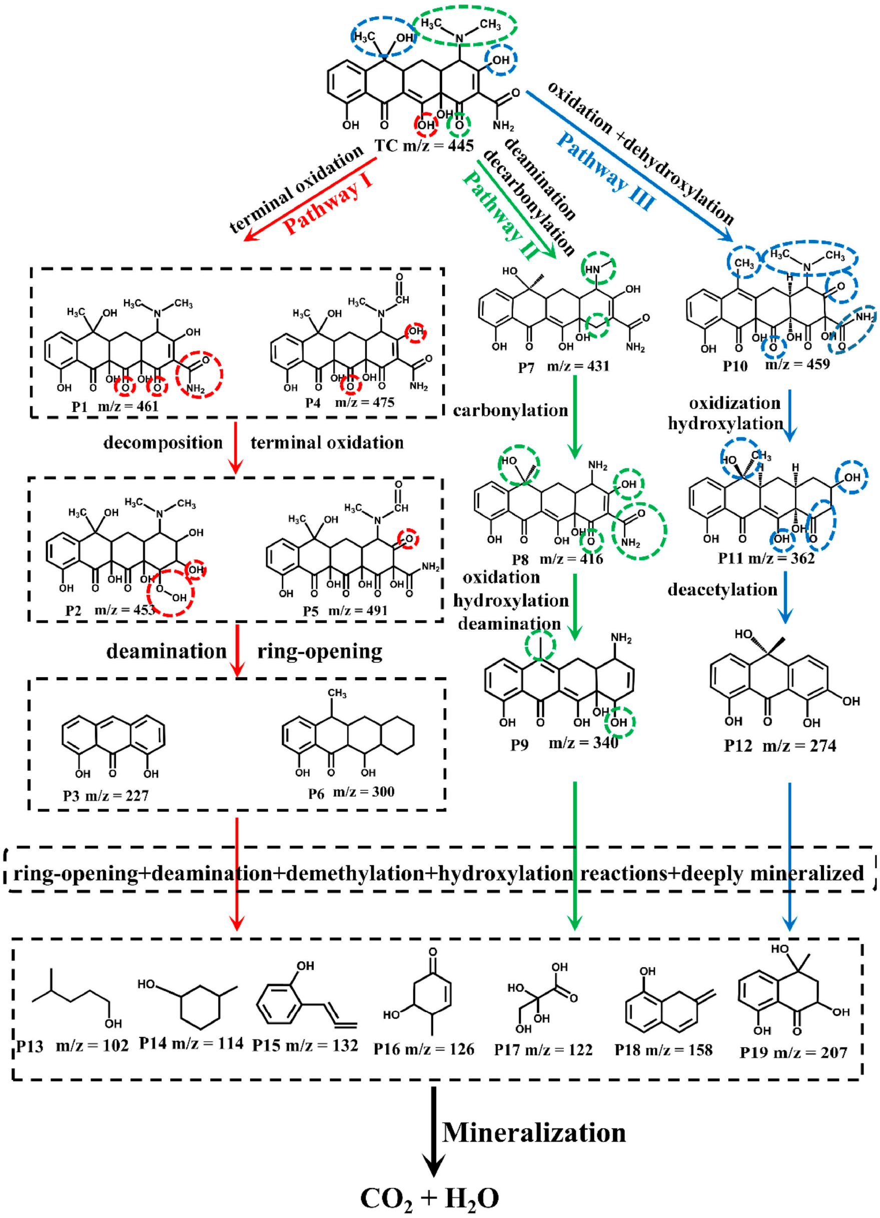

Figure 19. Possible degradation pathways of TC in CG/PMS system [164].

Table 6. Advantages of each catalyst.

Catalysts/Adsorbents	Advantage
Carbon supported catalysts	Low cost, high performance
Ni-based catalysts	Low cost and can be recycled many times
Copper-modified catalysts	Greatly accelerates catalytic speed
Copper and silver catalysts	Good stability

Currently, numerous domestic studies have found that coal gangue has a certain effect on removing some conventional pollutants, heavy metals, and organic substances [166,167]. Coal gangue's liquid permeability can meet regulatory requirements, and it has significant adsorption capacity for heavy metals such as lead and zinc [168]. By loading layered double hydroxides (LDH) on the inner pore walls of coal gangue's "ball window" porous monoliths (CBPM) to construct its framework, this structure displays a large specific surface area and abundant binding sites, making it especially suitable for removing trace emulsified water from contaminated oil, particularly as a flow-through filtration unit [169]. Coal gangue can be transformed into low-cost ceramic microsphere adsorbents for removing cationic dyes from aqueous solutions [170]. Layered porous carbon prepared from coal gangue exhibits excellent adsorption properties for heavy metals (such as Cr(VI)) and organic pollutants (such as Rhodamine B) [171]. Figure 20 shows the adsorption mechanism of coal gangue-RS600 for Cr(VI). Under acidic conditions, due to the positive charge on the CG-RS surface and the release of a large number of metal cations, Cr(VI) anions are attracted electrostatically to the positively charged biochar surface; adsorbed Cr(VI) ions are reduced to Cr(III) by electron donors composed of surface functional groups of CG-RS 600; the reduced Cr(III) reacts with the surface's C-O, Fe-O, forming stable Cr(III) on the surface of RS 600 and CG-RS 600, with the specific reaction equations as follows [172].

$$HCrO_4^- + 7H^+ + 3e^- \rightarrow Cr^{3+} + 4H_2O \quad (7)$$

$$3C_xOH + Cr_2O_7^{2-} + 4H^+ \rightarrow 3CxO + Cr^{3+} + 3H_2O \quad (8)$$

$$nCr^{3+} + (1 - n)Fe^{3+} + 2H_2O \rightarrow Cr_nFe_{(1-n)}OOH + 3H^+ \quad (9)$$

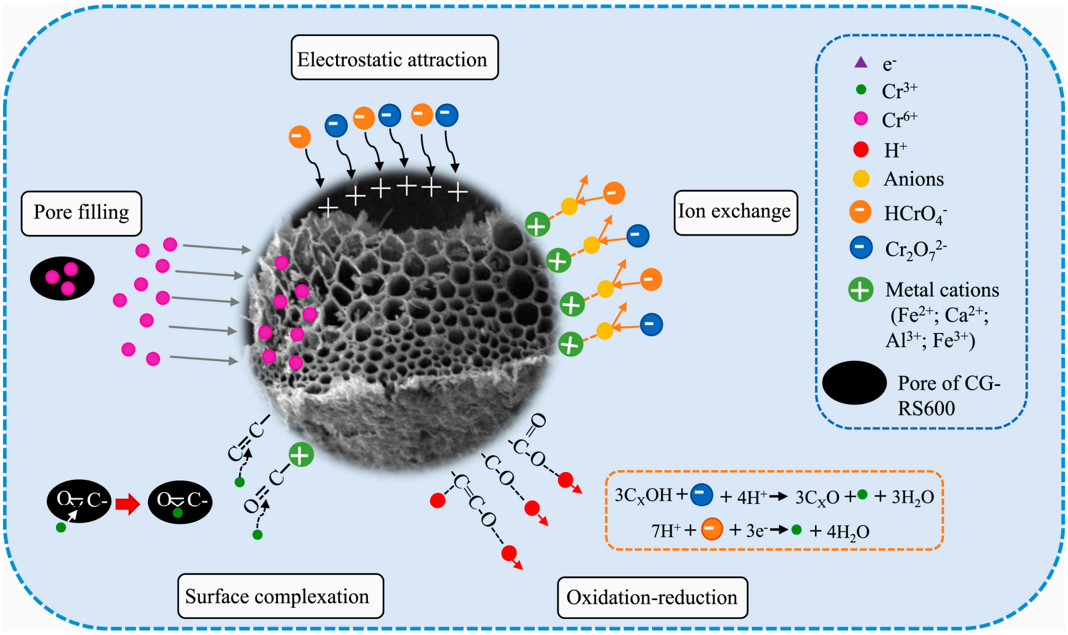

Figure 20. The adsorption mechanisms of Cr(VI) onto CG-RS600 [172].

Coal gangue geopolymers (GP) with a mesoporous structure can effectively interact with and capture Cu [47]. Magnetic zeolites synthesized from red mud and coal gangue through alkali reduction calcination-hydrothermal methods show maximum adsorption capacities for Cu^{2+}, Cd^{2+}, and Pb^{2+} of 76.2, 92.2, and 178.4 mg/g, respectively [173]. By modifying coal gangue through calcination and acid reflux, it can be used to treat fish pond aquaculture wastewater, achieving removal rates of 44.93% for COD (Chemical Oxygen Demand), 25.51% for turbidity, and 97.8% for total nitrogen [174]. Zeolite-activated carbon composite materials synthesized from coal gangue through CO_2 activation and hydrothermal synthesis methods exhibit efficient adsorption performance for Cu^{2+} and Rh-B, at 92.8% and 94.2%, respectively [160]. Figure 21 shows SEM images of zeolite (a-b) ZMC with different carbon contents. In low magnification (Figure 21a), zeolite exhibits good dispersibility, uniform particle size distribution, and regular geometric shapes without large impurities, indicating that carbon elements have been completely combusted. From high magnification (Figure 21b), individual zeolite is a regular hexahedron, with each side about 1.5–2 μm. For zeolite (ZTC) prepared from coal gangue that retains carbon elements, some zeolites show agglomeration (Figure 21c), suggesting that the introduction of carbon elements can form additional nucleation sites, and zeolites tend to grow on the exposed surfaces of carbon-based materials. From Figure 21d, it can be seen that the length variation in individual zeolites compared to ZMC is negligible. However, more zeolites in the ZTC sample show coplanar and co-facial phenomena. Using coal gangue as raw material mixed with a certain amount of coal, the resulting sample is called carbon-added zeolite (ZAC). In this sample, some irregular bulk materials appear, and more zeolites grow on the surface of these bulk materials to form larger agglomerates as in Figure 21e. The carbon-based material is activated carbon with a porous structure, which can be clearly observed in Figure 21f. The composite material (AICCG) made of iron alginate oxide and calcined coal gangue has an adsorption effect on zinc and manganese, with adsorption capacities of 115.6 mg/g and 101.8 mg/g under optimal conditions, respectively [175]. Using coal gangue-based zeolite particles in a fluidized bed to treat methylene blue in aqueous solutions, under specific conditions, this method can effectively adsorb and remove methylene blue from water, showing good adsorption performance and industrial application potential [176]. The adsorbent (HM-CFB-FA) made by hydrothermal modification can remove Cd^{2+} from wastewater, with a maximum adsorption capacity of 183.7 mg/g at 25 °C and an initial pH value of 6.0 [177]. Modified coal gangue-supported $FeCo_2O_4$ nanoparticles activating persulfate can effectively degrade humic acid, with an efficiency of up to 85% [178].

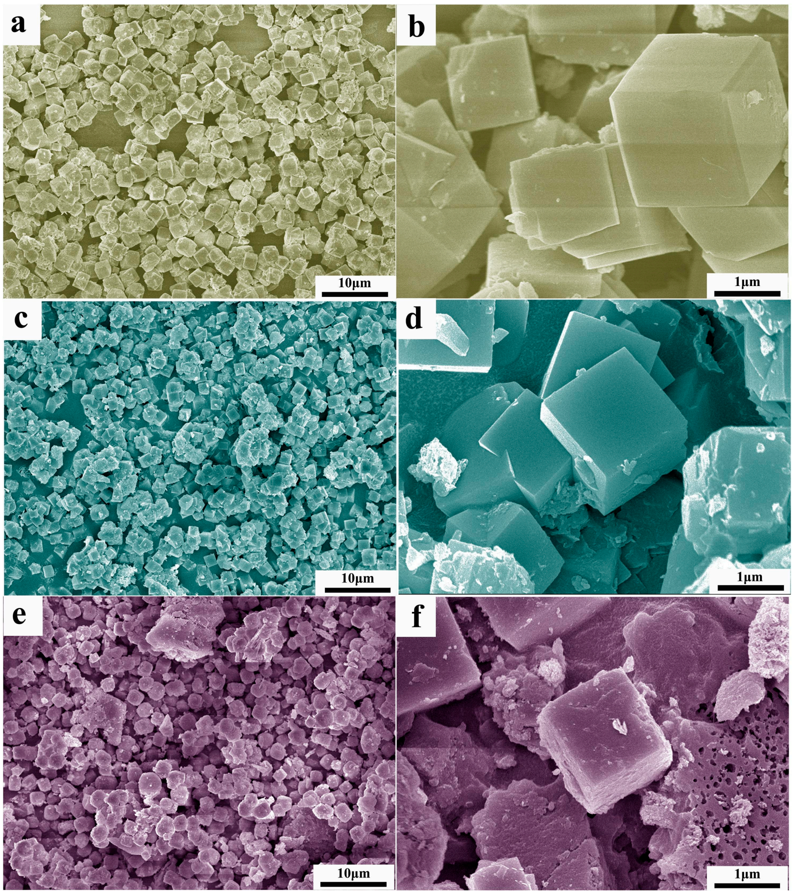

Figure 21. SEM images of zeolites containing different contents of carbon (**a**,**b**) ZMC, (**c**,**d**) ZTC, (**e**,**f**) ZAC [179].

In recent years, with the continuous advancement of materials science and technology, researchers have gradually realized that coal gangue is not merely a waste product but also holds great potential, especially in the development of high-performance materials. By applying advanced materials science technologies, the performance of coal gangue-based products can be significantly improved, thereby expanding their application across various fields. Table 7 presents the advantages of advanced technologies in coal gangue utilization.

Table 7. Advantages of advanced technologies in coal gangue utilization.

Advantages	Description	References
Enhanced Performance	Advanced technologies like nanotechnology and composite materials significantly improve the mechanical properties, durability, and corrosion resistance of coal gangue-based products, broadening their application fields.	[180]
Multifunctionality	Coal gangue can be functionalized with additional properties such as adsorption, antibacterial, and self-healing capabilities, making it useful for water treatment, environmental remediation, etc.	[166,172]
Improved Resource Efficiency	Advanced technologies allow for more diversified uses of coal gangue, increasing resource recovery efficiency and reducing reliance on single-use applications.	[181]
Higher Economic Value	Advanced techniques enable coal gangue to be transformed into high-value products, such as high-performance construction materials and chemical products, increasing economic benefits.	[58,60]
Higher Resource Recovery	Advanced materials technologies enable the extraction of valuable metals and other useful components from coal gangue, improving resource recovery rates.	[148,149]
Automation and Smart Processing	Future automated and smart technologies will optimize the processing and utilization of coal gangue, improving efficiency and reducing costs.	[10]

In addition, there are significant synergies between coal gangue utilization and emerging technologies such as carbon capture and storage (CCS), renewable energy integration, and the circular economy model. Coal gangue can react with carbon dioxide, helping to fix CO_2, reduce carbon emissions, and provide raw materials for products like construction materials, thereby promoting the development of carbon capture and storage technologies. It can also serve as a support material for renewable energy projects, enhancing the flexibility and stability of energy systems, for example, as an energy storage material or biomass fuel. Combined with the circular economy model, valuable resources in coal gangue, such as rare earth metals and aluminum, can be extracted and reused, reducing waste disposal and resource wastage. Furthermore, the application of intelligent technologies has improved the precision of coal gangue management, enhancing resource utilization rates through real-time monitoring and automated sorting. Through these synergies, the resource utilization of coal gangue not only contributes to environmental protection but also brings economic benefits, fostering a win-win situation for regional economies and sustainable development.

3.4.3. Environmental Impact of Coal Gangue in High-Value Applications

When extracting metals such as aluminum and silicon from coal gangue, attention should be paid to the gases emitted to avoid secondary pollution to the environment. Due to the very stable structure of the original minerals in coal gangue, high-temperature calcination activation and the use of strong acids and pressurized leaching are often required to achieve very high leaching rates [182]. If pyrite is present in the coal gangue, this process can produce sulfur dioxide, polluting the atmosphere, and the release rate may even be higher than that of pure pyrite [183]. Coal gangue is a huge reserve of aluminum and silicon resources. However, the acidic leaching process involved in extracting aluminum and silicon from coal gangue can negatively impact the environment. Acidic conditions can promote the release of heavy metals from coal gangue, potentially polluting groundwater resources [184,185]. When using coal gangue as an adsorbent, the treatment of the adsorbent after use can also impact the environment [170]. The adsorption study on zinc and manganese by the iron alginate oxide-coal gangue composite demonstrated effective adsorption but also raised concerns about the environmental impact of by-products from this process [175].

When extracting metals from coal gangue or using it as a catalyst, several factors must be carefully considered. First, the metal composition and content in coal gangue can vary significantly, so a thorough compositional analysis must be conducted before extraction. Appropriate extraction methods, such as acid leaching or alkaline leaching, should be selected to ensure efficient metal recovery while minimizing secondary pollution. Second, when using coal gangue as a catalyst, its activity and stability must be evaluated. High-temperature roasting or surface modification may be required to enhance its catalytic performance. Additionally, the physicochemical properties of coal gangue, such as specific surface area and pore structure, directly affect its catalytic efficiency, and thus physical or chemical modifications might be necessary. The selectivity and efficiency of catalytic reactions also need to be optimized to ensure high performance in specific reactions. Moreover, coal gangue may contain harmful components that could release toxic substances during the catalytic process. Therefore, environmental monitoring should be strengthened to ensure that harmful gas emissions during the catalytic reactions comply with environmental standards. The recovery and regeneration of the catalyst are also crucial, and effective methods for restoring its activity must be explored to improve resource utilization. Lastly, the economic feasibility of metal extraction and catalytic applications of coal gangue should be taken into account. Optimizing processes and reducing costs are essential to achieving sustainable development in these applications.

4. Future Development Directions and Suggestions

The future development trend of coal gangue resource utilization can be considered in conjunction with some popular research directions, including environmentally friendly technologies, innovative applications in material science, and the concept of a circular economy. Here are some specific views: environmentally friendly technologies: with the increase in environmental awareness and policy promotion, the development and application of coal gangue utilization technologies with low pollution and low emissions will become a trend. For example, researching how to effectively use coal gangue without generating or with minimal production of carbon dioxide. Comprehensive utilization: the composition of coal gangue is diverse, making it a source of various resources. For instance, it can be used as raw material for building materials or as a source for extracting rare metals and minerals. Future research may focus more on how to extract these valuable components from coal gangue efficiently and economically. Innovative applications in material science: transforming coal gangue into high-performance materials, such as lightweight building materials, adsorbents, or catalysts, using advanced material science technologies, could be a research hotspot in the future. Circular economy and sustainable development: integrating the concept of a circular economy, researching how to incorporate the use of coal gangue into a broader industrial ecosystem to maximize resource utilization and minimize environmental impact will be important.

Along with the increase in coal extraction, coal gangue, an inevitable solid waste produced during the coal mining and washing process, also expressed an increasing tendency. Coal gangue is generally regarded as an environmental burden, occupying a vast amount of land and potentially polluting the surrounding land and water bodies through weathering and rainwater erosion. In 2022, China's comprehensive utilization of coal gangue reached 597 million tons, a year-on-year increase of 9.94%. The utilization of coal gangue in power generation and heating accounted for approximately 6.87%, and other fields accounted for 93.13%. Despite the positive outcomes brought by the utilization of coal gangue resources, the process has also revealed some issues and challenges. Low economic benefits, slow technological updates, and technical complexity are the main problems faced in extracting the valuable components. In terms of energy applications, low thermal efficiency, high pollutant emissions, and related technical and economic challenges remain issues that need priority resolution. In agricultural applications, while the use of coal gangue provides a way of resource recovery, the potential risks of harmful substances and limitations on nutrient supply also need to be fully considered.

Moreover, while many studies focus on the utilization of coal gangue resources, there is relatively less concern for the potential environmental risks during its utilization process. Avoiding secondary pollution to the environment during resource utilization is an important consideration. Therefore, conducting environmental risk assessments, identifying and quantifying the potential impacts on the environment during the coal gangue utilization process are the key steps for ensuring the sustainable use of this resource. In this way, a better balance between economic benefits and environmental protection ought to be taking into account, promoting the resource utilization of coal gangue towards more efficient and eco-friendly directions. In summary, the resource utilization of coal gangue is not only an effective way to achieve the reduction, resource utilization, and harmlessness of solid waste, but also an important means to promote sustainable development and realize a green and low-carbon transition. With the advancement in energy technology and the enhancement of environmental protection awareness, the comprehensive utilization of coal gangue will show even greater potential in the future.

5. Conclusions

To fully utilize coal gangue and promote its resource utilization, the government can implement a series of policies and regulations to support the development of this field. The following are some recommendations: (1) Financial incentives and subsidies: The government can provide financial subsidies or tax incentives to enterprises engaged in the resource utilization of coal gangue, reducing their operational costs and encouraging investment in research and development. This could include tax exemptions on the import of related equipment, funding support for R&D, or offering lower interest rates on loans to such enterprises. (2) Establishing standards and certification systems: Developing quality and environmental standards for coal gangue products to ensure product quality and environmental safety. Additionally, setting up a certification system to certify products that meet the standards, thereby enhancing their market competitiveness. (3) Promoting industry-academia-research collaboration: Encouraging cooperation among enterprises, universities, and research institutions to jointly develop new technologies and products. The government can provide platforms to facilitate resource sharing and information exchange, as well as funding support for collaborative projects. (4) Environmental regulations and guidelines: Formulating clear environmental regulations to ensure that the utilization of coal gangue does not negatively impact the environment. This includes regulations on waste discharge, pollution control, and resource recycling.

In addition, based on the current research and practical status of coal gangue utilization, the main research gaps that need to be addressed are as follows: (1) Technological standardization and normalization: The technical standard system for the comprehensive utilization of coal gangue is still incomplete. There is a lack of specialized technical guidance and operating procedures for different regions and coal types, leading to uncertainties in practical operations. (2) High-value utilization technologies: The development of high-value-added products from coal gangue is relatively limited. How to transform coal gangue into high-value materials or products, such as high-performance building materials or chemical products, requires further in-depth research. (3) Environmental impact assessment and remediation: Coal gangue may cause secondary pollution, such as soil and water contamination, during its treatment and utilization processes. There is a need to strengthen research on the assessment of its environmental impact and the development of remediation technologies. (4) Regional differentiation studies: Due to the significant differences in coal gangue composition across regions, its comprehensive utilization approaches also vary. Currently, there is insufficient systematic research on regional differentiation.

Future research priorities: (1) Environmentally friendly utilization: Explore the application of coal gangue in soil remediation, heavy metal pollution control, and other fields, developing environmentally friendly utilization technologies to reduce its negative environmental impact. (2) Industry chain integration and optimization: Build a multi-level, comprehensive utilization industry chain for coal gangue, promote its synergistic use across different fields, and improve its overall utilization efficiency and economic benefits. (3) Interdisciplinary research integration: Strengthen the interdisciplinary integration of materials science, environmental science, chemical engineering, and other fields to drive innovation and breakthroughs in coal gangue comprehensive utilization technologies.

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References

1. Zhao, Z.-Y.; Hao, Y.-X.; Chang, R.-D.; Wang, Q.-C. Assessing the vulnerability of energy supply chains: Influencing factors and countermeasures. *Sustain. Energy Technol. Assess.* **2023**, *56*, 103018. [CrossRef]
2. Zhang, C.; Li, X.; Sun, Y.; Chen, J.; Streimikiene, D. Policy modeling consistency analysis during energy crises: Evidence from China's coal power policy. *Technol. Forecast. Soc. Change* **2023**, *197*, 122931. [CrossRef]
3. Li, D.; Wu, D.; Xu, F.; Lai, J.; Shao, L. Literature overview of Chinese research in the field of better coal utilization. *J. Clean. Prod.* **2018**, *185*, 959–980. [CrossRef]
4. Zhang, Y.; Nie, R.; Shi, R.; Zhang, M. Measuring the capacity utilization of the coal sector and its decoupling with economic growth in China's supply-side reform. *Resour. Conserv. Recycl.* **2018**, *129*, 314–325. [CrossRef]
5. Song, W.; Zhang, J.; Li, M.; Yan, H.; Zhou, N.; Yao, Y.; Guo, Y. Underground Disposal of Coal Gangue Backfill in China. *Appl. Sci.* **2022**, *12*, 12060. [CrossRef]
6. Shao, S.; Ma, B.; Wang, C.; Chen, Y. Extraction of valuable components from coal gangue through thermal activation and HNO3 leaching. *J. Ind. Eng. Chem.* **2022**, *113*, 564–574. [CrossRef]
7. Chen, Y.; Zhou, S.; Zhang, W. Effect of coal gangue with different kaolin content son compressive strength and pore. *J. Wuhan Univ. Technol.-Mat. Sci. Ed.* **2008**, *23*, 12–15. [CrossRef]
8. Wang, G.; Xie, Y.; Qin, Y.; Wang, J.; Shen, J.; Han, B.; Liang, C.; Wang, Q. Element geochemical characteristics and formation environment for the roof, floor and gangue of coal seams in the Gujiao mining area, Xishan coalfield, China. *J. Geochem. Explor.* **2018**, *190*, 336–344. [CrossRef]
9. Ke, G.; Jiang, H.; Li, Z. Study on the calorific value and cementitious properties of coal gangue with 0-1 mm particle size. *Constr. Build. Mater.* **2024**, *414*, 135061. [CrossRef]
10. Xue, G.; Li, S.; Hou, P.; Gao, S.; Tan, R. Research on lightweight Yolo coal gangue detection algorithm based on resnet18 backbone feature network. *Internet Things* **2023**, *22*, 100762. [CrossRef]
11. Moghadam, M.J.; Ajalloeian, R.; Hajiannia, A. Preparation and application of alkali-activated materials based on waste glass and coal gangue: A review. *Constr. Build. Mater.* **2019**, *221*, 84–98. [CrossRef]
12. Han, B.; Zhang, Y.; Zou, Z.; Wang, J.; Zhou, C. Study on controlling factors and developing a quantitative assessment model for spontaneous combustion hazard of coal gangue. *Case Stud. Therm. Eng.* **2024**, *54*, 104039. [CrossRef]

13. Wu, F.; Liu, Y.; Gao, R. Challenges and opportunities of energy storage technology in abandoned coal mines: A systematic review. *J. Energy Storage* **2024**, *83*, 110613. [CrossRef]
14. Zheng, Q.; Zhou, Y.; Liu, X.; Liu, M.; Liao, L.; Lv, G. Environmental hazards and comprehensive utilization of solid waste coal gangue. *Prog. Nat. Sci. Mater. Int.* **2024**, *34*, 223–239. [CrossRef]
15. Ju, Q.; Hu, Y.; Liu, Q.; Chai, H.; Chen, K.; Zhang, H.; Wu, Y. Source apportionment and ecological health risks assessment from major ions, metalloids and trace elements in multi-aquifer groundwater near the Sunan mine area, Eastern China. *Sci. Total Environ.* **2023**, *860*, 160454. [CrossRef] [PubMed]
16. Luo, C.; Li, S.; Ren, P.; Yan, F.; Wang, L.; Guo, B.; Zhao, Y.; Yang, Y.; Sun, J.; Gao, P.; et al. Enhancing the carbon content of coal gangue for composting through sludge amendment: A feasibility study. *Environ. Pollut.* **2024**, *348*, 123439. [CrossRef] [PubMed]
17. Jiang, C.; Zhao, D.; Chen, X.; Zheng, L.; Li, C.; Ren, M. Distribution, source and ecological risk assessment of polycyclic aromatic hydrocarbons in groundwater in a coal mining area, China. *Ecol. Indic.* **2022**, *136*, 108683. [CrossRef]
18. Xu, Z.; Qian, Y.; Hong, X.; Luo, Z.; Gao, X.; Liang, H. Contamination characteristics of polycyclic aromatic compounds from coal sources in typical coal mining areas in Huaibei area, China. *Sci. Total Environ.* **2023**, *873*, 162311. [CrossRef] [PubMed]
19. Qing, Z.; Guijian, L.; Shuchuan, P.; Chuncai, Z.; Arif, M. Immobilization of hexavalent chromium in soil-plant environment using calcium silicate hydrate synthesized from coal gangue. *Chemosphere* **2022**, *305*, 135438. [CrossRef]
20. Gasparotto, J.; Da Boit Martinello, K. Coal as an energy source and its impacts on human health. *Energy Geosci.* **2021**, *2*, 113–120. [CrossRef]
21. Wang, Y.; Bai, D.; Luo, X.; Zhang, Y. Effects of Setaria viridis on heavy metal enrichment tolerance and bacterial community establishment in high-sulfur coal gangue. *Chemosphere* **2024**, *351*, 141265. [CrossRef] [PubMed]
22. Wang, C.; Wang, D.; Xin, H.; Qi, Z.; Zhang, W.; Zhang, K. Study on secondary oxidation characteristics of coal gangue at different pyrolysis rank. *Fuel* **2023**, *345*, 128231. [CrossRef]
23. Liang, Y.; Liang, H.; Zhu, S. Mercury emission from spontaneously ignited coal gangue hill in Wuda coalfield, Inner Mongolia, China. *Fuel* **2016**, *182*, 525–530. [CrossRef]
24. Zhai, X.; Wu, S.; Wang, K.; Drebenstedt, C.; Zhao, J. Environment influences and extinguish technology of spontaneous combustion of coal gangue heap of Baijigou coal mine in China. *Energy Procedia* **2017**, *136*, 66–72. [CrossRef]
25. Li, X.; Qiao, Y.; Shao, J.; Bai, C.; Li, H.; Lu, S.; Zhang, X.; Yang, K.; Colombo, P. Sodium-based alkali-activated foams from self-ignition coal gangue by facile microwave foaming route. *Ceram. Int.* **2022**, *48*, 33914–33925. [CrossRef]
26. Wang, H.; Chen, Z.; Meng, Z.; Liu, L.; Wang, X.; Xing, Y. Integrated utilization of coal gangue for synthesis of β-Sialon multiphase ceramic materials. *Ceram. Int.* **2023**, *49*, 11275–11284. [CrossRef]
27. Feng, D.; Wang, J.; Wang, Y.; Xiao, X.; Hou, W.; Liang, S. Alkali-activated geopolymer materials prepared from coal gangue and municipal solid waste incineration byproducts. *J. Build. Eng.* **2023**, *80*, 108074. [CrossRef]
28. Jin, J.; Li, M.; Liu, T.; Chen, Y.; Qin, Z.; Liu, Q.; Liang, B.; Zhao, J.; Zuo, S. Insights into factors influencing coal gangue-filled backfill cemented by self-consolidating alkali-activated slag grouts. *Constr. Build. Mater.* **2024**, *411*, 134422. [CrossRef]
29. Wang, H.; Xiong, R.; Zong, Y.; Li, L.; Guo, H.; Wang, Z.; Guan, B.; Chang, M. Effect of raw material ratio and sintering temperature on properties of coal gangue-feldspar powder artificial aggregate. *Constr. Build. Mater.* **2023**, *384*, 131400. [CrossRef]
30. Zhang, Y.; Qi, X.; Zou, J.; Rao, Y.; Chen, L.; Zhang, L.; Ji, Y.; Liang, Z. Effects of water immersion on the pore structure and thermodynamic properties of coal gangue. *Fuel* **2023**, *346*, 128273. [CrossRef]
31. Zhang, M.; Qu, Z.; Xie, M.; Chen, X.; Yang, Y.; Bai, Y. Research on the regulatory mechanism of pore structure in soil matrix prepared by fluidized bed calcination of coal gangue. *Arab. J. Chem.* **2024**, *17*, 105814. [CrossRef]
32. Duan, X.; Huang, Y.; Li, Y.; Zhang, W.; Huang, Z. Evolution mechanism of pore structure in sintered coal gangue ceramsites. *Ceram. Int.* **2023**, *49*, 31385–31395. [CrossRef]
33. Li, C.; Zhang, P.; Li, D. Study on low-cost preparation of glass–ceramic from municipal solid waste incineration (MSWI) fly ash and lead–zinc tailings. *Constr. Build. Mater.* **2022**, *356*, 129231. [CrossRef]
34. Yu, L.; Feng, Y.; Yan, W. The Current Situation of Comprehensive Utilization of Coal Gangue in China. *Adv. Mater. Res.* **2012**, *524–527*, 915–918. [CrossRef]
35. Li, Z.; Gao, Y.; Zhang, J.; Zhang, C.; Chen, J.; Liu, C. Effect of particle size and thermal activation on the coal gangue based geopolymer. *Mater. Chem. Phys.* **2021**, *267*, 124657. [CrossRef]
36. Cheng, L.; Qin, Y.; Li, X.; Zhao, X. A Laboratory and Numerical Simulation Study on Compression Characteristics of Coal Gangue Particles with Optimal Size Distribution Based on Shape Statistics. *Math. Probl. Eng.* **2020**, *2020*, 046156. [CrossRef]
37. Akdemir, Ü.; Sönmez, İ. Investigation of coal and ash recovery and entrainment in flotation. *Fuel Process. Technol.* **2003**, *82*, 1–9. [CrossRef]
38. Huang, H.; Dou, D.; Liu, G. Modeling of coal and gangue volume based on shape clustering and image analysis. *Int. J. Coal Prep. Util.* **2023**, *43*, 329–345. [CrossRef]
39. Long, G.; Li, L.; Li, W.; Ma, K.; Dong, W.; Bai, C.; Zhou, J.L. Enhanced mechanical properties and durability of coal gangue reinforced cement-soil mixture for foundation treatments. *J. Clean. Prod.* **2019**, *231*, 468–482. [CrossRef]
40. Ma, Q.Q.; Liu, H. Analysis of Obstacle of Development and Application that Coal Gangue Used in China Road Engineering. *Adv. Mater. Res.* **2014**, *900*, 510–513. [CrossRef]

41. Li, S.; Li, N. Effects of composition and temperature on porosity and pore size distribution of porous ceramics prepared from $Al(OH)_3$ and kaolinite gangue. *Ceram. Int.* **2007**, *33*, 551–556. [CrossRef]
42. Feng, D.; Wang, J.; Chen, D.; Hou, W.; Liang, S. Experimental study on municipal solid waste incineration fly ash as a component of coal gangue geopolymer and the feasibility of making geopolymer mortar. *Constr. Build. Mater.* **2023**, *409*, 133862. [CrossRef]
43. Feng, X.; Liu, N.; Lu, X. Investigation of un-calcined coal gangue together with ground granulated blast furnace slag and fly ash to ambient-curing production high-strength geopolymer. *J. Mater. Res. Technol.* **2023**, *25*, 3985–3997. [CrossRef]
44. Wen, B.; Huang, D.; Zhang, L.; Song, Q.; Gao, G.; Huo, D. Study on mechanical properties and size effect of coal gangue concrete at mesoscale. *Constr. Build. Mater.* **2022**, *360*, 129551. [CrossRef]
45. Ye, T.; Min, X.; Li, X.; Zhang, S.; Gao, Y. Improved holding and releasing capacities of coal gangue toward phosphate through alkali-activation. *Chemosphere* **2022**, *287*, 132382. [CrossRef]
46. Zhao, H.; Li, P.; He, X. Remediation of cadmium contaminated soil by modified gangue material: Characterization, performance and mechanisms. *Chemosphere* **2022**, *290*, 133347. [CrossRef] [PubMed]
47. Mei, Y.; Pang, J.; Wang, X.; Chen, E.; Wu, D.; Ma, J. Coal gangue geopolymers as sustainable and cost-effective adsorbents for efficient removal of Cu (II). *Environ. Technol. Innov.* **2023**, *32*, 103416. [CrossRef]
48. Zhou, C.; Liu, G.; Fang, T.; Lam, P.K.S. Investigation on thermal and trace element characteristics during co-combustion biomass with coal gangue. *Bioresour. Technol.* **2015**, *175*, 454–462. [CrossRef] [PubMed]
49. Jiao, Y.; Qiao, J.; Jia, R.; Wei, P.; Li, Y.; Ke, G. The influence of carbon imperfections on the physicochemical characteristics of coal gangue aggregates. *Constr. Build. Mater.* **2023**, *409*, 133965. [CrossRef]
50. Guo, Z.; Xu, J.; Xu, Z.; Gao, J.; Zhu, X. Performance of cement-based materials containing calcined coal gangue with different calcination regimes. *J. Build. Eng.* **2022**, *56*, 104821. [CrossRef]
51. Zhang, J.; Han, H.; Wang, L. Pozzolanic activity experimental dataset of calcined coal gangue. *Data Brief* **2023**, *51*, 109802. [CrossRef] [PubMed]
52. Zhang, S.; Cao, M.; Zhang, K.; Yuan, J.; Wang, Y. Wrapped coal gangue aggregate enhancement ITZ and mechanical property of concrete suitable for large-scale industrial use. *J. Build. Eng.* **2023**, *72*, 106649. [CrossRef]
53. Wu, J.; Bai, G.; Wang, P.; Liu, Y. Mechanical properties of a new type of block made from shale and coal gangue. *Constr. Build. Mater.* **2018**, *190*, 796–804. [CrossRef]
54. Zhao, G.; Wu, T.; Ren, G.; Zhu, Z.; Gao, Y.; Shi, M.; Ding, S.; Fan, H. Reusing waste coal gangue to improve the dispersivity and mechanical properties of dispersive soil. *J. Clean. Prod.* **2023**, *404*, 136993. [CrossRef]
55. Cao, D.; Ji, J.; Liu, Q.; He, Z.; Wang, H.; You, Z. Coal Gangue Applied to Low-Volume Roads in China. *Transp. Res. Rec.* **2011**, *2204*, 258–266. [CrossRef]
56. Li, Y.; Zhang, J.; Yan, C.; Bold, T.; Wang, J.; Cui, K. Effect of activated coal gangue on the hydration and hardening of Portland cement. *Constr. Build. Mater.* **2024**, *422*, 135740. [CrossRef]
57. Wang, Y.; Wang, Y.; Nian, P.; Wang, W.; Wei, D.; Xu, N.; Wu, Z.; Zhu, T.; Wei, Y. Reaction-bonded robust SiC ceramic membranes sintered at low temperature with coal gangue. *Ceram. Int.* **2023**, *49*, 19798–19805. [CrossRef]
58. Li, Y.; Liu, S.; Guan, X. Multitechnique investigation of concrete with coal gangue. *Constr. Build. Mater.* **2021**, *301*, 124114. [CrossRef]
59. Zhang, J.; Chen, T.; Gao, X. Incorporation of self-ignited coal gangue in steam cured precast concrete. *J. Clean. Prod.* **2021**, *292*, 126004. [CrossRef]
60. Yu, L.; Xia, J.; Xia, Z.; Gu, J.; Xu, H.; Wang, Y. Axial compressive behavior of basalt and carbon FRP-confined coal gangue concrete. *Constr. Build. Mater.* **2023**, *371*, 130803. [CrossRef]
61. Yu, L.; Xia, J.; Xia, Z.; Chen, M.; Wang, J.; Zhang, Y. Study on the mechanical behavior and micro-mechanism of concrete with coal gangue fine and coarse aggregate. *Constr. Build. Mater.* **2022**, *338*, 127626. [CrossRef]
62. Liu, H.; Bai, G.; Gu, Y.; Yan, F. The influence of coal gangue coarse aggregate on the mechanical properties of concrete columns. *Case Stud. Constr. Mater.* **2022**, *17*, e01315. [CrossRef]
63. Zhang, T.; Wen, Q.; Gao, S.; Tang, J. Comparative study on mechanical and environmental properties of coal gangue sand concrete. *Constr. Build. Mater.* **2023**, *400*, 132646. [CrossRef]
64. Xiao, G.; Yang, G.; Jixi, C.; Ruyi, Z. Deterioration mechanism of coal gangue concrete under the coupling action of bending load and freeze–thaw. *Constr. Build. Mater.* **2022**, *338*, 127265. [CrossRef]
65. Al Khazaleh, M.; Kumar, P.K.; Mohamed, M.J.S.; Kandasamy, A. Influence of coarse coal gangue aggregates on properties of structural concrete with nano silica. *Mater. Today Proc.* **2023**, *72*, 2089–2095. [CrossRef]
66. Gao, W.-C.; Zhang, X.-L.; Du, G.-Z.; Ma, Y.-P.; Fan, J.-B.; Geng, Y.; Zhang, H. Shrinkage model for concrete incorporating coal gangue coarse and fine aggregates. *J. Build. Eng.* **2023**, *80*, 107865. [CrossRef]
67. Sun, J.; Liu, S.; Ma, Z.; Qian, H.; Wang, Y.; Al-azzani, H.; Wang, H. Mechanical properties prediction of lightweight coal gangue shotcrete. *J. Build. Eng.* **2023**, *80*, 108088. [CrossRef]
68. Moussadik, A.; Ouzoun, F.; Ez-zaki, H.; Saadi, M.; Diouri, A. Mineralogical study of a binder based on alkali-activated coal gangue. *Mater. Today Proc.* **2023**, 260256556. [CrossRef]

69. Luo, L.; Li, K.; Fu, W.; Liu, C.; Yang, S. Preparation, characteristics and mechanisms of the composite sintered bricks produced from shale, sewage sludge, coal gangue powder and iron ore tailings. *Constr. Build. Mater.* **2020**, *232*, 117250. [CrossRef]
70. Qiu, J.; Cheng, K.; Zhang, R.; Gao, Y.; Guan, X. Study on the influence mechanism of activated coal gangue powder on the properties of filling body. *Constr. Build. Mater.* **2022**, *345*, 128071. [CrossRef]
71. Cheng, Y.; Shen, H.; Zhang, J. Understanding the effect of high-volume fly ash on micro-structure and mechanical properties of cemented coal gangue paste backfill. *Constr. Build. Mater.* **2023**, *378*, 131202. [CrossRef]
72. Jiu, S.; Cheng, S.; Li, H.; Wang, L. Reaction mechanism of metakaolin materials prepared by calcining coal gangue. *Mater. Res. Express* **2021**, *8*, 015508. [CrossRef]
73. Cai, B.; Li, K.; Fu, F. Flexural behavior of steel fiber-reinforced coal gangue aggregate concrete beams. *Structures* **2023**, *52*, 131–145. [CrossRef]
74. Cao, Z.; Cao, Y.; Dong, H.; Zhang, J.; Sun, C. Effect of calcination condition on the microstructure and pozzolanic activity of calcined coal gangue. *Int. J. Miner. Process.* **2016**, *146*, 23–28. [CrossRef]
75. Guan, X.; Chen, J.; Zhu, M.; Gao, J. Performance of microwave-activated coal gangue powder as auxiliary cementitious mate-rial. *J. Mater. Res. Technol.* **2021**, *14*, 2799–2811. [CrossRef]
76. Li, Y.; Yao, Y.; Liu, X.; Sun, H.; Ni, W. Improvement on pozzolanic reactivity of coal gangue by integrated thermal and chemical activation. *Fuel* **2013**, *109*, 527–533. [CrossRef]
77. Zhao, Y.; Yang, C.; Qu, F.; Li, K.; Yang, J.; Wu, Z. Mechanical Properties and Drying Shrinkage of Alkali-Activated Coal Gangue Concrete. *Sustainability* **2022**, *14*, 14736. [CrossRef]
78. Zhang, X.; Xiao, Y.; Wang, T.; Xia, J.; Lu, M.; Xue, Y. Kill two birds with one stone: Contribution of steel slag on enhancing the performance of coal gangue-based cementitious materials and simultaneous sulfur fixation. *J. Environ. Chem. Eng.* **2023**, *11*, 111169. [CrossRef]
79. Wang, J.; Qin, Q.; Hu, S.; Wu, K. A concrete material with waste coal gangue and fly ash used for farmland drainage in high groundwater level areas. *J. Clean. Prod.* **2016**, *112*, 631–638. [CrossRef]
80. Gao, S.; Zhao, G.; Guo, L.; Zhou, L.; Yuan, K. Utilization of coal gangue as coarse aggregates in structural concrete. *Constr. Build. Mater.* **2021**, *268*, 121212. [CrossRef]
81. Qin, L.; Gao, X. Properties of coal gangue-Portland cement mixture with carbonation. *Fuel* **2019**, *245*, 1–12. [CrossRef]
82. Zhang, X.; Pang, S.; Su, L.; Geng, J.; Cai, G.; Liu, J. Triaxial mechanical properties and microscopic characterization of fiber-reinforced cement stabilized aeolian sand–coal gangue blends. *Constr. Build. Mater.* **2022**, *346*, 128481. [CrossRef]
83. Wang, C.; Duan, D.; Huang, D.; Chen, Q.; Tu, M.; Wu, K.; Wang, D. Lightweight ceramsite made of recycled waste coal gangue & municipal sludge: Particular heavy metals, physical performance and human health. *J. Clean. Prod.* **2022**, *376*, 134309. [CrossRef]
84. Liu, S.; Jin, J.; Yu, H.; Gao, Y.; Du, Y.; Sun, X.; Qian, G. Performance enhancement of modified asphalt via coal gangue with microstructure control. *Constr. Build. Mater.* **2023**, *367*, 130287. [CrossRef]
85. Li, J.; Cao, Y.; Sha, A.; Song, R.; Li, C.; Wang, Z. Prospective application of coal gangue as filler in fracture-healing behavior of asphalt mixture. *J. Clean. Prod.* **2022**, *373*, 133738. [CrossRef]
86. Dong, J.; Li, J.; Huang, Y.; Zhong, J.; Dun, K.; Wu, M.; Zhang, L.; Chen, Q.; Pan, B. Understanding the release, migration, and risk of heavy metals in coal gangue: An approach by combining experimental and computational investigations. *J. Hazard. Mater.* **2024**, *461*, 132707. [CrossRef]
87. Li, J.; Wang, J. Comprehensive utilization and environmental risks of coal gangue: A review. *J. Clean. Prod.* **2019**, *239*, 117946. [CrossRef]
88. Wang, J.L.; Hu, S.R.; Peng, J.C.; Zhang, Y.X.; Tong, W.B.; Chen, M.; Ji, C. Research Environmental Pollution and Management of Coal Gangue in Pingdingshan. *Adv. Mater. Res.* **2013**, *807–809*, 750–755. [CrossRef]
89. Du, Z.; Hong, X.; Yang, K.; Wang, Z.; Zhang, Y.; Wang, X.; Zhang, L.; Zhu, Y. Enrichment characteristics of polycyclic aromatic hydrocarbons in coal gangue of the Huaibei Coalfield, China. *Environ. Technol. Innov.* **2024**, *36*, 103769. [CrossRef]
90. Paoli, L.; Guttová, A.; Grassi, A.; Lackovičová, A.; Senko, D.; Loppi, S. Biological effects of airborne pollutants released during cement production assessed with lichens (SW Slovakia). *Ecol. Indic.* **2014**, *40*, 127–135. [CrossRef]
91. Li, J.; Feng, H.; Liu, Y.; Zhang, J.; Ma, Y.; Ma, T. Determining the optimal gradation of mixed recycled aggregate containing coal gangue brick aggregate. *Case Stud. Constr. Mater.* **2024**, *20*, e02968. [CrossRef]
92. Zhu, M.; Wang, H.; Liu, L.; Ji, R.; Wang, X. Preparation and characterization of permeable bricks from gangue and tailings. *Constr. Build. Mater.* **2017**, *148*, 484–491. [CrossRef]
93. Zhou, C.; Liu, G.; Cheng, S.; Fang, T.; Lam, P.K.S. The Environmental Geochemistry of Trace Elements and Naturally Radionuclides in a Coal Gangue Brick-Making Plant. *Sci. Rep.* **2014**, *4*, 6221. [CrossRef] [PubMed]
94. Zhang, Y.; Ling, T.-C. Reactivity activation of waste coal gangue and its impact on the properties of cement-based materials—A review. *Constr. Build. Mater.* **2020**, *234*, 117424. [CrossRef]
95. Cui, J.P.; Liu, Y.; Wang, Z.H.; Gong, X.Z.; Gao, F.; Zhao, L.L.; Hao, L. Life Cycle Assessment of Cement Clinker Production Using Coal Gangue as Alternative Raw Material and Fuel. *Mater. Sci. Forum* **2015**, *814*, 435–440. [CrossRef]
96. Zhao, J.; Liu, Q.; Long, B.; Cheng, Z.; Wang, H.; Wang, D. Utilization of coal gangue power generation industry by-product CFA in cement: Workability, rheological behavior and microstructure of blended cement paste. *Fuel* **2023**, *345*, 128185. [CrossRef]

97. Huang, X.; Jin, X.; Dong, L.; Li, R.; Yang, K.; Li, Y.; Deng, L.; Che, D. CPFD numerical study on tri-combustion characteristics of coal, biomass and oil sludge in a circulating fluidized bed boiler. *J. Energy Inst.* **2024**, *113*, 101550. [CrossRef]
98. Yuansheng, H.; Mengshu, S. What are the environmental advantages of circulating fluidized bed technology?—A case study in China. *Energy* **2021**, *220*, 119711. [CrossRef]
99. Yan, Y. Analysis and Discussion on Burning Low Calorific Value Fuel of Circulating Fluidized Bed Boiler. *E3S Web Conf.* **2021**, *329*, 01074. [CrossRef]
100. Peng, H.; Li, Y.; Jia, X. Experimental study on thermoelectric generation Device based on accumulated temperature waste heat of coal gangue. *Energy Rep.* **2022**, *8*, 210–219. [CrossRef]
101. Zhang, H.; Shu, Y.; Yue, S.; Yu, W.; Zhang, Y.; Wang, X. Process design and optimization on self-sustaining pyrolysis and carbonization of ultra-low calorific value coal gangue. *Sustain. Energy Technol. Assess.* **2023**, *60*, 103491. [CrossRef]
102. Zhou, X.; Guo, L.; Zhang, Y.; Wang, Z.; Ma, Y.; Li, X. Feasibility investigation of utilizing spontaneous combustion energy of abandoned coal gangue by constructing a novel artificial heat reservoir. *J. Clean. Prod.* **2022**, *373*, 133948. [CrossRef]
103. Liu, L.; Liu, Q.; Zhang, S.; Li, Y.; Yang, L. The thermal transformation behavior and products of pyrite during coal gangue combustion. *Fuel* **2022**, *324*, 124803. [CrossRef]
104. Zhou, C.; Liu, G.; Yan, Z.; Fang, T.; Wang, R. Transformation behavior of mineral composition and trace elements during coal gangue combustion. *Fuel* **2012**, *97*, 644–650. [CrossRef]
105. Wang, S.; Luo, K.; Wang, X.; Sun, Y. Estimate of sulfur, arsenic, mercury, fluorine emissions due to spontaneous combustion of coal gangue: An important part of Chinese emission inventories. *Environ. Pollut.* **2016**, *209*, 107–113. [CrossRef]
106. Zhou, C.; Liu, G.; Xu, Z.; Sun, H.; Lam, P.K.S. The retention mechanism, transformation behavior and environmental implication of trace element during co-combustion coal gangue with soybean stalk. *Fuel* **2017**, *189*, 32–38. [CrossRef]
107. Yang, Z.; Zhang, Y.; Liu, L.; Wang, X.; Zhang, Z. Environmental investigation on co-combustion of sewage sludge and coal gangue: SO2, NOx and trace elements emissions. *Waste Manag.* **2016**, *50*, 213–221. [CrossRef] [PubMed]
108. Huo, X.; Jia, X.; Song, C.; Yun, F.; Hao, S.; Ding, Y.; Liu, S.; Lei, M. Investigation of mitigation of nitric oxide emission characteristics and slagging properties from biomass combustion by the additive of coal gangue. *J. Environ. Chem. Eng.* **2022**, *10*, 107573. [CrossRef]
109. Liu, L.; Ren, S.; Yang, J.; Jiang, D.; Guo, J.; Pu, Y.; Meng, X. Experimental study on K migration, ash fouling/slagging behaviors and CO2 emission during co-combustion of rice straw and coal gangue. *Energy* **2022**, *251*, 123950. [CrossRef]
110. Ma, Z.; Cheng, L.; Li, L.; Luo, G.; Zhang, W.; Wu, Y. Pollutant emission and attrition performance of low calorific blended coals during co-combustion in fluidized bed. *Fuel* **2023**, *331*, 125782. [CrossRef]
111. Bi, H.; Wang, C.; Lin, Q.; Jiang, X.; Jiang, C.; Bao, L. Combustion behavior, kinetics, gas emission characteristics and artificial neural network modeling of coal gangue and biomass via TG-FTIR. *Energy* **2020**, *213*, 118790. [CrossRef]
112. Shafizadeh, A.; Shahbeik, H.; Rafiee, S.; Fardi, Z.; Karimi, K.; Peng, W.; Chen, X.; Tabatabaei, M.; Aghbashlo, M. Machine learning-enabled analysis of product distribution and composition in biomass-coal co-pyrolysis. *Fuel* **2024**, *355*, 129464. [CrossRef]
113. Zhang, Y.; Zhao, J.; Ma, Z.; Yang, F.; Cheng, F. Effect of oxygen concentration on oxy-fuel combustion characteristic and interactions of coal gangue and pine sawdust. *Waste Manag.* **2019**, *87*, 288–294. [CrossRef]
114. Zhang, Y.; Zhang, Z.; Zhu, M.; Cheng, F.; Zhang, D. Interactions of coal gangue and pine sawdust during combustion of their blends studied using differential thermogravimetric analysis. *Bioresour. Technol.* **2016**, *214*, 396–403. [CrossRef] [PubMed]
115. Niu, Y.; Hu, Y.; Wang, W. Co-gasification of coal gangue and pine sawdust on a self-made two-stage fixed bed: Effect of mixing ratio. *Int. J. Hydrogen Energy* **2022**, *47*, 21713–21724. [CrossRef]
116. Zhang, Y.; Li, W.; Cheng, X.; Yan, K.; Zhao, W.; Yang, F. Air and oxy-fuel combustion characteristics of coal gangue and weathered coal blends. *Energy* **2023**, *284*, 128660. [CrossRef]
117. Wu, M.; Li, H.; Wang, L.; Feng, S.; Wang, Y.; Yang, N.; Wang, K.; Yu, M. Investigation on coal/coal gangue mixtures co-combustion via TG-DSC tests, multicomponent reaction model, and artificial neural network. *Fuel* **2024**, *359*, 130443. [CrossRef]
118. Li, J.; Hu, X.; Qiao, X. Thermogravimetric experimental study on the co-combustion of coal gangue and polypropylene. *Thermochim. Acta* **2023**, *732*, 179660. [CrossRef]
119. Bi, H.; Ni, Z.; Tian, J.; Wang, C.; Jiang, C.; Zhou, W.; Bao, L.; Sun, H.; Lin, Q. Influence of biomass on multi-component reaction model and combustion products of coal gangue. *Combust. Flame* **2022**, *240*, 111999. [CrossRef]
120. Zhu, B.; Dong, X.; Fan, Y.; Ma, X.; Fu, Y.; Chang, M.; Xue, H. Investigation on pyrolysis mechanism and emission characteristics of CO_2, NOx and SO_2 during co-pyrolysis of coal gangue and sodium alginate/sodium carboxymethylcellulose/chitosan/guar gum. *Fuel* **2024**, *356*, 129600. [CrossRef]
121. Bi, H.; Ni, Z.; Jiang, C.; Zhou, W.; Sun, H.; Lin, Q.; He, L. Thermal degradation of cellulose and coal gangue based on lumped reaction model and principal component analysis. *Combust. Flame* **2022**, *245*, 112290. [CrossRef]
122. Bi, H.; Ni, Z.; Tian, J.; Wang, C.; Jiang, C.; Zhou, W.; Bao, L.; Sun, H.; Lin, Q. The effect of biomass addition on pyrolysis characteristics and gas emission of coal gangue by multi-component reaction model and TG-FTIR-MS. *Sci. Total Environ.* **2021**, *798*, 149290. [CrossRef] [PubMed]

123. Bi, H.; Wang, C.; Lin, Q.; Jiang, X.; Jiang, C.; Bao, L. Pyrolysis characteristics, artificial neural network modeling and environmental impact of coal gangue and biomass by TG-FTIR. *Sci. Total Environ.* **2021**, *751*, 142293. [CrossRef]
124. Ni, Z.; Bi, H.; Jiang, C.; Tian, J.; Sun, H.; Zhou, W.; Lin, Q. Research on the co-pyrolysis of coal gangue and coffee industry residue based on machine language: Interaction, kinetics, and thermodynamics. *Sci. Total Environ.* **2022**, *804*, 150217. [CrossRef] [PubMed]
125. Bi, H.; Ni, Z.; Tian, J.; Jiang, C.; Sun, H.; Lin, Q. Influence of lignin on coal gangue pyrolysis and gas emission based on multi-lump parallel reaction model and principal component analysis. *Sci. Total Environ.* **2022**, *820*, 153083. [CrossRef] [PubMed]
126. Hobson, D.M.; Carter, R.; Yan, Y.; Lv, Z. Differentiation between Coal and Stone through Image Analysis of Texture Features. In Proceedings of the 2007 IEEE International Workshop on Imaging Systems and Techniques, Krakow, Poland, 5 May 2007; pp. 1–4. [CrossRef]
127. Zhang, Y.; Nakano, J.; Liu, L.; Wang, X.; Zhang, Z. Trace element partitioning behavior of coal gangue-fired CFB plant: Experimental and equilibrium calculation. *Environ. Sci. Pollut. Res.* **2015**, *22*, 15469–15478. [CrossRef] [PubMed]
128. Su, R.J. Study and Analysis on Pollution of Expanding Project of Coal Gangue Power Plant. *Adv. Mater. Res.* **2012**, *485*, 518–521. [CrossRef]
129. Kumari, M.; Bhattacharya, T. A review on bioaccessibility and the associated health risks due to heavy metal pollution in coal mines: Content and trend analysis. *Environ. Dev.* **2023**, *46*, 100859. [CrossRef]
130. Dai, R.; Zhao, R.; Wang, Z.; Qin, J.; Chen, T.; Wu, J. Study on the oxy-fuel co-combustion of coal gangue and semicoke and the pollutants emission characteristics. *J. Fuel Chem. Technol.* **2022**, *50*, 152–159. [CrossRef]
131. Chuncai, Z.; Guijian, L.; Dun, W.; Ting, F.; Ruwei, W.; Xiang, F. Mobility behavior and environmental implications of trace elements associated with coal gangue: A case study at the Huainan Coalfield in China. *Chemosphere* **2014**, *95*, 193–199. [CrossRef]
132. Hua, C.; Zhou, G.; Yin, X.; Wang, C.; Chi, B.; Cao, Y.; Wang, Y.; Zheng, Y.; Cheng, Z.; Li, R. Assessment of heavy metal in coal gangue: Distribution, leaching characteristic and potential ecological risk. *Environ. Sci. Pollut. Res.* **2018**, *25*, 32321–32331. [CrossRef]
133. Halecki, W.; Klatka, S. Long term growth of crop plants on experimental plots created among slag heaps. *Ecotoxicol. Environ. Saf.* **2018**, *147*, 86–92. [CrossRef]
134. Song, W.; Xu, R.; Li, X.; Min, X.; Zhang, J.; Zhang, H.; Hu, X.; Li, J. Soil reconstruction and heavy metal pollution risk in reclaimed cultivated land with coal gangue filling in mining areas. *CATENA* **2023**, *228*, 107147. [CrossRef]
135. Guo, G.; Li, H.; Zha, J. An approach to protect cultivated land from subsidence and mitigate contamination from colliery gangue heaps. *Process Saf. Environ. Prot.* **2019**, *124*, 336–344. [CrossRef]
136. Marchuk, S.; Marchuk, A. Effect of applied potassium concentration on clay dispersion, hydraulic conductivity, pore structure and mineralogy of two contrasting Australian soils. *Soil. Tillage Res.* **2018**, *182*, 35–44. [CrossRef]
137. Li, X.; Zheng, J.; Zheng, K.; Su, F.; Zhao, Z.; Bai, C.; Zheng, T.; Wang, X.; Qiao, Y.; Colombo, P. Rapid fabrication of coal gangue-based alkali activated foams and application as pH regulators. *Mater. Lett.* **2023**, *338*, 134020. [CrossRef]
138. Haghighizadeh, A.; Rajabi, O.; Nezarat, A.; Hajyani, Z.; Haghmohammadi, M.; Hedayatikhah, S.; Delnabi Asl, S.; Aghababai Beni, A. Comprehensive analysis of heavy metal soil contamination in mining Environments: Impacts, monitoring Techniques, and remediation strategies. *Arab. J. Chem.* **2024**, *17*, 105777. [CrossRef]
139. Ge, Q.; Tian, Q.; Wang, S.; Zhu, F. Synergistic effects of phosphoric acid modified hydrochar and coal gangue-based zeolite on bioavailability and accumulation of cadmium and lead in contaminated soil. *Chin. J. Chem. Eng.* **2022**, *46*, 150–160. [CrossRef]
140. Zhu, X.; Gong, W.; Li, W.; Bai, X.; Zhang, C. Reclamation of waste coal gangue activated by Stenotrophomonas maltophilia for mine soil improvement: Solubilizing behavior of bacteria on nutrient elements. *J. Environ. Manag.* **2022**, *320*, 115865. [CrossRef] [PubMed]
141. Tong, W.; Ying, W.; Jun, W. Research on Potential Fertilization of Coal Gangue in the Weibei Coalfield, China. *Acta Geol. Sin.-Engl. Ed.* **2008**, *82*, 717–721. [CrossRef]
142. Lv, B.; Zhao, Z.; Deng, X.; Fang, C.; Dong, B.; Zhang, B. Sustainable and clean utilization of coal gangue: Activation and preparation of silicon fertilizer. *J. Mater. Cycles Waste Manag.* **2022**, *24*, 1579–1590. [CrossRef]
143. Wang, B.; Ma, Y.; Lee, X.; Wu, P.; Liu, F.; Zhang, X.; Li, L.; Chen, M. Environmental-friendly coal gangue-biochar composites reclaiming phosphate from water as a slow-release fertilizer. *Sci. Total Environ.* **2021**, *758*, 143664. [CrossRef]
144. Wu, H.; Kang, S.; Zhang, H.; Sun, Q.; Shen, R.; Shu, Z. Research of the workability, mechanical and hydration mechanism of coal gangue-construction solid waste backfilling materials. *Constr. Build. Mater.* **2023**, *408*, 133833. [CrossRef]
145. Chu, Z.; Wang, X.; Wang, Y.; Zha, F.; Dong, Z.; Fan, T.; Xu, X. Influence of coal gangue aided phytostabilization on metal availability and mobility in copper mine tailings. *Environ. Earth Sci.* **2020**, *79*, 68. [CrossRef]
146. Tang, Q.; Li, L.; Zhang, S.; Zheng, L.; Miao, C. Characterization of heavy metals in coal gangue-reclaimed soils from a coal mining area. *J. Geochem. Explor.* **2018**, *186*, 1–11. [CrossRef]
147. Zhang, P.; Han, Z.; Jia, J.; Wei, C.; Liu, Q.; Wang, X.; Zhou, J.; Li, F.; Miao, S. Occurrence and Distribution of Gallium, Scandium, and Rare Earth Elements in Coal Gangue Collected from Junggar Basin, China. *Int. J. Coal Prep. Util.* **2019**, *39*, 389–402. [CrossRef]
148. Zhang, Y.; Sun, J.; Lü, G.; Zhang, T.; Gong, Y. Kinetics of alumina extraction from coal gangue by hydrochloric acid leaching. *Trans. Nonferrous Met. Soc. China* **2023**, *33*, 1932–1942. [CrossRef]
149. Miao, H.; Wang, Z.; Wang, Z.; Sun, H.; Li, X.; Liu, Z.; Dong, L.; Zhao, J.; Huang, J.; Fang, Y. Effects of Na_2CO_3/Na_2SO_4 on catalytic gasification reactivity and mineral structure of coal gangue. *Energy* **2022**, *255*, 124498. [CrossRef]

150. Xie, M.; Liu, F.; Zhao, H.; Ke, C.; Xu, Z. Mineral phase transformation in coal gangue by high temperature calcination and high-efficiency separation of alumina and silica minerals. *J. Mater. Res. Technol.* **2021**, *14*, 2281–2288. [CrossRef]
151. Peng, B.; Li, X.; Zhao, W.; Yang, L. Study on the release characteristics of chlorine in coal gangue under leaching conditions of different pH values. *Fuel* **2018**, *217*, 427–433. [CrossRef]
152. Liu, F.; Xie, M.; Yu, G.; Ke, C.; Zhao, H. Study on Calcination Catalysis and the Desilication Mechanism for Coal Gangue. *ACS Sustain. Chem. Eng.* **2021**, *9*, 10318–10325. [CrossRef]
153. Zhang, K.; Liu, L.; Liu, L.; Yang, Y.; Liu, Q. Iron removal from kaolinitic coal gangue via magnetic separation after oxidizing calcination with the crystal structure of kaolinite protected. *Mater. Today Commun.* **2023**, *37*, 107175. [CrossRef]
154. Qin, Q.; Geng, H.; Deng, J.; Xu, H.; Ye, Y.; Li, B.; Gui, X.; Park, C. Waste-free technologies of coal gangue processing: Extraction of metals and improvement of soil. *Sep. Purif. Technol.* **2025**, *361*, 131203. [CrossRef]
155. Wang, H.; Cao, Z.; Wang, J.; Wang, Z.; Chen, J.; Shen, L. Alkali Methods for Alumina Extraction from the By-products of High Alumina Coal: A Review. *Min. Metall. Explor.* **2023**, *40*, 1681–1694. [CrossRef]
156. Xiao, J.; Li, F.; Zhong, Q.; Bao, H.; Wang, B.; Huang, J.; Zhang, Y. Separation of aluminum and silica from coal gangue by elevated temperature acid leaching for the preparation of alumina and SiC. *Hydrometallurgy* **2015**, *155*, 118–124. [CrossRef]
157. Miao, H.; Wang, Z.; Sun, H.; Li, X.; Mei, Y.; Liu, Z.; Dong, L.; Huang, J.; Bai, J.; Fang, Y. Gasification and activation behaviors of coal gangue with Na2CO3 in CO2 atmosphere. *Fuel Process. Technol.* **2022**, *228*, 107163. [CrossRef]
158. Dai, S.; Sun, F.; Wang, L.; Wang, L.; Zhang, R.; Guo, H.; Xing, Y.; Gui, X. A new method for pre-enrichment of gallium and lithium based on mode of occurrence in coal gangue from Antaibao surface mine, Shanxi Province, China. *J. Clean. Prod.* **2023**, *425*, 138968. [CrossRef]
159. Zhu, X.; Gong, W.; Li, W.; Zhang, C. Fixating lead in coal gangue with phosphate using phosphate-dissolving bacteria: Phosphorus dissolving characteristics of bacteria and adsorption mechanism of extracellular polymer. *J. Hazard. Mater.* **2023**, *458*, 131923. [CrossRef]
160. Du, S.; Mao, S.; Guo, F.; Dong, K.; Shu, R.; Bai, J.; Xu, L.; Li, D. Investigation of the catalytic performance of coal gangue char on biomass pyrolysis in a thermogravimetric analyzer and a fixed bed reactor. *Fuel* **2022**, *328*, 125216. [CrossRef]
161. Sun, Y.; Yan, Y.; Zheng, X.; Han, J.; Wang, B.; Wu, Q.; Bai, G. Fabrication of dual-activated coal gangue-loaded nickel-based catalyst for dioctyl phthalate hydrogenation. *Mol. Catal.* **2024**, *553*, 113732. [CrossRef]
162. Li, H.; Cheng, R.; Liu, Z.; Du, C. Waste control by waste: Fenton–like oxidation of phenol over Cu modified ZSM–5 from coal gangue. *Sci. Total Environ.* **2019**, *683*, 638–647. [CrossRef] [PubMed]
163. Li, H.; Wang, L.; Liu, Z.; Du, C. Cu, Ag–containing systems based on coal gangue as catalysts for highly efficient antibiotics removal via persulfate activation under visible light irradiation. *J. Environ. Chem. Eng.* **2021**, *9*, 105016. [CrossRef]
164. Zhang, P.; Zhang, H.; Liu, Z.; Du, C. Natural coal gangue activated persulfate for tetracycline hydrochloride degradation: Mechanisms, theoretical calculations, and comparative study. *J. Mol. Struct.* **2023**, *1291*, 136097. [CrossRef]
165. Li, C.; Yin, S.; Yan, Y.; Liang, C.; Ma, Q.; Guo, R.; Zhang, Y.; Deng, J.; Sun, Z. Efficient benzo(a)pyrene degradation by coal gangue-based catalytic material for peroxymonosulfate activation. *J. Environ. Manag.* **2024**, *351*, 119645. [CrossRef] [PubMed]
166. Wang, C.; Yang, Z.; Song, W.; Zhong, Y.; Sun, M.; Gan, T.; Bao, B. Quantifying gel properties of industrial waste-based geopolymers and their application in Pb2+ and Cu2+ removal. *J. Clean. Prod.* **2021**, *315*, 128203. [CrossRef]
167. Duan, D.; Wang, C.; Bai, D.; Huang, D. Representative coal gangue in China: Physical and chemical properties, heavy metal coupling mechanism and risk assessment. *Sustain. Chem. Pharm.* **2024**, *37*, 101402. [CrossRef]
168. Wu, H.; Wen, Q.; Hu, L.; Gong, M.; Tang, Z. Feasibility study on the application of coal gangue as landfill liner material. *Waste Manag.* **2017**, *63*, 161–171. [CrossRef] [PubMed]
169. Sun, G.; Zhang, J.; Li, X.; Hao, B.; Xu, F.; Liu, K. Reuse of coal gangue to prepare adsorbent with multiscale pore structure for emulsified water removal. *Inorg. Chem. Commun.* **2023**, *151*, 110632. [CrossRef]
170. Zhou, L.; Zhou, H.; Hu, Y.; Yan, S.; Yang, J. Adsorption removal of cationic dyes from aqueous solutions using ceramic adsorbents prepared from industrial waste coal gangue. *J. Environ. Manag.* **2019**, *234*, 245–252. [CrossRef] [PubMed]
171. Wu, J.; Yan, X.; Li, L.; Gu, J.; Zhang, T.; Tian, L.; Su, X.; Lin, Z. High-efficiency adsorption of Cr(VI) and RhB by hierarchical porous carbon prepared from coal gangue. *Chemosphere* **2021**, *275*, 130008. [CrossRef] [PubMed]
172. Zhao, R.; Wang, B.; Zhang, X.; Lee, X.; Chen, M.; Feng, Q.; Chen, S. Insights into Cr(VI) removal mechanism in water by facile one-step pyrolysis prepared coal gangue-biochar composite. *Chemosphere* **2022**, *299*, 134334. [CrossRef] [PubMed]
173. Yan, K.; Zhang, J.; Liu, D.; Meng, X.; Guo, Y.; Cheng, F. Feasible synthesis of magnetic zeolite from red mud and coal gangue: Preparation, transformation and application. *Powder Technol.* **2023**, *423*, 118495. [CrossRef]
174. Abdelwahab, O.; Thabet, W.M. Natural zeolites and zeolite composites for heavy metal removal from contaminated water and their applications in aquaculture Systems: A review. *Egypt. J. Aquat. Res.* **2023**, *49*, 431–443. [CrossRef]
175. Mohammadi, R.; Azadmehr, A.; Maghsoudi, A. Enhanced competitive adsorption of zinc and manganese by alginate-iron oxide-combusted coal gangue composite: Synthesizing, characterization and investigation. *J. Environ. Chem. Eng.* **2021**, *9*, 105003. [CrossRef]
176. Lv, B.; Dong, B.; Zhang, C.; Chen, Z.; Zhao, Z.; Deng, X.; Fang, C. Effective adsorption of methylene blue from aqueous solution by coal gangue-based zeolite granules in a fluidized bed: Fluidization characteristics and continuous adsorption. *Powder Technol.* **2022**, *408*, 117764. [CrossRef]

177. Qiu, R.; Cheng, F.; Huang, H. Removal of Cd2+ from aqueous solution using hydrothermally modified circulating fluidized bed fly ash resulting from coal gangue power plant. *J. Clean. Prod.* **2018**, *172*, 1918–1927. [CrossRef]
178. Zhao, B.-H.; Zhu, Y.-H.; Wang, C. Degradation of humic acid via peroxymonosulfate activation by $FeCo_2O_4$ nanoparticles supported on modified coal gangue. *Inorg. Chem. Commun.* **2023**, *152*, 110736. [CrossRef]
179. Li, H.; Zheng, F.; Wang, J.; Zhou, J.; Huang, X.; Chen, L.; Hu, P.; Gao, J.; Zhen, Q.; Bashir, S.; et al. Facile preparation of zeolite-activated carbon composite from coal gangue with enhanced adsorption performance. *Chem. Eng. J.* **2020**, *390*, 124513. [CrossRef]
180. Yang, F.; Lv, J.; Zheng, Y.; Cui, J.; Huang, Y.; Cao, X.; Liu, H.; Zhao, L. Enhancement of coal gangue performance by surface micro-crystalline glaze derived from mineral powder. *Sci. Total Environ.* **2023**, *858*, 159986. [CrossRef]
181. Zhao, G.; Chang, F.; Chen, J.; Si, G. Research and prospect of underground intelligent coal gangue sorting technology: A review. *Miner. Eng.* **2024**, *215*, 108818. [CrossRef]
182. Li, X.; Wang, H.; Zhou, Q.; Qi, T.; Liu, G.; Peng, Z. Efficient separation of silica and alumina in simulated CFB slag by reduction roasting-alkaline leaching process. *Waste Manag.* **2019**, *87*, 798–804. [CrossRef] [PubMed]
183. Qin, Q.; Geng, H.; Deng, J.; Su, X.; Chen, M.; Park, C.B. Al and other critical metals co-extraction from coal gangue through delamination pretreatment and recycling strategies. *Chem. Eng. J.* **2023**, *477*, 147036. [CrossRef]
184. Li, C.; Zheng, L.; Jiang, C.; Chen, X.; Ding, S. Characteristics of leaching of heavy metals from low-sulfur coal gangue under different conditions. *Int. J. Coal Sci. Technol.* **2021**, *8*, 780–789. [CrossRef]
185. Dong, L.; Li, Y.; Yan, J.; Shu, X.Q. Efficient Extraction of SiO_2 and Al_2O_3 from Coal Gangue by Means of Acidic Leaching. *Adv. Mater. Res.* **2014**, *878*, 149–156. [CrossRef]