Environmental Science and Pollution Research
https://doi.org/10.1007/s11356-024-34895-2

REVIEW ARTICLE

Opportunities, challenges and modification methods of coal gangue as a sustainable soil conditioner—a review

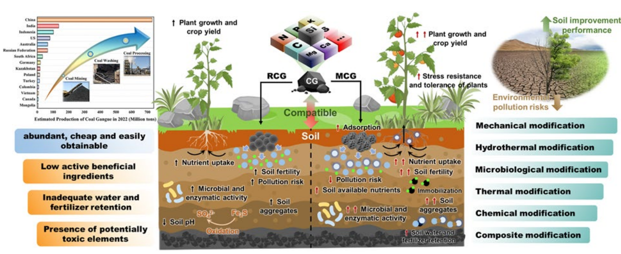
Tian Tang[1] · Zheng Wang[1] · Liuzhou Chen[1] · Shu Wu[1] · Yangsheng Liu[1]

Received: 11 December 2023 / Accepted: 29 August 2024

Abstract

The persistent reliance on coal has resulted in the accumulation of substantial coal gangue, a globally recognized problematic solid waste with environmental risks. Given the coal gangue properties and global land degradation severity, the resourceful utilization of coal gangue as soil conditioners is believed to be a universally applicable, cost-effective, high-demand and environment-friendly model with broad application prospect. The direct application of raw coal gangue faces challenges of low active beneficial ingredients, inadequate water and fertilizer retention, presence of potentially toxic elements, resulting in limited efficacy and environmental contamination. This paper provided a comprehensive review of various modification methods (including mechanical, chemical, microbiological, thermal, hydrothermal and composite modifications) employed to enhance the soil improvement performance and reduce the environmental pollution of coal gangue. Furthermore, an analysis was conducted on the potential application of modified coal gangue as a muti-function soil conditioner based on its altered properties. The modified coal gangue is anticipated to effectively enhance soil quality, exhibiting significant potential in mitigating carbon emissions and facilitating soil carbon sequestration. This paper provided innovative ideas for future research on the comprehensive treatment of coal gangue and restoration of degraded soil in order to achieve the dual goals of zero-coal gangue waste and sustainable agriculture.

Graphical Abstract



Keywords Coal gangue · Soil conditioner · Modification · Resourceful utilization · Soil remediation · Sustainable

Introduction

Coal is the largest source of global energy, accounting for over 26% of the world's primary energy with a total consumption of 161.47 EJ in 2022 (IEA 2023). Despite renewable energy sources (e.g., wind, sun, biomass) gain the increasing global focus and are generally proposed as potential substitutes for fossil fuels in recent years (Brockway et al. 2019; Devlin et al. 2023; Smith et al. 2022), fossil fuels particularly coal, still dominate the world energy

Responsible Editor: Shimin Liu

Yangsheng Liu
yshliu@pku.edu.cn

[1] College of Environmental Sciences and Engineering, Beijing Key Laboratory for Solid Waste Utilization and Management, Peking University, Beijing 100871, China

Published online: 17 September 2024

consumption as illustrated in Fig. 1a. The global coal consumption witnessed a growth of over 7% in 2022, with China and India accounting for more than 70% (Debiagi et al. 2022). Consequently, the dominant role of coal in global energy supply is anticipated to remain unchanged for the foreseeable future.

However, a substantial amount of coal gangue was generated and discharged during the coal mining, washing and processing processes. Coal gangue, a black-gray rock with lower carbon content and heat value compared to coal, accounts for about 15%-20% of coal production (Li et al. 2006). The production of coal gangue was conservatively estimated based on the published coal production data from the Energy Institute (Energy Institute 2023), as shown in Fig. 1b. As the world's largest coal producer, China produced nearly half of coal gangue. The amount of accumulated coal gangue in China has exceeded 7 billion tons as of 2022 (Wang et al. 2023), and is still rising at an alarming rate of more than 300 million tons per year (Li and Wang 2019). The utilization rate of coal gangue in China only reached 73.1% as of 2023 with a consistent flat trend as depicted in Fig. 1c (Li and Wang 2019; Wu et al. 2023a). Therefore, the utilization amount of coal gangue still falls short in comparison to its vast production and reserves, making it one of the largest industrial solid wastes (Wu et al. 2017).

The accumulation of enormous coal gangue not only occupies a significant amount of land resource, but also causes severe safety and environmental issues (Fig. 1c), including soil deterioration, spontaneous combustion, the release of toxic gases, heavy metal contamination and geological hazards (Ma et al. 2019a; Sun et al. 2021; Wu et al. 2023b). Hence, numerous countries have been actively exploring various utilization ways to eliminate the threats triggered by coal gangue accumulation. At present, considerable research has been conducted on the resourceful utilization of coal gangue as value-added products. The global comprehensive utilization of coal gangue encompasses various sectors, including construction materials (e.g., cement and concrete) (Qin et al. 2021), energy generation (e.g., power generation) (Peng and Li 2018), filling applications (e.g., underground backfill) (Li et al. 2020c) and emerging industries (e.g. chemical products) (Cao et al. 2021). The applications mentioned above are extensively employed in economically developed and densely populated areas, yielding remarkable economic and social benefits. Conversely, in underdeveloped areas with a substantial stock of coal gangue, they fail to achieve the anticipated outcomes due to the low local demand and exorbitant export costs.

Moreover, the excessive cultivation and prolonged use of chemical fertilizer have resulted in the gradual depletion

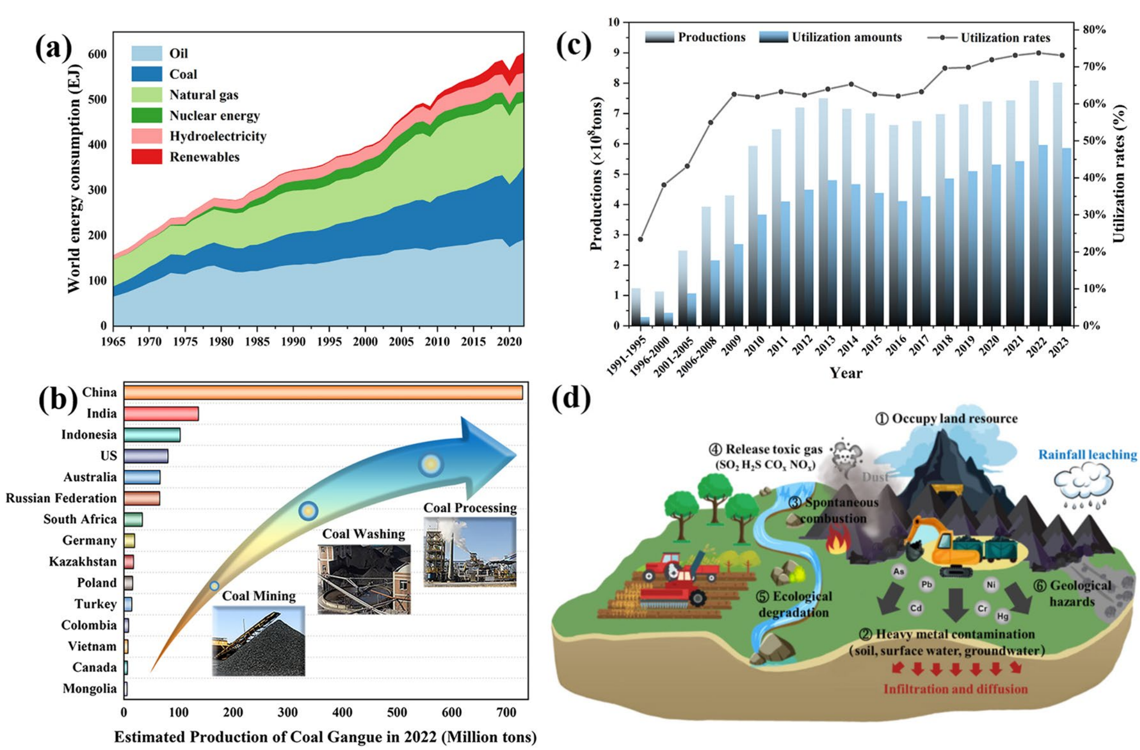


Fig. 1 **a** The global energy consumption by source in exajoules (EJ) from 1965 to 2022; **b** The coal gangue generation links and estimated production of coal gangue in various countries in 2022; **c** Production, comprehensive utilization, and utilization rate of coal gangue in China from 1991 to 2023; **d** The harm caused by the accumulation of enormous coal gangue

of organic matter and humus in soil, leading to increasingly serious soil degradation (Babla et al. 2022). Severe soil degradation has occurred in one-third of the world as a result of soil erosion, desertification, salinization, compaction, and pollution (Hou et al. 2020), thereby diminishing soil productivity and often necessitating soil conditioners to replenish the soil (for the lost nutrients). However, the utilization of commercial soil conditioners incurs substantial costs, constituting 10 to 90% of the overall expenses associated with farm treatment (Yunusa et al. 2012). Previous studies have indicated that scientific and reasonable addition of coal gangue holds the potential to improve soil quality, which will effectively overcome the negative effects caused by traditional fertilizers on soils (Tang et al. 2014). Hence, the utilization of coal gangue as soil conditioners is presumed to be a universally applicable, affordable, high consumption and efficient sustainable approach, which can tackle the issues of coal gangue management and soil degradation simultaneously.

Currently, an increasing work has been reported on the resourceful utilization of coal gangue as soil conditioners, however there is a lack of comprehensive summary in this field. To fill this vacancy, the properties of coal gangue with a specific focus on the analysis of its overlooked agricultural value were summarized in this paper. Then, this review identified the opportunities and challenges related to using raw coal gangue as soil conditioners from previous studies. Furthermore, the mechanisms, effects, and limitations of several modification methods for coal gangue were comprehensively integrated and evaluated in order to enhance soil improvement performance and ensure environmental safety. The potential application and environmental implication of modified coal gangue were also discussed. This review aims to provide valuable insights and references for utilizing coal gangue in soil practices and sustainable agriculture.

Properties of coal gangue

Coal gangue is a complex industrial solid waste mixed with organic compounds, inorganic compounds and minerals (Fabiańska et al. 2013). Its major chemical compositions are SiO_2, Al_2O_3 and Fe_2O_3, with traces of CaO, P_2O_5, MgO and MnO_2. The chemical composition of coal gangue from various sources and its comparison with soil reference values were tabulated in Table 1. It can be concluded that the chemical composition of coal gangue and soil exhibits similarities, suggesting compatibility between them, which may be attributed to the fact that they are both formed in strata (Wang et al. 2016b). It is worth noting that the majority of coal gangue samples present a high loss on ignition (LOI), indicating a higher proportion of organic carbon (Zhao et al. 2022b), which is conducive to the soil utilization of coal gangue. Besides, coal gangue predominantly consists of quartz and clay minerals (kaolinite, illite, etc.) (Cao et al. 2016). The abundance of clay minerals provides convenient for the enhancement of soil structure and fertility (Grim 1962).

There is a growing stockpiles of the industrial byproducts including coal gangue, fly ash, red mud and flue gas desulfurization gypsum which may potentially give rise to environmental concerns (Koshy et al. 2019). The comparison with other industrial solid wastes (Table 2) reveals that coal gangue exhibits higher levels of nitrogen (N), phosphorus (P), potassium (K) and sulfur (S), contributing to improve soil fertility. Although sulfur is considered detrimental in certain coal processing and utilization projects, it can effectively stimulate crop growth and productivity in moderate quantities (Mu et al. 2021; Yuan et al. 2021). Coal gangue possesses developed pores and specific surface area, thereby aiding soil aeration and preventing compaction (Zhang et al. 2022a). The organic carbon content in coal gangue is typically 2 to 10 times higher than that found in soils, making it possible to produce multi-functional soil conditioners using coal gangue as a raw material.

In addition, coal gangue contains various trace elements such as Mn, Mo, B, Zn, Cu, Cr, Cd, Pb, Ni, As, Hg, Se, and Co (Table S1), both as essential micronutrients and environmental pollutants (He et al. 2005). Compared with other industrial solid wastes, the potential hazardous trace elements of coal gangue are generally within acceptable limits, as displayed in Fig. 2. This means that coal gangue contains adequate and safe levels of trace elements to ameliorate the soil and support plant growth more securely and effectively. Currently, the research on trace elements in coal gangue primarily focuses on their adverse aspects, including the distribution, leaching, diffusion and environmental risk assessment of heavy metals such as zinc (Zn), copper (Cu), chromium (Cr), cadmium (Cd), nickel (Ni), arsenic (As), mercury (Hg), among others (Ashfaq et al. 2020; Gao et al. 2021a), the migration and release of potentially deleterious trace elements during combustion (George et al. 2020; Wang et al. 2021b). However, there is a lack of attention to the nutritional value and benefits associated with trace elements like molybdenum (Mo), boron (B), selenium (Se) contained within coal gangue.

Utilization of coal gangue as soil conditioners

Owing to excessive reclamation and intensive use of fertilizers, the organic matter and humus in soil are gradually depleted, soil degradation has become a global issue. Because of the remarkable effect of soil conditioner in improving soil quality, it has received extensive attention in

Table 1 Chemical composition of coal gangues (wt. %) sourced from regions and cities

Sources	SiO_2	Al_2O_3	CaO	Fe_2O_3	Na_2O	MgO	Ti_2O	K_2O	SO_3	P_2O_5	MnO_2	LOI	Refs
Beijing, China	49.90	24.41	0.82	6.42	1.46	1.59	0.88	2.06	0.12	-	-	11.76	(Li et al. 2006)
Beijing, China	56.11	16.78	3.11	7.02	1.84	1.68	-	6.98	-	-	-	6.38	(Li et al. 2010)
Xuzhou, China	55.50	18.15	3.38	5.42	0.64	1.23	-	1.67	0.64	-	-	13.20	(Li et al. 2006)
Shanxi, China	56.56	36.78	0.62	1.95	0.42	0.22	2.10	-	-	-	-	-	(Ma et al. 2019b)
Shanxi, China	55.65	29.00	0.53	5.01	0.85	0.49	1.13	1.81	5.01	-	-	-	(Li et al. 2022a)
Shanxi, China	54.63	24.63	0.15	2.17	0.349	0.815	0.682	2.52	-	0.074	0.006	13.45	(Li et al. 2023)
Inner Mongolia, China	45.90	16.00	0.74	4.71	0.99	1.37	0.78	3.36	-	-	-	8.03	(Guan et al. 2021)
Inner Mongolia, China	59.33	30.23	0.41	4.88	0.07	0.75	1.12	2.35	0.26	0.11	0.09	-	(Li et al. 2020a)
Hebei, China	57.74	30.58	0.20	4.31	1.10	1.00	-	2.76	0.16	-	-	-	(Guo et al. 2022)
Heilongjiang, China	58.82	27.87	0.78	8.31	-	-	-	1.74	0.51	-	-	1.97	(Qin and Gao 2019)
Anhui, China	58.20	32.00	1.01	3.96	0.34	-	1.23	1.74	-	-	-	1.52	(Jin et al. 2022)
Anhui, China	53.24	22.09	1.43	5.97	0.32	0.39	-	0.95	0.08	-	-	13.36	(Wang et al. 2022a)
Anhui, China	51.13	25.51	0.44	3.10	0.30	1.16	0.88	1.10	-	0.32	0.06	-	(Fu et al. 2018)
Wuhan, China	69.30	20.80	0.24	3.81	0.36	0.43	1.34	2.07	1.25	-	0.05	11.5	(Liu et al. 2021c)
Henan, China	51.66	17.77	3.82	3.67	0.53	1.01	0.71	1.21	-	0.05	0.04	19.53	(Xu et al. 2017)
Spain	43.70	21.35	0.89	5.57	0.11	0.77	1.05	0.16	1.02	0.16	-	25.18	(Frías et al. 2012)
	57.20	18.69	1.86	6.25	046	1.42	0.95	0.14	0.08	0.14	-	9.28	
	46.86	17.15	7.60	7.67	0.15	0.99	0.78	0.16	0.34	0.16	-	15.80	
Spain	49.79	21.77	3.84	4.07	0.13	0.64	1.07	2.74	0.27	0.13	0.08	15.18	(Caneda-Martínez et al. 2019)
Brazil	55.91	24.81	0.28	8.73	-	-	1.17	2.02	2.11	-	0.01	4.50	(Frasson et al. 2019)
Poland	58.95	20.50	0.35	6.63	0.54	1.93	1.05	3.19	0.17	0.06	0.05	5.50	(Jabłońska et al. 2017)
Poland	45.80	24.00	0.60	4.30	0.40	0.90	1.30	2.30	1.90	0.50	-	-	(Záleská et al. 2023)
India	52.70	22.60	2.45	6.37	0.65	1.22	0.98	2.48	0.43	-	-	12.65	(Ashfaq et al. 2020)
India	59.20	18.00	2.10	7.29	-	-	2.67	2.71	5.23	-	0.096	-	(Sahu et al. 2019)
Iran	58.80	23.10	1.59	5.30	-	1.68	2.69	3.23	0.95	-	-	2.28	(Mohammadi et al. 2019)
Morocco	52.40	21.90	0.81	4.55	1.53	1.26	-	2.24	3.54	0.135	-	10.70	(Moussadik et al. 2022)
Australia	59.24	23.41	2.16	9.53	-	1.16	0.98	0.67	0.45	-	-	-	(Tang et al. 2020)
Columbia, USA	33.99	13.54	0.34	3.49	0.25	0.51	0.53	1.19	4.97	0.14	0.02	40.96	(Rodríguez et al. 2021)
Soil reference value	37.10–77.70	6.86–32.38	0.50–5.19	2.18–11.33	0.48–4.90	0.41–4.90	0.23–1.83	1.34–5.69	-	-	-	-	(Wang et al. 2018)

L.O.I. represents the loss on ignition

Table 2 Comparison of physicochemical properties in several typical industrial solid wastes

Physicochemical properties	Coal gangue [a]	Coal fly ash [b]	Red mud [c]	Flue gas desulfurization gypsum [d]
pH (1:5)	6.90–8.93	3.1–12.8	9.0–13.1	6.5–8.46
EC (ms cm^{-1})	0.26–2.2	3.2–7.6	10.0–60.8	0.84–2.6
Specific surface areas (m^2/g)	0.52–7.24	2.5–14.8	5.31–64.09	0.38–6.68
Organic carbon (%)	3.5–21.2	0.45–1.7	0.60–1.28	0.16–2.4
Total nitrogen (%)	0.19–0.87	0.01–0.12	< 0.02	< 0.01
Total phosphorus (%)	0.23–0.47	0.01–1.08	0.01–0.08	0.01–0.42
Total potassium (%)	0.86–2.71	0.01–0.28	0.10–1.82	0.05–1.35
Total sulfur (%)	0.55–4.90	0.01–0.58	0.10–0.60	8.2–20.9

a (Ashfaq et al. 2020; Du et al. 2020; Jabłońska et al. 2017; Li et al. 2020a; Li et al. 2022a; Tong et al. 2008; Zhou et al. 2015; Zhou et al. 2012)

b (Bhattacharya et al. 2012; Chen et al. 2010; He et al. 2017; Jankowski et al. 2006; Sarbak et al. 2004; Singh et al. 2010; Yunusa et al. 2012)

c (Anam et al. 2019; Berta et al. 2021; Garau et al. 2011; Gräfe and Klauber 2011; Hua et al. 2017; Liu et al. 2014; Liu et al. 2021b)

d (Aakriti et al. 2023; DeSutter et al. 2014; Li et al. 2022b; Liu et al. 2021a; Sun et al. 2014; Wang et al. 2017)

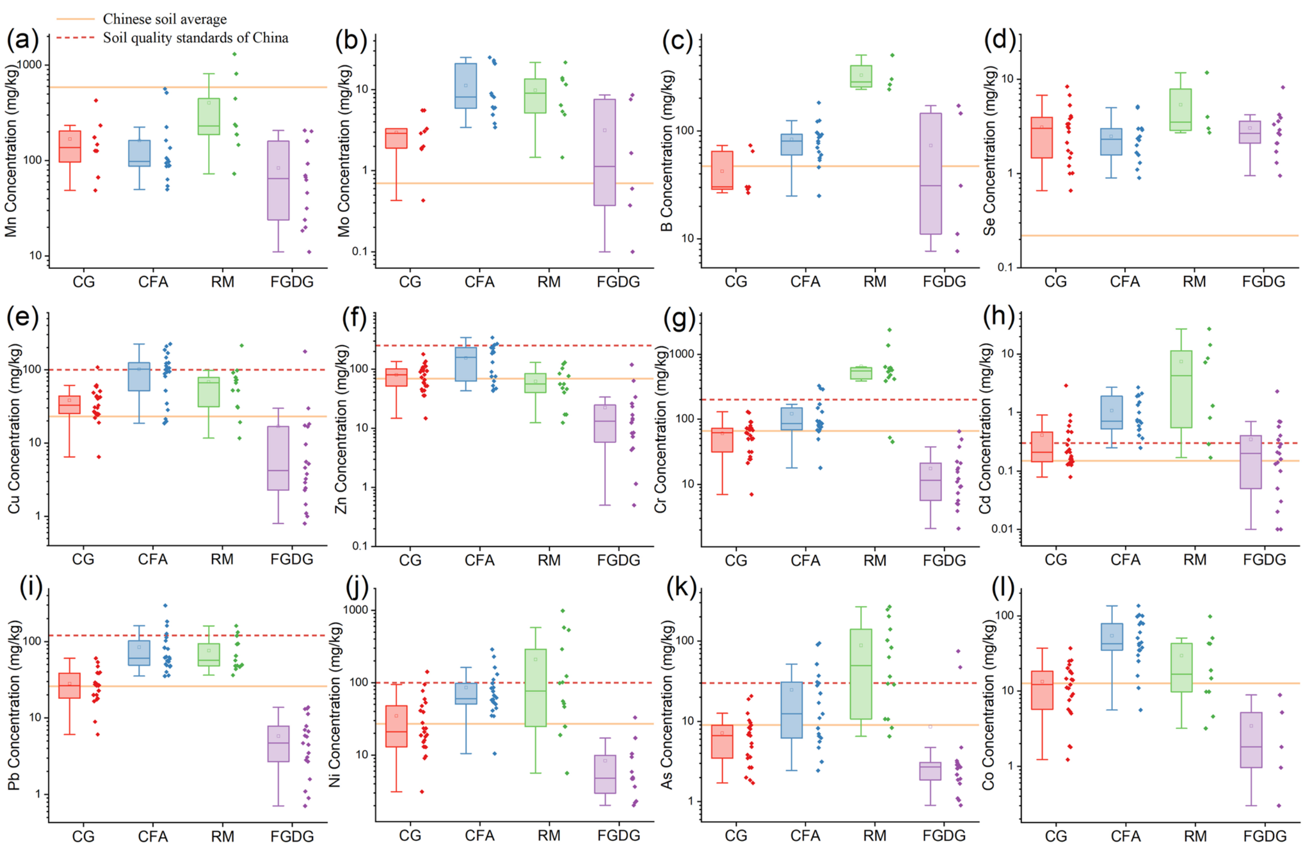


Fig. 2 The summary and comparison of trace element contents in coal gangue (CG), fly ash (CFA), red mud (RM), and flue gas desulfurization gypsum (FGDG) based on the existing literature

recent years (Amoah-Antwi et al. 2020; Rakshit et al. 2019). Current research mainly focuses on artificial synthetic polymer soil conditioners, natural soil conditioners and microbial soil conditioners (Saha et al. 2020; Song et al.

2018; Zhou et al. 2019). Coal gangue, the main object of this review, is a kind of natural soil conditioner. As a kind of industrial solid waste, it is abundant, cheap and easily obtainable, and its composition closely resembles that of known soil (Tong et al. 2008). Consequently, the coal gangue-derived soil conditioner exhibits superior compatibility with soil compared to artificial synthetic and microbial soil conditioner (Han et al. 2021), enabling its extensive and prolonged utilization while achieving mass-scale production at low cost. If the substantial accumulated coal gangue can be utilized to ameliorate and remediate extensive areas of potentially available degraded soil worldwide, it will give a promising solution for addressing both coal gangue management and soil degradation problems simultaneously. It represents an effective and feasible way for local resourceful utilization of coal gangue as soil conditioners.

Soil improvement application of raw coal gangue

As mentioned above, coal gangue is primarily composed of clay minerals, quartz and carbon. Its organic matter content ranges from 15 to 25%, and it contains nutrients such as nitrogen, phosphorus, potassium, calcium, magnesium, silicon and trace elements required for plant growth (Tong et al. 2008). The coal gangue-derived soil conditioner has the combined effects of natural organic and mineral conditioners, which can be used not only for light soils with poor organic matter and nutrients (NPK), but also as a fertilizer (supply mainly Si, Ca, Mg and trace elements) or to restore degraded soil (Garbowski et al. 2023; Long et al. 2019). Previous studies have documented the excellent efficacy of coal gangue in optimizing soil structure, enhancing soil water retention, augmenting soil fertility and stimulating plant growth (Babla et al. 2022), as detailed in Table 3.

Furthermore, numerous scholars have explored the impact of the amount and particle size of raw coal gangue on soil properties, nutrient content and plant growth characteristics. The research findings of Zhou et al. (2010) demonstrated that as the addition of coal gangue increases, both the infiltration rate and saturated water conductivity decrease while the water retention performance of sand improves. Nan et al. (2023) revealed that coal gangue can alter soil moisture and aggregate structural stability. They identified that coal gangue content is the primary driving factor influencing soil moisture and plant growth, whereas particle size is the main determinant affecting soil aggregate structural stability, and the optimal coal gangue content is 30%, with a particle size ranging from 5 to 8 mm. Han et al. (2021) pointed out that the application of coal gangue mulch could enhance soil water status through increased water infiltration and reduced cumulative evaporation. Among different mulch models, the most effective one is characterized by a thickness ranging from 8 to 16 cm and particle sizes between 0.5 and 2 cm. The literature indicates that the typical upper limit for untreated raw coal gangue is approximately 20%.

In conclusion, the scientific and rational addition of raw coal gangue can effectively enhance soil properties and facilitate plant growth. Moreover, the harmless treatment of coal gangue prior to application can further optimize its utilization efficiency and improve the overall soil improvement effect.

Problems of direct application of raw coal gangue

The bottleneck problem of directly applying coal gangue as a soil conditioner has emerged, thereby impeding its further development. The relatively stable chemical structure and inert organic carbon of coal gangue result in less active beneficial components, thereby limiting direct absorption of nutrients by plants and microorganisms, leading to poor fertilizer efficiency when utilized as a fertilizer (Zhu et al. 2022). Additionally, the coal gangue with large particle size and low capillary porosity makes it resistant to weathering, which leads to soil structure loosening when directly applied, thus hindering its functions in water holding, fertilizer retention, and internal nutrient release (Du et al. 2020; Wang et al. 2016a). Consequently, it fails to effectively improve degraded soil such as sandy soil. Moreover, the addition of overmuch coal gangue will lead to excessive accumulation of trace elements, sulfur, and salt in the soil, causing environmental pollution and impeding plant growth (Singh et al. 2010). The long-term weathering and rain leaching of coal gangue will generate acidic wastewater, causing the release of toxic and harmful elements and subsequent contamination of soil and underground water (Gao et al. 2021b; Li and Wang 2019). The maximum feasible amount of coal gangue addition can be increased if the harmful substances in it are effectively controlled (Clavier et al. 2020).

To sum up, the direct application of coal gangue to improve degraded soil presents challenges such as low activity of beneficial ingredients, poor water and fertilizer retention performance, environmental pollution, etc., resulting in limited efficacy, restricted application amount and hidden safety risks. Therefore, it is crucial to thoroughly analyze the activity, structural characteristics and pollutants contents present in coal gangue prior to application. Additionally, considering the specific requirements of soil and crops, a rational modification treatment is imperative for producing high-quality and eco-friendly soil conditioners. This approach aims at achieving the harmless resource utilization of accumulated coal gangue while promoting sustainable agricultural development efficiently.

Table 3 Raw coal gangue-based soil conditioners and their effects on soil properties, plant growth and development (CG—coal gangue, EC—electrical conductivity, OM—organic matter)

Used as	Application rate (%, w/w)	Plant species	Claimed effects on soil	Claimed effects on plants	Ref
Fertilizer and soil amendment	50%	*Alfalfa*	The levels of soil OM, total N, total P, total K, available N and available P exhibited significant improvements	The germination of plants initially increases and then decreases with the increase of CG. A moderate addition of CG significantly enhances plant growth (including plant height, root length, fresh and dry weight)	(Du et al. 2020)
Fertilizer and soil amendment	20%	*Lyme grass*	The soil exhibits enhanced pore structure, water and fertilizer retention capabilities compared to natural soil	The promotion of plant survival and growth was observed, with a 10% increase in seedling emergence rate and an average plant height increase of 53.65%	(Su 2021)
Fertilizer and Soil amendment	10%	*Vetiveria zizanioides*	It not only improves pH, EC (12.6%), OM (222.7%), N (52.1%), P (55.1%) and K (57.7%) content, but also reduces the bioavailability and mobility of most heavy metals (Zn, Pb, Cd, Cu)	Biomass and plant height increased by about 16.12% and 19.24%. Zn, Pb, Cd and Cu concentrations decreased by about 27.47%, 37.64%, 40.54% and 28.11%, respectively, and Cr concentration increased by 45.30%	(Chu et al. 2020)
Fertilizer and Soil amendment	10–50%	*Forage maize*	With increasing coal gangue percent in the soil, the amounts of soil OM, total N, P, Zn, Fe, available P, available K, microbial activity, soil microbial population and respiration increased	Plant nutrient content increased significantly. The increase of CG to 10% resulted in a significant augmentation of root and ground dry weight, whereas higher CG content (> 20%) led to a decline in both root and ground dry weight	(Motesharezadeh et al. 2017)
Soil amendment	26%	*Pachoi*	Improve the physical and chemical properties of soil and increase the nutrients required for plant growth process	The germination rate, plant height above ground, and dry weight increased by 23%, 23.05%, and 20.62% respectively. Additionally, the product met the requirements for cleanliness	(Luo et al. 2015)
Soil amendment	20%	*Medicago sativa*	The EC, pH and alkali-hydrolyzed nitrogen content of saline-alkali soil exhibited a decrease, whereas the contents of total C, total N, total P, and available P demonstrated an increase	The average plant height and biomass exhibited a significant increase of 21.45% and 25.89%, respectively	(Zhang et al. 2021b)
Soil amendment	20%	*Alfalfa*	Soil microbial biomass, urease, catalase and dehydrogenase activities showed an increasing trend	The plant height and fresh weight of alfalfa were significantly increased by 34.86% and 45.28% respectively	(Kong et al. 2018)
Soil amendment	1–10%	*Tomato*	The soil OM content can be significantly enhanced, while the soil pH can be regulated effectively. It can also promote soil aggregation and enhance microbial activity in the soil	The germination rate of tomato seeds was enhanced, and the levels of K, Ca, and Mg in tomato leaves were elevated	(Yong et al. 2022)

Table 3 (continued)

Used as	Application rate (%, w/w)	Plant species	Claimed effects on soil	Claimed effects on plants	Ref
Soil amendment	40%	*Ryegrass*	The soil enzymes were more active, microbial diversity increased, and organic matter utilization and PAHS degradation were promoted	The chlorophyll content and peroxidase activity were increased by 21.69% and 62.44% respectively	(Zhou et al. 2023)
Soil amendment	1–10%	-	Soil dispersity is restrained, and water stability of dispersed soil is improved, making it change from dispersive to non-dispersive. The soil compressive strength and tensile strength were increased by 591% and 192% respectively	-	(Zhao et al. 2023a)
Soil amendment	15–60%	-	The permeability is reduced by 30–80%, the saturation water conductivity is decreased by 25–60%, the dispersity is increased by 130–760%, and the flow water component experiences a reduction of 12–31%	-	(Zhou et al. 2010)

The modification methods of coal gangue

The raw coal gangue requires appropriate modification to improve its performance, activate its beneficial ingredients, enhance its water and fertilizer retention, and mitigate its pollution and biological toxicity. Therefore, this chapter provided a comprehensive overview of the current research status on coal gangue modification technologies. It further examined the impact of various modification methods on soil improvement-related indicators and conducts a comparative analysis to identify their respective advantages and disadvantages.

At present, the common modification methods of coal gangue include mechanical modification, chemical modification, microbiological modification and thermal activation (Han et al. 2022; Lv et al. 2022; Zhang and Ling 2020). As an advanced modification method, hydrothermal method has garnered significant attention in recent years (Chao et al. 2022; Lachos-Perez et al. 2022; Munir et al. 2018).

Mechanical modification

Mechanical modification refers to the physical and chemical changes of the material under the action of mechanical forces, causing the particle size reduction, specific surface area enhancement, particle structure destruction, fracture of inter-particle hydrogen bonds and Al–O–Si bonds of kaolinite, thus promoting the defects or displacement of the lattice or even the amorphous state, and achieving the activation of beneficial elements (Said et al. 2018). Mechanical grinding was employed to modify the structure and enhance the pozzolanic reactivity of coal gangue (Zhao et al. 2022b). It has been observed that during the progressive grinding process, the coal gangue particles undergo sequential stages of particle size reduction, particle agglomeration and aggregate dispersion (Guo et al. 2016), leading to gradual improvements in both dehydroxylation degree and activity of coal gangue (Guo et al. 2009). The ball mill can transform Muscovite into amorphous state at 600 rpm, which significantly enhances the dissolution rate of silicon from 0.23% to 16.05%, as well as boosts the dissolution rate of potassium from 2.62% to 81.39%, rendering it suitable as a silica-potash fertilizer (Liu et al. 2020b). The mechanical modification is characterized by its simplicity of operation and low cost; however, it exhibits limited functionality and activation effectiveness, which fails to eliminate the pollution risk associated with coal gangue. Therefore, it is commonly combined with other modification technologies to enhance activation efficiency and mitigate pollutants (Fig. 3).

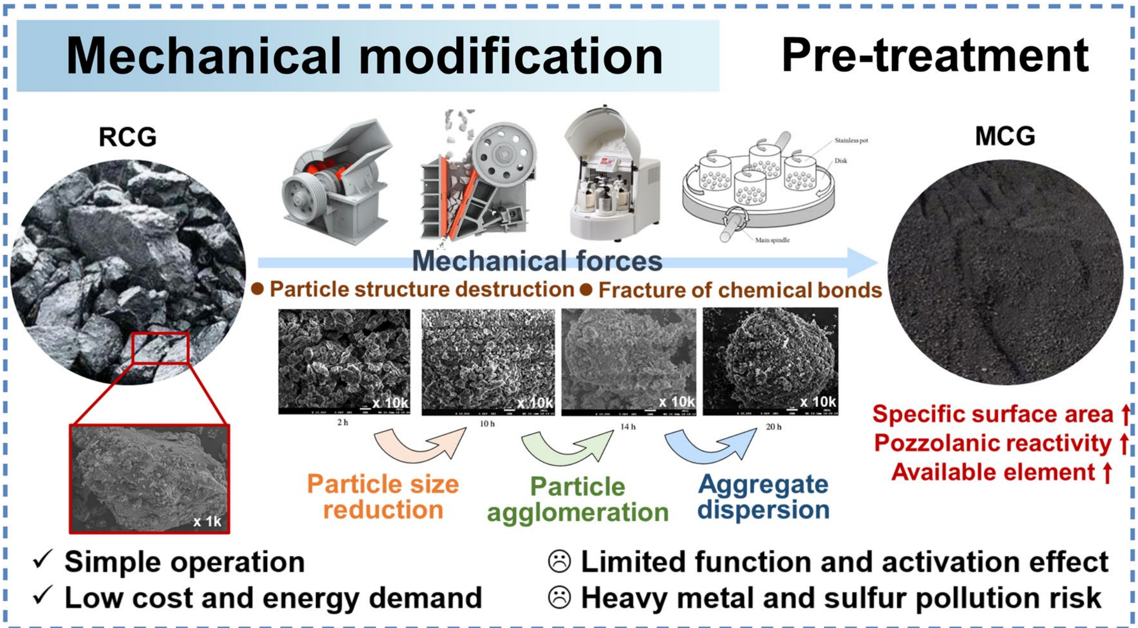


Fig. 3 The process, principle, effects and defects of mechanical modification (Guo et al. 2016; Liu et al. 2020b; Zhao et al. 2021b)

Chemical modification

The chemical modification is to modify the coal gangue with alkaline solution (such as Na_2CO_3, NaOH, KOH) or acidic solution (such as HNO_3, HCl). This modification disrupts the chemical bonds and alters the crystal structure and surface activity of coal gangue. Consequently, there is a significant enhancement in pore size distribution, active sites, and adsorption performance of coal gangue (Gao et al. 2015; Qian and Li 2015). As a result, the preparation of functional materials, the removal of impurities and the extraction of valuable components can be realized. Valuable elements can be extracted from coal gangue through heating and HNO_3 leaching, with extraction efficiency of 95.2%, 56.4% and 80.5% for Al, Ga and Li respectively. Additionally, the leaching residue possessed a large BET surface area and high available silicon content that can be utilized as silicon fertilizer (Shao et al. 2022). Alkaline solution destroyed the skeleton of silicoaluminate, so that Si–O-Si and Si–O-Al bonds quickly dissolved into the solution to form $[SiO_4]^{4-}$ and $[AlO_4]^{5-}$, thus enhancing gel performance (Cao et al. 2022). The addition of CaO facilitated a reaction between SiO_4^{4-} and AlO_4^{5-} with alkaline $Ca(OH)_2$, yielding calcium silicate hydrate (C-S–H) and calcium aluminate hydrate (C-A-H), further improving gel properties (Li et al. 2006; Zhang et al. 2021a). The surface of alkali-modified coal gangue exhibited a rougher texture and displayed a distinct pore structure, whereas the acid-modified coal gangue merely present numerous grooves on its surface (Guo et al. 2021). In general, alkalinity is mostly used to activate the gel properties of coal gangue, while acidity is mainly employed to leach rare earth elements and heavy metals, as well as improve pore structure and adsorption properties simultaneously. Chemical modification entails a straightforward operation with limited activation effects, typically combined with thermal activation (Fig. 4).

Microbiological modification

The metabolic processes of microorganisms are harnessed in microbiological modification to degrade minerals present in coal gangue, facilitating the release of nutrient elements and ultimately obtaining microbial fertilizers (He 2010). The study conducted by Bi et al. (2019) has proved the beneficial role of both arbuscular mycorrhizal fungi (AMF) and phosphate solubilizing bacteria (PSB) in the decomposition of organic matter and subsequent release of nutrients. PSB had the function of converting organic and inorganic phosphorus into soluble forms, which sensibly improved the availability of phosphorus in minerals and promotes plant growth (Benbrik et al. 2020). Silicate bacteria exhibited selectivity towards silicate minerals with distinct crystal structures, obviously promoting the dissolution of silicon and potassium (Lv et al. 2020). Moreover, scholars successfully isolated a strain of *Stenotrophomonas maltophilia* YZ1, which effectively dissolved nutrients and fix Pb^{2+} in coal gangue, thereby prominently increasing the content of available phosphorus, potassium, silicon and reduce the lead released (> 91.1%) in the modified coal gangue (Zhu et al. 2022; Zhu et al. 2023).

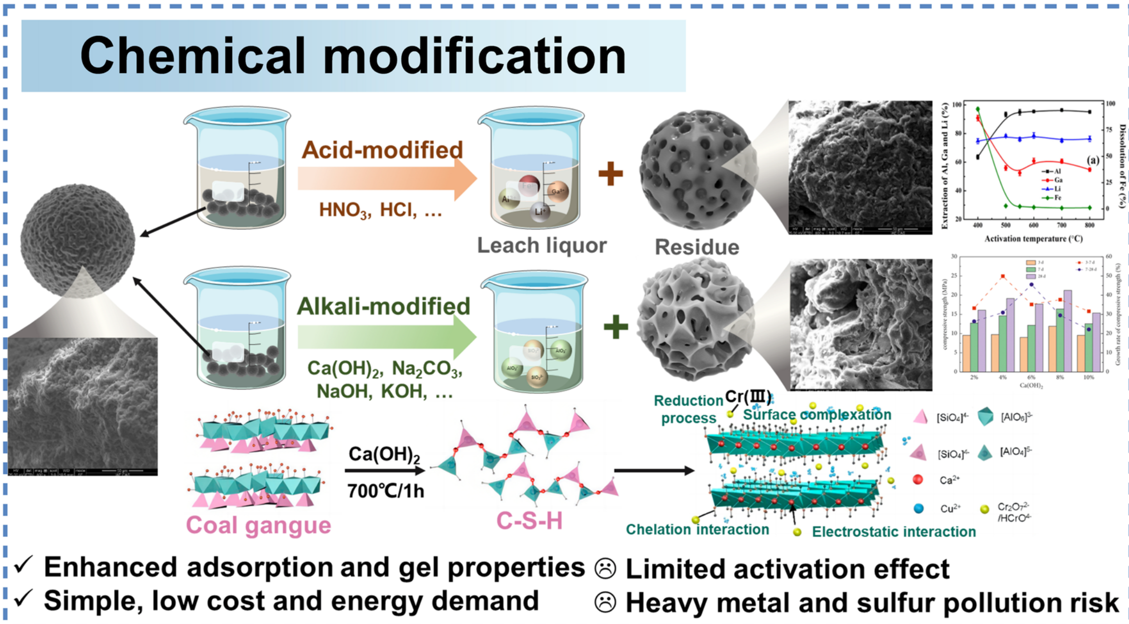


Fig. 4 The process, principle, effects and defects of chemical modification (Cao et al. 2022; Guo et al. 2021; Zhang et al. 2021a)

Organic acids produced through microbial metabolism can effectively enhance the solubilization and activation of mineral nutrient elements (Rezakhani et al. 2019), as well as the adsorption and immobilization of heavy metal ions (Yuan et al. 2017). Therefore, the screening of appropriate and efficient strains is anticipated to facilitate nutrient activation in coal gangue while mitigating its pollution. Due to the intricate composition of coal gangue, its microbiological modification necessitates the screening of a diverse range of functional bacteria for synergistic compounding, which is a complex and time-consuming endeavor and crucial challenge. However, it is noteworthy that the microbiological approach offers advantages such as low energy consumption, environmental friendliness and remarkable efficacy, making it deserving of extensive attention and research (Fig. 5).

Thermal modification

According to the literature, thermal activation is the most normally employed method for modification, which is utilized to enhance the activity of beneficial elements through breaking down polymerized long chains of silico-oxygen tetrahedrons and alumino-oxygen octahedrons at high temperatures (Jabłońska et al. 2017). The key factors influencing thermal activation efficiency are temperature and time. The reported optimal temperature and time for achieving maximum activity of coal gangue vary in different literature sources, which could be attributed to disparities in the composition and structure of the coal gangue (Arribas et al. 2018; Zhao et al. 2022b). It is noteworthy that the optimal activation temperature for a specific clay mineral may induce recrystallization in another mineral (Zhang and Ling 2020). The presence of clay minerals in coal gangue renders it a potential pozzolanic material upon thermal activation at temperatures up to 600—800 °C. With the temperature rising from 100 °C to 900 °C, coal gangue experiences dehydroxylation and structural transformation, causing a significant enhancement in reactivity and a gradual increase in available silicon content (Li et al. 2016; Lv et al. 2022). The uncalcined coal gangue has a scaly-like layered structure that remains unchanged below 500 °C and becomes porous and irregular at 600—800 °C. This transformation may be caused by the phase transition of metakaolin, dehydroxylation of kaolinite, as well as the reduction of bound water and organic matter (Cao et al. 2016). Excessive calcination above 950 °C causes the active amorphous material to recrystallize into stable mullite, severely reducing the reactivity (Frías et al. 2012).

In addition to conventional calcination, microwave thermal activation has gained increasing attention. The micro-morphology and micro-aggregate effects induced by microwave activated coal gangue conferred it with strong hydrophilicity, water fixation and water retention capabilities (Qiu et al. 2022). Besides, microwave thermal activation altered the mineral composition and gelling properties of coal gangue. The microwave-thermally activated products can serve as auxiliary gelling materials that are conducive to the formation of micro-aggregates (Guan et al. 2021). Thermal activation is an effective, simple and feasible approach for industrial applications; however, its implementation is

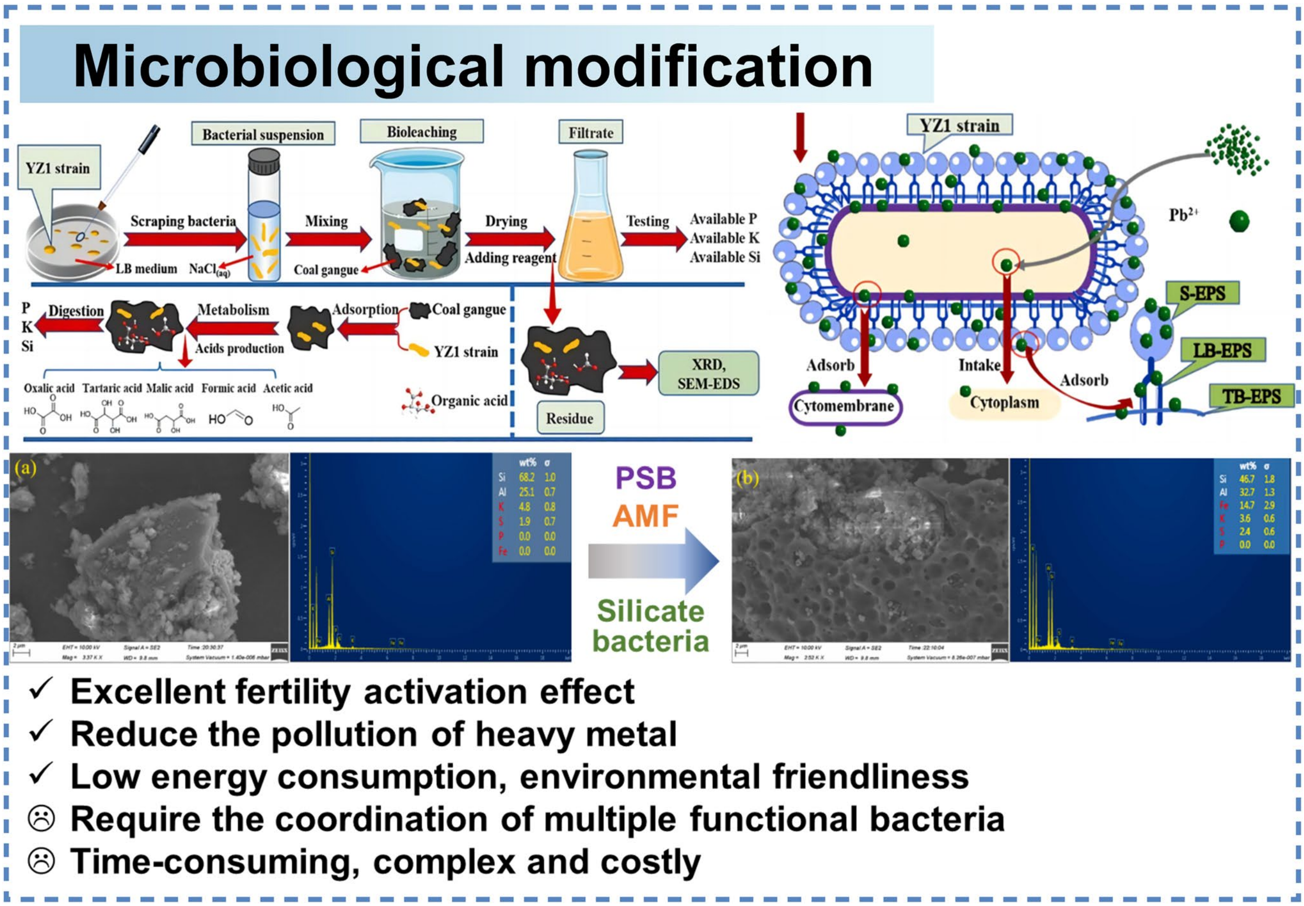


Fig. 5 The process, principle, effects and defects of microbiological modification (Zhu et al. 2022; Zhu et al. 2023)

hindered by its high energy consumption. Additionally, carbonaceous minerals and organic carbon are oxidized and emitted as greenhouse gases during the high-temperature activation process (Huang et al. 2018; Wang et al. 2022b), resulting in a substantial loss of organic matter, and thus observably diminishing the soil improvement value of coal gangue (Fig. 6).

Hydrothermal modification

The hydrothermal modification process takes place within a specialized closed reaction vessel, utilizing an aqueous solution as the reaction medium. Under high temperature and pressure conditions, a sub-critical water state is formed in the vessel (Kumar et al. 2018), promoting multiple conversions of coal gangue including hydrolysis, depolymerization, polymerization, isomerization, dehydration, aromatization, condensation, and other transformation reactions (Lachos-Perez et al. 2022). Because of its splendid activation effect, milder operating conditions and faster reaction rate, it has been widely applied in the field of solid waste disposal and resource recovery. The key parameters for hydrothermal modification of coal gangue include reaction temperature, residence time, pressure, solid–liquid ratio and reaction medium. Among these factors, temperature is the most critical determinant (Munir et al. 2018). When the temperature reaches the activation energy threshold for the reaction, chemical bond are broken, resulting in a variety of reactions (Sabio et al. 2016).

The commonly employed reaction medium for hydrothermal modification of coal gangue typically involves an alkaline solution, which accelerates the fracture of Si–O-Si and Si–O-M (M: Al, Mg, or others) bonds (Zhao et al. 2023b), thereby enabling the synthesis of novel functional materials with diverse morphology and properties through hydrothermal condensation or gel reaction (Fan et al. 2023; Zhao et al. 2023b). In comparison with chemical modification, the surface of coal gangue appears a higher abundance of basic functional groups and micro-pores after alkaline hydrothermal modification, which brings an augmented specific surface area, a more extensive distribution of pore sizes, and a significantly enhanced adsorption capacity (Jin et al. 2022; Li et al. 2016). The latest research demonstrated that alkaline hydrothermal modification activated nutrients and

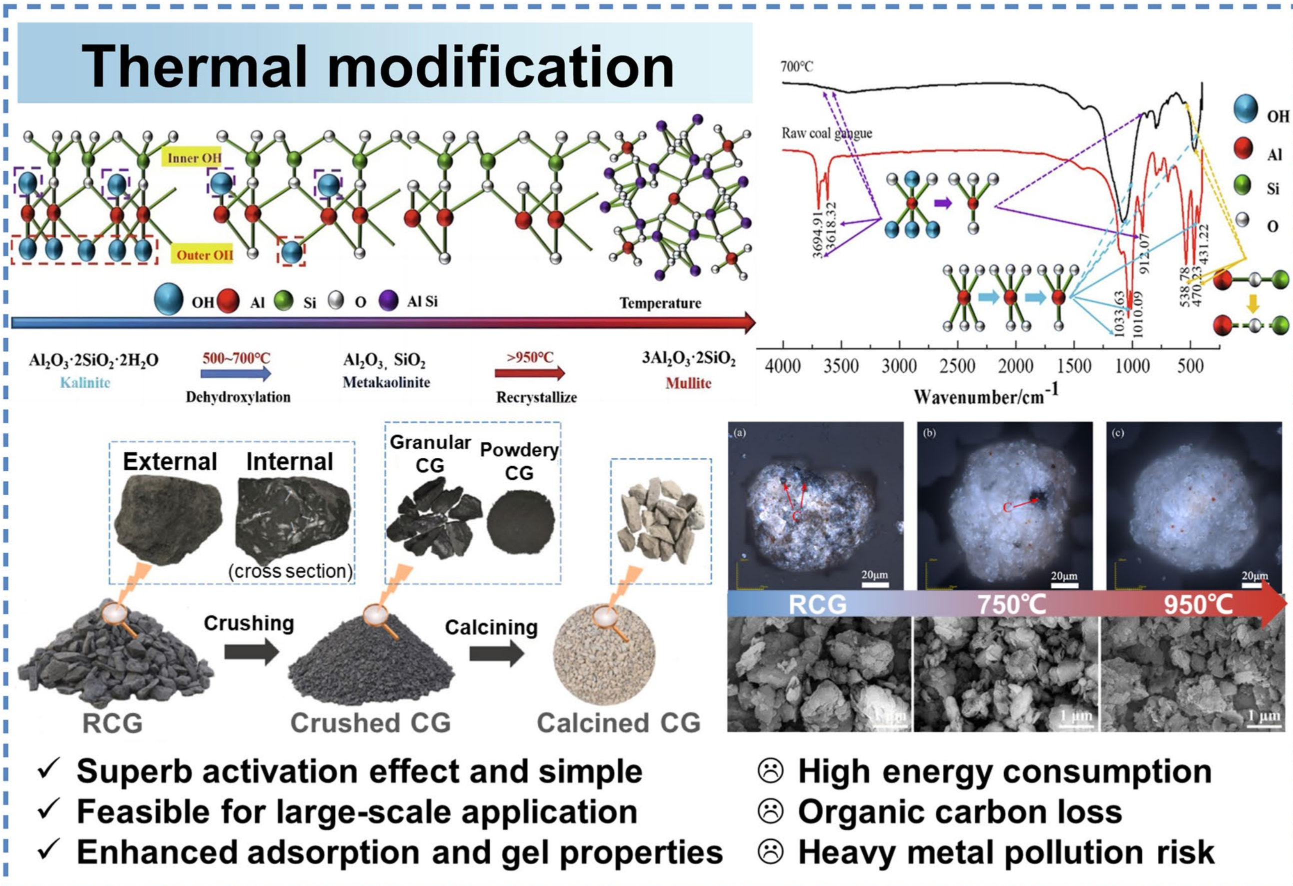


Fig. 6 The process, principle, effects and defects of thermal modification (Shao et al. 2022; Wang et al. 2022b; Zhao et al. 2022b)

removed pollutants in coal gangue simultaneously, yielding a highly active and eco-friendly silicon-based compound fertilizer (Tang et al. 2024). The subsequent sections provided a comprehensive account of the various specific functions associated with hydrothermal modification on soil improvement performance. Despite being a scientific, efficient, and versatile modification technology, the hydrothermal method still remains on laboratory or demonstration scale and has not yet been fully commercialized due to its reliance on expensive and intricate reactors (Munir et al. 2018) (Fig. 7).

Activate beneficial components

A vast body of literature has confirmed that alkaline hydrothermal treatment can effectively activate the beneficial components of silicaluminate minerals, and it is worth noting that red mud and coal gangue primarily consist of silicaluminate minerals. Chao et al. (2022) subjected red mud to hydrothermal conditions at 360 g/L K_2O and 240 ℃ for 1 h, resulting in solid phase effective K_2O and SiO_2 contents of 12.20% and 18.59%, respectively, meeting the market demand for multi-element compound fertilizer. The excessively prolonged reaction time caused a decrease in the available silicon content in solid products, which was attributed to the partial overlap between the reaction conditions for aluminosilicate hydrothermal activation and zeolite hydrothermal crystallization, bringing about a tendency for structural stability and reduced activity during the transition from activation to crystallization conditions (Liu et al. 2022). The availability of nutrients in the hydrothermal process was closely correlated with the severity of the hydrothermal reaction. For example, the total phosphorus content in the solid phase increased as the degree of reaction improved, while nitrogen exhibited a significant exponential decrease (Wang et al. 2019). The hydrothermal reaction motivated the gradual degradation of polyphosphate and organophosphate into orthophosphate (inorganic phosphorus), which was more favorable for crop uptake, while ensuring relatively stable phosphorus leaching (Huang et al. 2017). The nitrogen in the raw material underwent polymerization or condensation reactions in the hydrothermal solid phase, forming more stable quaternary ammonium compounds (Xiao et al. 2017). Consequently, hydrothermal methods can be employed to

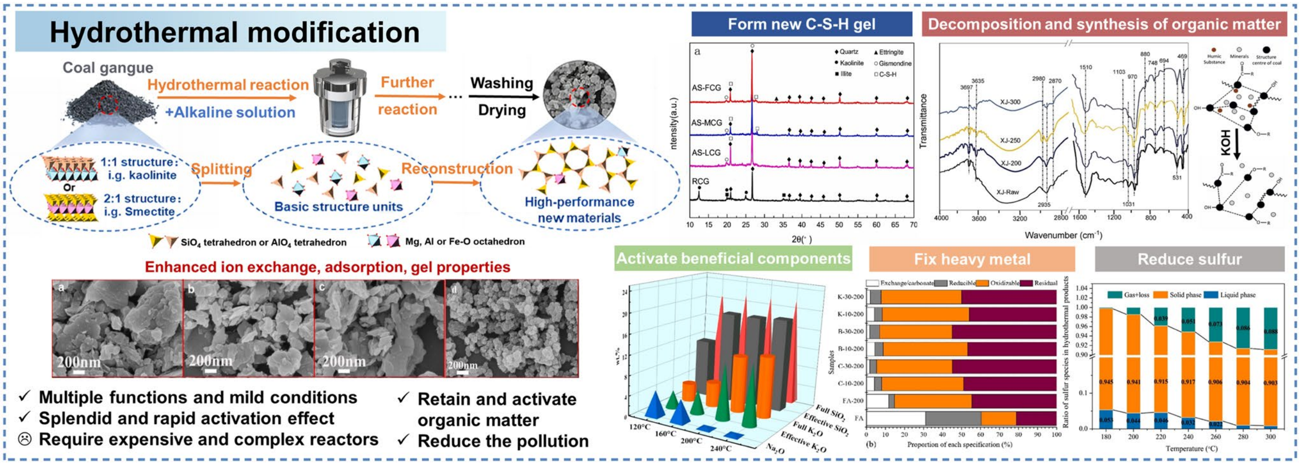


Fig. 7 The process, principle, effects and defects of hydrothermal modification (Chao et al. 2022; Wang et al. 2016c; Zhang et al. 2022b; Zhao et al. 2023b)

regulate the form and properties of nutrients, achieving a balance between plant absorption and soil fertility retention.

Improve the performance of coal gangue

According to the existing literature, the hydrothermal method is a viable way for removing inorganic ions from industrial solid waste and promoting the development of porous structures, while inducing alterations in mineral composition (Bayuseno et al. 2009; Cao et al. 2020). The high-quality zeolite with excellent properties, such as a high cation exchange capacity (CEC) and specific surface area, can be synthesized by alkaline hydrothermal methods. It is capable of stabilizing heavy metal ions and nutrients through cation exchange and adsorption (Li et al. 2020b; Li et al. 2014). Moreover, several literatures have stated the formation of new C-S–H and tobermolite phases from coal gangue after undergoing hydrothermal modification (Cao et al. 2022; Ye et al. 2022). The development of porous structure and clay minerals in these hydrothermally modified products can confer them with robust ion exchange, adsorption, and gel properties, which are positive for soil structure reconstruction, remediation of heavy metal pollution, and maintenance of soil nutrients.

Reduce the pollution of coal gangue

The application of hydrothermal modification has been revealed effective in the treatment of metal-contaminated soil, fly ash, and incineration bottom ash (Chen et al. 2020; Chen et al. 2019). Alkaline hydrothermal processes facilitated the conversion of silicon and aluminum into stable silico-aluminate minerals, thereby immobilizing heavy metals within the lattice structure and impeding their reactivation (Bayuseno et al. 2009; Shi et al. 2017). In comparison to conventional methods such as chelating agent stabilization and cement fixation technology, hydrothermal treatment offers simultaneous stabilization of diverse heavy metals, along with advantages in terms of simplicity, rapid, efficiency, as well as environmental and economic benefits (Hu et al. 2015; Zhang et al. 2022b). Not only that, hydrothermal modification triggered the destruction, decomposition and transformation of organic sulfur, thereby elevating the stability of sulfur structure in hydrothermal products (Chen et al. 2020; Wang et al. 2016c), which efficiently mitigated soil sulfur pollution and alleviated plant growth inhibition caused by excessive available sulfur in coal gangue.

Maximize the utilization of organic matter in coal gangue

Coal gangue is characterized by a high proportion of stable recalcitrant organic matter (ROM) (Bi et al. 2020). The organic matter underwent a complex process of decomposition and synthesis during hydrothermal processes (Hou et al. 2022). However, the structure and compositional changes of organic matter in coal gangue during the hydrothermal process have not been elucidated. Subsequent research is essential to focus on investigating suitable conditions to regulate the proportion of two organic matters with distinct functions, in order to ensure a sufficient supply of stable macromolecules ROM for promoting the formation of soil aggregates (Qin et al. 2021), and an appropriate labile organic matter (LOM) that can be directly absorbed and utilized by plants and microorganisms (Muqaddas et al. 2019). Additionally, coal gangue contains stable organic matter and humus that can be solubilized in an alkaline hydrothermal environment (Kappler and Brune 1999; Sriramoju et al. 2022). In the future, it is also considered to extract humus from the hydrothermal liquid phase to further improve the added value of coal gangue.

Combined modification

In practical applications, a combination of multiple modification methods is recommended to achieve optimal effectiveness and maximum benefits. Combined modification methods, such as chemically assisted mechanical milling (Zhao et al.. 2021b), thermal activation coupled with chemical modification (Dong et al. 2023), mechanical pulverization combined with microbiological modification (Zhu et al. 2022), chemical regent facilitated hydrothermal treatment (Jin et al. 2022), hydrothermal method coupled with chemical, mechanical and thermal modification (Li et al. 2010; Li et al. 2020b) have attracted a lot of attention. The combined technology can effectively address the limitations associated with a single technology; however, it necessitates intricate and multifaceted operational procedures.

Potential applications of modified coal gangue

The soil conditioners derived from different modification methods of coal gangue exhibit diverse properties, showing varying degrees of enhancement in soil improvement performance and safety. The potential applications of modified coal gangue soil conditioner are thoroughly analyzed in this chapter.

Used as fertilizers to supply nutrients

The modified coal gangue derived-soil conditioner is anticipated to exhibit enhanced efficacy as a fertilizer compared to the raw coal gangue, owing to the activation of beneficial components. It generally serves as silicon fertilizers, micronutrient fertilizers, as well as nutritious supplementary.

The modified coal gangue exhibits a significantly elevated effective silicon content (Chao et al. 2022; Liu et al. 2020b), rendering it suitable as a silicon fertilizer to mitigate transpiration loss, enhance nutrient utilization efficiency, and augment plant resilience against abiotic and biotic stresses, thus enhancing the survival ability of plants in extremely harsh environments (Castro and Crusciol 2013). Furthermore, It has been confirmed that supplementing available silicon can remarkably upgrade soil water availability and holding capacity (Kuhla et al. 2021), enhance soil microbial community and mitigate heavy metal accumulation in plants (Wang et al. 2020; Zhao et al. 2022a).

Micronutrient deficiency in soil may impede agricultural productivity and affect human nutrition either directly or indirectly (Steinnes 2009). The modified coal gangue contains an abundant amount of available micronutrient. Taking selenium as an example, the activation rate of modified coal gangue towards selenium reaches a remarkable 81.24% (Liu et al. 2020a). In China, it is estimated that approximately 72% of the territory suffers from selenium deficiency. The application of selenium fertilizer derived from modified coal gangue in soil will contribute to enhancing crop resistance and ensuring optimal crop yield in saline-alkali land and arid areas (Long et al. 2019).

Besides, the modified coal gangue can function as a multi-nutrient supplementary, providing moderate available organic matter, N, P, K for the poor soil. While ensuring the provision of essential nutrients for plant and microorganism growth, it effectively prevents nutrient loss. Additionally, modified coal gangue possesses the capacity to absorb nutriment while maintaining them molecular state, thereby facilitating their absorption by crops and effectively improving nutrient utilization rates (Wang et al. 2021a; Zhou and Shan 2008).

Used as soil amendments to improve degraded soil

The modified coal gangue is expected to serve as an eco-friendly soil amendment with exceptional soil improvement performance, primarily attributed to its enhanced pore structure, water retention capacity, fertilizer retention ability, and environmental safety, as well as remarkable ion exchange, adsorption, and gel properties.

The addition of porous modified coal gangue can improve soil structure, which is conducive to nutrient absorption and respiration of plant roots, and significantly boost the biomass of soil microorganisms (Ananyeva et al. 2013). The abundance of soil microorganisms plays a pivotal role in effectively increasing soil humus content, maintaining the dynamic transformation of nutrients, improving soil fertility, and ultimately promoting plant growth (Blagodatskaya and Kuzyakov 2013).

In addition, the properties of modified coal gangue make it applicable for the remediation of sandy soil and heavy metal-contaminated soil. The activated organic matter in modified coal gangue serves as the foundation for soil aggregate formation, thereby influencing soil structure and porosity and subsequently altering water holding capacity and infiltration capacity of the sandy soil (Gao et al. 2016). After the application of modified coal gangue, the effective Cd content in soil decreased by 21.2–33.9% (Zhao et al. 2021a). The coal gangue-based material modified by (Chen et al. 2023) effectively reduces the available As and Cd by 17.94–29.81% and 14.22–30.41%, respectively. These findings suggest that modified coal gangue can reconstruct sandy soil function and immobilize heavy metals availably, rendering it an ideal amendment for remediating sandy soil and co-contaminated soil with multiple heavy metal (Fig. 8).

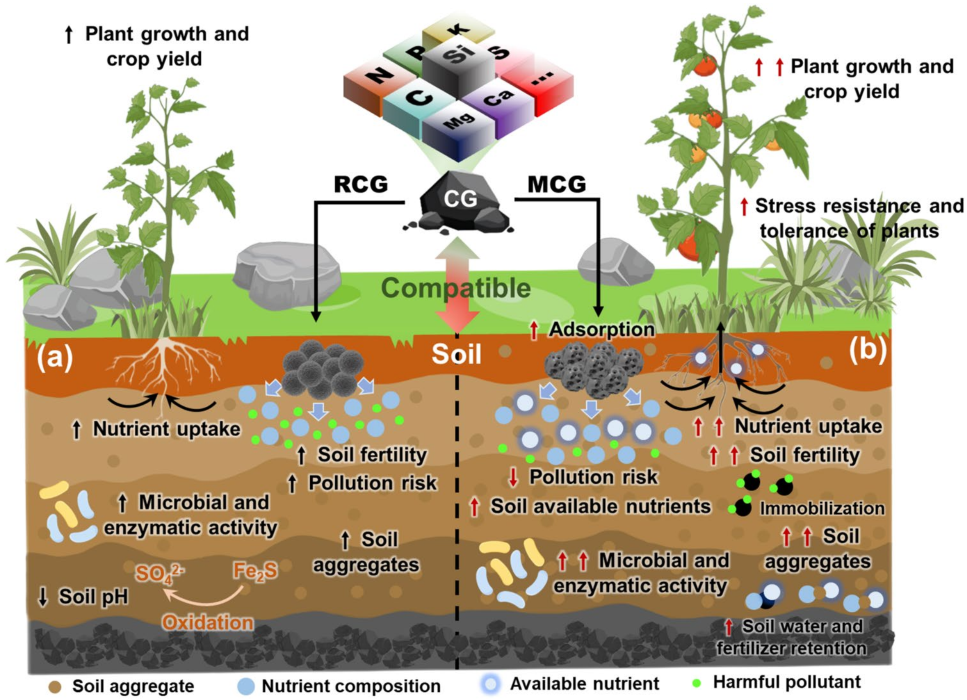


Fig. 8 Intended benefits and unintended risks of (a) raw coal gangue (RCG)-based soil conditioners and (b) modified coal gangue (MCG)-based soil conditioners on soil properties, plant growth and development

Environmental consideration

The resourceful utilization of coal gangue as soil conditioners, particularly the modified coal gangue, not only facilitates the harmless and resource treatment of substantial quantities of coal gangue, but also realize the restoration of degraded soil, thereby yielding positive economic, social, ecological, and environmental benefits. Additionally, it plays an important role in carbon reduction. The spontaneous combustion, pollution, and soil degradation caused by centralized stacking coal gangue will lead to a decline in surrounding vegetation and reduction of carbon sink capacity. However, the utilization of coal gangue as a soil amendment or fertilizer can effectively restore degraded soil and improve stable ecological carbon sinks such as soil aggregates and phytic carbon (Liu 2023). Su et al. (2010) demonstrated that over the 7-year and 32-year recovery periods of sandy land, soil carbon sequestration in the 0–15 cm layer reached 1.8–9.4 Mg ha^{-1} and 7.5–17.3 Mg ha^{-1}, respectively. Hence, modified coal gangue exhibits significant potential for enhancing soil quality and promoting soil carbon sequestration in desertification region. According to the carbon footprint analysis conducted by (Ashfaq et al. 2021), the procurement and transportation of raw materials exhibit the highest carbon emissions compared to other stages of utilization. Therefore, employing modified coal gangue for enhancing local degraded soil through in-situ utilization can yield significant reductions in carbon emissions.

It needs to be emphasized that although heavy metal levels in coal gangue generally remain below the threshold, prolonged usage may result in the accumulation of heavy metals and pose a threat to crop safety. Current research primarily focuses on the influence of modification methods on coal gangue characteristics, with limited attention given to the impact of modified coal gangue on soil and plant growth. It is imperative to closely monitor the environmental impact of modified coal gangue throughout its cradle-to-grave life cycle and ensure both environmental protection and crop safety. In practical applications and subsequent research endeavors, an appropriate modification method should be selected to obtain modified coal gangue with matching performance based on specific local soil improvement requirements, thereby facilitating in-situ treatment of coal gangue while yielding positive environmental, economic, and social benefits.

Conclusions

As one of the largest industrial solid wastes in the world, coal gangue not only poses a pollution risk but also holds immense untapped potential for soil improvement that is often overlooked. The raw coal gangue is cost-effective, easily accessible and compatible with soil. Incorporating less than 20% of raw coal gangue typically optimizes soil structure, enhances soil fertility, and stimulates plant growth. The limited effectiveness and application amount of raw coal gangue are attributed to the low reactivity of beneficial components, inadequate water and fertilizer retention, as well as a high risk of pollution. The modification technologies, including mechanical, chemical, microbiological, thermal, hydrothermal and combined modifications, are effective to enhance the soil improvement performance while mitigating pollution of coal gangue. This enables the acquisition of high-quality and pollution-free multi-functional soil conditioner. Among them, hydrothermal and combined modification stands out due to its comprehensive and effective functions, making it deserving of attention. The modified coal gangue not only serves as a multi-nutrient source, providing essential nutrients for the soil, but also acts as an effective soil amendment in rehabilitating degraded soils such as sandy soil, heavy metal-contaminated soil. This not only facilitates the conversion of coal gangue waste into valuable resources but also effectively rehabilitates degraded soil and fosters the establishment of a stable ecological carbon sink. This paper provided an innovative approach to achieving clean coal production and promoting sustainable agriculture.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11356-024-34895-2.

Acknowledgements The authors gratefully acknowledge the financial support from the National Natural Science Foundation of China (NSFC) (No.52170147).

Author contributions All authors contributed to the study conception and design. Literature search and data collection and analysis were performed by Tian Tang, Zheng Wang, Liuzhou Chen and Shu Wu. The idea and first draft of the manuscript was written by Tian Tang and the work was critically revised by Yangsheng Liu. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding This work was supported by the National Natural Science Foundation of China (NSFC) (No.52170147).

Data availability The authors declare that the data supporting the findings of this study are available within the paper and its Supplementary Information files. Should any raw data files be needed in another format they are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

References

Aakriti et al (2023) A comprehensive review of flue gas desulphurized gypsum: production, properties, and applications. Constr Build Mater 393:131918. https://doi.org/10.1016/j.conbuildmat.2023.131918

Amoah-Antwi C et al (2020) Restoration of soil quality using biochar and brown coal waste: a review. Sci Total Environ 722:137852. https://doi.org/10.1016/j.scitotenv.2020.137852

Anam GB et al (2019) Characterization of Trichoderma asperellum RM-28 for its sodic/saline-alkali tolerance and plant growth promoting activities to alleviate toxicity of red mud. Sci Total Environ 662:462–469. https://doi.org/10.1016/j.scitotenv.2019.01.279

Ananyeva K et al (2013) Can intra-aggregate pore structures affect the aggregate's effectiveness in protecting carbon? Soil Biol Biochem 57:868–875. https://doi.org/10.1016/j.soilbio.2012.10.019

Arribas I et al (2018) The deterioration and environmental impact of binary cements containing thermally activated coal mining waste due to calcium leaching. J Clean Prod 183:887–897. https://doi.org/10.1016/j.jclepro.2018.02.127

Ashfaq M et al (2020) Static and dynamic leaching studies on coal gangue. In: Reddy KR et al (eds) Sustainable environmental geotechnics, vol 89. Springer International Publishing, Cham, pp 261–270. https://doi.org/10.1007/978-3-030-51350-4_28

Ashfaq M et al (2021) Utilization of coal gangue for earthworks: sustainability perspective. In: Hazarika H et al (eds) Advances in sustainable construction and resource management. Springer Singapore, Singapore, pp 203–218. https://doi.org/10.1007/978-981-16-0077-7_20

Babla M et al (2022) Value-added products as soil conditioners for sustainable agriculture. Resour Conserv Recycl 178:106079. https://doi.org/10.1016/j.resconrec.2021.106079

Bayuseno AP et al (2009) Hydrothermal processing of MSWI fly ash-towards new stable minerals and fixation of heavy metals. J Hazard Mater 167:250–259. https://doi.org/10.1016/j.jhazmat.2008.12.119

Benbrik B et al (2020) Reusing phosphate sludge enriched by phosphate solubilizing bacteria as biofertilizer: growth promotion of Zea Mays. Biocatal Agric Biotechnol 30:101825. https://doi.org/10.1016/j.bcab.2020.101825

Berta KM et al (2021) Red mud with other waste materials as artificial soil substitute and its effect on Sinapis alba. J Environ Manage 287:112311. https://doi.org/10.1016/j.jenvman.2021.112311

Bhattacharya SS et al (2012) Vermicomposting converts fly ash to enrich soil fertility and sustain crop growth in red and lateritic soils. Resour Conserv Recycl 65:100–106. https://doi.org/10.1016/j.resconrec.2012.05.008

Bi Y et al (2019) Response of arbuscular mycorrhizal fungi and phosphorus solubilizing bacteria to remediation abandoned solid waste of coal mine. Int J Coal Sci Technol 6:603–610. https://doi.org/10.1007/s40789-019-00270-7

Bi H et al (2020) Combustion behavior, kinetics, gas emission characteristics and artificial neural network modeling of coal gangue and biomass via TG-FTIR. Energy 213:118790. https://doi.org/10.1016/j.energy.2020.118790

Blagodatskaya E, Kuzyakov Y (2013) Active microorganisms in soil: critical review of estimation criteria and approaches. Soil Biol Biochem 67:192–211. https://doi.org/10.1016/j.soilbio.2013.08.024

Brockway PE et al (2019) Estimation of global final-stage energy-return-on-investment for fossil fuels with comparison to renewable energy sources. Nat Energy 4:612–621. https://doi.org/10.1038/s41560-019-0425-z

Caneda-Martínez L et al (2019) Water transport in binary eco-cements containing coal mining waste. Cement Concr Compos 104:103373. https://doi.org/10.1016/j.cemconcomp.2019.103373

Cao Z et al (2016) Effect of calcination condition on the microstructure and pozzolanic activity of calcined coal gangue. Int J Miner Process 146:23–28. https://doi.org/10.1016/j.minpro.2015.11.008

Cao P et al (2020) Alkali-reinforced hydrothermal synthesis of lathy tobermorite fibers using mixture of coal fly ash and lime. Constr Build Mater 238:117655. https://doi.org/10.1016/j.conbuildmat.2019.117655

Cao P et al (2021) Extraction and value-added utilization of alumina from coal fly ash via one-step hydrothermal process followed by carbonation. J Clean Prod 323:129174. https://doi.org/10.1016/j.jclepro.2021.129174

Cao P et al (2022) Extraction of alumina from low-grade kaolin in the presence of lime and NaOH via multi-stage hydrothermal process. Appl Clay Sci 229:106675. https://doi.org/10.1016/j.clay.2022.106675

Castro GSA, Crusciol CAC (2013) Effects of superficial liming and silicate application on soil fertility and crop yield under rotation. Geoderma 195–196:234–242. https://doi.org/10.1016/j.geoderma.2012.12.006

Chao X et al (2022) Sustainable application of sodium removal from red mud: cleaner production of silicon-potassium compound fertilizer. J Clean Prod 352:131601. https://doi.org/10.1016/j.jclepro.2022.131601

Chen C et al (2010) Sewage sludge conditioning with coal fly ash modified by sulfuric acid. Chem Eng J 158:616–622. https://doi.org/10.1016/j.cej.2010.02.021

Chen Z et al (2019) Research on synergistically hydrothermal treatment of municipal solid waste incineration fly ash and sewage sludge. Waste Manage 100:182–190. https://doi.org/10.1016/j.wasman.2019.09.006

Chen C et al (2020) From wasted sludge to valuable biochar by low temperature hydrothermal carbonization treatment: Insight into the surface characteristics. J Clean Prod 263:121600. https://doi.org/10.1016/j.jclepro.2020.121600

Chen M et al (2023) Coal gangue-based magnetic porous material for simultaneous remediation of arsenic and cadmium in contaminated soils: performance and mechanisms. Chemosphere 338:139380. https://doi.org/10.1016/j.chemosphere.2023.139380

Chu Z et al (2020) Influence of coal gangue aided phytostabilization on metal availability and mobility in copper mine tailings. Environmental Earth Sciences 79:68. https://doi.org/10.1007/s12665-020-8807-x

Clavier KA et al (2020) Opportunities and challenges associated with using municipal waste incineration ash as a raw ingredient in cement production – a review. Resour Conserv Recycl 160:104888. https://doi.org/10.1016/j.resconrec.2020.104888

Debiagi P et al (2022) Iron as a sustainable chemical carrier of renewable energy: analysis of opportunities and challenges for retrofitting coal-fired power plants. Renew Sustain Energy Rev 165:112579. https://doi.org/10.1016/j.rser.2022.112579

DeSutter TM et al (2014) Application of flue gas desulfurization gypsum and its impact on wheat grain and soil chemistry. J Environ Qual 43:303–311. https://doi.org/10.2134/jeq2012.0084

Devlin A et al (2023) Global green hydrogen-based steel opportunities surrounding high quality renewable energy and iron ore deposits. Nat Commun 14:2578. https://doi.org/10.1038/s41467-023-38123-2

Dong C et al (2023) Optimized preparation of gangue waste-based geopolymer adsorbent based on improved response surface methodology for Cd(II) removal from wastewater. Environ Res 221:115246. https://doi.org/10.1016/j.envres.2023.115246

Du T et al (2020) Optimizing the formulation of coal gangue planting substrate using wastes: the sustainability of coal mine ecological restoration. Ecol Eng 143:105669. https://doi.org/10.1016/j.ecoleng.2019.105669

Fabiańska MJ et al (2013) Gaseous compounds and efflorescences generated in self-heating coal-waste dumps — a case study from the Upper and Lower Silesian Coal Basins (Poland). Int J Coal Geol 116–117:247–261. https://doi.org/10.1016/j.coal.2013.05.002

Fan X et al (2023) Subcritical hydrothermal treatment of municipal solid waste incineration fly ash: a review. Sci Total Environ 865:160745. https://doi.org/10.1016/j.scitotenv.2022.160745

Frasson BJ et al (2019) Influence of different sources of coal gangue used as aluminosilicate powder on the mechanical properties and microstructure of alkali-activated cement. Mater Constr. https://doi.org/10.3989/mc.2019.12618

Frías M et al (2012) Effect of activated coal mining wastes on the properties of blended cement. Cement Concr Compos 34:678–683. https://doi.org/10.1016/j.cemconcomp.2012.02.006

Fu B et al (2018) A comparative study on the mineralogy, chemical speciation, and combustion behavior of toxic elements of coal beneficiation products. Fuel 228:297–308. https://doi.org/10.1016/j.fuel.2018.04.085

Gao Y et al (2015) Preparation and characterization of a novel porous silicate material from coal gangue. Microporous Mesoporous Mater 217:210–218. https://doi.org/10.1016/j.micromeso.2015.06.033

Gao Y et al (2016) Relationship between soil organic carbon distribution and soil chemical properties in mining area. J Inn Mong Agric Univ (Natural Science Edition) 37:54–60. https://doi.org/10.16853/j.cnki.1009-3575.2016.01.009

Gao H et al (2021a) Explanation of heavy metal pollution in coal mines of china from the perspective of coal gangue geochemical characteristics. Environ Sci Pollut Res 28:65363–65373. https://doi.org/10.1007/s11356-021-14766-w

Gao S et al (2021b) Application of coal gangue as a coarse aggregate in green concrete production: a review. Materials 14. https://doi.org/10.3390/ma14226803.

Garau G et al (2011) Long-term influence of red mud on as mobility and soil physico-chemical and microbial parameters in a polluted sub-acidic soil. J Hazard Mater 185:1241–1248. https://doi.org/10.1016/j.jhazmat.2010.10.037

Garbowski T et al (2023) An overview of natural soil amendments in agriculture. Soil Tillage Res 225:105462. https://doi.org/10.1016/j.still.2022.105462

George A et al (2020) Emission control strategies of hazardous trace elements from coal-fired power plants in China. J Environ Sci 93:66–90. https://doi.org/10.1016/j.jes.2020.02.025

Gräfe M, Klauber C (2011) Bauxite residue issues: IV. Old obstacles and new pathways for in situ residue bioremediation. Hydrometallurgy 108:46–59. https://doi.org/10.1016/j.hydromet.2011.02.005

Grim RE (1962) Clay mineralogy. Science 135:890–898. https://doi.org/10.1126/science.135.3507.890

Guan X et al (2021) Performance of microwave-activated coal gangue powder as auxiliary cementitious material. J Market Res 14:2799–2811. https://doi.org/10.1016/j.jmrt.2021.08.106

Guo W et al (2009) Structure and pozzolanic activity of calcined coal gangue during the process of mechanical activation. J Wuhan Univ Technol-Mater Sci Ed 24:326–329. https://doi.org/10.1007/s11595-009-2326-7

Guo Y et al (2016) Improved extraction of alumina from coal gangue by surface mechanically grinding modification. Powder Technol 302:33–41. https://doi.org/10.1016/j.powtec.2016.08.034

Guo X et al (2021) Study on the treatment of acid mine drainage containing Fe2+ and Mn2+ using modified spontaneous combustion gangue. J Renew Mater 9:541–555. https://doi.org/10.32604/jrm.2021.012335

Guo L et al (2022) Preparation of coal gangue-slag-fly ash geopolymer grouting materials. Constr Build Mater 328:126997. https://doi.org/10.1016/j.conbuildmat.2022.126997

Han X et al (2021) Influence of coal gangue mulching with various thicknesses and particle sizes on soil water characteristics. Sci Rep 11:15368. https://doi.org/10.1038/s41598-021-94806-0

Han R et al (2022) Activation mechanism of coal gangue and its impact on the properties of geopolymers: a review. Polymers 14. https://doi.org/10.3390/polym14183861

He ZL et al (2005) Trace elements in agroecosystems and impacts on the environment. J Trace Elem Med Biol 19:125–140. https://doi.org/10.1016/j.jtemb.2005.02.010

He H et al (2017) Impacts of coal fly ash on plant growth and accumulation of essential nutrients and trace elements by alfalfa

(Medicago sativa) grown in a loessial soil. J Environ Manage 197:428–439. https://doi.org/10.1016/j.jenvman.2017.04.028
He W (2010) Research and application prospects of micro-silicon fertilizer on rice production. https://doi.org/10.3969/j.issn.1673-6737.2010.05.027
Energy Institute (2023) Statistical review of world energy 2023. Energy Institute
Hou D et al (2020) Sustainable soil use and management: an interdisciplinary and systematic approach. Sci Total Environ 729:138961. https://doi.org/10.1016/j.scitotenv.2020.138961
Hou J et al (2022) Restoration of organic-matter-impoverished arable soils through the application of soil conditioner prepared via short-time hydrothermal fermentation. Environ Res 204:112088. https://doi.org/10.1016/j.envres.2021.112088
Hu Y et al (2015) Stabilization and separation of heavy metals in incineration fly ash during the hydrothermal treatment process. J Hazard Mater 299:149–157. https://doi.org/10.1016/j.jhazmat.2015.06.002
Hua Y et al (2017) The use of red mud as an immobiliser for metal/metalloid-contaminated soil: a review. J Hazard Mater 325:17–30. https://doi.org/10.1016/j.jhazmat.2016.11.073
Huang R et al (2017) Transformation of phosphorus during (Hydro) thermal treatments of solid biowastes: reaction mechanisms and implications for P reclamation and recycling. Environ Sci Technol 51:10284–10298. https://doi.org/10.1021/acs.est.7b02011
Huang G et al (2018) Improving strength of calcinated coal gangue geopolymer mortars via increasing calcium content. Constr Build Mater 166:760–768. https://doi.org/10.1016/j.conbuildmat.2018.02.005
IEA (2023) World Energy Outlook 2023. International Energy Agency Statistics
Jabłońska B et al (2017) The structural and surface properties of natural and modified coal gangue. J Environ Manage 190:80–90. https://doi.org/10.1016/j.jenvman.2016.12.055
Jankowski J et al (2006) Mobility of trace elements from selected Australian fly ashes and its potential impact on aquatic ecosystems. Fuel 85:243–256. https://doi.org/10.1016/j.fuel.2005.05.028
Jin Y et al (2022) Synthesis of coal-analcime composite from coal gangue and its adsorption performance on heavy metal ions. J Hazard Mater 423:127027. https://doi.org/10.1016/j.jhazmat.2021.127027
Kappler A, Brune A (1999) Influence of gut alkalinity and oxygen status on mobilization and size-class distribution of humic acids in the hindgut of soil-feeding termites. Appl Soil Ecol 13:219–229. https://doi.org/10.1016/S0929-1393(99)00035-9
Kong T et al (2018) Effects of coal gangue on revegetation and microbial properties of an alkali-saline soil. J Soil Water Conserv 32:321–3265. https://doi.org/10.13870/j.cnki.stbcxb.2018.06.046
Koshy N et al (2019) Synthesis and characterization of geopolymers derived from coal gangue, fly ash and red mud. Constr Build Mater 206:287–296. https://doi.org/10.1016/j.conbuildmat.2019.02.076
Kuhla J et al (2021) Effect on soil water availability, rather than silicon uptake by plants, explains the beneficial effect of silicon on rice during drought. Plant Cell Environ 44:3336–3346. https://doi.org/10.1111/pce.14155
Kumar M et al (2018) A review on the current status of various hydrothermal technologies on biomass feedstock. Renew Sustain Energy Rev 81:1742–1770. https://doi.org/10.1016/j.rser.2017.05.270
Lachos-Perez D et al (2022) Hydrothermal carbonization and Liquefaction: differences, progress, challenges, and opportunities. Biores Technol 343:126084. https://doi.org/10.1016/j.biortech.2021.126084
Li J, Wang J (2019) Comprehensive utilization and environmental risks of coal gangue: a review. J Clean Prod 239:117946. https://doi.org/10.1016/j.jclepro.2019.117946
Li D et al (2006) Research on cementitious behavior and mechanism of pozzolanic cement with coal gangue. Cem Concr Res 36:1752–1759. https://doi.org/10.1016/j.cemconres.2004.11.004
Li C et al (2010) Investigation on the activation of coal gangue by a new compound method. J Hazard Mater 179:515–520. https://doi.org/10.1016/j.jhazmat.2010.03.033
Li J et al (2014) Synthesis of merlinoite from Chinese coal fly ashes and its potential utilization as slow release K-fertilizer. J Hazard Mater 265:242–252. https://doi.org/10.1016/j.jhazmat.2013.11.063
Li L et al (2016) The thermal activation process of coal gangue selected from Zhungeer in China. J Therm Anal Calorim 126:1559–1566. https://doi.org/10.1007/s10973-016-5711-4
Li B et al (2020a) Study of combustion behaviour and kinetics modelling of Chinese Gongwusu coal gangue: model-fitting and model-free approaches. Fuel 268:117284. https://doi.org/10.1016/j.fuel.2020.117284
Li H et al (2020b) Facile preparation of zeolite-activated carbon composite from coal gangue with enhanced adsorption performance. Chem Eng J 390:124513. https://doi.org/10.1016/j.cej.2020.124513
Li M et al (2020c) Reutilisation of coal gangue and fly ash as underground backfill materials for surface subsidence control. J Clean Prod 254:120113. https://doi.org/10.1016/j.jclepro.2020.120113
Li C et al (2022a) In-situ preparation of coal gangue-based catalytic material for efficient peroxymonosulfate activation and phenol degradation. J Clean Prod 374:133926. https://doi.org/10.1016/j.jclepro.2022.133926
Li M et al (2022b) Effects of flue gas desulfurization gypsum incorporation and curing temperatures on magnesium oxysulfate cement. Constr Build Mater 349:128718. https://doi.org/10.1016/j.conbuildmat.2022.128718
Li J et al (2023) Enrichment of lithium in the claystone coal gangue from the Malan mine, Xishan Coalfield, Shanxi Province, Northern China. Geochemistry:125972. https://doi.org/10.1016/j.chemer.2023.125972
Liu X (2023) Low-carbon utilization of coal gangue under the carbon neutralization strategy: a short review. J Mater Cycles Waste Manage 25:1978–1987. https://doi.org/10.1007/s10163-023-01712-w
Liu W et al (2014) Environmental assessment, management and utilization of red mud in China. J Clean Prod 84:606–610. https://doi.org/10.1016/j.jclepro.2014.06.080
Liu X et al (2020a) Activation of Se-enriched coal gangue and the efficient use of coal gangue Se fertilizer. J Plant Nutr Fertil 26:1526–1535. https://doi.org/10.11674/zwyf.19260
Liu Y et al (2020b) Cogrinding with alkaline metal salts to enhance the reactivity of silicate mineral to serve as silicon fertilizer. Chem Phys Lett 747:137347. https://doi.org/10.1016/j.cplett.2020.137347
Liu S et al (2021a) Production and resource utilization of flue gas desulfurized gypsum in China - A review. Environ Pollut 288:117799. https://doi.org/10.1016/j.envpol.2021.117799
Liu X et al (2021b) Characteristic, hazard and iron recovery technology of red mud - a critical review. J Hazard Mater 420:126542. https://doi.org/10.1016/j.jhazmat.2021.126542
Liu Y et al (2021c) Synergic performance of low-kaolinite calcined coal gangue blended with limestone in cement mortars. Constr Build Mater 300:124012. https://doi.org/10.1016/j.conbuildmat.2021.124012
Liu H et al (2022) Green conversion of coal fly ash into soil conditioner: technological principle and process development. Minerals 12. https://doi.org/10.3390/min12030276

Long J et al (2019) Selenium in Chinese coal gangue: distribution, availability, and recommendations. Resour Conserv Recycl 149:140–150. https://doi.org/10.1016/j.resconrec.2019.05.039

Luo G et al (2015) Migration rules of Pb and the effects of coal gangue–soil mixture media on the growth of pachoi. Earth Environ 43:14–20. https://doi.org/10.14050/j.cnki.1672-9250.2015.01.003

Lv Y et al (2020) Bioleaching of silicon in electrolytic manganese residue (EMR) by Paenibacillus mucilaginosus: Impact of silicate mineral structures. Chemosphere 256:127043. https://doi.org/10.1016/j.chemosphere.2020.127043

Lv B et al (2022) Sustainable and clean utilization of coal gangue: activation and preparation of silicon fertilizer. J Mater Cycles Waste Manage 24:1579–1590. https://doi.org/10.1007/s10163-022-01426-5

Ma D et al (2019a) The role of gangue on the mitigation of mining-induced hazards and environmental pollution: An experimental investigation. Sci Total Environ 664:436–448. https://doi.org/10.1016/j.scitotenv.2019.02.059

Ma H et al (2019b) Study on the drying shrinkage of alkali-activated coal gangue-slag mortar and its mechanisms. Constr Build Mater 225:204–213. https://doi.org/10.1016/j.conbuildmat.2019.07.258

Mohammadi R et al (2019) Fabrication of the alginate-combusted coal gangue composite for simultaneous and effective adsorption of Zn(II) and Mn(II). J Environ Chem Eng 7:103494. https://doi.org/10.1016/j.jece.2019.103494

Motesharezadeh B et al (2017) The Use of Coal Gangue as a Cultivation Bed Conditioner in Forage Maize Inoculated with Arbuscular Mycorrhizal Fungi. Commun Soil Sci Plant Anal 48:1266–1279. https://doi.org/10.1080/00103624.2017.1322602

Moussadik A et al (2022) Chemical, mineralogical and thermal characterization of a composite alkali-activated binder based on coal gangue and fly ash. Mater Today: Proc 58:1452–1458. https://doi.org/10.1016/j.matpr.2022.02.477

Mu X et al (2021) Microwave-assisted removal of sulfur in large particle size coal by bromine water. Fuel 289:119838. https://doi.org/10.1016/j.fuel.2020.119838

Munir MT et al (2018) Resource recovery from organic solid waste using hydrothermal processing: Opportunities and challenges. Renew Sustain Energy Rev 96:64–75. https://doi.org/10.1016/j.rser.2018.07.039

Muqaddas B et al (2019) Responses of labile soil organic carbon and nitrogen pools to long-term prescribed burning regimes in a wet sclerophyll forest of southeast Queensland, Australia. Sci Total Environ 647:110–120. https://doi.org/10.1016/j.scitotenv.2018.07.416

Nan Y et al (2023) Effects of coal gangue on soil property and plant growth in mining area. Chin J Appl Ecol 34:1253–1262. https://doi.org/10.13287/j.1001-9332.202305.028

Peng B, Li X (2018) Release and Transformation characteristics of modes of occurrence of chlorine in coal gangue during combustion. Energy Fuels 32:9926–9933. https://doi.org/10.1021/acs.energyfuels.8b02019

Qian T, Li J (2015) Synthesis of Na-A zeolite from coal gangue with the in-situ crystallization technique. Adv Powder Technol 26:98–104. https://doi.org/10.1016/j.apt.2014.08.010

Qin L, Gao X (2019) Properties of coal gangue-Portland cement mixture with carbonation. Fuel 245:1–12. https://doi.org/10.1016/j.fuel.2019.02.067

Qin L et al (2021) Effect of carbonation curing on sulfate resistance of cement-coal gangue paste. J Clean Prod 278:123897. https://doi.org/10.1016/j.jclepro.2020.123897

Qiu J et al (2022) Study on the influence mechanism of activated coal gangue powder on the properties of filling body. Constr Build Mater 345:128071. https://doi.org/10.1016/j.conbuildmat.2022.128071

Rakshit A et al (2019) Soil amendments for sustainability: challenges and perspectives

Rezakhani L et al (2019) Phosphate–solubilizing bacteria and silicon synergistically augment phosphorus (P) uptake by wheat (Triticum aestivum L.) plant fertilized with soluble or insoluble P source. Ecotoxicol Environ Saf 173:504–513. https://doi.org/10.1016/j.ecoenv.2019.02.060

Rodríguez J et al (2021) Eco-efficient cement based on activated coal washing rejects with low content of kaolinite. Constr Build Mater 274:122118. https://doi.org/10.1016/j.conbuildmat.2020.122118

Sabio E et al (2016) Conversion of tomato-peel waste into solid fuel by hydrothermal carbonization: influence of the processing variables. Waste Manage 47:122–132. https://doi.org/10.1016/j.wasman.2015.04.016

Saha A et al (2020) Superabsorbent hydrogel (SAH) as a soil amendment for drought management: a review. Soil Tillage Res 204:104736. https://doi.org/10.1016/j.still.2020.104736

Sahu D et al (2019) Mineralogical characterization and washability of Indian coal from Jamadoba. Energ Source Part A: Recovery Util Environ Eff 41:517–526. https://doi.org/10.1080/15567036.2018.1520336

Said A et al (2018) Mechanochemical activation of phlogopite to directly produce slow-release potassium fertilizer. Appl Clay Sci 165:77–81. https://doi.org/10.1016/j.clay.2018.08.006

Sarbak Z et al (2004) Characterisation of surface properties of various fly ashes. Powder Technol 145:82–87. https://doi.org/10.1016/j.powtec.2004.04.041

Shao S et al (2022) Extraction of valuable components from coal gangue through thermal activation and HNO3 leaching. J Ind Eng Chem 113:564–574. https://doi.org/10.1016/j.jiec.2022.06.033

Shi D et al (2017) Silicon-aluminum additives assisted hydrothermal process for stabilization of heavy metals in fly ash from MSW incineration. Fuel Process Technol 165:44–53. https://doi.org/10.1016/j.fuproc.2017.05.007

Singh RP et al (2010) Coal fly ash utilization in agriculture: its potential benefits and risks. Rev Environ Sci Bio/Technol 9:345–358. https://doi.org/10.1007/s11157-010-9218-3

Smith O et al (2022) The effect of renewable energy incorporation on power grid stability and resilience. Sci Adv 8:eabj6734. https://doi.org/10.1126/sciadv.abj6734

Song S et al (2018) Research on soil absorbent polymer and microbial fertiliser to improve semi-arid soil and afforestation. J Soil Water Conserv 32:334–339. https://doi.org/10.13870/j.cnki.stbcxb.2018.03.050

Sriramoju SK et al (2022) Effective utilization of coal processing waste: separation of low ash clean coal from washery rejects by hydrothermal treatment. Miner Process Extr Metall Rev 43:165–181. https://doi.org/10.1080/08827508.2020.1833196

Steinnes E (2009) Soils and geomedicine. Environ Geochem Health 31:523–535. https://doi.org/10.1007/s10653-009-9257-2

Su D (2021) Study on preparation technology and properties of artificial soil based on coal gangue. Shanxi University. https://doi.org/10.27284/d.cnki.gsxiu.2021.001194

Su YZ et al (2010) Effects of sandy desertified land rehabilitation on soil carbon sequestration and aggregation in an arid region in China. J Environ Manage 91:2109–2116. https://doi.org/10.1016/j.jenvman.2009.12.014

Sun M et al (2014) The relationship between speciation and release ability of mercury in flue gas desulfurization (FGD) gypsum. Fuel 125:66–72. https://doi.org/10.1016/j.fuel.2014.02.012

Sun Y-Q et al (2021) Evaluating the distribution and potential ecological risks of heavy metal in coal gangue. Environ Sci Pollut Res 28:18604–18615. https://doi.org/10.1007/s11356-020-11055-w

Tang JJ et al (2014) Air conditioning compressor front cover of squeeze casting process design and numerical simulation. Appl

Mech Mater 602–605:209–213. https://doi.org/10.4028/www.scientific.net/AMM.602-605.209
Tang Z et al (2020) Durability of Sustainable Construction Materials with Solid Wastes. In: Wang CM et al (eds) ACMSM25. Springer Singapore, Singapore, pp 3–13. https://doi.org/10.1007/978-981-13-7603-0_1
Tang T et al (2024) Simultaneous nutrients activation and pollutants removal of coal gangue in one step to acquire silicon-based compound fertilizers. J Clean Prod 466:142866. https://doi.org/10.1016/j.jclepro.2024.142866
Tong W et al (2008) Research on potential fertilization of coal gangue in the Weibei Coalfield, China. Acta Geol Sin-Engl Ed 82:717–721. https://doi.org/10.1111/j.1755-6724.2008.tb00623.x
Wang J et al (2016a) A concrete material with waste coal gangue and fly ash used for farmland drainage in high groundwater level areas. J Clean Prod 112:631–638. https://doi.org/10.1016/j.jclepro.2015.07.138
Wang P et al (2016b) Mineralogical compositions of Late Permian coals from the Yueliangtian mine, western Guizhou, China: comparison to coals from eastern Yunnan, with an emphasis on the origin of the minerals. Fuel 181:859–869. https://doi.org/10.1016/j.fuel.2016.05.043
Wang Z et al (2016c) Transformation of nitrogen and sulphur impurities during hydrothermal upgrading of low quality coals. Fuel 164:254–261. https://doi.org/10.1016/j.fuel.2015.10.015
Wang SJ et al (2017) Research on saline-alkali soil amelioration with FGD gypsum. Resour Conserv Recycl 121:82–92. https://doi.org/10.1016/j.resconrec.2016.04.005
Wang J et al (2018) The identification of bedrock types based on soil chemical composition. Geophys Geochem Explor 42:1180–1185. https://doi.org/10.11720/wtyht.2018.0299
Wang L et al (2019) Fate and distribution of nutrients and heavy metals during hydrothermal carbonization of sewage sludge with implication to land application. J Clean Prod 225:972–983. https://doi.org/10.1016/j.jclepro.2019.03.347
Wang B et al (2020) Ameliorative effects of silicon fertilizer on soil bacterial community and pakchoi (Brassica chinensis L.) grown on soil contaminated with multiple heavy metals. Environ Pollut 267:115411. https://doi.org/10.1016/j.envpol.2020.115411
Wang B et al (2021a) Environmental-friendly coal gangue-biochar composites reclaiming phosphate from water as a slow-release fertilizer. Sci Total Environ 758:143664. https://doi.org/10.1016/j.scitotenv.2020.143664
Wang X et al (2021b) Partitioning behavior during coal combustion of potentially deleterious trace elements in Ge-rich coals from Wulantuga coal mine, Inner Mongolia. China Fuel 305:121595. https://doi.org/10.1016/j.fuel.2021.121595
Wang A et al (2022a) Separation of calcined coal gangue and its influence on the performance of cement-based materials. J Build Eng 51:104293. https://doi.org/10.1016/j.jobe.2022.104293
Wang A et al (2022b) Mechanism of thermal activation on granular coal gangue and its impact on the performance of cement mortars. J Build Eng 45:103616. https://doi.org/10.1016/j.jobe.2021.103616
Wang C et al (2023) Study on secondary oxidation characteristics of coal gangue at different pyrolysis rank. Fuel 345:128231. https://doi.org/10.1016/j.fuel.2023.128231
Wu H et al (2017) Feasibility study on the application of coal gangue as landfill liner material. Waste Manage 63:161–171. https://doi.org/10.1016/j.wasman.2017.01.016
Wu C et al (2023a) Research status and innovative utilization strategy of coal gangue resource in building material field. Energy Environ Prot 37:167–177. https://doi.org/10.20078/j.eep.20230112
Wu Y et al (2023b) Insights into relationships between polycyclic aromatic hydrocarbon concentration, bacterial communities and organic matter composition in coal gangue site. Environ Res 236:116502. https://doi.org/10.1016/j.envres.2023.116502
Xiao K et al (2017) Comparison of different treatment methods for protein solubilisation from waste activated sludge. Water Res 122:492–502. https://doi.org/10.1016/j.watres.2017.06.024
Xu H et al (2017) Utilization of coal gangue for the production of brick. J Mater Cycles Waste Manage 19:1270–1278. https://doi.org/10.1007/s10163-016-0521-0
Ye T et al (2022) Improved holding and releasing capacities of coal gangue toward phosphate through alkali-activation. Chemosphere 287:132382. https://doi.org/10.1016/j.chemosphere.2021.132382
Yong M-T et al (2022) Coal tailings as a soil conditioner: evaluation of tailing properties and effect on tomato plants. Plant Growth Regul 98:439–450. https://doi.org/10.1007/s10725-022-00870-5
Yuan Z et al (2017) Application of phosphate solubilizing bacteria in immobilization of Pb and Cd in soil. Environ Sci Pollut Res 24:21877–21884. https://doi.org/10.1007/s11356-017-9832-5
Yuan H et al (2021) Sulfur nanoparticles improved plant growth and reduced mercury toxicity via mitigating the oxidative stress in Brassica napus L. J Clean Prod 318:128589. https://doi.org/10.1016/j.jclepro.2021.128589
Yunusa IAM et al (2012) Application of coal fly ash in agriculture: a strategic perspective. Crit Rev Environ Sci Technol 42:559–600. https://doi.org/10.1080/10643389.2010.520236
Záleská M et al (2023) Thermally treated coal mining waste as a supplementary cementitious material – case study from Bogdanka mine, Poland. J Build Eng 68:106036. https://doi.org/10.1016/j.jobe.2023.106036
Zhang Y, Ling T-C (2020) Reactivity activation of waste coal gangue and its impact on the properties of cement-based materials – a review. Constr Build Mater 234:117424. https://doi.org/10.1016/j.conbuildmat.2019.117424
Zhang Q et al (2021a) Synthesis of calcium silicate hydrate from coal gangue for Cr(VI) and Cu(II) removal from aqueous solution. Molecules 26. https://doi.org/10.3390/molecules26206192
Zhang Y et al (2021b) Amelioration effect of coal gangue on physical and chemical properties of saline-alkaline soil. Ecol Environ Sci 30:195–204. https://doi.org/10.16258/j.cnki.1674-5906.2021.01.023
Zhang Y et al (2022a) Co-spontaneous combustion of coal and gangue: Thermal behavior, kinetic characteristics and interaction mechanism. Fuel 315:123275. https://doi.org/10.1016/j.fuel.2022.123275
Zhang Z et al (2022b) Stabilization of heavy metals in municipal solid waste incineration fly ash via hydrothermal treatment with coal fly ash. Waste Manage 144:285–293. https://doi.org/10.1016/j.wasman.2022.03.022
Zhao H et al (2021a) Potential of a novel modified gangue amendment to reduce cadmium uptake in lettuce (Lactuca sativa L.). J Hazard Mater 410:124543. https://doi.org/10.1016/j.jhazmat.2020.124543
Zhao Y et al (2021b) Eco-friendly treatment of coal gangue for its utilization as supplementary cementitious materials. J Clean Prod 285:124834. https://doi.org/10.1016/j.jclepro.2020.124834
Zhao K et al (2022a) Silicon-based additive on heavy metal remediation in soils: toxicological effects, remediation techniques, and perspectives. Environ Res 205:112244. https://doi.org/10.1016/j.envres.2021.112244
Zhao Y et al (2022b) Toward understanding the activation and hydration mechanisms of composite activated coal gangue geopolymer. Constr Build Mater 318:125999. https://doi.org/10.1016/j.conbuildmat.2021.125999
Zhao G et al (2023a) Reusing waste coal gangue to improve the dispersivity and mechanical properties of dispersive soil. J Clean Prod 404:136993. https://doi.org/10.1016/j.jclepro.2023.136993

Zhao W et al (2023b) Sustainable green conversion of coal gangue waste into cost-effective porous multimetallic silicate adsorbent enables superefficient removal of Cd(II) and dye. Chemosphere 324:138287. https://doi.org/10.1016/j.chemosphere.2023.138287

Zhou C, Shan S (2008) The harms of gangue and research of resourceful use technology. Environ Dev:32–35. https://doi.org/10.3969/j.issn.1007-0370.2008.04.011

Zhou B et al (2010) Effects of coal gangue content on water movement and solute transport in a China Loess Plateau soil. CLEAN – Soil Air Water 38:1031–1038. https://doi.org/10.1002/clen.201000056

Zhou C et al (2012) Transformation behavior of mineral composition and trace elements during coal gangue combustion. Fuel 97:644–650. https://doi.org/10.1016/j.fuel.2012.02.027

Zhou C et al (2015) Investigation on thermal and trace element characteristics during co-combustion biomass with coal gangue. Biores Technol 175:454–462. https://doi.org/10.1016/j.biortech.2014.10.129

Zhou L et al (2019) Effect of bentonite-humic acid application on the improvement of soil structure and maize yield in a sandy soil of a semi-arid region. Geoderma 338:269–280. https://doi.org/10.1016/j.geoderma.2018.12.014

Zhou Z et al (2023) Coal slime as a good modifier for the restoration of copper tailings with improved soil properties and microbial function. Environ Sci Pollut Res 30:109266–109282. https://doi.org/10.1007/s11356-023-30008-7

Zhu X et al (2022) Reclamation of waste coal gangue activated by Stenotrophomonas maltophilia for mine soil improvement: Solubilizing behavior of bacteria on nutrient elements. J Environ Manage 320:115865. https://doi.org/10.1016/j.jenvman.2022.115865

Zhu X et al (2023) 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 458:131923. https://doi.org/10.1016/j.jhazmat.2023.131923