

Review

Coal Gangue: Sources, Environmental Risks, and Advances in Resource Utilization

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Abstract

Coal gangue, a major by-product of coal mining, has long posed significant environmental and resource management challenges. With increasing global emphasis on energy transition and environmental sustainability, the comprehensive utilization of coal gangue has emerged as a critical research and policy priority. This review systematically examines the sources, characteristics, environmental impacts, and integrated utilization pathways of coal gangue. First, the formation mechanisms, mineralogical composition, and physico-chemical properties of coal gangue are summarized, with particular attention to hazardous constituents and associated environmental risks, including soil and groundwater contamination, atmospheric pollution, and ecological degradation. Subsequently, current technological approaches for coal gangue management and comprehensive utilization are evaluated, including subsidence areas reclamation and underground backfilling, applications in construction materials and energy conversion, extraction of valuable chemical elements and functional materials, ecological soil engineering, and carbon sequestration. The potential contributions of these pathways to waste reduction, resource efficiency, and low-carbon development are critically discussed. Finally, key environmental, technological, and socio-economic considerations influencing sustainable coal gangue utilization are emphasized. This review provides a comprehensive synthesis of existing knowledge and identifies future research directions aimed at advancing environmentally sound, economically viable, and large-scale utilization strategies. The findings are intended to support researchers, policymakers, and industry stakeholders in promoting circular resource systems and sustainable development.

Keywords: coal gangue; resource utilization; environmental impacts; sustainable development

Academic Editor: Olusola Ololade

Received: 29 June 2026

Revised: 20 July 2026

Accepted: 21 July 2026

Published: 24 July 2026

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1. Introduction

Coal remains a pivotal fossil fuel in the global energy landscape. In 2021, worldwide coal production reached approximately 8.17 billion tonnes, with China contributing more than 50% of the total output [1]. While the coal industry underpins the global energy system and plays an important role in socio-economic development, it also generates substantial quantities of coal-based solid wastes. These wastes primarily include coal gangue, fly ash, boiler slag, desulfurization gypsum, coal gasification slag, and coal liquefaction residues [2,3]. Among these by-products, coal gangue and fly ash together account for more than 85% of the total coal-derived solid waste generation. Coal gangue is a dark-grey rock associated with coal seams and produced during coal mining and processing [4,5]. It is characterized by a relatively low carbon content (20–30%), greater hardness than that of raw coal, and a heterogeneous composition dominated by carbonaceous, argillaceous, and sandy shale components. Certain types of coal gangue also contain appreciable amounts of humic substances, including humic acid [6,7].

As a by-product of coal mining and processing, coal gangue typically accounts for 10–25% of raw coal production [8]. It can be broadly classified into three categories: (1) excavation gangue (also referred to as white gangue, ~45%), generated from overburden stripping in open-pit mining and from drifting in semi-coal and rock roadways; (2) mining gangue (or common gangue, ~35%), derived from the roof, floor, and interlayers during coal excavation; (3) washing gangue (or separation gangue, ~20%), separated during coal washing and beneficiation processes [9]. In China, raw coal production reached 4.13 billion tonnes in 2021, representing a 5.7% increase over the previous year and accounting for 56.0% of the nation's total energy consumption [10]. Concurrently, the stockpile has continued to accumulate at an estimated annual rate of approximately 280 million tonnes [11].

Coal gangue constitutes the largest fraction of coal-based solid wastes by volume. Due to its low calorific value and substantial challenges associated with utilization, coal gangue has traditionally been managed through backfilling of mining voids or open dumping in the vicinity of mining areas [12]. However, the presence of combustible components, such as residual coal and carbonaceous mudstone, renders open-air stockpiles susceptible to spontaneous combustion. In addition, wind-driven dispersion of fine particles contributes to airborne particulate pollution [13–15].

Consequently, coal gangue piles are commonly subjected to reclamation measures, such as surface soil covering and vegetation establishment. However, reclamation effectiveness is often limited due to inadequate cover soil thickness, poor water-holding capacity, and insufficient nutrient availability, which collectively inhibit plant growth and ecosystem recovery [16–18]. Furthermore, long-term stockpiling of coal gangue can result in the leaching of potentially toxic elements, including lead (Pb), chromium (Cr), and zinc (Zn), leading to contamination of surrounding soils and groundwater [19–21]. As a result, coal gangue is widely regarded as a significant environmental pollutant [22,23], posing serious threats to local ecological ecosystems and human health [24,25].

Over recent decades, many innovative approaches for the treatment and utilization of coal gangue have been proposed by researchers worldwide, aiming to mitigate its environmental impacts through cross-sectoral applications [26–30]. For example, Huang and Guo [31] demonstrated that concrete produced using coal gangue with appropriate mix ratios exhibited mechanical properties that met engineering standards. Tong, Chen [32] developed an organic, ecological, soilless cultivation substrate using coal gangue and decomposed rapeseed straw, with vegetables grown on this medium meeting food safety standards. Additionally, Kong, Wu [33] successfully synthesized 4A molecular sieves from iron-rich and quartz-bearing coal gangue sourced from the Liupanshui mining area in Guizhou Province, achieving compliance with relevant national standards. These stud-

ies highlight the potential of coal gangue to be transformed from an environmental liability into a value-added resource, thereby contributing to circular economy development. Nevertheless, coal gangue treatment and resource utilization remain constrained by multiple challenges, including technological limitations, policy and regulatory barriers, and economic pressures affecting the long-term sustainability of industrial applications [34–36].

This study presents a systematic review and analysis of coal gangue management and resource utilization pathways. It systematically examines various dimensions, including sources, composition, physicochemical properties, environmental pollution hazards, relevant policies and regulatory frameworks, industrial demands, and resource utilization technologies. Particular emphasis is placed on the current applications and future prospects of coal gangue-based ecological soil, with a focus on assessing the feasibility and sustainability of this emerging resource recovery pathway. By synthesizing and critically analyzing the challenges and opportunities related to coal gangue, this work seeks to provide valuable insights for researchers, policymakers, and industry stakeholders. Ultimately, it aims to promote sustainable development in coal gangue management and resource utilization, contributing to enhanced resource recycling and environmental protection.

2. Coal Gangue Bibliometrics

A comprehensive dataset of Chinese- and English-language publications on coal gangue was compiled using a systematic bibliometric approach. Literature retrieval was conducted in the China National Knowledge Infrastructure (CNKI) and Web of Science (WOS) Core Collection databases using the topic keyword “coal gangue.” All retrieved records were exported in plain-text format and imported into EndNote for reference management. The combined dataset was then subjected to screening and deduplication to ensure data consistency and integrity. The resulting curated dataset served as the basis for subsequent bibliometric analysis. Data visualization and analysis were performed using VOSviewer 1.6.15 [37] and CiteSpace 7.0.1 [38], enabling the analysis of publication trends, collaborative networks, and research hotspots within the coal gangue research field.

2.1. Annual Publication Output

The bibliometric search identified a total of 16,887 Chinese and English publications on “coal gangue” published between 1961 and July 2026, comprising 12,746 Chinese articles and 4141 English articles. Over time, annual publication output exhibited an exponential growth trend from 1960 to 2025, followed by a peak around 2025, with an average of over 500 publications per year. During this period, the proportion of English-language publications increased steadily (Figure 1), indicating a gradual internationalization of coal gangue research. These trends suggest that the study and utilization of coal gangue have attracted sustained scholarly attention and have progressively emerged as a topic of international concern.

2.2. Author Co-Authorship Network

The 16,877 publications included in this analysis were authored by more than 20,000 researchers. Using VOSviewer, co-authorship networks were constructed for authors with more than seven English-language publications or more than eight Chinese-language publications. In the resulting visualization maps (Figure 2), node size represents an author’s publication output, while the thickness of connecting lines reflects the strength of co-authorships. The analysis reveals the formation of several major collaborative clusters, highlighting stable research teams and sustained cooperation within the field. In particular, Professors Zhenqi Hu and Jixiong Zhang from the China University of Mining and

Technology occupy central positions in the networks, indicating their leading roles in coal gangue research in terms of both publication output and collaborative influence.

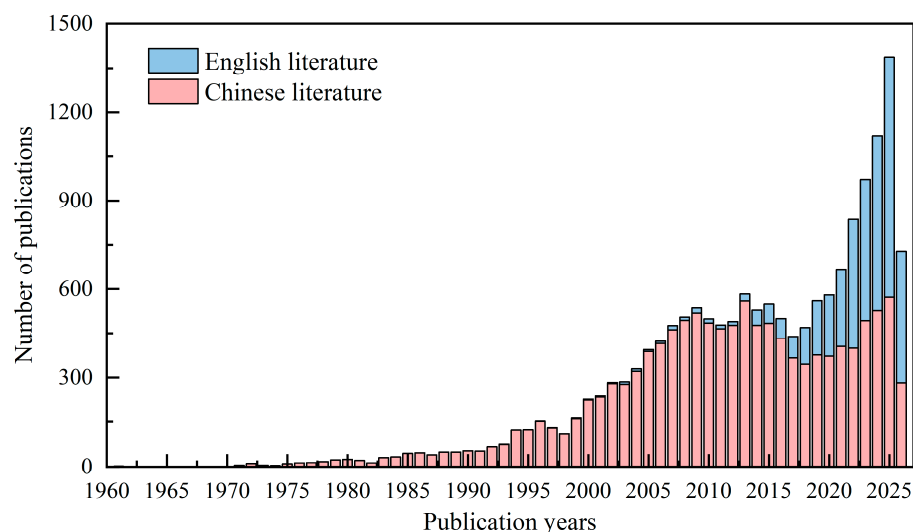


Figure 1. Annual publication volume of Chinese and English-language literature on coal gangue.

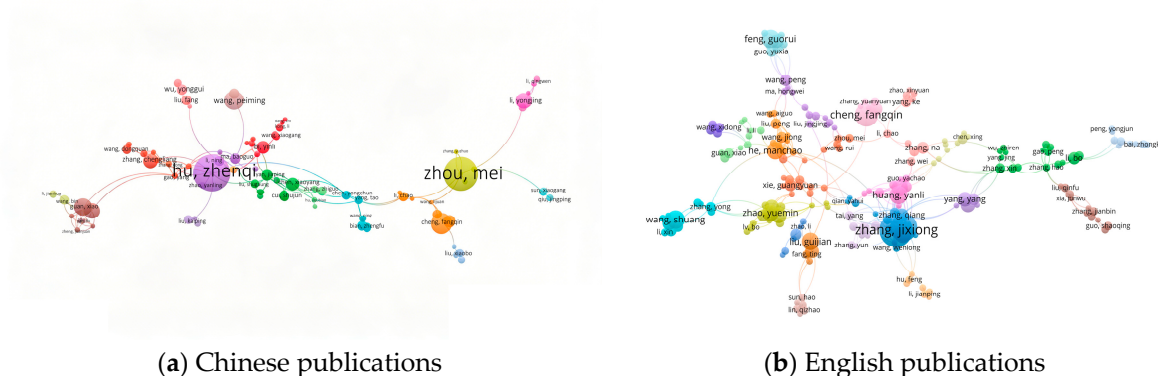


Figure 2. Co-authorship network of coal gangue publications.

2.3. Keyword Co-Occurrence Network

Keyword co-occurrence networks for both Chinese- and English-language coal gangue literature were constructed using VOSviewer (Figure 3). High-frequency keywords identified in the network include comprehensive utilization of coal gangue, fly ash, coal gangue hills (gangue piles), coal gangue bricks, coal gangue power generation, and compressive strength. The prominence of these terms indicates that research in this field has largely focused on the compositional characteristics of coal gangue and its pathways for resource utilization. Overall, the keyword distribution reveals that transforming coal gangue from a waste by-product into a usable resource has emerged as a dominant research theme. This trend reflects the urgent demand within the coal mining industry to address large-scale gangue accumulation and underscores the significance of coal gangue utilization for environmental protection, resource efficiency, and broader socio-economic benefits.

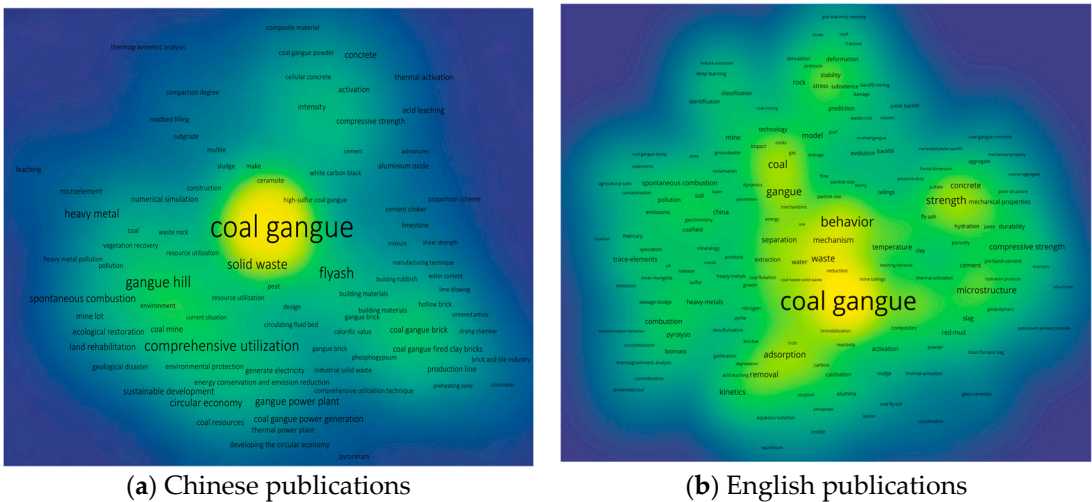


Figure 3. Keyword co-occurrence network in coal gangue research.

2.4. Temporal Trends in Research Topics

Using CiteSpace, a keyword burst detection analysis was conducted to explore the temporal evolution of research themes in coal gangue studies from 1992 to 2026 (Figure 4). In the visualization, blue lines represent the time span during which a keyword appeared in the literature, whereas red segments indicate burst periods, reflecting a rapid increase in research attention. The results reveal a distinct shift in research focus over time. In the early stages, coal gangue research was primarily oriented toward its utilization in construction materials, including hollow bricks, cement, concrete, and wall materials. Since approximately 2000, the dominant research direction has progressively shifted toward soil improvement and ecological remediation applications. This transition reflects changing societal and environmental priorities, moving from waste disposal and material substitution toward ecological restoration and sustainable resource management. At the same time, it also signifies advancements in coal gangue processing technologies and a growing recognition of its potential role in environmental remediation.

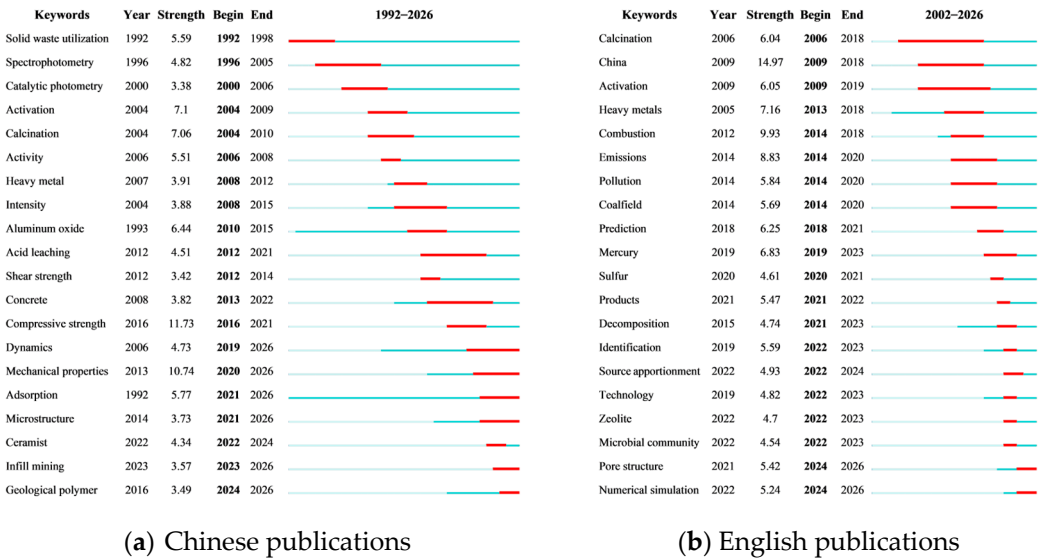


Figure 4. Keywords with the strongest citation bursts.

3. Source, Classification, Composition, Properties, and Hazards of Coal Gangue

3.1. Production and Inventory Distribution of Coal Gangue

Coal gangue generally accounts for 10–25% of raw coal production [8]. Its generation is therefore widespread across global mining regions and has increased steadily with the expansion of global coal extraction activities. Major coal gangue-producing countries include China, the United States, India, and Russia [39,40]. As the world's largest coal producer, China generates particularly large quantities of coal gangue. According to the Statistical Review of World Energy 2025, China's coal production reached 9.23 billion tonnes in 2024, constituting 55.91% of the global total and 62.86% of the combined production of the world's top ten coal-producing countries (Figure 5). Moreover, from 2000 to 2022, both coal production and consumption in China exhibited an overall upward trend. Notably, coal consumption fell below production for the first time in 2022, indicating a potential structural shift in coal supply–demand dynamics (Figure 6).

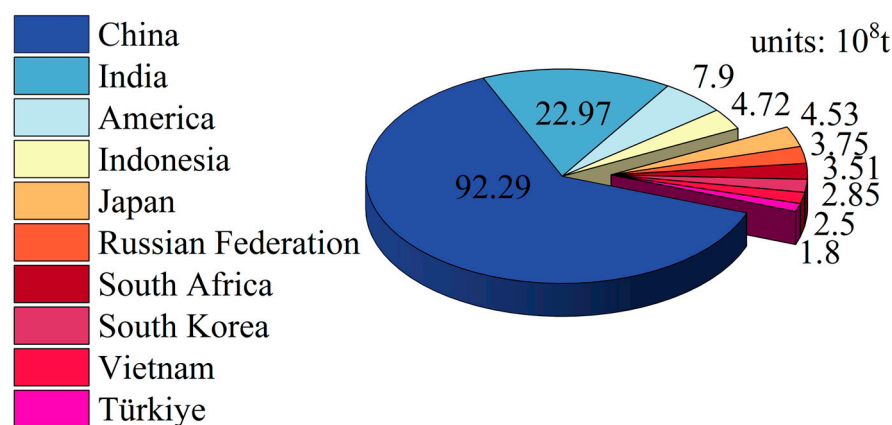


Figure 5. Global coal production and share.

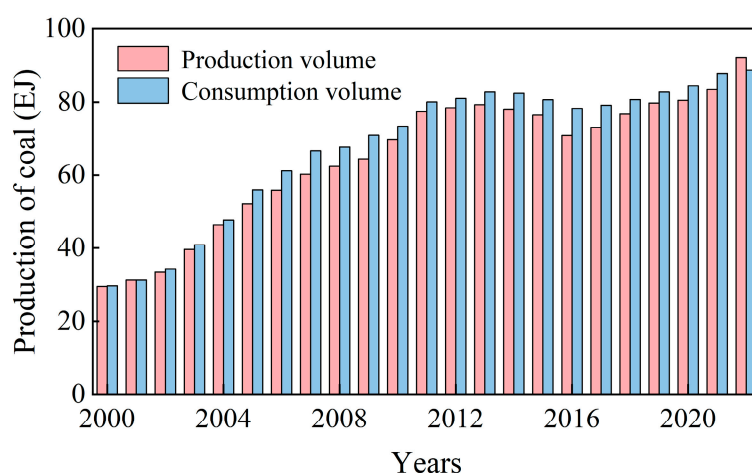


Figure 6. China's Coal Production and Consumption (2000–2022).

The distribution of coal gangue production within China exhibits pronounced regional disparities (Figure 7). Output is particularly high in major coal-producing provinces such as Shanxi, Shaanxi, and Hebei, reflecting their abundant coal resources and long history of mining activities [41]. Large-scale exploitation of northern coalfields, driven by sustained energy demand, has resulted in the generation of substantial quantities of coal gangue. Eastern regions, including Shandong, Anhui, and Jiangsu, also experience considerable gangue production, closely associated with rapid economic develop-

ment and high regional energy consumption. In contrast, coal gangue output in western regions such as Xinjiang, Gansu, and Inner Mongolia has historically been lower, as large-scale coal development commenced later in these areas. Nevertheless, with the ongoing expansion of coal resource exploitation in western China, coal gangue accumulation is emerging as an increasingly prominent environmental and management challenge [42].

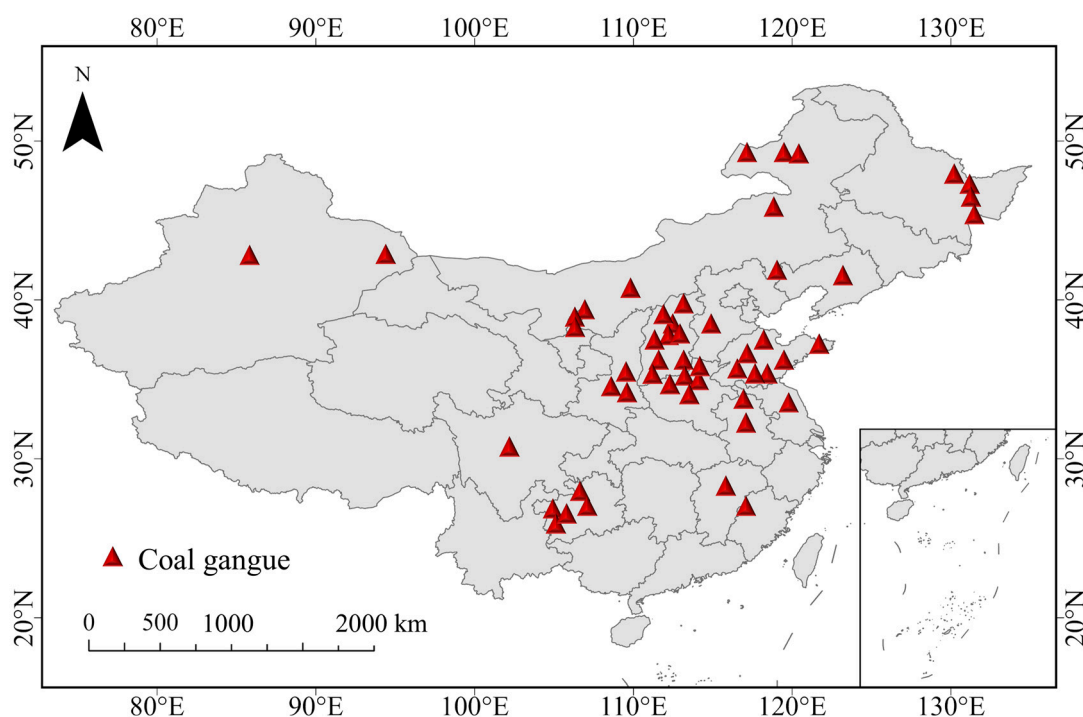


Figure 7. Distribution of coal gangue in China [43].

3.2. Classification of Coal Gangue

Coal gangue is a solid residue generated during coal mining, beneficiation, and associated processing activities. Its appearance typically ranges from gray and black to brown, depending on factors such as organic matter content, mineral composition, and thermal history (e.g., calcination temperature) [44]. Variations in these characteristics reflect differences in geological conditions, mining methods, and post-extraction treatments. Based on its origin, physical and chemical composition, mineralogical constituents, and physicochemical properties, coal gangue can be categorized as follows (Table 1). This classification framework provides a basis for understanding the heterogeneity of coal gangue and is essential for evaluating its environmental risks, utilization potential, and suitability for different resource recovery pathways.

Table 1. Classification of coal gangue types.

Classification Indicators	Types
Source	Coal gangue in coal road
	Rock gangue in rock road
	Burnt gangue
	Washed gangue
	Hand-selected gangue
Color	Strip gangue
	Black coal gangue
	Gray coal gangue
	White coal gangue
	Red coal gangue

Self-ignition property	Coal-burnable gangue
	Non-coal-burnable gangue
Degree of weathering	Not weathered
	Slightly weathered
	Moderately weathered
	Fully weathered
Rock properties	Kaolinite mudstone
	Illite mudstone
	Sandy mudstone
	Sandstone
	Limestone
Organic carbon content (%)	Low-carbon coal gangue (<6)
	Medium-carbon coal gangue (6–20)
	High-carbon coal gangue (>20)
Total sulfur content (%)	Low-sulfur coal gangue (0, 1]
	medium-sulfur coal gangue (1, 3]
	medium-high-sulfur coal gangue (3, 6]
	high-sulfur coal gangue (>6)
Silica-alumina ratio	Low-silica-alumina ratio coal gangue (<0.3)
	Medium-silica-alumina ratio coal gangue (0.3, 0.5]
	High-silica-aluminum ratio coal gangue (>0.5)
Iron mass fraction (%)	Low iron coal gangue (<1)
	Medium iron coal gangue (1, 3.5]
	Sub-high iron coal gangue (3.5, 8]
	High iron coal gangue (8, 18]
	Super high iron coal gangue (>18)
Ash melting point (°C)	Low-temperature coal gangue (<1100)
	Medium-temperature coal gangue (1100, 250]
	High-temperature coal gangue (1250, 1500]
	Extra-high-temperature coal gangue (>1500)
Ash yield (%)	Low-sulfur coal gangue (≤ 70)
	Medium-sulfur coal gangue (70, 85]; High-sulfur coal gangue (>85)
Ash content (%)	Silica-alumina type coal gangue (0, 10]
	Calcium-magnesium type coal gangue (>10)

Note: The data is sourced from [1,45–48].

3.3. Composition and Physicochemical Properties of Coal Gangue

Coal gangue exhibits a highly complex composition, reflecting the diverse impurities and waste materials generated during coal mining and beneficiation processes (Table 2). Its major constituents can be broadly classified into inorganic particles, organic matter, mineral phases, and chemical elements. Inorganic particles mainly include residual coal fragments, rock debris, and fine particulate matter. Organic matter consists primarily of organic carbon, organic nitrogen, and organic sulfur originally present in coal [49]. The mineral fraction comprises both detrital and authigenic minerals inherent to coal-bearing strata, such as quartz, pyrite, dolomite, and kaolinite [50,51]. In addition, coal gangue contains a wide range of chemical elements, including trace and potentially toxic elements such as selenium, nickel, arsenic, cadmium, zinc, copper, and mercury [52]. The compositional characteristics of coal gangue vary markedly across regions, largely due to differences in lithology and mineral assemblages of coal-bearing strata formed during distinct coal-forming periods. These geological variations result in pronounced heterogeneity in both mineralogical composition and elemental distribution.

Coal gangue also exhibits substantial variability in particle size, ranging from fine powders to large blocks, primarily as a consequence of mechanical fragmentation during

mining, transportation, and processing. Beyond mere size reduction, the milling process induces mechanochemical activation that governs long-term durability, a relationship well-documented in studies on binder durability [53]. As a granular material, coal gangue particles are generally non-cohesive, and load transfer within gangue piles is dominated by interparticle friction rather than cementation [54]. From a chemical perspective, the intrinsic composition of coal gangue may pose environmental risks. Elevated sulfur content can promote acid generation, while high concentrations of arsenic, cadmium, and other heavy metals may lead to soil and water contamination, posing threats to ecosystems and human health [55,56].

Table 2. Mineral composition of coal gangue in various countries.

Minerals	China	Czechoslovakia	Germany	Spain	England
illite	10–30	10–45	41–66	20–60	10–31
kaolinite	10–67	20–45	4–25	3–30	10–40
chlorite	2–11	0–15	1–3	0–7	2–7
quartz	15–35	10–50	13–27	5–57	15–25
ore	2–10	0–25	0.5–5	-	2–10
organics	5–25	0–25	5–10	4–30	5–25

Note: The data is sourced from [57].

3.4. Environmental Impacts of Coal Gangue

Coal gangue contains a range of hazardous substances, including volatile organic compounds, organic nitrogen compounds, and heavy metal elements (Figure 8). Through prolonged atmospheric exposure and the leaching action of precipitation, these substances can be released into the environment, adversely affecting air quality, water bodies, soil, and ecosystems [52].



Figure 8. Environmental hazards induced by coal gangue. (a) atmospheric pollution; (b) groundwater pollution; (c) soil pollution; (d) ecological degradation [49].

3.4.1. Atmospheric Pollution

Coal gangue commonly contains combustible materials such as residual coal and carbonaceous mudstone. During long-term exposure to atmospheric conditions, weathering processes may trigger spontaneous combustion [58]. This combustion releases harmful gases, including SO_2 , H_2S , CO , CO_2 , and NO_x , thereby contributing to atmospheric pollution [59,60]. Furthermore, wind erosion of gangue stockpiles generates fugitive dust emis-

sions. These airborne particulates may contain fine mineral particles and associated heavy metals, posing risks to ambient air quality and human respiratory health [61].

3.4.2. Soil Pollution

Long-term stockpiling, weathering and leaching processes can facilitate the migration of heavy metals and other toxic substances from coal gangue into adjacent soils [62–64]. This contamination degrades soil quality, disrupts soil ecological functions, and negatively affects crop growth [65]. A particular concern is the accumulation of heavy metals such as lead (Pb) and cadmium (Cd), which may enter the food chain through plant uptake, thereby posing potential risks to food safety and human health [66].

3.4.3. Groundwater Pollution

During prolonged stockpiling, coal gangue undergoes continuous physical, chemical, and geochemical transformations. Inorganic salts and heavy metals may dissolve and form soluble pollutants, which are transported via leachate into surrounding groundwater systems [67]. In some cases, highly mineralized seepage water may emerge at the surface as overflow springs. Mining-induced ground subsidence and fissures further facilitate water infiltration, creating preferential pathways for contaminant migration and intensifying groundwater pollution. Such contamination can adversely affect industrial and agricultural production, as well as the livelihoods of communities in mining regions.

3.4.4. Ecological Degradation

Large-scale stockpiling of coal gangue occupies extensive land resources and leads to soil and water contamination. Beyond chemical impacts, gangue piles can destabilize local topography and geological structures, increasing the risk of slope instability and collapses [68–71]. Concurrently, gangue stockpiles often destroy native vegetation and wildlife habitats, compressing ecological niches and reducing biodiversity [72]. These combined effects undermine ecosystem integrity and disrupt regional ecological balance.

4. Integrated Utilization of Coal Gangue

4.1. Policies and Key Regulations of Coal Gangue

In recent years, growing environmental awareness has prompted governments globally to strengthen the regulation and resource-oriented management of coal gangue. To mitigate environmental risks and reduce indiscriminate dumping, various policy instruments and regulatory frameworks have been introduced to encourage its safe treatment and value-added utilization (Table 3). These measures aim to transform coal gangue from an environmental burden into a strategic resource within circular economy systems.

Table 3. Policies and key regulations.

Name	Years	No.	Description	Official Website
Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal	5 May 1992	Article 6	This convention regulates the transboundary movement and disposal of wastes. It stipulates rules for the cross-border transfer of wastes such as coal gangue, encouraging their proper disposal and resource utilization to prevent environmental pollution.	http://www.bcrc.cn/atm/7/20230810172707626.pdf (accessed on 15 April 2026)
Technical Policy Guidelines for Comprehensive Utilization of Coal Gangue	20 October 1999	All Provisions	This policy advocates for the comprehensive utilization of coal gangue, prioritizing the consolidation and promotion of existing technologies while also improving and developing new ones.	https://www.mee.gov.cn/yw/gz/fgbz/bz/bzwb/wrfzjszc/200607/t20060725_91275.shtml (accessed on 15 April 2026)
Stockholm Convention on Persistent Organic Pollutants	17 May 2004	Article 6	This convention aims to eliminate or reduce persistent organic pollutants, which may be present in coal gangue. It encour-	https://www.un.org/zh/docu-

			ages countries to take measures to reduce emissions of these pollutants.	ments/treaty/WIPO-2001 (accessed on 15 April 2026)
Recommendation of the OECD Council on the Environmentally Sound Management of Waste	9 June 2004 (revised 2022)	All provisions	This OECD recommendation provides guidance to member countries on the environmentally sound management of all wastes, including industrial residues like coal gangue, emphasizing waste prevention, resource recovery, and proper disposal to minimise environmental impact.	https://legalinstruments.oecd.org/en/instruments/OECD-LEGAL-0320 (accessed on 15 July 2026)
Directive 2006/21/EC of the European Parliament and of the Council on the management of waste from extractive industries (Mining Waste Directive)	1 May 2006	Articles 4, 5, 6, 12	This directive sets out measures to prevent or reduce adverse environmental and health effects from the management of extractive waste, including coal gangue. It requires waste management plans, safe operation and closure of waste facilities, and prevention of major accidents.	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32006L0021 (accessed on 15 July 2026)
Administrative Measures for the Certification of National-Encouraged Resource Comprehensive Utilization	1 October 2006	Article 6	This policy outlines the basic requirements and standards for coal gangue power generation.	https://www.gov.cn/govweb/zwgk/2006-09/13/content_387619.htm (accessed on 15 April 2026)
Directive 2008/98/EC of the European Parliament and of the Council on waste (Waste Framework Directive)	12 December 2008	Articles 4, 8, 11, 13	This directive establishes the basic concepts and definitions for waste management, including mining waste such as coal gangue. It introduces the waste hierarchy (prevention, reuse, recycling, recovery, disposal), extended producer responsibility, and targets for re-use and recycling to protect the environment and human health.	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32008L0098 (accessed on 15 July 2026)
Coal Industry Policy	22 August 2011	Article 36	This policy encourages coal enterprises to carry out resource utilization and comprehensive utilization of coal gangue, promote green mine construction, and advance the management and sustainable development of coal gangue.	http://www.nea.gov.cn/2011-08/22/c_131065989.htm (accessed on 15 April 2026)
Guiding Opinions on Coal Mine Backfill Mining	9 January 2013	Article 10, 11	These guiding opinions encourage coal mines to perform pre-dumping of run-of-mine coal or establish underground coal preparation systems, allowing gangue to be directly used for backfill mining underground to reduce hoisting energy consumption and ineffective transportation.	http://zfxgk.nea.gov.cn/auto85/201302/t20130204_1580.htm (accessed on 15 April 2026)
Measures for the Administration of Comprehensive Utilization of Coal Gangue (2014 Revision)	1 March 2015	All Provisions	These measures guide and standardize comprehensive utilization of coal gangue, reduce its occupation of land resources and environmental impact, promote the development of a circular economy, and advance ecological civilization construction.	https://zfxgk.ndrc.gov.cn/web/item-info.jsp?id=18486 (accessed on 15 April 2026)
Air Pollution Prevention and Control Law	1 January 2016	Article 34, 35, 72	This law stipulates regulations on air pollutant emissions from the combustion of coal gangue, encouraging the adoption of advanced coal gangue combustion technologies to reduce pollutant emissions.	https://www.mee.gov.cn/ywgz/fgbz/fl/201811/t20181113_673567.shtml (accessed on 15 April 2026)
Environmental Protection Tax Law of the People's Republic of China	1 January 2018	Environmental Protection Tax Catalog and Tax Amount Table	This law includes coal gangue in the Environmental Protection Tax Catalog and Tax Amount Table, facilitating the establishment of a green fiscal and taxation system, regulating polluters' pollution control behaviors, and fostering a green production and consumption system for coal gangue.	https://www.chinatax.gov.cn/chinatax/n610/c5178958/content.html (accessed on 15 April 2026)
Soil Pollution Prevention and Control Law	1 January 2019	Articles 16, 17, 23, 28, 33	This law requires that the disposal of coal gangue must not cause soil pollution. It encourages efforts in soil pollution prevention and control to ensure soil environmental safety.	https://iehs.chinacdc.cn/fgbz/flfg/202108/P020210816495223144505.pdf (accessed on 15 April 2026)
Australia National Waste Policy Action Plan 2019	13 August 2019	Targets and Action Area 3	Although not a single legislative Act, this national policy sets targets to reduce waste generation and increase resource recovery, including for industrial and mining waste. It encourages the beneficial use of coal mine spoil (coal gangue) through innovation and circular economy approaches to minimize landfill and environmental harm.	https://www.dcccew.gov.au/environment/protection/waste/publications/national-waste-policy-action-plan (accessed on 15 July 2026)

Guiding Opinions on Building a Modern Environmental Governance System	3 March 2020	Article 8	These opinions involve formulating and revising laws and regulations related to solid waste pollution prevention and control, aiming to improve the comprehensive utilization rate of solid waste.	https://www.gov.cn/zhengce/2020-03/03/content_5486380.htm (accessed on 15 April 2026)
Law on the Prevention and Control of Environmental Pollution by Solid Waste	1 September 2020	Article 42, 100	This law requires that the generation, storage, transportation, treatment, and disposal of coal gangue comply with environmental protection requirements. It promotes resource utilization and encourages waste classification and reduction.	https://www.mee.gov.cn/ywgz/fgbz/fl/202004/t20200430_777580.shtml (accessed on 15 April 2026)
Ecological Environment Protection Law	1 February 2021	Article 2, 50	This law requires the implementation of environmental impact assessments for the storage, disposal, and utilization of coal gangue. It encourages the resource utilization and harmless disposal of coal gangue.	https://www.gov.cn/gongbao/content/2021/content_5588823.htm (accessed on 15 April 2026)
Guiding Opinions on the Comprehensive Utilization of Bulk Solid Waste during the 14th Five-Year Plan Period	18 March 2021	All Provisions	The guiding opinions specify that by 2025, the comprehensive utilization capacity of bulk solid waste such as coal gangue and fly ash should be significantly enhanced. They aim to improve the resource efficiency of bulk solid waste, broaden utilization pathways, and expand the scale of comprehensive utilization.	https://www.gov.cn/zhengce/zhengceku/2021-03/25/content_5595566.htm (accessed on 15 April 2026)
National Cleaner Production Promotion Plan for the 14th Five-Year Plan Period	29 October 2021	Article 13	This plan encourages the development of coal gangue resource utilization technologies and promotes government–enterprise collaboration to address coal gangue-related issues.	https://www.gov.cn/zhengce/zhengceku/2021-11/10/content_5650026.htm (accessed on 15 April 2026)
Implementation Plan on Accelerating the Comprehensive Utilization of Industrial Resources	27 January 2022	Article 4, 16	This plan promotes technological upgrades to reduce the intensity of solid waste generation and increase the comprehensive utilization rate of coal gangue.	https://www.gov.cn/zhengce/zhengceku/2022-02/11/content_5673067.htm (accessed on 15 April 2026)

These laws and regulations encompass the entire lifecycle of coal gangue, from generation to final disposal, including production, transportation, storage, treatment, and resource recovery. Building upon the preceding analyses of coal gangue’s intrinsic properties, its environmental hazards, and the modification technologies developed to mitigate these risks, the policy landscape emerges not merely as a backdrop but as the decisive driver that translates scientific capability into industrial practice. In the early stage, international instruments such as the Basel Convention (1992) and the EU Mining Waste Directive (2006/21/EC) framed coal gangue primarily as a hazardous or extractive waste requiring environmentally sound disposal, a logic rooted in the very hazards of heavy metal leaching and spontaneous combustion identified in earlier sections. China’s domestic policies evolved in parallel, beginning with the 1999 Technical Policy Guidelines for Comprehensive Utilization of Coal Gangue, which encouraged utilization but lacked binding force. A turning point was reached in the mid-2010s, when policies shifted from voluntary encouragement to a combination of mandatory liability and economic incentives. The 2018 Environmental Protection Tax Law, by explicitly listing coal gangue in its tax catalogue, created a direct financial disincentive for landfilling, while the 2015 revised Measures for the Administration of Comprehensive Utilization of Coal Gangue and subsequent five-year plans set quantified targets for bulk solid waste recovery. This alignment of incentives with industrial ecology goals was reinforced by the 2020 Solid Waste Law, which extended producer responsibility, and by sector-specific plans such as the 2021 Guiding Opinions on the Comprehensive Utilization of Bulk Solid Waste, which explicitly called for broader utilization pathways. These measures have clearly stimulated the adoption of technologies such as backfill mining and power generation. While economic instruments such as environmental protection taxes and comprehensive-utilization

certification favors established routes—notably power generation and building materials—they have not been sufficiently tailored to high-value-added, non-traditional applications such as soil amelioration with modified coal gangue. The lack of dedicated product standards and green-labelling pathways for modified coal gangue used in agriculture or ecological restoration creates market uncertainty and restricts its uptake, even when the modifications studied in the previous section effectively reduce environmental risk and enhance nutrient availability. Second, the existing regulatory framework remains fragmented across institutional boundaries (mining, environment, agriculture) and lacks life-cycle safety criteria for novel utilization modes. For example, neither the Soil Pollution Prevention and Control Law (2019) nor the Air Pollution Prevention and Control Law (2016) provide specific permissible limits or long-term monitoring protocols for the slow release of trace metals or persistent organic pollutants from treated gangue in soil systems, leaving a gap between the hazard characterization and the governance of modified products. Third, at the international level, instruments such as the Stockholm Convention and the OECD Council's recommendation on environmentally sound waste management establish general principles but do not offer a coherent transboundary framework for secondary resources derived from coal waste, which could hinder the global diffusion of emerging modification technologies. In essence, the policy system has successfully driven the reduction and basic utilization of coal gangue, yet it lags behind the frontier of low-risk, functional material development, highlighting the need for adaptive, risk-based legislation. Governments, enterprises, and research institutions worldwide are required to formulate management and disposal strategies in compliance with specific regulatory frameworks to ensure environmentally sound handling and minimize resource wastage. The implementation of environmental policies has also stimulated technological innovation in coal gangue processing. Regulatory pressure has encouraged enterprises to adopt cleaner and more efficient treatment methods, thereby reducing ecological footprints. At the same time, policy incentives have promoted increased investment in research and development by both academic institutions and industry stakeholders, supporting advancements in coal gangue management technologies and aligning with broader sustainable development objectives.

4.2. Current Status of Comprehensive Utilization of Coal Gangue

In China, systematic research on the comprehensive utilization of coal gangue began relatively late, with formal investigations into resource recovery emerging in the 1960s. A phase of rapid expansion occurred between 1995 and 2005, during which technological development and industrial applications accelerated significantly. After 2005, the growth rate moderated, and the comprehensive utilization rate stabilized at above 60% (Figure 9). By 2021, China's coal gangue processing capacity for comprehensive utilization had increased approximately twentyfold compared to 1990 levels, reflecting substantial progress in industrial-scale implementation.

Despite these achievements, current utilization patterns remain largely concentrated in relatively conventional applications, particularly in ecological remediation and low-value material substitution. Overall technological sophistication remains limited. The highly heterogeneous composition of coal gangue presents significant challenges for technology development, requiring interdisciplinary research efforts spanning materials science, environmental engineering, geochemistry, and process engineering. Moreover, given the potential presence of hazardous substances, strict environmental risk controls must be implemented throughout processing and utilization stages to prevent secondary pollution. Ensuring environmental safety while improving value-added utilization remains a central challenge for the sustainable development of coal gangue resource recovery systems.

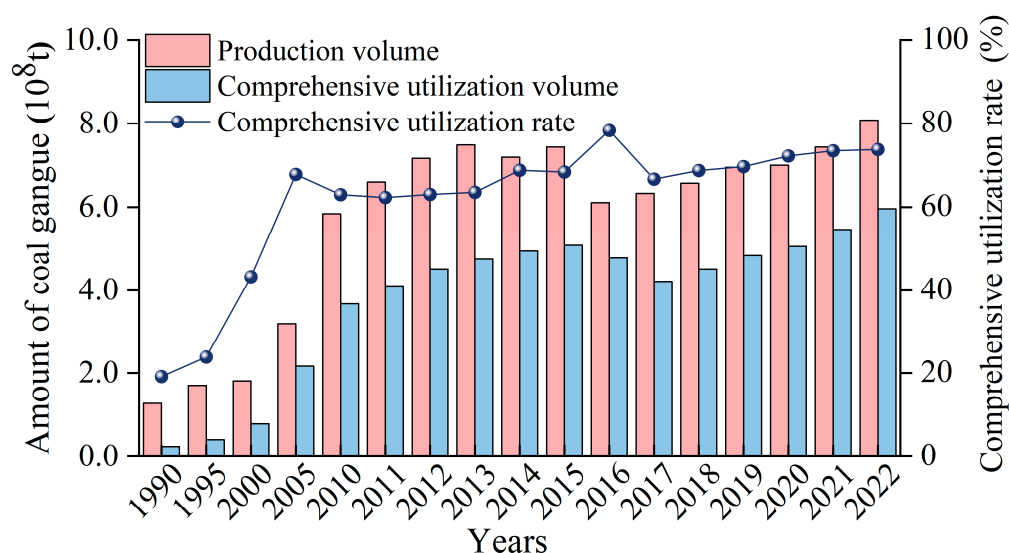


Figure 9. Coal gangue Production and Comprehensive utilization rate in China (1990–2022) [1].

4.3. Landfill in Subsidence Areas and Underground Backfilling

Coal mining activities inevitably lead to surface subsidence and ground collapse. Filling these areas entirely with soil to the designed elevation would substantially increase both transportation and material costs [73]. Due to its composition, primarily sandstone and limestone fragments, coal gangue exhibits considerable mechanical strength and structural stability, making it a suitable filling material for subsidence and collapse areas. This application not only reduces engineering costs but also decreases the volume of gangue requiring surface stockpiling [74,75]. For improved land reclamation outcomes, coal gangue fill can be mechanically compacted and subsequently covered with a soil layer to support vegetation and agricultural production. The thickness of the soil cover is a critical parameter influencing reclamation effectiveness, soil quality and overall economic feasibility [76]. Guo, Li [77] suggested that a 70 cm soil cover thickness provides optimal conditions for vegetation growth in combined gangue–soil filling systems. Additionally, buried gangue may gradually release certain nutrients and organic components, potentially enhancing crop development [78]. However, this method primarily serves as a disposal strategy rather than a high-value utilization pathway. It does not fully exploit the intrinsic resource potential of coal gangue, and long-term environmental risks may persist due to the possible release of hazardous substances from the fill material.

Beyond surface landfill in subsidence areas, underground backfilling represents another effective management strategy [79]. In this technique, coal gangue is used as a solid backfill material to fill underground voids and fissures created by coal extraction. This approach simultaneously disposes of waste and mitigates surface subsidence, thereby improving the structural stability of the mine site and its surrounding areas [80,81]. Studies have shown that combining coal gangue with loess enhances the mechanical strength of the backfill mass, significantly improving operational safety and structural reliability [82].

4.4. Building Materials and Energy Production

In addition to subsidence filling and underground backfilling, a substantial proportion of coal gangue in China is utilized in energy generation and construction materials. Approximately one-third of the annual coal gangue output is used for power generation, while another portion is incorporated into building material production [4,73]. Pre-treatment processes such as crushing and sieving improve particle size distribution and uniformity, facilitating better integration with other raw materials to form stable composite systems [83]. Furthermore, the incorporation of modifiers such as cement, lime, or fly ash

can regulate acidity/alkalinity, enhance stability, and improve binding performance, thereby tailoring coal gangue for specific engineering applications [84]. Given its high alumina and silica content, processed coal gangue can partially substitute clay in the production of bricks, tiles, cement, and concrete [85]. Batool, Rafi [86] and Ramamurthy, Kunhanandan Nambiar [87] found that coal gangue powder can partially or entirely replace clay in cement production. In another application, Wu, Ma [88] produced permeable bricks using coal gangue combined with aluminum hydroxide through pretreatment, mixing, isostatic pressing, firing, and self-curing processes, achieving compliance with Chinese industry standards for compressive strength and water permeability.

Beyond serving as a primary raw material, coal gangue can also function as a performance-enhancing additive. Incorporation into concrete influences properties such as compressive strength, chloride resistance, and freeze–thaw durability [89]. The addition of mineral admixtures can refine cement paste pore structure and improve interfacial bonding between cement matrix and gangue aggregates, thereby enhancing overall durability and mechanical performance [90]. The durability of coal gangue building materials is not solely dependent on chemical composition; pre-treatment via milling significantly dictates pore structure and interfacial bonding, as demonstrated in general cementitious systems [53]. Coal gangue has also been applied in specialized construction materials. For example, Zhu, Cheng [91] successfully substituted fine-grained coal gangue for sand in tile adhesive formulations. After curing, the adhesive achieved the C1 strength grade standard (greater than 0.5 MPa) for tile adhesives. Guo [92] evaluated the road performance of coal gangue used in subgrade filling and reported relatively low settlement and deflection values. Notably, the single-layer compaction thickness of coal gangue subgrades exceeded that of conventional soil materials by more than twofold, demonstrating strong structural stability and engineering feasibility. Overall, while construction and energy applications represent relatively mature and large-scale utilization pathways, further technological refinement is necessary to enhance product performance, ensure environmental safety, and increase value-added potential.

Coal gangue is susceptible to spontaneous combustion due to the significant heat accumulation within its piles. To address this issue while recovering energy, Peng, Li [93] proposed the concept of waste heat recovery from gangue piles for thermoelectric power generation. In a parallel pathway for energy valorization, coal gangue can be gasified in a gasifier to produce syngas. This syngas can subsequently undergo the Fischer-Tropsch synthesis reaction, yielding a wide distribution of liquid hydrocarbons. Through further refining processes such as distillation, hydrogenation, and reforming, these liquids can be upgraded into qualified liquid fuels [94]. Such thermochemical conversion routes not only enable secondary energy recovery but also reduce the environmental and safety risks associated with spontaneous combustion and long-term stockpiling. However, a key challenge for these thermal processes lies in the relatively low calorific value of coal gangue, which constrains reaction efficiency and energy yield. Co-processing coal gangue with an appropriate proportion of biomass has been shown to enhance thermochemical reactivity and increase heating rates, thereby improving overall conversion efficiency and process performance [95,96].

4.5. Extraction of Chemical Elements and Functional Materials from Coal Gangue

Coal gangue is enriched in aluminum and silicon, making it a viable and cost-effective raw material for the chemical industry [97]. Acid leaching has been widely investigated as a method for alumina recovery, with reported extraction efficiencies exceeding 79%. Studies further indicate that prolonged mechanical grinding enhances the leaching efficiency of alumina by increasing mineral activation and surface area [98–100]. The silica fraction of coal gangue, following activation and purification, can be converted into high-

value silicon-based products such as silicon carbide and precipitated silica. These applications represent an important pathway toward value-added resource recovery beyond conventional construction uses.

In addition to aluminum and silicon, trace valuable metals such as titanium and gallium may also be recovered through chemical activation and leaching processes. However, large-scale implementation of such extraction technologies remains constrained by high operational costs, complex process flows, and difficulties associated with multi-metal separation from heterogeneous leachates. The intricate composition of leaching solutions presents significant technical challenges, making selective separation and purification a key research focus [97]. Beyond elemental recovery, activated coal gangue can serve as a precursor for functional materials. Treatment with acids, alkalis, or steam, followed by calcination, significantly increases its specific surface area and enhances adsorption properties. As a result, modified coal gangue has been utilized in the production of wastewater adsorbents and zeolite molecular sieves, among other functional materials [101,102]. These applications demonstrate the potential of coal gangue to transition from a bulk waste material to a functional material platform.

4.6. Soil Amendment and Ecological Soil Utilization

Coal gangue contains relatively high levels of organic matter and active humic acid substances and can serve as an effective matrix for soil nutrient retention. When properly treated and applied in controlled proportions, coal gangue has the potential to improve soil pore structure, enhance water-holding capacity, and promote moisture retention, thereby creating a more favorable growth environment for crops [103]. Gao, Li [104] utilized coal gangue to construct sand barriers for dune stabilization, which not only improved local soil and water conservation but also increased the content of organic matter, nitrogen, phosphorus, and potassium in the soil. Additionally, coal gangue has been reported to reduce soil pH under certain conditions, indicating its potential ameliorative effects in saline-alkali regions. Following desulfurization treatment, He, Ren [105] demonstrated that coal gangue substrates exhibited low bulk density and good aeration properties, supporting their feasibility as components in soilless cultivation systems.

Coal gangue also contains appreciable quantities of macroelements (such as N, P, and K) and microelements (such as Fe, Mn, Zn, and Cu) essential for plant growth. However, most of these nutrients are present in mineral-bound or otherwise insoluble forms that are not directly bioavailable [97]. Microbial activation offers a promising strategy to enhance nutrient availability. Functional microorganisms, including phosphate-solubilizing bacteria, potassium-releasing bacteria, and silicate bacteria, can transform mineral-bound nutrients into plant-available forms such as available phosphorus, exchangeable potassium, and alkali-hydrolysable nitrogen [97,106–108]. Through microbial inoculation and biotechnological processing, coal gangue can therefore be converted into bio-activated soil conditioners or compound fertilizers. Such applications not only improve soil aeration and structural stability but also enhance soil fertility and nutrient cycling efficiency [49]. Commonly used microbial strains and their specific functions nutrient transformation are summarized in Table 4.

The production of ecological soil using coal gangue as a raw material or soil amendment represents an innovative approach for high-value resource utilization. Such engineered soils not only provide a structural growth matrix for crops but also improve soil physical and chemical properties, thereby enhancing agricultural productivity. This approach holds particular significance for the construction of high-standard farmland, land reclamation, and terrace development in ecologically fragile regions.

Table 4. Common microbial strains involved in nutrient mobilization and element extraction from coal gangue.

Name	Strain	Elements Converted	References
Micrococcus luteus	GZU-Mic02	N; P; K	[108]
Bacillus megaterium	ACCC1011	N; P; K	[107,108]
Silicate bacteria	GY03	K; P	[109]
FP.18bacterium	-	K	[110]
Potassium-releasing bacterium JX-10	-	K	[111]
Stenotrophomonas maltophilia	SM1	P	[112]
TK.1 bacterium	-	P	[113]
Myroides sp.	GZ-8	P	[114]

4.7. Carbon Sequestration with Coal Gangue

Enhanced rock weathering has emerged as a promising negative-emission strategy. Yin, Zhang [115] found that the application of coal gangue and its derivatives has a suppressive effect on the cumulative priming of soil organic carbon, mitigating the loss of “old carbon” and encouraging the generation of “new carbon”. This alteration in carbon dynamics supports the net accumulation and stabilization of soil organic carbon. Furthermore, these additions significantly bolster the levels of labile organic carbon in the soil, contributing to an overall enhancement of the soil organic carbon stock. Beerling, Kantzas [116] proposed the application of silicate powders to agricultural soils, where silicates react with carbonic acid in the soil, converting atmospheric and soil CO₂ into dissolved inorganic carbon. It is then transported to the oceans via surface runoff for long-term storage or precipitates as carbonate minerals within the soil, thereby achieving carbon sequestration. Coal gangue, enriched in silicon-bearing minerals, presents a potential alternative feedstock for this process. Silica and reactive silicate phases can be extracted or activated through alkali treatment and other chemical modification methods [117], enabling its application in carbon mineralization systems. Utilizing coal gangue for carbon sequestration offers dual benefits: reducing the costs associated with silicate sourcing while simultaneously mitigating the environmental burden of gangue accumulation. However, practical implementation requires careful assessment of mineral reactivity, heavy metal mobility, lifecycle emissions, and long-term environmental impacts. Integrating carbon sequestration with soil amendment or ecological restoration strategies may further enhance the overall sustainability and multifunctionality of coal gangue utilization.

Overall, the pathways for comprehensive coal gangue utilization are diverse, ranging from bulk disposal and construction applications to functional materials development, ecological soil engineering, and carbon sequestration. Each technological route possesses specific applicability, advantages, and limitations. The direct underground backfilling of coal gangue or its use in soil engineering may pose a certain risk of environmental pollution. Meanwhile, owing to its stable chemical structure and inert organic carbon, coal gangue generally contains low levels of active beneficial constituents, which can restrict the direct uptake of nutrients by plants and microorganisms during soil improvement. It is therefore necessary to modify and activate coal gangue. Modification technologies—including mechanical modification, chemical modification, microbial modification, thermal modification, hydrothermal modification, and composite modification—can effectively enhance the soil amelioration performance of coal gangue while reducing its associated pollution risks [4,100,118–122]. Therefore, selecting an appropriate utilization strategy requires holistic evaluation of gangue characteristics, regional conditions, economic feasibility, environmental risk, and regulatory frameworks. In many cases, the synergistic integration of multiple technologies such as combining resource recovery with ecological restoration or carbon sequestration may yield optimal environmental and economic out-

comes. Continued advancements in materials science, environmental engineering, biotechnology, and carbon management are expected to drive further innovation in coal gangue treatment and valorization, supporting the transition toward circular resource systems and sustainable development.

5. Conclusions and Prospects

This study reviewed the sources, characteristics, environmental impacts, and utilization pathways of coal gangue within the broader framework of resource efficiency and sustainable development. Bibliometric analysis indicates sustained and increasing research attention, highlighting coal gangue as an issue of growing global significance. The formation and properties of coal gangue are strongly influenced by geological conditions and mining practices, resulting in considerable compositional heterogeneity. Environmental risks associated with coal gangue include soil and groundwater contamination, atmospheric pollution from spontaneous combustion, and the release of heavy metals and organic pollutants during long-term weathering and leaching. These impacts pose tangible threats to ecosystem stability and human health. Although conventional disposal methods such as subsidence filling and underground backfilling remain widely practiced, their absorption capacity is limited and often constrained by regulatory, technical, and environmental considerations. Various resource utilization pathways, including construction materials production, thermochemical energy conversion, elemental extraction, ecological soil preparation, and carbon sequestration, have demonstrated potential for transforming coal gangue from waste into value-added products. Nevertheless, current technologies remain insufficient in scale and efficiency to offset the massive stockpiles and continuous annual generation.

Future efforts should prioritize the development of integrated, environmentally sound utilization strategies tailored to regional conditions. Strengthening fundamental research on mineral reactivity, contaminant behavior, and lifecycle environmental impacts will support more scientifically grounded management policies. Simultaneously, advancing innovative processing technologies and promoting interdisciplinary collaboration will be essential to accelerate sustainable coal gangue valorization and contribute to circular resource systems and environmental protection.

Author Contributions: Conceptualization, H.H. and X.L.; methodology, X.L.; investigation, X.L.; sources, J.D. and C.Z.; data curation, X.L. and C.Z.; writing—original draft preparation, X.L.; writing—review and editing, H.H., Y.L. (Yongzhe Liang), F.C., J.L. (Jialong Lv), Y.L. (Yongtao Liu), J.L. (Jinbo Li), W.Q. and V.F.; visualization, X.L.; funding acquisition, F.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Open Competition for Tackling Key Problems Program of Power China Guiyang: Land Reclamation & Improvement Technologies Based on Cultivated Land Balance (YJZDXM240012).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: Authors Xiaobin Li, Yongzhe Liang, Fan Chen and Yongtao Liu are employed by Power China Guiyang Engineering Corporation Limited. Author Weiwen Qiu is employed by New Zealand Institute for Bioeconomy Science Limited. Authors declare that the research was conducted in the absence of any commercial or financial relationship that could be considered as a potential conflict of interest.

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