Feasibility and challenges of multi-source coal-based solid waste (CSW) for underground backfilling − A case study

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Feasibility and challenges of multi-source coal-based solid waste (CSW) for underground backfilling- a case study

Abstract: The multi-source CSW produced in coal mining, power generation and coal chemical industry has become a bottleneck that restricts the green, low-carbon and high-quality development of coal power and coal chemical bases (CPCCBs) in China due to its large stock, many increments and low utilization rate. Underground backfilling has opened up a new way for CPCCBs to dispose of multi-source CSW, and it is also the most practical way, which is conducive to solve the surface accumulation of CSW and reducing the environmental pollution risk. Based on the physicochemical properties and pollution, the feasibility of underground backfilling with multi-source CSW was systematically analyzed from four aspects: environment, technology, economy and policy. Most CSWs can be directly for underground backfilling; the high potential pollution risks of individual CSWs can reduce through technical measures such as heavy metal adsorption and complex passivation, then safely for underground backfilling. Although underground backfilling with multi-source CSWs is feasible, there are still some challenges before achieving large-scale engineering applications, such as potential risks of CGS, technical maturity, economic investment and administration. It requires the joint efforts and cooperation of research institutions, enterprises and governments to realize the harmless and large-scale underground backfilling with multi-source CSW.

Keywords: Industrial solid waste; Coal-based solid waste; Underground backfilling; Green development; Coal gasification slag

List of abbreviations

Coal-based solid waste	CSW
Coal power and coal chemical base	CPCCB
Coal gangue	CG
Coal fly ash	CFA
Flue gas desulfurization gypsum	FGD gypsum
Coal gasification slag	CGS
Furnace bottom slag	FBS
Biochemical oxygen demand	BOD
Chemical Oxygen Demand	COD
Inductively Coupled Plasma Mass Spectrometry	ICP-MS
Coal gasification coarse slag from coal-to-liquid	CGCS-CTL
Coal gasification fine slag from coal-to-liquid	CGFS-CTL
Coal gasification coarse slag from coal-to-methanol	CGCS-CTM
Coal gasification fine slag from coal-to-methanol	CGFS-CTM
Chinese Yuan	CNY
Humic acid	HA
Solid waste transportation costs	SWTC
Slag yard storage costs,	SYSC
Coal sales profits from mining coal pillars	CSP-MCP
Subsidence land treatment and restoration costs	SLTRC
Construction cost of the backfilling station	CCBS
Operating cost of the backfilling station	OCBS

Financial subsidy fee	FSF
Environmental impact assessment	EIA

1. INTRODUCTION

Along with the simultaneous production and consumption activities of humans, an enormous amount of industrial solid waste is produced from various activities, such as mining, power generation, chemical manufacturing industry [1]. Industrial solid waste is one of the solid waste types with the largest per capita output among all solid waste categories in the world [2]. The World Bank Report [3] showed that the per capita daily production of industrial solid waste in the world reached 12.73 kg, far exceeding that of agricultural solid waste (3.35kg), construction solid waste (1.68kg) and municipal solid waste (0.74kg). Globally, open dump, unspecified landfill and incineration are still the mainstream solid waste disposal methods, accounting for more than 60%. These solid waste disposal methods are more common in low- and middle-income developing countries and regions, such as central and southern Africa and South Asia[4-6].

As far as China is concerned, with the rapid economic and social development, it has become one of the countries with the largest total output of industrial solid waste in the world [7, 8]. According to the *China Environmental Statistical Yearbook*, the total amount of industrial solid waste in China has continued to grow since 2011. Although the amount of industrial solid waste in 2020 has declined due to the COVID-19 epidemic [9, 10], the amount still exceeds 3.5 billion tons (per year). The amount of unutilized industrial solid waste is about (1.0-1.5) billion tons per year, the accumulated amount of industrial solid waste over the years has exceeded 60 billion tons [11]. Fig.1 shows the proportion of industrial solid waste generated by each industry in China each year. The solid waste generated in the electricity/heat production supply industry and the coal mining-washing industry accounts for more than one-third of the total solid waste generated in each industry. The solid waste generated by other industries such as coal chemical industry, chemical raw material and chemical product manufacturing accounts for more than 20%.

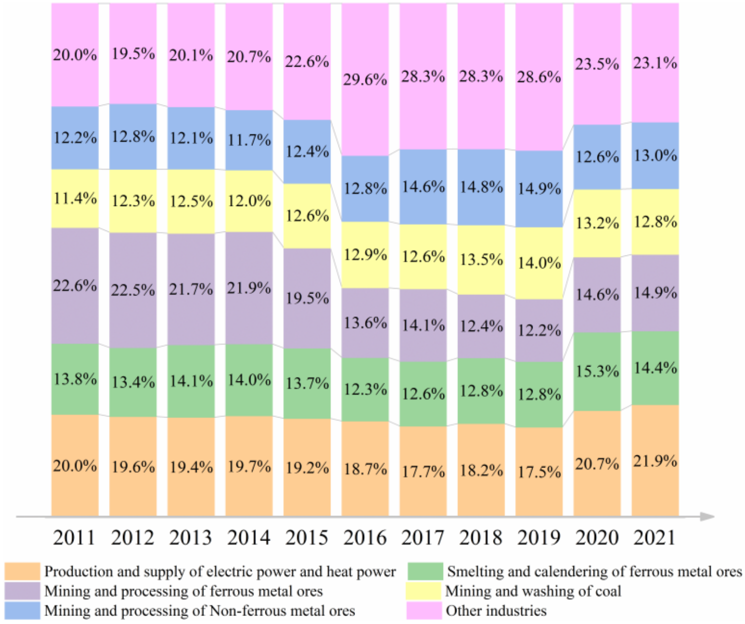


Fig. 1 Proportion of solid waste production from various industries in China since 2011

The main types of industrial solid waste generated by electricity/heat production supply industry, the coal mining-washing industry and coal chemical industry include coal gangue (CG), coal fly ash (CFA), flue gas desulfurization gypsum (FGD gypsum), furnace bottom slag (FBS) and coal gasification slag (CGS) [12, 13]. Part of these solid wastes are recycled and reused [14]. For example, aluminum and silicon or rare (earth ?) elements and minerals are extracted from CFA or CG [15]; CFA and FGD gypsum are used as components of building materials [16]; CG is widely used in making bricks and paving materials [17]. Industrial solid waste is also widely used in agriculture [18]. However, not all industrial solid waste can be utilized due to market size constraints, production cost constraints or environmental constraints [17, 19].

The unutilized industrial solid waste generated is generally landfilled and disposed in stockpiles, which not only occupy land, but also have a high pollution risk to the surface environment, such as water, soil, and atmosphere [20]. This disposal method is strictly restricted by the government department [21-23]. In western China, the problem of safe and large-scale disposal of industrial solid waste has become a bottleneck restricting the green development and transformation of enterprises.

Underground backfilling in mines is a large-scale solid waste disposal technology that has been widely used in several countries, such as Chile, Brazil, Sweden, Australia, Canada, and India [24]. Most of these countries use tailings from metal mines mixed with CFA, slag and other industrial solid waste for paste backfill. Numerous studies have evaluated the environmental performance (including leachability) of paste backfill materials before underground backfilling, showing that paste backfill materials made from tailings mixed with CFA, slag and adhesives can reduce the risk of releasing harmful substances[25-28]. In China, underground backfilling technology is not only used in metal mines, but also widely used in coal mines [29-32]. Underground backfilling in coal mines generally uses the materials such as CG, CFA, wind-blown sand and construction and demolition waste [33-35]. Studies showed that these backfill materials also have a low impact on the environment [36, 37]. However, in some cluster areas with many coal mines, coal-fired power plants, and coal chemical plants in China, in addition to CG and CFA produced by coal mines and coal-fired power plants, the coal chemical plants also produce a large amount of industrial solid waste, such as CGS, etc. The scale of disposal and utilization of these coal chemical solid waste is very limited. Underground backfilling with a variety of solid waste generated by the coal chemical industry and coal power industry for coal mines is a potential large-scale disposing method, but its research and application cases are relatively few. It is still unknown whether these multi-source CSWs with huge output, various sources, complex components and unknown risks can be for underground backfilling in mines; the primary issue facing underground backfilling with multi-source CSW is whether this method is environmentally friendly and economically feasible. Therefore, it is necessary to study its feasibility and challenges from multiple aspects.

The present paper, focused on the Ningdong Base study area, reports the physical and chemical properties, harmfulness, and heavy metal content of multi-source CSW, furthermore, the feasibility of multi-source coal-based solid waste for underground backfilling is analyzed from the perspectives of environment, technology, economy, and policy. Problems and challenges faced by the application of underground backfilling with multi-source solid waste in coal mine are here analysed. This research can provide new ideas and new approaches for the large-scale disposal of CSWs discharged from CPCCBs in Western China.

2. OVERVIEW OF CSW

2.1 Scope of CSW

In China, coal-rich areas are generally distributed with a large number of coal mines and coal-fired power plants, forming coal-power bases [38, 39]. Due to the implementation of energy strategies and technological development in recent years, large coal chemical bases, mainly coal-to-liquid and coal-to-methanol plants, have been successively established near large coal-power bases. The CPCCBs have formed a series of coal-based industrial chains such as coal mining, utilization and deep processing [40, 41]. The most concentrated areas of China's large CPCCBs are in Shanxi, Shaanxi, western Inner Mongolia and eastern Ningxia, and the main CPCCBs are Yulin Base, Ordos Base, Ningdong Base and Jinzhong Base [38, 42]. The CPCCB is one of the main concentrated areas of multi-source CSW in China [43].

Multi-source CSW refers to the solid waste generated and discharged in the process of coal mining, washing, utilization and processing, from coal mines, coal-fired power plants, and coal chemical plants (coal-to-liquid, coal-to-methanol, etc.) in the CPCCB, and mainly includes CG, CFA, FGD gypsum, CGS and FBS [44-46], as shown in Fig. 2. Since the FGD gypsum from coal-fired power plants belongs to the solid waste discharged from the coal-based industrial chain, it is classified into the scope of CSW in this study. According to the production statistical data of industrial solid waste from key monitoring enterprises in China, in the past decade, the annual output of CFA and CG exceeds 1 billion tons [47]. If the output of solid waste such as CGS, FBS and FGD gypsum is included, it is estimated that the annual output of multi-source CSWs will exceed 1.2 billion tons, but the comprehensive utilization rate is generally low.

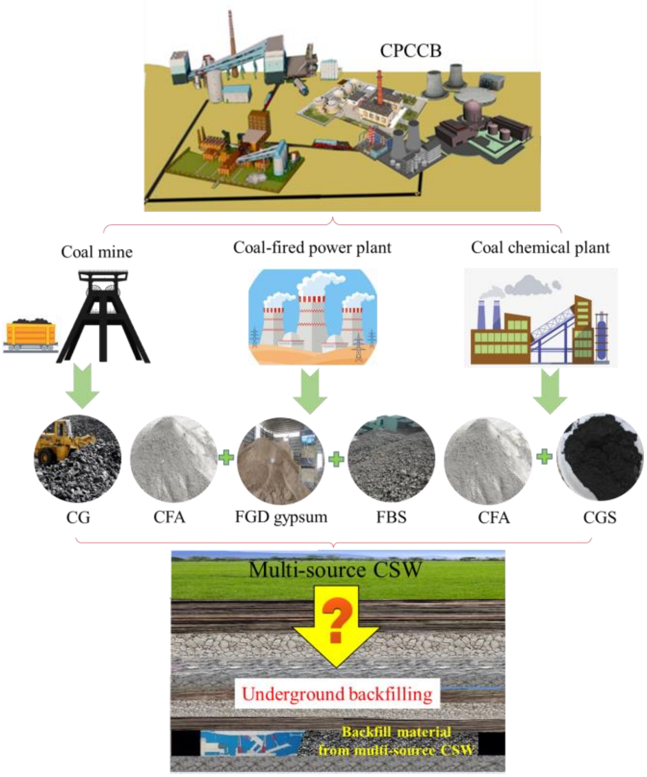


Fig. 2 Sources and objects of multi-source CSW

2.2 Study area

Ningdong Base is as a study area, its location and enterprise distribution are shown in Fig.3. Ningdong Base is located in the middle-east of Ningxia Hui Autonomous Region, with a core area of 800 km^2. It is adjacent to Shaanxi Province in the east, Inner Mongolia Autonomous Region in the west and north, and Gansu Province in the south. There are many coal mines, coal-fired power plants and coal chemical plants in Ningdong Base, forming the "Golden Triangle" of energy and chemical industry together with Yulin Base and Ordos Base [41].

Fig.3 The location of Ningdong Base and the distribution of enterprises in its core area

As a typical CPCCB in China, Ningdong Base has produced more than 15 million tons of multi-source CSWs every year since 2018, and the output of multi-source CSWs in 2022 has reached 27 million tons, as shown in Fig.4. The type of CSW with the largest output is CFA, followed by CG and CGS. The comprehensive utilization rate of multi-source CSW does not exceed 60% [48], especially CGS, which has a large output but a significantly low utilization rate. CSW can achieve high-value utilization [2, 49-52], such as the preparation of high-value building materials. However, it is found that affected by the region, recognition, transportation radius, etc., the high-value utilization project of CSW has many shortcomings, such as large investment, slow effect, high risk and low income, which leads to a small number of solid waste utilization enterprises in the western China, and a small scale of solid waste utilization. Therefore, underground backfilling is a practical and effective new way to realize harmless and large-scale disposal of multi-source CSWs in large CPCCBs.

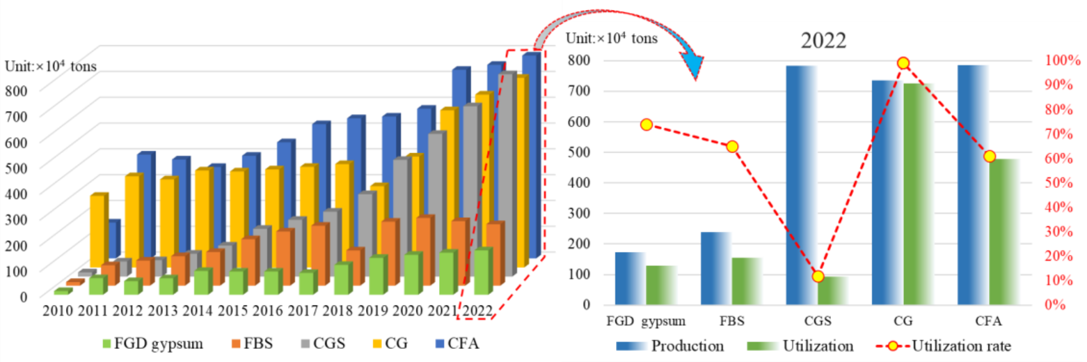


Fig. 4 Types and annual output of multi-source CSWs in Ningdong Base

In 2021, National Key Research and Development Program of China launched a multi-source CSW underground backfilling program in Ningdong Base, and the pilot enterprise is Renjiazhuang Coal Mine. After completion, the program is expected to dispose of more than 300,000 tons of multi-source CSW per year, which can create a demonstration effect for other coal mines using underground backfilling and provide a model case for the large-scale disposal of multi-source CSW in CPCCBs.

3. PROPOPERTIES OF CSW

3.1 Sample collection

The typical solid waste samples discharged by coal mines, coal-fired power plants and coal chemical plants in the Ningdong Base are collected for testing. The samples were CG from Renjiazhuang Coal Mine, CFA, FGD gypsum and FBS from Yuanyanghu Power Plant, and CGS from coal-to-methanol and coal-to-liquid enterprises. All samples were randomly selected from different points in the area where the enterprise temporarily piled up solid waste. In order to obtain representative samples, the whole sampling process lasted 7 days, sampling twice a day, a total of 14 sets of duplicate samples were collected and mixed evenly. CG samples were firstly crushed and grinded to obtain powder samples for testing. All powder samples were dried in a vacuum oven at 60°C for 12 hours, and then stored in sealed bags to prevent oxidation and contamination. The test samples were selected using coning and quartering methods [53-55].

3.2 Test methods

3.2.1 Geochemical characterization

The chemical and mineral components in the samples were analyzed by XRD and XRF. The XRD test equipment is Japan Rigaku ultima4, the scanning rate is 4 °/min, the step size of 0.02 °, the range is 5~70 °, Cu target, Ka radiation, continuous scanning mode, and the standard PDF card in the JADE software is used to retrieve the phase [56]. The XRF test equipment is Shimadzu XRF-1800, Japan [57]. The grain size distribution of powder solid waste is tested by dry method with OMEC laser particle size analyzer (test range is 0.1um-2000um) [58]. For granular solid waste, the particle size range is determined by grading sieves. The scanning electron microscope (SEM) test was carried out with a Zeiss Merlin Compat instrument, the magnification scale was 20-100 μm, the accelerating voltage was 5kV, and the sample was sprayed with gold before the test [59]. SEM testing methods mainly include sampling, cleaning, pasting samples, and platinum coating. Specifically, a small amount of clean and impurity-free powder samples are taken and firmly pasted on clean conductive adhesive, coated, and finally started to adjust the instrument parameters for magnified observation [60].

3.2.2 Leaching toxicity test

The pH is measured using a temperature compensation pH meter (Seven Excellence S500–B). The sample processing of the leaching toxicity test is carried out according to the relevant methods in GB5085.3-2007 and HJ577-2009 [37, 61]. The test method of five-day biochemical oxygen demand (BOD) refers to HJ505-2009, the test method of hexavalent chromium is diphenylcarbazide spectrophotometry, the test method of total mercury and total chromium is the Inductively Coupled Plasma Mass Spectrometry (ICP-MS) in GB5085.3-2007, the test method of suspended matter content and Chemical Oxygen Demand (COD) is spectrophotometry, the test method for animal and vegetable oils is infrared spectrophotometry (HJ 637-2018), The test method for total α and total β radioactivity is thick source method (HJ 898-2017 and HJ 899-2017).

3.2.3 Heavy metal content test

The samples were digested by the microwave digestion instrument (Shanghai Sineo, Jupiter) at the microwave power of 1200 W. About 50 mg of the sample was mingled with the digestion solution (6 mL HNO_3, 1 mL $HClO_4$, 1 mL HF, and 2 mL H_2O_2) in the polytetrafluoroethylene vessels. Then, the microwave digestion instrument was heated from room temperature to 150 °C within 10 min, kept at 180 °C for 5 min, and finally held at 200 °C for 90 min. After that, the digested solution was filtrated and then diluted to 100 mL. The inductively coupled plasma mass spectrometer (ICP-MS, Agilent 7900) was applied to measure the total concentration of heavy metal. References [62] provide other processing procedures of samples.

3.2.4 Improved tessier chemical extraction method

According to the references [62, 63], the detailed procedure of the improved Tessier chemical extraction method is shown in Fig.5. The supernatant was obtained by centrifuging after each step. The supernatant was filtered through a 0.45 μm filter membrane and then tested by ICP-MS.

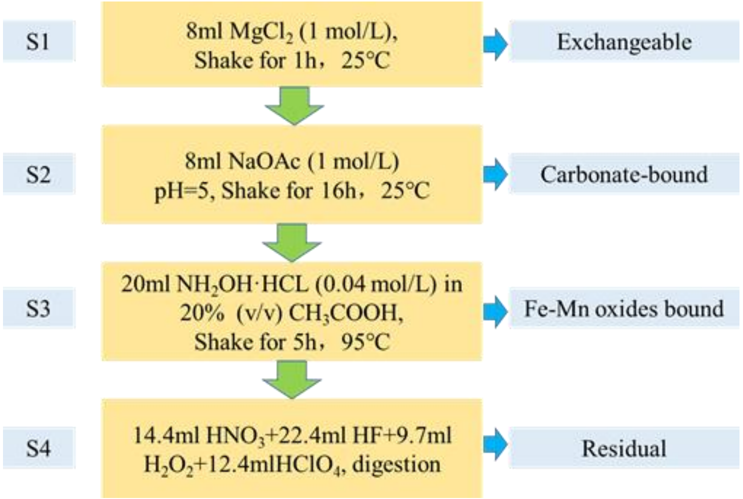
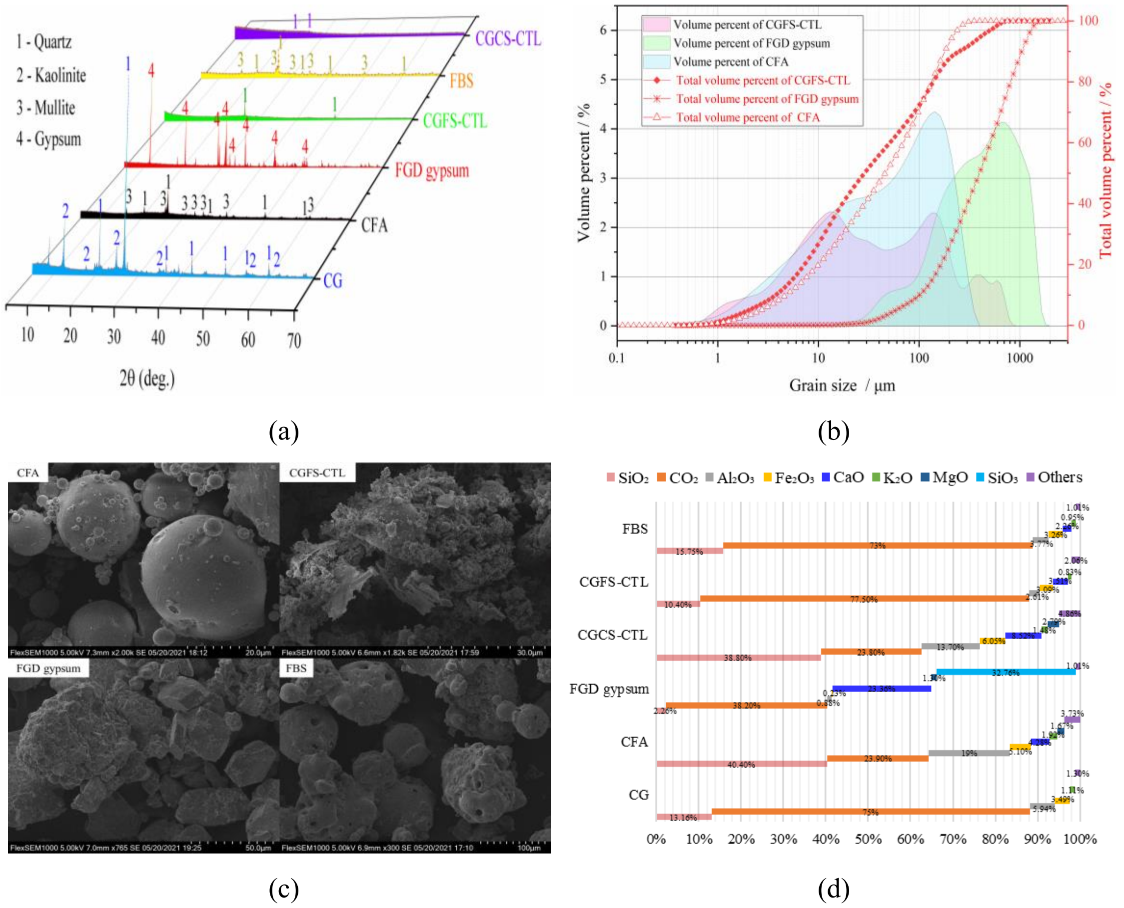


Fig. 5 Test procedure of the improved Tessier chemical extraction method

3.3 Results

3.3.1 Physicochemical properties

The results of different physical and chemical properties of solid waste are shown in Fig. 6 and Table 1.



(a) (b)

(c) (d)

Fig. 6 Test results of some CSW[64] (a) Mineral composition (b) Grain size distribution (c) SEM images (d) Chemical composition

Fig. 6(a) is the mineral composition tested by XRD, the main mineral phases contained in CSW are quartz, kaolinite, mullite and gypsum. Fig. 6(b) is the grain size distribution of coal gasification fine slag, CFA and FGD gypsum, their grain size range is generally 0.5-2000 μm. Fig. 6(c) is the SEM image, it can be seen that CFA microparticles showed obvious smooth spherical, which results in a ball effect [65, 66]. FGD gypsum microparticles were mostly irregular blocks, and FBS and CGS microparticles showed porous characteristics. Fig. 6(d) is the chemical composition tested by XRF. The common chemical components in multi-source CSW are CO_2, SO_2, Al_2O_3 and Fe_2O_3. FGD gypsum contains more CaO and SO_3.

Table 1 Some physical characteristics of CSW

CSW	Density (kg/m^3)	Color	Shape	Moisture rate	Description of other physical properties
CG	2350-2550	Gray and gray-black	Irregular block	＜1%	Hard, mainly sandstone and mudstone
CFA	2150	Gray white	Powdery	≤1%	Loss on ignition≈1%, specific surface area≈350m^2/kg
CGS	2300-2400	Black	Rough sand-like and mud blocks	10%	High carbon content, porous
FBS	1800	Gray-brown blocks	Coarse sand-like, irregular block	1%	Hard texture, rough surface, porous, burning marks
FGD gypsum	2500	Dark yellow	Wet powder	5%	Without irritating smell

Table 1 shows the density, appearance color, shape, moisture rate and other physical descriptions of multi-source CSW. Especially, CGS can be divided into coal gasification coarse slag and coal gasification fine slag due to different discharge methods [67]. Each solid waste has different physical properties, which can make up for the disadvantages of other solid wastes in underground backfilling. For example, powdery solid waste can reduce the transportation resistance of block solid waste in underground backfilling.

3.4 Environmental risk

3.4.1 Hazard identification

The hazard identification of the typical CSW discharged from Ningdong Base was carried out. The limit value refers to GB8978-1996 [68], as shown in Table 2.

Table 2 Hazard index identification results of CSW

Items	Limit value	CG	CFA	FGD gypsum	FBS	CGCS-CTL	CGFS-CTL
pH	6-9	8.75	**10.8**	8.55	**11.67**	8.28	8.47
Total α radiation	1Bq/L	ND	ND	0.07	0.18	0.06	0.08
Total β radiation	10Bq/L	0.05	0.2	0.38	0.23	0.17	0.11
Hexavalent chromium	0.5mg/L	ND	0.07	0.09	ND	0.02	ND
Total chromium	1.5 mg/L	ND	0.17	0.19	ND	0.11	ND
Total mercury	0.05mg/L	0.00005	0	ND	0.00009	0.00024	0.00015
Suspended solid	100 mg/L	38	38	45	67	74	31
Cod	100 mg/L	23	11	45	32	10	12
Animal and vegetable oils	20 mg/L	0.8	0.25	ND	ND	0.47	ND
5-day BOD	30 mg/L	1.4	ND	0.6	0.6	1.4	0.9

Note: ND: Not detected; Coal gasification coarse slag from coal-to-liquid: CGCS-CTL; Coal gasification fine slag from coal-to-liquid: CGFS-CTL.

The identification results of most CSWs in Ningdong Base, such as radioactivity, suspended solids, COD, etc., are lower than the maximum allowable emission concentration of Class I non-hazardous industrial solid waste specified in GB8978-1996, and individual components in solid waste could not be detected due to their extremely low content, so they can be safely backfilled underground according to GB18599-2020. However, the pH of individual CSWs such as CFA and FBS exceeds that of Class I non-hazardous industrial solid wastes specified in GB18599-2020 due to the high calcium oxide content, and its direct use for underground backfilling is strictly limited. Therefore, CFA and FBS can be modified by mixing with solid phase high alkali modifiers to reduce their pH value. The pH value of the modified CFA and FBS is between 6.5 and 7.5, which is in line with the Class I non-hazardous industrial solid waste in GB18599-2020.

3.4.2 Heavy metal content

Heavy metals are an important indicator for evaluating the environmental risk of CSW [17, 69]. The heavy metal content of typical CSWs discharged from Ningdong Base was tested, and the heavy metals tested were Cd, As, Pb, Cr, Cu, Zn and Hg, as shown in Table 3.

Table 3 Test results of heavy metal content in CSW (mg/kg)

Heavy metal	Screening value	Control value	CG	CFA	FGD gypsum	FBS	CGCS-CTL	CGFS-CTL
Cd	0.6	4	0.17	0.47	**0.79**	0.03	0.08	**0.99**
As	20	100	8.92	12.83	**33.4**	1.46	4.35	9.82
Pb	170	1000	65.1	92.24	20.37	16.4	14	140.37
Cr	250	1300	67.58	98.83	12.84	57	**439.23**	111.89
Cu	100	-	25.04	32.08	33.68	35	37.45	80.25
Zn	300	-	105.05	195.3	47.85	43	20.1	**318.44**
Hg	1	6	0.492	0.399	0.252	0.02	0.032	0.028

The soil pH value in the Ningdong Base was greater than 7.5. The heavy metal content of CG, CFA and FBS is less than the screening value specified in GB15618-2018, and the environmental pollution risk of heavy metal is extremely low and generally negligible. However, the content of individual heavy metals in the CGS discharged from the coal-to-liquid plant exceeds the screening value. For example, the content of Cr in the CGCS-CTL is 439.23mg/kg, which is much higher than the screening value of 250mg/kg; the content of Cd in the CGFS-CTL is 0.99mg/kg, exceeding the screening value of 0.6mg/kg. There is a potential pollution risk of heavy metals from CGS. However, the heavy metal content of CGS is far less than the control value specified in GB 15618-2018, which shows that the heavy metal pollution risk of CGS is controllable and limited.

3.4.3 Leaching amount of heavy metals

CGS as a new component of multi-source CSW for underground backfilling, needs to be focused on its pollution. The leaching amount of heavy metal elements was tested on the CGCS-CTL, CGFS-CTL, coal gasification coarse slag from coal-to-methanol (CGCS-CTM) and coal gasification fine slag from coal-to-methanol (CGFS-CTM), as shown in Table 4. It can be seen that the leaching amount of heavy metals such as Cd, As, Pb, Cr, Cu and Zn in the CGS discharged by coal chemical plants is lower than the safety limit, and the leaching risk of heavy metals in water is extremely low and can be ignored.

Table 4 The leaching amount of heavy metal elements in CGS (mg/kg)

Heavy metal	Safety limit	CGCS-CTL	CGFS-CTL	CGCS-CTM	CGFS-CTM

Cd	0.1	0.01	<0.01	<0.01	<0.01
As	0.5	0.04	0.05	0.05	0.01
Pb	0.5	0.17	0.15	0.15	0.12
Cr	1.5	0.02	0.01	0.01	0.01
Cu	-	0.24	0.02	0.08	0.08
Zn	2	0.86	1.43	1.44	0.52

3.4.4 Chemical speciation of heavy metals

The chemical speciation of heavy metals in CGCS-CTL, CGFS-CTL, CGCS-CTM and CGFS-CTM were shown in Fig. 7. The content of exchangeable fractions, carbonate bound fractions and Fe-Mn oxide bound fractions of Cr, Cd, Pb, Zn in CGS is relatively high. Among them, the above three speciations of Cr in CGCS-CTL accounted for 71.24%, and the three speciations of Cd in CGFS-CTL accounted for 94.96%; the three speciations of Pb and Zn in CGFS-CTM account for 47.97% and 84.18%, respectively. It can be seen that the chemical speciation of individual heavy metals in CGS is unstable, and there is a risk that the release of heavy metals exceeds the standard.

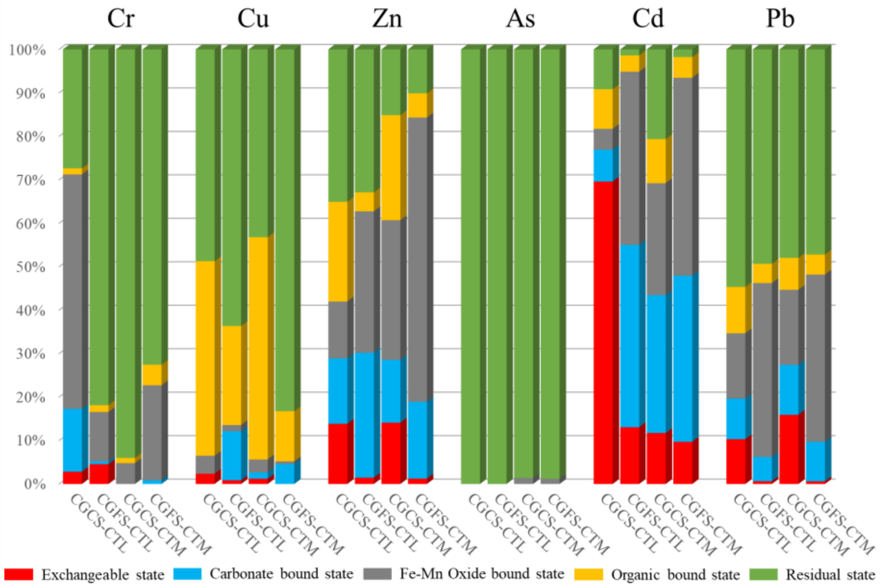


Fig. 7 Chemical speciations of heavy metals in CGS

4. Feasibility analysis for underground backfilling

Whether multi-source CSW can be used for underground backfilling in a harmless and large-scale manner is evaluated and analyzed from four aspects: environment, technology, economy and policy. The feasibility evaluation system of multi-source CSW for underground green backfilling are shown in Fig. 8.

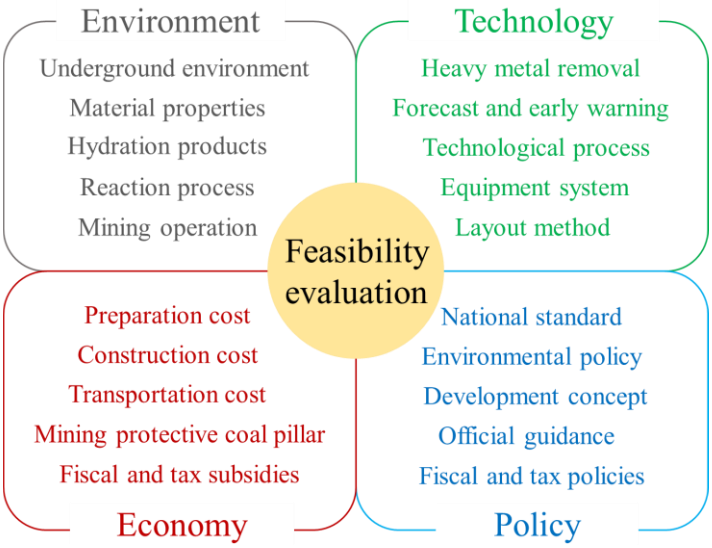


Fig. 8 Feasibility evaluation system of underground backfilling with multi-source CSWs

4.1 Environment

Multi-source CSW is stored on the surface, which will cause direct pollution risk to the surface environment [22, 70], such as encroaching on the land and destroying the surface vegetation. Carbon-sulfur oxide gases, such as CO_2 and SO_2, are volatilized from solid waste dumps, which will increase carbon emissions and the risk of acidic precipitation [71]. The leaching of harmful substances and heavy metal ions from CSW occurs under the action of precipitation, and the leachate flows into reservoirs and farmland, and harmful substances accumulate in animals and plants, threatening the safety of human drinking water and diet. For example, the accumulation of heavy metals in the human body will cause cancer, kidney damage and cardiovascular disease, and harmful gases will cause respiratory tract damage and fetal congenital malformation. Therefore, the human food chain becomes a heavy metal accumulation chain when at risk of environmental pollution, human beings are not only solid waste producers, but also victims at the end of the food chain. as shown in Fig. 9. Leachate seeps into the surface soil along with precipitation, and there is a risk of contaminating shallow soil and surface water [72, 73]. The impact of multi-source CSW piled on the surface environment is obvious, while the backfilling of solid waste in the deep underground space can greatly reduce the direct impact of it on the surface environment.

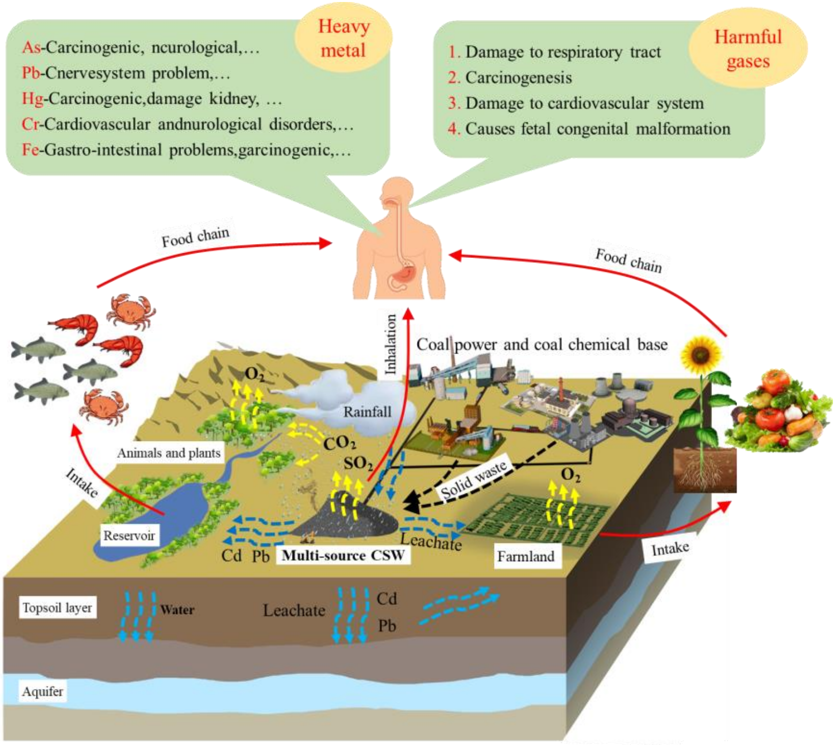


Fig. 9 Impact of multi-source CSW stockpiling on surface environment

The environmental impact of underground backfilling with multi-source CSW can be evaluated from several aspects, such as the toxicity of the material itself, the pollution of the physical and chemical reaction process between the various components in the backfill material, the stability and toxicity of the backfill material in mine water, surrounding rocks and air environments. These aspects can be evaluated by the amount and leaching content of heavy metal elements, toxicity indicators, etc. The amount and leaching content of heavy metal elements contained in the material itself or the physical and chemical reaction products should not exceed the national standard limitation (GB18599-2020, GB15618-2018, GB/T-14848, GB16297, GB8978).

Although the multi-source CSW comes from multiple industries and is discharged by different production processes and equipment, it is found through testing and research that the CSW does not have significant and direct toxicity and environmental pollution. It can be seen from the experiment results of backfill material mix proportion [56, 74, 75], there is no adverse reaction between multi-source CSWs, no toxic reaction products are generated after CSWs are mixed with water or cement, and no adverse chemical reaction occurs with mine gas. According to the pollution analysis results, the heavy metal content and leaching amount of most CSWs in compliance with the Class I non-hazardous industrial solid waste in GB 18599-2020. The heavy metal content in a small amount of CSWs is higher than the screening value, and the occurrence of heavy metals is unstable. However, their potential pollution risk can be reduced by complex passivation and other technical means before underground backfilling [76, 77].

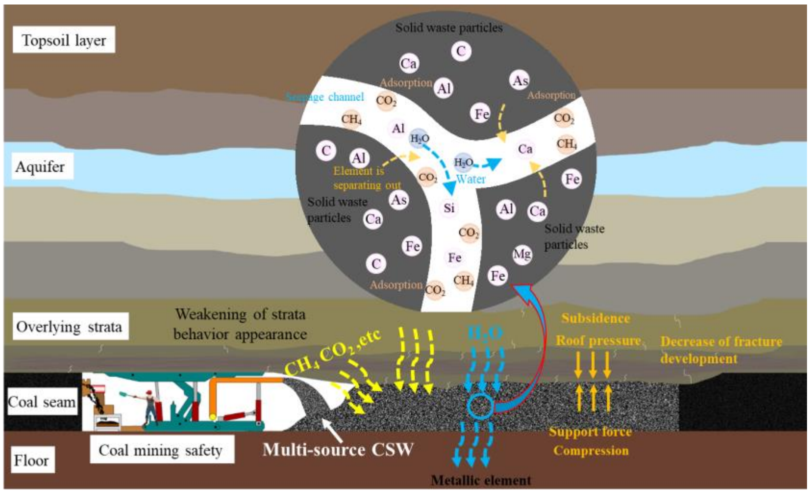


Fig. 10 Multi-field coupling of backfill materials and underground environment [64]

In addition, the behavior and effect of underground backfilling with multi-source CSW also improve the safe operating environment for miners conducting underground mining. After the multi-source CSW is backfilled into the underground goaf, the coupling effect of multi-field such as the physical field, chemical field and seepage field will inevitably occur between the multi-source CSW and the underground environment (Fig. 10). For example, the support of the backfill body restricts the subsidence of the roof, reduces the damage degree of the overlying strata, protects the overlying aquifer, reduces the accidents and disasters from coal mining, coal fires and ground pressure behavior, and is conducive to the safe operation of the coalface [78, 79]; the seepage behavior of mine water and gas occurs in the pores of the backfill body, and the interaction between CSW and the gas and liquid in the seepage channel occurs, such as molecular exchange, element precipitation, adsorption, aggregation, etc.[80, 81]. Although there are multiple field coupling effects between the backfill material and the underground environment, the leaching experiment results show that the leaching amount of heavy metals from CSWs in compliance with GB18599-2020, which is safe for groundwater. It should be noted that after backfilling the underground space with multi-source CSWs, long-term monitoring should be carried out on the soil, surface water and groundwater that may be affected according to the environmental risk assessment results, with the monitoring frequency at least once a year. To sum up, underground backfilling with multi-source CSW not only reduces the risk of pollution to the surface ecological environment, but also is safe for the underground environment and personnel operation in coal mine.

4.2 Technology

4.2.1 Heavy metal complex passivation technology

The content and unsteady speciation proportion of individual heavy metal elements in individual CSWs such as CGS are large, that amount may cause potential pollution to groundwater when used for mine backfilling. Therefore, the CSW with high potential pollution risk of heavy metals can be treated by complexation passivation technology [82, 83].

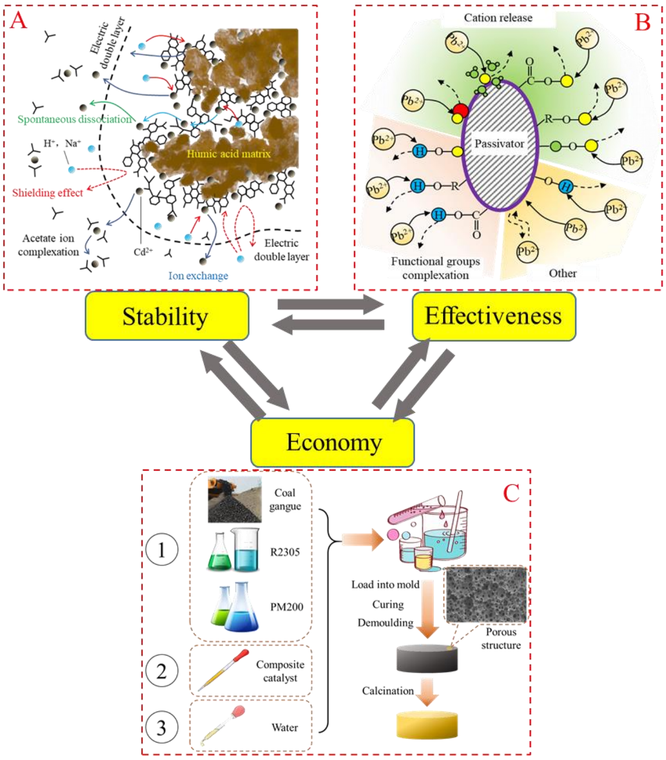


Fig. 11 Schematic diagram of technical principle [64, 84, 85] (a) Adsorption of heavy metals by humic acid (b) Passivation of Pb2+ by passivating agent (c) Preparation of porous adsorbent material from CG

The complexation passivation technology of CGS is as an example. On the one hand, the CGS is complexed and passivated with a passivating agent to effectively solidify and passivate the unsteady heavy metal ions, thereby reducing the release risk of heavy metal ions (Fig. 11A). For example, adding oxidants or reducing agents to CGS can convert active heavy metal ions into stable compounds or complexes [86, 87]. CGS and the silicon-aluminum additives or passivators added to it undergo chemical bond reorganization under mechanical or chemical action to form a new crystal structure, which wraps the heavy metals in it and transforms the heavy metals into a more stable state [61, 88, 89]. In addition, studies have found that cement can also passivate and solidify heavy metal pollutants in CGS [90, 91].

On the other hand, materials with adsorption functions can be added to CGS to adsorb heavy metal ions, thereby reducing heavy metal release and diffusion. For example, alkali slag has the effect of adsorbing Pb. Adding alkali slag to the CGS can adsorb the Pb and reduce Pb leaching [92, 93]. The technologies and methods for remediating soil contaminated by heavy metals with adsorption materials such as humic acid (HA) and zeolites are also suitable for adsorbing heavy metal elements in CGSs [94], but it is necessary to study the adsorption performance of HA on Pb^{2+} and Cd^{2+} and the desorption performance of Pb^{2+} and Cd^{2+} in HA-Pb and HA-Cd systems [95], and optimize the zeolite-HA synergistic adsorption system based on the adaptability of pH (Fig. 11B). In order to test the adsorption effect of the composite adsorbent, a single sodium humate, a single zeolite and a zeolite-sodium humate composite adsorbent were added to the $Pb(NO_3)_2$ solution and oscillated in a water bath at a speed of 150 rpm to carry out an adsorption experiment for the heavy metal Pb^{2+} [96]. The results show that the adsorption performance of the composite system is much better than that of the single system [82]. Under the condition of lead solution pH=3, the ratio of the composite adsorption system with the best heavy metal removal rate and adsorption capacity is zeolite: sodium humate = 2:1, as shown in Fig. 12.

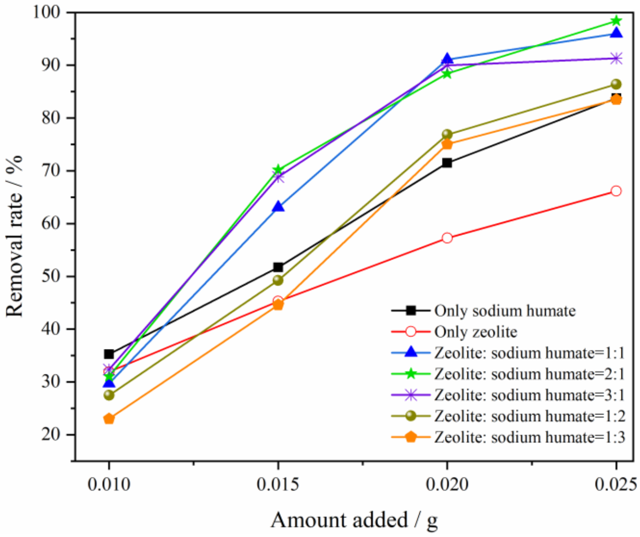


Fig. 12 Heavy metal removal effect of single and composite adsorption systems

In addition, in order to improve the economy of heavy metals complex passivation and adsorption, the porous structure of individual CSWs can be fully utilized to develop low-cost adsorption materials [97, 98]. CG conforming to GB 15618-2018 and GB 18599-2020 as an example, the technical principle is shown in Fig. 11C. By grinding, purifying, adding additives, modifying, curing and calcining, the powdery CG is prepared into a porous material with high porosity and high specific surface area, which is backfilled underground to exert its coupling adsorption effect with mine water and heavy metals. The impurities adsorbed by the powdery CG can form a package and barrier for the heavy metals, block the leaching channel, and make the heavy metals in the CG adsorption material more stable. Even if the powdery CG is soaked for a long time, the leaching amount of heavy metals can also be in compliance with the standard.

4.2.2 Mine backfilling technology

After decades of development and application, a mature underground backfilling technology system and process equipment have been formed in China's coal and metal mines [29, 31]. Multi-source CSW is suitable for backfilling with paste or slurry transported by pipelines, so that it can be backfilled into underground spaces at different depths. There are generally three types of backfilling layout in coal mines according to the overburden conditions, namely, goaf backfilling, caving area backfilling and overburden bed separation backfilling [43, 64]. The three types of backfilling layout are shown in Fig. 13. Goaf backfilling and overburden bed separation backfilling are widely used in China’s coal mines. According to the backfilling amount, goaf backfilling can be divided into complete goaf backfilling and partial goaf backfilling, which are complete mining and complete backfilling, partial mining and partial backfilling, etc. [99]. The monitoring and early warning technologies for equipment operation, ground pressure behavior, surface subsidence and underground water environment in backfilling engineering are also mature. To sum up, it is technically feasible to multi-source CSW for underground backfilling.

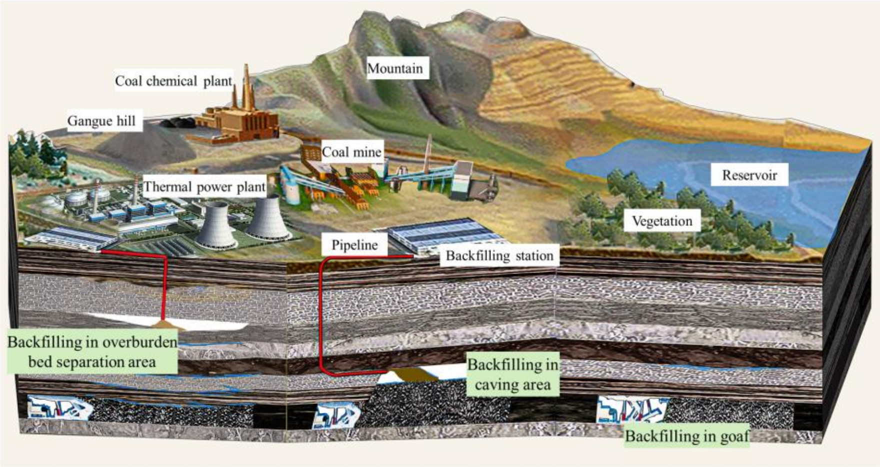


Fig. 13 Backfilling layout in different strata positions [64]

4.3 Economy

The multi-source CSW for underground backfilling is the solid waste discharged from coal mines, coal-fired power plants and coal chemical plants, the water for backfill material is mine drainage. Therefore, multi-source CSW for underground backfilling has the advantages of wide sources and rich types of materials, local materials and low preparation cost. The solid waste discharge and transportation radius of upstream and downstream enterprises in the coal-power and coal chemical industry chain in the core area of Ningdong Base is not exceed 40 km, the maximum distance from coal chemical plants and coal-fired power plants to nearby coal mines is no more than 30km, as shown in Fig. 14. It can be seen that the distribution of CSW in the CPCCB is relatively concentrated, which is conducive to nearby disposal and reduces material transportation cost. Moreover, CSWs with similar particle sizes, such as CFA, CGS and FGD gypsum, can share storage bins in the backfilling station, and CG and FBS can share crushers and screeners, further reducing the cost of backfilling equipment purchase and backfilling station construction.

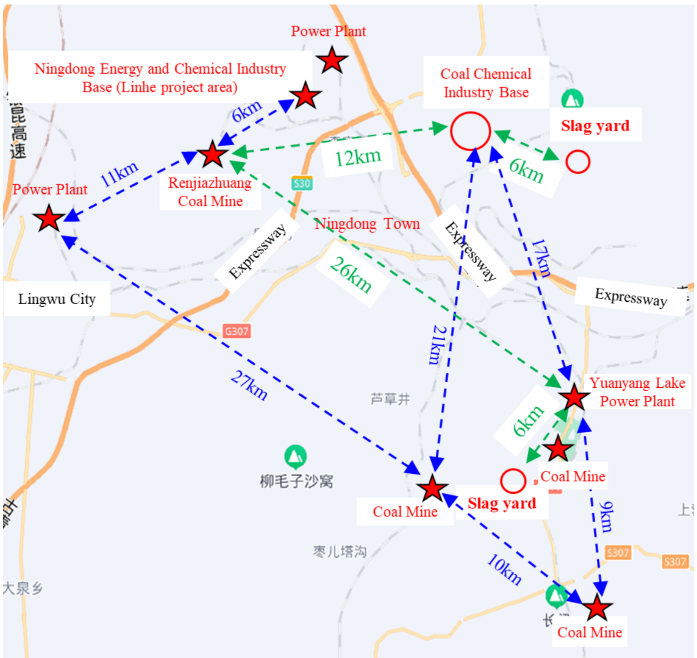


Fig. 14 Transportation distance of CSW in the core area of Ningdong Base

Underground backfilling with multi-source CSW is an effective method to reduce the coal resources under buildings, railways and water-bodies and prolong the service life of coal mines [100], also can effectively reduce the economic losses caused by the underground goaf in the coal mine and coal mining subsidence area. Since 2010, the annual output of coal from underground mining in Ningdong Base has basically stabilized between 50 million and 90 million tons. If the average density of coal is 1500kg/m³, it is calculated that the volume of goaf formed by underground mining in Ningdong Base is (33-60)×10^6 m³ per year. If the underground space of the abandoned mine is included, the space volume for underground backfilling with CSW will be larger [101, 102]. The huge underground space provides a good storage place for multi-source CSW, and also reduces the ground storage cost and disposal cost of CSW. If the average mining height of the coal face is 5m, the area of ground subsidence caused by the goaf is estimated to be at least 6-12 km^2 [103]. Local enterprises and governments have invested tens of millions of Chinese Yuan (CNY) in the treatment of coal mining subsidence areas and compensation for ecological disasters, involving land restoration, compensation and repairs for damaged roads, etc. Backfilling underground mining space with multi-source CSW can reduce the degree and scope of surface subsidence, thereby saving a lot of treatment and compensation costs. The solid waste backfilled underground and the coal replaced by solid waste can apply for subsidies from the government, and enjoy preferential fiscal policies such as fee and tax reduction.

Taking Renjiazhuang Coal Mine in Ningdong Base as an example, the economics of underground backfilling with multi-source CSW were calculated and compared. In the initial stage, the project plans to consume 100,000 tons of CG (Renjiazhuang Coal Mine), 100,000 tons of coal chemical industry solid waste (coal-to-liquid plants) and 100,000 tons of power plant solid waste (Yuanyanghu Power Plant) every year. The service period of the underground backfilling project is initially estimated to be 5 years, as shown in Table 5. Solid waste transportation costs (SWTC), slag yard storage costs (SYSC), and coal sales profits from mining coal pillars (CSP-MCP) are calculated by equations (1)-(4) respectively. Subsidence land treatment and restoration costs (SLTRC) mainly include landfill restoration of ground subsidence areas, road restoration and building (structure) compensation, etc. The construction cost of the backfilling station (CCBS) mainly includes the cost of site planning, construction and backfilling equipment purchase. The operating cost of the backfilling station (OCBS) includes equipment maintenance, energy consumption and labor costs, and is calculated at 3 million CNY per year. The financial subsidy fee (FSF) mainly includes the solid waste disposal subsidy provided by the government, and the subsidy standard is calculated at 2 CNY per ton. The above expenses were obtained through field visits and research.

$$f_T = f_t \times d \times s \tag{1}$$

$$f_S = f_{ss} \times s \tag{2}$$

$$f_C = (f_{sc} - f_{cc}) \times w \tag{3}$$

$$f_A = f_a \times s \tag{4}$$

Where, f_T is the solid waste transportation cost, million CNY/year; f_t is the unit price of transportation, which is 2 CNY/ton·km; *d* is the distance of solid waste transportation, km, as shown by the green marked line in Fig. 14; *s* is the backfilling amount of solid waste, 10,000 tons/year; f_S is the storage cost of the slag yard, million CNY/year; f_{ss} is the unit price of solid waste storage in the slag yard, which is 25 CNY/ton per year; f_C is the sales profit of mined coal pillars, million CNY; f_{sc} is the unit price of coal sales, which is 1500 CNY/ton; f_{cc} is the cost of coal mining, which is 300 yuan/ton; *w* is the resource amount of the mined coal pillar, calculated as 100,000 tons; f_A is the total annual cost of financial subsidies, million CNY/year; f_a is the unit price of financial subsidies, which is 2 CNY/ton.

Table 5 Calculation of 5-year economic input (Unit: million CNY/ USD)

Condition	SWTC	SYSC	SLTRC	CCBS	OCBS	CSP-MCP	FSF	Total cost
Non-backfilling	-24/-3.4	-25/-3.6	-30/-4.3	0	0	0	0	-79/-11.3

Backfilling	-38/-5.4	0	0	-33/-4.7	-15/-2.2	0	+3/+0.4	-83/-11.9
Coal pillar mining and backfilling	-38/-5.4	0	0	-33/-4.7	-15/-2.2	+120/+17.2	+3/+0.4	+37/+5.3

Note: “-” means expenditure, the exchange rate is converted according to CNY:USD ≈ 7:1.

It can be seen that in the case of non-backfilling, the five-year investment cost of waste production enterprises is about 79 million CNY, which is only 3 million CNY less than that of backfilling. If the goaf in Renjiazhuang Coal Mine is backfilled with solid waste discharged from a closer coal-fired power plant, the transportation costs will be lower. In this way, there is not much difference between the economic input of backfilling and non-backfilling. Moreover, the underground backfilling with multi-source CSW also has potential priceless environmental and social benefits. In addition, the use of CSW to backfill the underground space formed by mining coal pillars under buildings has significant economic benefits, and the greater the amount of coal pillar resources mined, the higher the economic income. In summary, underground backfilling with multi-source CSW is economically feasible.

4.4 Policy

It can be seen from the environmental risk analysis that the hazard identification results, heavy metal content and leaching amount of most CSWs are in compliance with GB18599-2020. The excessive release risk of heavy metals in CGS can be reduced by technical measures such as coagulation sedimentation and complex passivation, so that the amount of heavy metal leaching in the underground can be in compliance with GB18599-2020 [104]. Underground backfilling with multi-source CSW can greatly reduce surface stockpiles, effectively protect water, soil and air, which comply with a series of environmental policies [105]. It can also protect underground aquifers, reduce mining disasters and surface subsidence, which is in line with the concept of green mining.

CSW for underground backfilling is in line with national and local solid waste management policies and regulations [20]. The Council of State Governments (CSG) in China publishes more than 20 policies and regulations every year, which shows that China's top management attaches great importance to solid waste management [106]. Although there are regional differences in the number of solid waste management policies and regulations, the policies and regulations issued by provinces and cities are more specific and targeted, and help to promote the standardized management and disposal of regional solid wastes, such as underground backfilling with CSW.

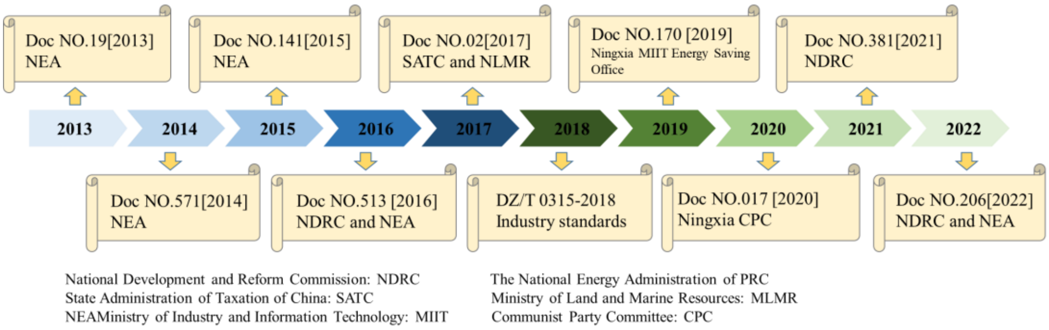


Fig. 15 Some documents on solid waste backfilling issued in China and Ningxia since 2013

Underground backfilling with CSW is supported by the government's guidance documents to encourage the comprehensive utilization of solid waste and the encouragement of backfill mining in coal mines. Since the "Guiding Opinions on Coal Mine Backfilling and Mining Work" issued by four Chinese ministries and commissions in 2013, a series of relevant policy documents and guidance opinions have been issued successively by various national departments, as shown in Fig. 15. It can be seen that the state and local institutions have paid attention and support to the synergistic utilization of CSW and coal mine backfill mining. The financial institution has also adopted support measures such as fee reductions, tax exemptions and financial subsidies for underground backfilling with CSW [20, 107]. Underground backfilling with multi-source CSW can not only dispose of solid waste on a large scale, but also has ecological, social and economic benefits brought about by backfill mining, which conforms to the era theme of green low-carbon, high-quality development and achieving the goal of carbon peaking and carbon neutrality. Underground backfilling with multi-source CSW is feasible in policy.

5. Challenges and strategies of multi-source CSW for underground backfilling

Although multi-source CSW has the feasibility of underground backfilling in terms of environment, technology, economy and policy, there are still some issues and challenges before large-scale engineering application.

5.1 Potential risks of CGS

Although the toxicity and heavy metal test results of the CSW samples in this study performed well, due to the difference in production processes and equipment, not all CSWs discharged by enterprises in Ningdong Base meet the landfill standards, especially solid wastes discharged by coal chemical plants. The use of solid waste from coal chemical plants for underground backfilling will receive particular attention from the government. The references [108, 109] reveals the high potential environmental risks of CGS discharged by individual coal chemical plants by analyzing the chemical forms of heavy metals. As a Class II non-hazardous industrial solid waste, its direct use for underground backfilling will be restricted. With the strict enforcement of environmental protection, the high potential pollution risk of coal chemical solid waste is not allowed in western China. As a key indicator for evaluating the feasibility of CSW for underground backfilling, environmental safety plays a veto role in the government's approval process for engineering projects. If the individual toxic parameters of CGS exceed the standard, it will directly lead to the failure of its environmental impact assessment (EIA), and then it cannot be directly used for underground backfill. Therefore, the amount and scope of coal chemical solid waste that can be safely used for underground backfill will become very limited. For CSW whose toxic index exceeds the standard and has high potential pollution risk, some technical measures can be adopted to reduce its toxicity and pollution.

5.2 Maturity of technology

There are many application cases of CSW such as CG and CFA for underground backfilling in China [29, 31, 32, 43]. However, CSWs from coal chemical plants, such as CGS and FBS, are rarely used as components of underground backfilling materials. For coal chemical solid wastes such as CGS with high potential pollution risks, it is necessary to take technical measures to reduce the pollution risk of CGS before underground backfilling. The main technical measures include chemical coagulation, precipitation filtration, adsorption and complex passivation [110, 111]. However, these technical measures to reduce the pollution risk of solid waste are still in the laboratory stage or small-scale application stage, the maturity of complex passivation technology is not high, and large-scale commercial application has not yet been achieved, or large-scale industrial application requires higher costs. The low maturity of the technology limits the scope and amount of the CSW from coal chemical plants, such as CGS, for underground backfilling without risk. Therefore, reducing the threshold of complex passivation and other technologies and developing low-cost passivation materials are the future development priorities. As the maturity of the technology increases, the prices of chemical reagents and equipment are further reduced, and the technological process is simpler, making complex passivation technology of heavy metals for large-scale commercial industrial application.

5.3 Economic investment

The implementation of underground backfilling with multi-source CSW requires costs for plant construction, equipment purchase, and material transportation, which far exceed the cost of ground storage for CSW. Huge economic investment in the early stage has dampened the enthusiasm of enterprises to implement underground backfilling with CSW. The backfilling cost of multi-source CSWs is further increased by the implementation of heavy metal complex passivation and chemical modification for CSWs with high potential pollution risks, and the long-term monitoring measures for the groundwater environment after underground backfilling. Therefore, underground backfilling with multi-source CSW is mostly used in the mining coal resources under buildings, railways and water-bodies at this stage, so that the coal pillars mining income is sufficient to cover the backfilling cost [112]. High investment limit the large-scale application of underground backfilling technology with multi-source CSW. This is not just a problem unique to the Ningdong Base.

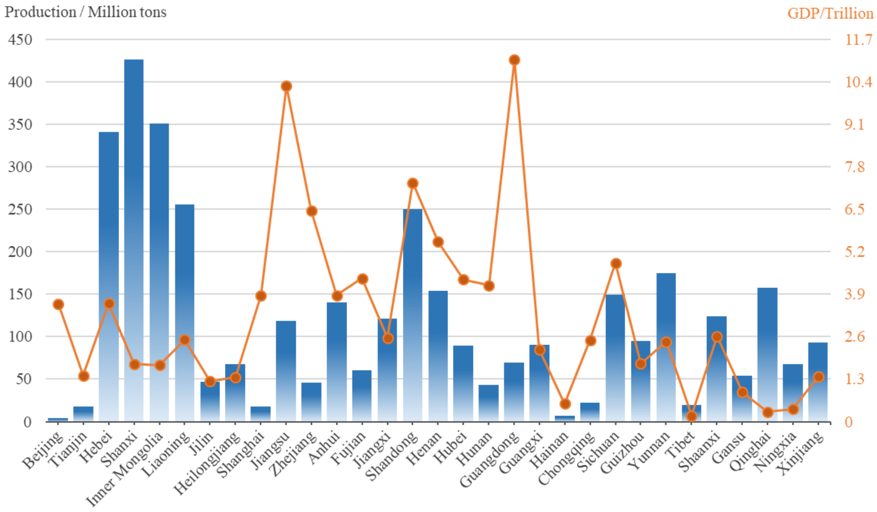


Fig. A.7 The relationship between industrial solid waste production and GDP in various provinces

The regional output of multi-source CSW in China is unbalanced and often has a negative correlation with GDP, as shown in Fig. 16. The output of industrial solid waste in the central and western regions such as Inner Mongolia, Shanxi and Hebei is large, but the GDP is low and the economy is underdeveloped, resulting in less financial investment by the government and enterprises in the disposal of industrial solid waste, and insufficient support for large-scale underground backfilling with multi-source CSW [113]. For example, in Tangshan Coal Mine (Hebei), 0.86 million tons of coal were mined and 1.105 million tons of solid waste were backfilled through the backfill mining method, but the reduced coal resource tax is about 1.8 million CNY, with an average reduction of only 2.1 CNY per ton of coal. Therefore, the government should strengthen the implementation of policy such as financial subsidies, tax exemption and fee reductions for underdeveloped areas with huge CSW production, so as to increase the enthusiasm of enterprises to adopt underground backfilling technology with CSW.

Although the preferential fiscal policy of 50% reduction in coal resource tax has been implemented (Announcement on the website of the Ministry of Finance of China, No. 36 in 2023), this is far from enough for the huge economic investment of mining enterprises that apply CSW underground backfilling technology. Financial support from the government needs to be greater. For example, income tax should be deducted from the income derived from resources mined through CSW underground backfilling. Solid waste backfilling equipment can be added to the "*Environmental Protection Special Equipment Income Tax Preferential Catalog*" to reduce the initial investment of mining enterprises in carrying out CSW underground backfilling projects; It is suggested that the government reduce environmental management deposits or reduce subsidence control reserved funds for mining enterprises that use CSW underground backfilling. In addition, government departments can establish research and development funds and technology promotion funds for CSW underground backfilling, which will help promote scientific research and technology development and application of CSW underground backfilling.

5.4 Administration

Before the engineering practice of underground backfilling with multi-source CSW, an EIA is a necessary process. After the EIA is completed, it needs to be filed and approved by the regulatory authorities. Especially in key ecological and environmental protection areas in western China, strict EIA and approval procedures are required before the construction of large-scale projects. Take the ongoing CSW underground backfilling project at Renjiazhuang Coal Mine in Ningdong Base as an example. During the process from project establishment to construction, it was found that the EIA procedures is complicated and tedious with a lot of documents, the waiting time for approval is long. The whole process from application, document filing to approval involves multiple departments such as the natural resources department, environmental protection department, land management department, construction department, management committee, etc., and usually takes more than one year, which leads to a delay in the construction period of the backfilling station, which may further affect the normal mining plan of the coal mine [42]. Therefore, it is necessary for the regulatory authorities to simplify the EIA approval procedures and shorten the approval time for the EIA materials that in compliance with the backfilling standards for solid waste. Efficient approval is conducive to promoting the large-scale application of underground backfilling with multi-source CSW.

In addition, government regulatory authorities lack strong and mandatory enforcement against illegal waste discharge by large companies. The government's low management costs for solid waste discharge and storage have led to large companies preferring to dump CSW legally or illegally into slag yards or wilderness Gobi in a low-cost way, rather than using higher-cost underground backfilling methods. Therefore, government regulatory authorities should adopt more mandatory restraint measures, increase the cost of solid waste discharge and storage, and strictly enforce the law. For example, in the ecologically fragile areas of western China, government departments should give priority to approval of new coal mine projects with CSW underground backfilling; Enterprises that illegally discharge CSW in the open air should be resolutely punished with high fines and suspension of operations for rectification.

6. FURTHER RESEARCH

Underground backfilling with multi-source CSW is a complex project, and faces some issues that still require in-depth research before and during its widespread application. Several examples of potential future research content are as follow.

(1) Synergistic effect of adsorbing and passivating heavy metals from multi-source CSW. The adsorption or passivation of heavy metals in solid waste is often accomplished by using additives, but additives undoubtedly increase the cost of the industrial application of heavy metal complex passivation technology. In the future, the porous structure, gelling characteristics, and chemical reaction mechanism of multi-source CSW should be fully utilized. The CSW with the potential to adsorb or solidify heavy metals can be modified and optimized to stimulate its adsorption and passivation functions, so that the multi-source CSW can exert a synergistic effect of adsorption and passivation of heavy metals by the components, thereby improving the safety and stability of the multi-source CSW to the underground environment.

(2) Coupling characteristics of multi-source CSW and goaf waste rock. A large amount of waste rock is left in the goaf space after coal mining [114, 115]. When multi-source CSW is grouted and backfilled into the goaf and caving areas, the backfill material will flow and fill the gaps in the waste rock. The mixture of waste rock and CSW will become the backfill that supports the overlying strata [116]. The mechanical

properties of this mixture will inevitably have an important impact on the geomechanical state of the surrounding rock. Therefore, the interface morphology, reinforcement micro-mechanism and material coupling characteristics of multi-source CSW and waste rock need be further studied to provide a more scientific solution for the material ratio of multi-source CSW and the collaborative stratum control of backfill materials and waste rock [117, 118].

(3) Temporal and spatial migration patterns and influencing effects of heavy metals in multi-source CSW backfill. Each coal mine has a unique geological environment, such as different degrees of surrounding rock fragmentation, the acidity and alkalinity of old goaf water, and the degree of ground pressure behavior. After the multi-source CSW is backfilled in the underground space, under the coupling effect of multiple complex environments, the leaching, migration and distribution laws of heavy metal elements are still unclear. Long-term environmental monitoring is needed to reveal the spatiotemporal migration patterns, distribution range and impact of heavy metals in the backfill on groundwater, surrounding rock and mining environment.

7. SUMMARY

The hazard indicators, heavy metal content and leaching amount of most CSW in the Ningdong Base meet environmental standards. However, individual CGS have potential environmental risks. The exchangeable fraction, carbonate bound fraction and Fe-Mn oxide bound fraction of Cr, Cd, Pb and Zn in the CGS from coal-to-liquid and coal-to-methanol account for 47.97%-94.96%, and there is a risk of heavy metal release.

The environmental feasibility of underground backfilling with multi-source CSW was analyzed from the multiple aspects, such as the toxicity of the material itself, the pollution of the physical and chemical reflection process and products between material components, the stability and toxicity of backfill materials in mine water, rock formations and air environments, and the improvement of underground mining safety environment for miners, etc.

The mature development of mine backfilling equipment, technology, and layout systems shows the technical feasibility of underground backfilling with multi-source CSW; Technologies such as heavy metal complex passivation and adsorption can be used to reduce the potential risk of heavy metal pollution in CGS.

The economic feasibility of underground backfilling with multi-source CSW was analyzed from the aspects of material sources, transportation distance, equipment investment, etc. Comparing the investment and benefits of CSW disposal under backfilling and non-backfilling conditions, it shows that the investment cost of CSW disposal in these two cases has a small difference, and the economic benefits of CSW used in backfilling the underground space formed by mining coal pillars are the most significant.

Underground backfilling with multi-source CSW helps protect the environment, is in line with sustainable and high-quality development policy and the green mining concept in the coal mine, and has received certain financial support.

Although underground backfilling with multi-source CSW has environmental, technical, economic and policy feasibility, it still faces some challenges, mainly in several aspects, such as the high environmental risk of some CGSs, the low industrialization maturity of heavy metal complex passivation technology, low and regional imbalance in economic investment of CSW underground backfilling, as well as the long EIA approval cycle for backfilling projects, and weak government enforcement against illegal waste discharge. Finally, some future research is prospected.

It is foreseeable that with the further promotion of technology, economic investment and policies, the underground backfilling with multi-source CSW is no longer limited to basic research in the laboratory, but more and more engineering demonstration and application, become the most practical and effective way to dispose of multi-source CSW with large-scale and environment-friendly, so that multi-source CSW are no longer stockpiled on the surface, which requires the joint efforts and cooperation of the government, enterprises, and research institutions.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] B. Ren, Y.L. Zhao, H.Y. Bai, S.C. Kang, T.T. Zhang, S.X. Song, Eco-friendly geopolymer prepared from solid wastes: A critical review, Chemosphere, 267 (2021).

[2] H.-X. Zhao, F.-S. Zhou, A. Evelina L.M, J.-L. Liu, Y. Zhou, A review on the industrial solid waste application in pelletizing additives: Composition, mechanism and process characteristics, Journal of Hazardous Materials, 423 (2022) 127056.

[3] S. Kaza, L.C. Yao, P. Bhada-Tata, F. Van Woerden, What a Waste 2.0 : A Global Snapshot of Solid Waste Management to 2050, Urban Development;. Washington, DC: World Bank. , 2018.

[4] E. Beguedou, S. Narra, K. Agboka, D.M. Kongnine, E. Afrakoma Armoo, Review of Togolese Policies and Institutional Framework for Industrial and Sustainable Waste Management, Waste, 1 (2023) 654-671.

[5] N. Ferronato, V. Torretta, Waste Mismanagement in Developing Countries: A Review of Global Issues, International Journal of Environmental Research and Public Health, 16 (2019) 1060.

[6] H. Tian, J. Gao, L. Lu, D. Zhao, K. Cheng, P. Qiu, Temporal Trends and Spatial Variation Characteristics of Hazardous Air Pollutant Emission Inventory from Municipal Solid Waste Incineration in China, Environmental Science & Technology, 46 (2012) 10364-10371.

[7] J. Li, K. Liu, S. Yan, Y. Li, D. Han, Application of thermal plasma technology for the treatment of solid wastes in China: An overview, Waste Management, 58 (2016) 260-269.

[8] H. Schandl, A. Miatto, Data on the domestic processed output, balancing items, and solid waste potential for five major world economies, Data in brief, 22 (2019) 662-675.

[9] C.B. Felix, A.T. Ubando, W.-H. Chen, V. Goodarzi, V. Ashokkumar, COVID-19 and industrial waste mitigation via thermochemical technologies towards a circular economy: A state-of-the-art review, Journal of Hazardous Materials, 423 (2022) 127215.

[10] H.B. Sharma, K.R. Vanapalli, V.R.S. Cheela, V.P. Ranjan, A.K. Jaglan, B. Dubey, S. Goel, J. Bhattacharya, Challenges, opportunities, and innovations for effective solid waste management during and post COVID-19 pandemic, Resources Conservation and Recycling, 162 (2020).

[11] S. Wang, Comprehensive utilization of 60 billion tons of solid waste is a huge market, Green Living, 129 (2018) 104-105.

[12] A.S. Meawad, D.Y. Bojinova, Y.G. Pelovski, An overview of metals recovery from thermal power plant solid wastes, Waste Management, 30 (2010) 2548-2559.

[13] G. Liao, L. Liu, F. Zhang, E. Jiaqiang, J. Chen, A novel combined cooling-heating and power (CCHP) system integrated organic Rankine cycle for waste heat recovery of bottom slag in coal-fired plants, Energy Conversion and Management, 186 (2019) 380-392.

[14] F. Han, Industrial solid waste recycling in western China, Springer, 2019.

[15] Y.K. Cho, S.H. Jung, Y.C. Choi, Effects of chemical composition of fly ash on compressive strength of fly ash cement mortar, Construction and Building Materials, 204 (2019) 255-264.

[16] Y. Luo, Y. Wu, S. Ma, S. Zheng, Y. Zhang, P.K. Chu, Utilization of coal fly ash in China: a mini-review on challenges and future directions, Environmental Science and Pollution Research, 28 (2021) 18727-18740.

[17] J. Li, J. Wang, Comprehensive utilization and environmental risks of coal gangue: A review, Journal of Cleaner Production, 239 (2019) 117946.

[18] X. Peng, Y. Jiang, Z. Chen, A.I. Osman, M. Farghali, D.W. Rooney, P.-S. Yap, Recycling municipal, agricultural and industrial waste into energy, fertilizers, food and construction materials, and economic feasibility: a review, Environmental Chemistry Letters, 21 (2023) 765-801.

[19] J. Li, E. Yilmaz, S. Cao, Influence of industrial solid waste as filling material on mechanical and microstructural characteristics of cementitious backfills, Construction and Building Materials, 299 (2021) 124288.

[20] W. Guo, B. Xi, C. Huang, J. Li, Z. Tang, W. Li, C. Ma, W. Wu, Solid waste management in China: Policy and driving factors in 2004–2019, Resources, Conservation and Recycling, 173 (2021) 105727.

[21] X.H. Zhu, Y.F. Cui, J.B. Peng, C. Jiang, W.L. Guo, Erosion and transport mechanisms of mine waste along gullies, Journal of Mountain Science, 16 (2019) 402-413.

[22] A. Siddiqua, J.N. Hahladakis, W. Al-Attiya, An overview of the environmental pollution and health effects associated with waste landfilling and open dumping, Environmental Science and Pollution Research.

[23] Z.A. Wei, G.Z. Yin, J.G. Wang, L. Wan, G.Z. Li, Design, construction and management of tailings storage facilities for surface disposal in China: case studies of failures, Waste Management & Research, 31 (2013) 106-112.

[24] S.K. Behera, D.P. Mishra, P. Singh, K. Mishra, S.K. Mandal, C.N. Ghosh, R. Kumar, P.K. Mandal, Utilization of mill tailings, fly ash and slag as mine paste backfill material: Review and future perspective, Construction and Building Materials, 309 (2021) 125120.

[25] A.J. Bull, M. Fall, Thermally induced changes in metalloid leachability of cemented paste backfill that contains blast furnace slag, Minerals Engineering, 156 (2020) 106520.

[26] Y. Li, X. Min, Y. Ke, J. Fei, D. Liu, C. Tang, Immobilization potential and immobilization mechanism of arsenic in cemented paste backfill, Minerals Engineering, 138 (2019) 101-107.

[27] A. Tariq, E.K. Yanful, A review of binders used in cemented paste tailings for underground and surface disposal practices, Journal of Environmental Management, 131 (2013) 138-149.

[28] S. Coussy, M. Benzaazoua, D. Blanc, P. Moszkowicz, B. Bussière, Arsenic stability in arsenopyrite-rich cemented paste backfills: A leaching test-based assessment, Journal of Hazardous Materials, 185 (2011) 1467-1476.

[29] S.H. Yin, Y.J. Shao, A.X. Wu, H.J. Wang, X.H. Liu, Y. Wang, A systematic review of paste technology in metal mines for cleaner production in China, Journal of Cleaner Production, 247 (2020).

[30] S.K. Behera, D.P. Mishra, P. Singh, K. Mishra, S.K. Mandal, C.N. Ghosh, R. Kumar, P.K. Mandal, Utilization of mill tailings, fly ash and slag as mine paste backfill material: Review and future perspective, Construction and Building Materials, 309 (2021).

[31] Q.L. Chang, J.H. Chen, H.Q. Zhou, J.B. Bai, Implementation of Paste Backfill Mining Technology in Chinese Coal Mines, Scientific World Journal, (2014).

[32] J.X. Zhang, M. Li, A. Taheri, W.Q. Zhang, Z.Y. Wu, W.J. Song, Properties and Application of Backfill Materials in Coal Mines in China, Minerals, 9 (2019).

[33] M.G. Karfakis, C.H. Bowman, E. Topuz, Characterization of coal-mine refuse as backfilling material, Geotechnical & Geological Engineering, 14 (1996) 129-150.

[34] N. Jiang, J. Zhao, X. Sun, L. Bai, C. Wang, Use of fly-ash slurry in backfill grouting in coal mines, Heliyon, 3 (2017) e00470.

[35] M. Li, J. Zhang, A. Li, N. Zhou, Reutilisation of coal gangue and fly ash as underground backfill materials

for surface subsidence control, Journal of Cleaner Production, 254 (2020) 120113.

[36] J. Xin, L. Liu, L. Xu, J. Wang, P. Yang, H. Qu, A preliminary study of aeolian sand-cement-modified gasification slag-paste backfill: Fluidity, microstructure, and leaching risks, Science of The Total Environment, 830 (2022) 154766.

[37] H. Liu, J. Zhang, B. Li, N. Zhou, X. Xiao, M. Li, C. Zhu, Environmental behavior of construction and demolition waste as recycled aggregates for backfilling in mines: Leaching toxicity and surface subsidence studies, Journal of Hazardous Materials, 389 (2020) 121870.

[38] X. Gao, Y. Zhao, S. Lu, Q. Chen, T. An, X. Han, L. Zhuo, Impact of coal power production on sustainable water resources management in the coal-fired power energy bases of Northern China, Applied Energy, 250 (2019) 821-833.

[39] J. Yuan, Q. Lei, M. Xiong, J. Guo, Z. Hu, The prospective of coal power in China: Will it reach a plateau in the coming decade?, Energy Policy, 98 (2016) 495-504.

[40] K. Xie, W. Li, W. Zhao, Coal chemical industry and its sustainable development in China, Energy, 35 (2010) 4349-4355.

[41] X. Liang, T. Huang, S. Lin, J. Wang, J. Mo, H. Gao, Z. Wang, J. Li, L. Lian, J. Ma, Chemical composition and source apportionment of PM1 and PM2.5 in a national coal chemical industrial base of the Golden Energy Triangle, Northwest China, Science of The Total Environment, 659 (2019) 188-199.

[42] J. Shi, W. Huang, H. Han, C. Xu, Pollution control of wastewater from the coal chemical industry in China: Environmental management policy and technical standards, Renewable and Sustainable Energy Reviews, 143 (2021) 110883.

[43] K. Yang, X. Zhao, Z. Wei, J. Zhang, Development overview of paste backfill technology in China's coal mines: a review, Environmental Science and Pollution Research, 28 (2021) 67957-67969.

[44] Y. Huang, W. WANG, Z. BIAN, Prospects of resource utilization and disposal of coal - based solid wastes in Xinjiang, Coal Science and Technology, 49 (2021) 319-330.

[45] Z. Wei, K. Yang, X. He, J. Zhang, G. Hu, Experimental Study on the Optimization of Coal-Based Solid Waste Filling Slurry Ratio Based on the Response Surface Method, Materials, 15 (2022) 5318.

[46] P. Yang, L. Liu, Y. Suo, M. Zhu, G. Xie, S. Deng, Mechanical properties, pore characteristics and microstructure of modified magnesium slag cemented coal-based solid waste backfill materials: Affected by fly ash addition and curing temperature, Process Safety and Environmental Protection, 176 (2023) 1007-1020.

[47] MEE, National Annual Report of Solid Waste Pollution Prevention and Control in Big and Medium-Sized Cities (in Chinese), in, 2020.

[48] H. Zhao, S. Wang, R. Wang, L. Shen, Q. Wang, Utilization of raw coal gangue as coarse aggregates in pavement concrete, Construction and Building Materials, 378 (2023) 131062.

[49] J. Qu, J. Zhang, H. Li, S. Li, A high value utilization process for coal gasification slag: Preparation of high modulus sodium silicate by mechano-chemical synergistic activation, Science of the Total Environment, 801 (2021).

[50] C. Wang, G. Xu, X. Gu, Y. Gao, P. Zhao, High value-added applications of coal fly ash in the form of porous materials: A review, Ceramics International, 47 (2021) 22302-22315.

[51] H.A. Abdel-Gawwad, M.S. Mohammed, M. Heikal, Ultra-lightweight porous materials fabrication and hazardous lead-stabilization through alkali-activation/sintering of different industrial solid wastes, Journal of Cleaner Production, 244 (2020).

[52] J. Zhu, M.R. Chertow, Greening Industrial Production through Waste Recovery: “Comprehensive Utilization of Resources” in China, Environmental Science & Technology, 50 (2016) 2175-2182.

[53] M. Campos-M, R. Campos-C, Applications of quartering method in soils and foods, Int. J. Eng. Res. Appl, 7 (2017) 35-39.

[54] G.A. Dino, A. Cavallo, P. Rossetti, E. Garamvölgyi, R. Sándor, F. Coulon, Towards Sustainable Mining:

Exploiting Raw Materials from Extractive Waste Facilities, Sustainability, 12 (2020) 2383.

[55] G.A. Dino, P. Rossetti, L. Perotti, W. Alberto, H. Sarkka, F. Coulon, S. Wagland, Z. Griffiths, F. Rodeghiero, Landfill mining from extractive waste facilities: The importance of a correct site characterisation and evaluation of the potentialities. A case study from Italy, Resources Policy, 59 (2018) 50-61.

[56] X. Zhao, K. Yang, X. He, Z. Wei, J. Zhang, Study on proportioning experiment and performance of solid waste for underground backfilling, Materials Today Communications, 32 (2022) 103863.

[57] O. Kotova, New adsorbent materials on the base of minerals and industrial waste, IOP Conference Series: Materials Science and Engineering, 613 (2019) 012001.

[58] B. Chang, C. Du, Y. Wang, X. Chu, L. Zhang, Modeling of Permeability Coefficient Calculations Based on the Mesostructure Parameters of Tailings, ACS Omega, 7 (2022) 5625-5635.

[59] S. Wang, R. Yang, Y. Li, B. Xu, B. Lu, Single-factor analysis and interaction terms on the mechanical and microscopic properties of cemented aeolian sand backfill, International Journal of Minerals, Metallurgy and Materials, 30 (2023) 1584-1595.

[60] H. Stegmann, Basics and Current Aspects of Scanning Electron Microscopy, in: ISTFA 2021, 2021, pp. k1-k87.

[61] X. Wei, C. Dong, F. Xie, P. Wang, F. Yan, Z. Zhang, Co-disposal of hazardous waste incineration fly ash and bottom ash through alkaline-activation: Effects of added CaO on solidification of heavy metals, Journal of Environmental Chemical Engineering, 11 (2023) 110924.

[62] Y. Guo, Y. Zhang, X. Zhao, J. Xu, G. Qiu, W. Jia, J. Wu, F. Guo, Multifaceted evaluation of distribution, occurrence, and leaching features of typical heavy metals in different-sized coal gasification fine slag from Ningdong region, China: A case study, Science of The Total Environment, 831 (2022) 154726.

[63] M. Frankowski, A. Zioła-Frankowska, A. Kowalski, J. Siepak, Fractionation of heavy metals in bottom sediments using Tessier procedure, Environmental Earth Sciences, 60 (2010) 1165-1178.

[64] K. Yang, X. Zhao, X. He, Z. Wei, Basic theory and key technology of multi-source coal-based solid waste for green backfilling, Journal of China Coal Society, 47 (2022) 4201-4216.

[65] L. Wang, Y. Zhang, The ball effect and lubricity contrast analysis of concrete mixed with fly ash, Bulletin of Science and Technology, 33 (2017) 154-158.

[66] D.L. Li, R. Sun, D.M. Wang, C.F. Ren, K.Z. Fang, Study on the pozzolanic activity of ultrafine circulating fluidized-bed fly ash prepared by jet mill, Fuel, 291 (2021).

[67] Y. Wang, Y. Tang, B. Huan, X. Guo, R.B. Finkelman, Mineralogical examination of the entrained-flow coal gasification residues and the feed coals from northwest China, Advanced Powder Technology, 32 (2021) 3990-4003.

[68] M.o.E.a.E.o.t.P.s.R.o. China, Integrated wastewater discharge standard, in, Ministry of Ecology and Environment of the People's Republic of China, 1998.

[69] Y. Yang, M. Chu, X. Shi, F. Lyu, X. Sun, C. Jia, Grading Characteristics of Texaco Gasification Fine Slag: Quality Distinction and Selective Distribution of Trace Elements, ACS Omega, 5 (2020) 26883-26893.

[70] P. Wijekoon, P.A. Koliyabandara, A.T. Cooray, S.S. Lam, B.C.L. Athapattu, M. Vithanage, Progress and prospects in mitigation of landfill leachate pollution: Risk, pollution potential, treatment and challenges, Journal of Hazardous Materials, 421 (2022).

[71] N.T. Hoa, Y. Matsuoka, The analysis of greenhouse gas emissions/reductions in waste sector in Vietnam, Mitigation and Adaptation Strategies for Global Change, 22 (2017) 427-446.

[72] D. Huang, Y. Du, Q. Xu, J.H. Ko, Quantification and control of gaseous emissions from solid waste landfill surfaces, Journal of Environmental Management, 302 (2022) 114001.

[73] A.H. Khan, E.A. López-Maldonado, N.A. Khan, L.J. Villarreal-Gómez, F.M. Munshi, A.H. Alsabhan, K. Perveen, Current solid waste management strategies and energy recovery in developing countries - State of art review, Chemosphere, 291 (2022) 133088.

[74] X. Zhao, K. Yang, Z. Wei, X. He, R. Chen, Study on the effect of multi-source solid waste on the performance of its backfill slurry, Heliyon, 9 (2023).

[75] J. Zhang, K. Yang, X. He, L. Zhang, Z. Wei, X. Zhao, J. Fang, Study on mechanical properties and damage characteristics of coal-based solid waste cemented backfill, Construction and Building Materials, 368 (2023) 130373.

[76] Z. He, Y. Xu, W. Wang, X. Yang, Z. Jin, D. Zhang, X. Pan, Synergistic mechanism and application of microbially induced carbonate precipitation (MICP) and inorganic additives for passivation of heavy metals in copper-nickel tailings, Chemosphere, 311 (2023) 136981.

[77] A.K. Pandey, S.D. Pandey, V. Misra, Removal of Toxic Metals from Leachates from Hazardous Solid Wastes and Reduction of Toxicity to Microtox by the Use of Calcium Alginate Beads Containing Humic Acid, Ecotoxicology and Environmental Safety, 52 (2002) 92-96.

[78] X.Y. Zhao, X.W. Li, K. Yang, Z. Wei, The Spatiotemporal Characteristics of Coupling Effect between Roof and Backfill Body in Dense Backfill Mining, Geofluids, 2021 (2021).

[79] X. Zhao, K. Yang, X. He, Z. Wei, J. Zhang, X. Yu, Study on Characteristics of Compression Deformation and Post-Peak Stress Rebound for Solid Waste Cemented Body, Minerals, 13 (2023) 108.

[80] J. Hou, Z. Guo, J. Li, L. Zhao, Study on triaxial creep test and theoretical model of cemented gangue-fly ash backfill under seepage-stress coupling, Construction and Building Materials, 273 (2021) 121722.

[81] N. Shiqing, G. Qian, L. Zenghui, Numerical Simulation of Fluid-Solid Coupling in Surrounding Rock and Parameter Optimization for Filling Mining, Procedia Engineering, 26 (2011) 1639-1647.

[82] N.K. Soliman, A.F. Moustafa, Industrial solid waste for heavy metals adsorption features and challenges; a review, Journal of Materials Research and Technology-Jmr&T, 9 (2020) 10235-10253.

[83] X.Y. Zhang, C.Q. Li, S.L. Zheng, Y.H. Di, Z.M. Sun, A review of the synthesis and application of zeolites from coal-based solid wastes, International Journal of Minerals Metallurgy and Materials, 29 (2022) 1-21.

[84] F. LYU, H. Yl, Y. WANG, Y. HAO, Q. BAl, M. CHU, Characteristics of Cd^{2+} adsorption and desorption of coal humic acid, Coal Engineering, 54 (2022) 172-176.

[85] H.L. Lu, W.H. Zhang, Y.X. Yang, X.F. Huang, S.Z. Wang, R.L. Qiu, Relative distribution of Pb2+ sorption mechanisms by sludge-derived biochar, Water Research, 46 (2012) 854-862.

[86] J.-C. Yoo, C. Lee, J.-S. Lee, K. Baek, Simultaneous application of chemical oxidation and extraction processes is effective at remediating soil Co-contaminated with petroleum and heavy metals, Journal of Environmental Management, 186 (2017) 314-319.

[87] K.-H. Wei, J. Ma, B.-D. Xi, M.-D. Yu, J. Cui, B.-L. Chen, Y. Li, Q.-B. Gu, X.-S. He, Recent progress on in-situ chemical oxidation for the remediation of petroleum contaminated soil and groundwater, Journal of Hazardous Materials, 432 (2022) 128738.

[88] X. Li, Q. Chen, Y. Zhou, M. Tyrer, Y. Yu, Stabilization of heavy metals in MSWI fly ash using silica fume, Waste Management, 34 (2014) 2494-2504.

[89] Y. Dong, Y. Xiang, J. Lan, H. Hou, Passivation and Stabilization of Heavy Metals in Soil Via Coal Bottom Ash-Based Geopolymer: Macroscopic Anisotropy and Mechanism, Available at SSRN 4157309.

[90] R. Bie, P. Chen, X. Song, X. Ji, Characteristics of municipal solid waste incineration fly ash with cement solidification treatment, Journal of the Energy Institute, 89 (2016) 704-712.

[91] Y. Xue, X. Liu, Detoxification, solidification and recycling of municipal solid waste incineration fly ash: A review, Chemical Engineering Journal, 420 (2021) 130349.

[92] F. Zha, H. Wang, L. Xu, C. Yang, B. Kang, C. Chu, Y. Deng, X. Tan, Initial feasibility study in adsorption capacity and mechanism of soda residue on lead (II)-contaminated soil in solidification/stabilization technology, Environmental Earth Sciences, 79 (2020) 230.

[93] B. Chen, Z. Xiong, Y. Zhao, J. Zhang, Migration pattern and solidification treatment technology of heavy metals in coal gasification slag: A review., Clean Coal Technology, 29 (2023) 173-188.

[94] W.-y. Shi, H.-b. Shao, H. Li, M.-a. Shao, S. Du, Progress in the remediation of hazardous heavy metal-polluted soils by natural zeolite, Journal of Hazardous Materials, 170 (2009) 1-6.

[95] Y. Xiang, Y. Xiang, X. Gao, Humic acid coupled with coal gasification slag for enhancing the remediation of Cd-contaminated soil under alternated light/dark cycle, Environmental science and pollution research international, (2022).

[96] M. Chu, Y. Hao, Y. Liu, J. Xiao, F. Lyu, A method for preparing heavy metal composite adsorbent by coal-based sodium humate/zeolite, in: C.N.I.P. Administration (Ed.), Chinese Patent, 2021.

[97] Y. Jin, Z. Liu, L. Han, Y. Zhang, L. Li, S. Zhu, Z.P.J. Li, D. Wang, Synthesis of coal-analcime composite from coal gangue and its adsorption performance on heavy metal ions, Journal of Hazardous Materials, 423 (2022) 127027.

[98] X. Li, J. Shao, J. Zheng, C. Bai, X. Zhang, Y. Qiao, P. Colombo, Fabrication and application of porous materials made from coal gangue: A review, International Journal of Applied Ceramic Technology, 20 (2023) 2099-2124.

[99] J. ZHANG, F. JU, M. Ll, N. ZHOU, Q. ZHANG, Method of coal gangue separation and coordinated in-situ backfill mining, Journal of China Coal Society, 45 (2020) 131-140.

[100] T. WU, X. FANG, S. NING, Z. WU, F. XU, Study on status quo and development as well as utilization of coal resources “under buildings, water bodies, railways and above confined water” in North China Coalfields, Coal Science and Technology, 49 (2021) 129-135.

[101] L. Yuan, K. YANG, Further discussion on the scientific problems and countermeasures in the utilization of abandoned mines, Journal of China Coal Society, 46 (2021) 16-24.

[102] C. Zhang, F.T. Wang, Q.S. Bai, Underground space utilization of coalmines in China: A review of underground water reservoir construction, Tunnelling and Underground Space Technology, 107 (2021).

[103] Z. HU, L. DUO, X. WANG, Principle and method of reclaiming subsidence land with inter-layers of filling materals, Journal of China Coal Society, 43 (2018) 198-206.

[104] F. Xu, Review of analytical studies on TiO2 nanoparticles and particle aggregation, coagulation, flocculation, sedimentation, stabilization, Chemosphere, 212 (2018) 662-677.

[105] B. Xiong, R.M. Wang, Effect of Environmental Regulation on Industrial Solid Waste Pollution in China: From the Perspective of Formal Environmental Regulation and Informal Environmental Regulation, International Journal of Environmental Research and Public Health, 17 (2020).

[106] Z.H. Xie, China's historical evolution of environmental protection along with the forty years' reform and opening-up, Environmental Science and Ecotechnology, 1 (2020).

[107] W. Pan, X. Wu, T. Zhang, Research of preferential tax policies for backfill coal mining in China, BioTechnology: An Indian Journal, 10 (2014).

[108] Y. Tang, Y. Wang, B. Huan, X. Guo, R.B. Finkelman, Leachability of Hazardous Trace Elements from Entrained-Flow Coal Gasification Residues in Ningdong, China, Energy & Fuels, 31 (2017) 9703-9716.

[109] J. Qu, J. Zhang, H. Li, S. Li, D. Shi, R. Chang, W. Wu, G. Zhu, C. Yang, C. Wang, Occurrence, leaching behavior, and detoxification of heavy metal Cr in coal gasification slag, Chinese Journal of Chemical Engineering, 58 (2023) 11-19.

[110] Z.B. Luo, S.K. Lam, S.Y. Hu, D.L. Chen, From generation to treatment: A systematic reactive nitrogen flow assessment of solid waste in China, Journal of Cleaner Production, 259 (2020).

[111] L. Zhan, L. Jiang, Y.L. Zhang, B. Gao, Z.M. Xu, Reduction, detoxification and recycling of solid waste by hydrothermal technology: A review, Chemical Engineering Journal, 390 (2020).

[112] P. Hai, Z. Jian, Research on protecting the safety of buildings by using backfill mining with solid, Procedia Environmental Sciences, 12 (2012) 191-198.

[113] I.A. Al-Khatib, H.A. Arafat, T. Basheer, H. Shawahneh, A. Salahat, J. Eid, W. Ali, Trends and problems of solid waste management in developing countries: A case study in seven Palestinian districts, Waste Management,

27 (2007) 1910-1919.

[114] A. Smoliński, D. Malashkevych, M. Petlovanyi, K. Rysbekov, V. Lozynskyi, K. Sai, Research into Impact of Leaving Waste Rocks in the Mined-Out Space on the Geomechanical State of the Rock Mass Surrounding the Longwall Face, Energies, 15 (2022) 9522.

[115] D. Malashkevych, M. Petlovanyi, K. Sai, S. Zubko, Research into the coal quality with a new selective mining technology of the waste rock accumulation in the mined-out area, Mining of Mineral Deposits, 16 (2022).

[116] J.-q. Zhang, X. He, K. Yang, Z. Wei, X.-Y. Zhao, J.-j. Fang, Diffusion law of coal gangue slurry and the application of fluidized filling technology of gangue in caving area, Scientific Reports, 13 (2023) 13226.

[117] X. Zhao, K. Yang, X. He, Z. Wei, X. Yu, J. Zhang, Study on Mix Proportion Optimization and Microstructure of Coal-Based Solid Waste (CSW) Backfill Material Based on Multi-Objective Decision-Making Model, Materials, 15 (2022) 8464.

[118] X. Zhao, K. Yang, X. Li, L. Cheng, The Material Mix Proportion of Roadside Backfill Body (RBB) Based on Spatiotemporal Law of Ground Pressure: A Case Study, Energy Exploration & Exploitation, (2023) 01445987231190786.