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Ecological risk assessment of heavy metals in coal gasification slags and their leaching toxicity from China

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ABSTRACT

The coal gasification process produces a large amount of coal gasification slag (CGS), which enriches the heavy metals in the raw coal. The CGS will not only occupies land resources in the long-term storage, but also has potential ecological pollution risks. In this study, eight kinds of CGS samples from different regions of China were subjected, and their chemical composition and environmental risks were studied. Two leaching methods issued by the ministry of ecology and environment of China were used to carry out leaching experiments for evaluating the hazardous waste level of CGS. The results show that, among eight samples, the comprehensive potential ecological risk of all samples did not reach high risk, and there are two kinds of CGCS and two kinds of CGFS reach middle risk. In general, CGS is not hazardous solid wastes, most of which are Class I general industrial solid wastes, and a few are Class II general industrial solid wastes. These conclusions indicate that heavy metals in CGS have certain potential ecological risks. Under different leaching conditions, except for Be, the precipitation amount of heavy metals in CGS is basically within the limited range of relevant standards, but its environmental risks cannot be ignored.

KEYWORDS:

Coal gasification slag, Heavy metals, Potential risk assessment, Leaching toxicity

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Introduction

Coal is China's main energy source and will continue to play an important role in China's achievement of its energy goals. Coal gasification technology is a very typical technical means in the region of clean and efficient utilization of coal. After years of development, China's coal gasification process has formed a large industrial scale, and the gas produced can be widely used in industrial gas, civil gas and other fields (He et al. 2020, Wang et al. 2019, Mingaleeva et al. 2021). Statistics show that in 2020, China's coal resources converted through coal gasification technology will be about 300 million tons, accounting for 6% of the country's total coal consumption (Wang and Song 2021). However, the coal gasification process also produces coal gasification slag (CGS) as a solid waste. CGS is divided into coal gasification coarse slag (CGCS) and coal gasification fine slag (CGFS). CGCS is mainly produced during the atomization and combustion of coal slurry particles in the gasifier. CGFS include the particles obtained from gas-solid separation of crude syngas, as well as the residual solids in the drainage of slag ponds and washing towers (Guo et al. 2021, Liu et al. 2021). Typical gasification process and generation mode of CGCS and CGFS are shown in Fig. 1. With the promotion of coal gasification technology, the amount of CGS is increasing day by day, and it is currently estimated that the output of CGS in China will exceed $5000 \times 10^4$ t/a (Zhang et al. 2019). Landfill is currently the main treatment method for CGS (Yu et al. 2022). However, during the gasification process, a large amount of heavy metals in the raw coal will be enriched in CGS, making it possible to become hazardous waste (Vargas et al. 2017, Hoang et al. 2021). In addition, due to environmental effects such as acid rain and groundwater leaching, heavy metals in CGS may also enter the soil and groundwater during the storage process (Śwagała-Wilczek and Stańczyk 2016).
Fig. 1 Typical gasification process

The potential ecological risk assessment and leaching toxicity identification of heavy metals in China's CGS are of great significance for the reasonable storage and in-depth utilization of it. Previous studies on CGS mainly focus on its particle size distribution, mineral composition and thermochemical transformation (Liu et al. 2022, Hong et al. 2022, Wang et al. 2021, Dong et al. 2022), and there are few related studies on the environmental risk characteristics of CGS. Wang et al. (2021) studied the leaching characteristics of potentially hazardous elements from two kinds of entrained-bed CGS. The results showed that most of the potentially hazardous elements in CGS were in a stable state, posing only a slight risk to the ecosystem. However, in the leaching solution of some samples, the content of As, Se, Mo and other elements exceeds the upper limit of the third-grade groundwater in the Chinese groundwater quality standard, so the potential environmental risks of these elements still need to be considered. He et al. (2014) studied the leaching characteristics, morphological distribution and environmental stability of heavy metals in CGS of fixed-bed gas-exhaust furnace. It was found that Cd and Cr in CGS have high potential harm to the environment, while Zn, Pb and other elements mainly exist in the form of residues, which have less direct harm to the environment. Guo et al. (2022) studied CGFS in Ningdong, China, and analyzed the distribution characteristics and leaching behavior.
of typical heavy metals in CGFS with different particle sizes. The results showed that some heavy metals have a significant particle size dependence in CGFS, and the smaller particle size is easier to enrich more heavy metals. The leaching results showed that Cr, Mn, Ni, Zn, Ba all have different degrees of danger to the environment. The research ideas on the characteristics of heavy metals in solid wastes are relatively complete (Kumar et al. 2012, Li et al. 2020, Yu et al. 2014), but the research on CGS is still scarce, and most studies still have certain limitations in the comprehensiveness of sample selection and evaluation.

In this paper, eight kinds of CGS samples from four regions in China will be studied. Firstly, the basic properties of CGS will be analyzed, with emphasis on its chemical composition. Besides, the digestion experiment and leaching experiment of nine heavy metals (Ba, Be, Cd, Cr, Cu, Ni, Zn, Ag, Pb) in CGS will be carried out. Based on the experiment data, a detailed assessment of the potential ecological risks and leaching toxicity of CGS in China will be established.

Materials and methods

Raw materials and sample preparation

Eight kinds of CGS samples were obtained from coal chemical plants in four regions of China. Samples from the same area come from the same gasifier. In order to distinguish CGCS from CGFS, C and X are used for classification when the samples are named. The locations, names and corresponding gasifier types of samples are shown in Fig. 2. These samples were stored in the natural environment (25 °C) until their weight never change to obtain air-dry basis samples. Then they were respectively packed in polyethylene ziplock bags for preservation. At the same time, in order to meet the needs of experiments, each sample was ground by ball mill until passing a 74 μm sieve, and the ground samples were also separately packaged and retained.
Scanning electron microscopy (SEM) observations were performed on each air-dry basis sample (Fig. 3). It can be observed that the microscopic morphologies of CGCS and CGFS are significantly different. CGCS is mainly composed of irregular large particles and a small amount of smooth spherical particles, while CGFS is mainly composed of many spherical particles, floculent particles and porous matrix. Besides, there are some spherical particles are broken on the surface of CGFS and embedded with tiny particles. Both CGCS and CGFS have pore structure (Yuan et al. 2022), and the pore structure of CGFS is more obvious than that of CGCS.
Characterization method

Various analytical techniques were applied to characterize CGS. The microscopic morphology of CGS was magnified 5000 times by SEM (Fig. 3). The chemical composition of the samples was tested by X-Ray fluorescence spectrometer (XRF, Bruker S8 Tiger), and X-ray diffraction (XRD, Bruker D8 Advance) was used to analyse the mineralogical phases of the samples. For the liquids obtained in the digestion and leaching experiments, heavy metals were detected by Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES). The tested elements and their characteristic spectral lines include: Ba (455.403 nm), Be (313.042 nm), Cd (214.439 nm), Cr (267.716 nm), Cu (327.395 nm), Ni (231.604 nm), Zn (213.857 nm), Ag (328.068 nm), Pb (220.353 nm).

Digestion and leaching experiment

In order to obtain the original heavy metals contents in CGS samples, perchloric acid-hydrofluoric acid digestion method was used to digest the solid original sample (Mullapudi et al. 2019). Weigh 0.1g of sample, add it together with 2 ml of perchloric acid and 4 ml of hydrofluoric acid into a polytetrafluoroethylene digestion tank, and heat it to 250 °C for acid-rushing treatment.
Rinse the residual solids in the container with water, and heat the washing water until smoking, and after the solution is observed to become clear, repeat 2 to 3 times to ensure that the digestion is complete and the acid in the solution has been driven out. After the solution was cooled to room temperature, the digestion solution and washing solution were transferred to a volumetric flask, and deionized water was added to make up the volume to 50 ml to obtain the solution to be tested and stored at 4 °C.

Besides, in order to assess the potential leaching toxicity of heavy metals in various CGS samples to the environment, the leaching of CGS was carried out based on "Sulfuric Acid Nitric Acid Method" (AM) and "Horizontal Oscillation Method" (HM) in the Chinese standard. Both methods can be used to simulate the leaching of solid waste, the difference is that the former is used to simulate acid rain environment, while the latter is used to simulate the leaching of groundwater. Due to the limited quantity of samples, the leaching method used in this study is adjusted from 100 g to 5 g in sample weight (Jin et al. 2014).

The leaching procedure of AM is shown in Fig. 4(a). To obtain the extraction agent, the concentrated sulfuric acid and nitric acid are mixed at a mass ratio of 2:1, and the mixed solution was added to the reagent water. The added amount was controlled so that the pH of the solution was $3.20 \pm 0.05$. Weigh 5 g of the sample in a polyethylene extraction bottle, add the extraction agent according to the liquid-solid ratio of 10:1 (L/kg), close the bottle cap tightly, and place the extraction bottle on the flip oscillator, adjust the speed to $30 \pm 2$ r/min, and shake at room temperature for 18 hours. After the leaching was completed, the solution was collected by a pressure filter and a microporous membrane, and stored it in a refrigerator at 4 °C. The specific method of HM is shown in Fig. 4(b), which is partially different from the AM. The leaching agent was changed to deionized water that meets the international standard. The leaching device was changed to a horizontal reciprocating oscillator, and adjust the oscillation frequency to $110 \pm 10$ times/min and the amplitude to 40 mm. The leaching process was changed to shake at room
temperature for 8 hours, then take out the extraction bottle and let it stand for 16 hours (Mohamad et al. 2021).

(a)

![Diagram of AM leaching procedure]

(b)

![Diagram of HM leaching procedure]

**Fig. 4 Leaching procedure of (a) AM and (b) HM**

**Heavy metals analysis**

The potential ecological risk assessment method of heavy metals proposed by Swedish scientist Hakanson was considered as a good means to evaluate the potential pollution risks of heavy metals in solid wastes (Singovszka et al. 2015, Xie et al. 2020, Zhao et al. 2021). The calculation method is Eq. (1) ~ Eq. (3):

\[
C_f^i = C^i / C_n^i \quad (1)
\]

\[
E_r^i = T_r^i \times C_f^i \quad (2)
\]
\[ RI = \sum E^i \]  

(3)

where \( C^i \) is the pollution parameter of an element defined by the evaluation method. \( C^i \) is the measured value of an element in CGS (mg/kg). \( C_n^i \) is the average background value of the element in Chinese soil (mg/kg). \( E^i \) represents the potential ecological risk index of one element in CGS. \( T^i \) represents the toxicity coefficient corresponding to one element, which reflects the toxicity level of different pollutant elements and the sensitivity of organisms to them, and it is given by the evaluation method. \( RI \) represents the comprehensive potential ecological risk index of CGS. The elements Cd, Cr, Cu, Ni, Pb, and Zn measured in the experiment are included in this evaluation system, and their \( C_n^i \) and \( T^i \) are shown in Table 1. In order to calculate the pollution parameter of the above elements in each sample by Eq. (1), the original experimental results should be converted according to the preparation process of the digestion solution. The mass of each heavy metal in each kilogram of CGS sample should be obtained. The conversion formula is as Eq. (4):

\[ C^i = \frac{c \times V}{m} \]  

(4)

where \( c \) is the concentration of each heavy metal measured in the digestion solution (mg/L). \( V \) is the volume of the digestion solution after constant volume, which is 50 ml in this study. \( m \) is the mass of CGS sample used for experiment, which is 0.1 g in this study.

<table>
<thead>
<tr>
<th>Heavy metals</th>
<th>Cd</th>
<th>Cr</th>
<th>Cu</th>
<th>Ni</th>
<th>Pb</th>
<th>Zn</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_n^i /\text{mg·kg}^{-1} )</td>
<td>0.081</td>
<td>66.8</td>
<td>25.5</td>
<td>33.8</td>
<td>21.9</td>
<td>69.6</td>
</tr>
<tr>
<td>( T^i )</td>
<td>30</td>
<td>2</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>1</td>
</tr>
</tbody>
</table>

The potential risk level of one element can be divided into five levels according to the criteria given by Hakanson: <40, 40~80, 80~160, 160~320 and >320 that mean low risk (LR) medium
risk (MR), high risk (HR), serious risk (SR) and very serious risk (VSR) respectively. Since the selected heavy metals in this study are less than the total number of Hakanson risk assessment factors, the $RI$ standard should be revised according to previous research experience (Ma and Wang 2003), and it is divided into four levels: $<53$, $53~106$, $106~212$ and $>212$ that mean low risk LR, MR, HR, and SR respectively.

Besides, in order to evaluate the leaching toxicity of CGS and its existing environmental risks, the Chinese standard "Hazardous Waste Identification Standard Leaching Toxicity Identification" and "Sewage Comprehensive Discharge Standard" are used as the evaluation criteria, and the concentration of each heavy metal in the leaching solution of AM and HM are compared respectively. The hazardous waste level of CGS is judged according to whether there are elements exceeding corresponding standard.

**Result and discussion**

**Basic characteristics**

The ground particles of each raw material were taken for XRF test, and the results are shown in Table 2. It demonstrated that, CGS is mainly composed of $SiO_2$, $Al_2O_3$ and $Fe_2O_3$, indicating that it still has a certain pozzolanic activity as an aluminosilicate solid waste (Fu et al. 2022). In addition, since it is necessary to add alkali metals or alkaline earth metals oxidation as flux during gasification process, CGS also contains a certain amount of $CaO$, $MgO$, $K_2O$ and $Na_2O$. Comparing the element content in CGCS and CGFS, it can be found that the content of alkali metal oxide ($K_2O$, $Na_2O$, etc.) in CGCS is lower than that of CGFS, while the content of alkaline earth metal oxide ($CaO$, $MgO$, etc.) is greater than that of CGFS. This is because that, during the gasification process, the alkali metals with poor stability are more likely to enter the gas phase, and eventually form CGFS by gas-solid separation, while the alkaline earth metals can form non-volatile substances that remain in the solid particles and eventually form CGCS (Qiu 2021).
Table 2 Chemical compositions (wt.%) of CGS by XRF

<table>
<thead>
<tr>
<th>Indicators</th>
<th>SiO$_2$</th>
<th>Al$_2$O$_3$</th>
<th>CaO</th>
<th>Fe$_2$O$_3$</th>
<th>K$_2$O</th>
<th>BaO</th>
<th>Na$_2$O</th>
<th>MgO</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>NMG-C</td>
<td>44.2</td>
<td>16.9</td>
<td>14.2</td>
<td>11.9</td>
<td>3.07</td>
<td>0.91</td>
<td>2.10</td>
<td>1.26</td>
<td>5.46</td>
</tr>
<tr>
<td>YL-C</td>
<td>29.7</td>
<td>15.2</td>
<td>13.1</td>
<td>23.5</td>
<td>1.89</td>
<td>0.63</td>
<td>2.29</td>
<td>0.80</td>
<td>12.89</td>
</tr>
<tr>
<td>XJ-C</td>
<td>24.3</td>
<td>11.5</td>
<td>25.8</td>
<td>25.9</td>
<td>0.90</td>
<td>0.64</td>
<td>3.84</td>
<td>3.97</td>
<td>3.15</td>
</tr>
<tr>
<td>NX-C</td>
<td>28.1</td>
<td>17.4</td>
<td>18.7</td>
<td>16.3</td>
<td>0.42</td>
<td>0.57</td>
<td>4.24</td>
<td>2.89</td>
<td>11.38</td>
</tr>
<tr>
<td>NMG-X</td>
<td>50.8</td>
<td>17.4</td>
<td>9.96</td>
<td>9.73</td>
<td>3.92</td>
<td>0.72</td>
<td>2.15</td>
<td>1.17</td>
<td>4.16</td>
</tr>
<tr>
<td>YL-X</td>
<td>33.0</td>
<td>17.0</td>
<td>13.0</td>
<td>20.8</td>
<td>2.58</td>
<td>1.22</td>
<td>2.62</td>
<td>1.18</td>
<td>8.60</td>
</tr>
<tr>
<td>XJ-X</td>
<td>31.6</td>
<td>16.8</td>
<td>14.5</td>
<td>19.9</td>
<td>1.85</td>
<td>0.53</td>
<td>4.58</td>
<td>3.69</td>
<td>6.55</td>
</tr>
<tr>
<td>NX-X</td>
<td>32.4</td>
<td>21.0</td>
<td>14.9</td>
<td>14.0</td>
<td>0.93</td>
<td>0.46</td>
<td>5.15</td>
<td>3.14</td>
<td>8.02</td>
</tr>
</tbody>
</table>

The mineralogical composition of various CGS samples are shown in Fig. 5. CGCS, shown in Fig. 5(a), mainly consists of SiO$_2$, CaMgSi$_2$O$_6$ and Fe$_2$O$_3$, and some samples also contain CaSO$_4$, CaO and other substances. CGFS, shown in Fig. 5(b), generally has diffraction peaks of SiO$_2$ and Fe$_2$O$_3$, and some samples contain Ca$_2$Al$_2$SiO$_7$, Ca(OH)$_2$ and other substances. The results of XRD and XRF confirm each other.

Fig. 5 XRD pattern of (a) CGCS and (b) CGFS

**Potential ecological risk assessment**

The content of heavy metals in each CGS sample digestion solution were obtained by ICP-OES test, and the original results were converted according to Eq. (4) to obtain the content of each heavy metal in each kilogram of CGS sample. The results are shown in Table 3.
Table 3 The contents of heavy metals in CGS

<table>
<thead>
<tr>
<th>Indicators</th>
<th>Heavy metals (mg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ba</td>
</tr>
<tr>
<td>NMG-C</td>
<td>6846.0</td>
</tr>
<tr>
<td>YL-C</td>
<td>5645.5</td>
</tr>
<tr>
<td>XJ-C</td>
<td>3751.4</td>
</tr>
<tr>
<td>NX-C</td>
<td>6272.0</td>
</tr>
<tr>
<td>NMG-X</td>
<td>5408.0</td>
</tr>
<tr>
<td>YL-X</td>
<td>8449.0</td>
</tr>
<tr>
<td>XJ-X</td>
<td>3884.0</td>
</tr>
<tr>
<td>NX-X</td>
<td>3206.5</td>
</tr>
</tbody>
</table>

Note: "-" indicates that this heavy metal is not detected in the digestion solution.

Comparing the content of each heavy metal in the same CGS sample, it can be found that the content of Be, Cd and Ag in CGS is basically low. This is because heavy metals such as Be and Cd has strong volatility and is easier to enter into the crude gas during the gasification process. Therefore, they are difficult to enrich in CGS. On the contrary, heavy metals such as Cu and Cr are difficult to volatilize, so they are more likely to occur in the solid particles (Xuan et al. 2022). In addition, the XRF analysis (Table 2) of CGS showed that, compared with other heavy metals, the content of Ba in CGS is higher, which is consistent with the results of digestion experiment. By comparing the content of each heavy metal in CGCS and CGFS, it is found that the content of Cu and Zn in CGFS is higher than that in CGCS. By refering to previous researches (Fan 2014, Zhang 2017), it is believed that Cu is more likely to be enriched in small particles, so its content is higher in CGFS. In addition, during the process of discharging of the crude gas, Zn is oxidized to ZnO, which is not easily volatile, and adheres to CGFS in the external low-temperature oxidizing atmosphere. By comparing HT-L CGS (NMG) and Texaco CGS (YL, XJ, NX), it is found that there is a significant difference in the content of Cr between them. The content of Cr in CGS of HT-L is lower than that of Texaco. Combined with the characteristics of the two gasification processes, it is believed that the difference of gasifier wall materials is the cause. Water wall is usually used in HT-L gasifier, while firebrick is used in Texaco gasifier. During the formation of CGS, complex reactions occurring at high...
temperature have erosion effect on the gasifier wall, and there is a certain amount of Cr in firebrick. Therefore, the Texaco gasifier using firebrick will enrich more Cr in CGS.

Cd, Cr, Cu, Ni, Pb and Zn are included in the Hakanson risk assessment system. Take the data in Table 4 into Eq. (1)~(2) to calculate their $RI$ in CGS. The results are shown in Table 4. Cd, Cr, Ni and Zn show LR in all samples, while Cu and Pb show MR or HR in some samples. The mean value of $E_i^\tau$ of CGCS and CGFS are calculated and shown in Table 4. The potential ecological risks of each heavy metal in CGCS are ranked as Cu>Pb>Ni>Cr>Zn>Cd in descending order, while the order of CGFS is Cu>Ni>Zn>Cr>Pb>Cd. Calculating the $RI$ of each sample by Eq. (3), and comparing them with the risk level interval. The results are shown in Fig. 6. The comprehensive potential ecological risk of all samples did not reach HR, and there are two kinds of CGCS and two kinds of CGFS reach MR. By comparing the $RI$ of CGCS and CGFS from the same region, it was found that among the four groups of samples, CGFS of three groups of samples (NMG, YL, NX) have more potential ecological risks than CGCS. This is precisely because Cu and Zn are more easily enriched in CGFS. On the other hand, the $RI$ of XJ-C is higher than that of XJ-X, which is found to be caused by massive Pb enrichment in combination with Table 4. In summary, CGFS has more potential ecological risks than CGCS, but CGCS is also easy to accumulate non-volatile heavy metals, so the risk should not be ignored.

<table>
<thead>
<tr>
<th>Indicators</th>
<th>$E_i^\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cd</td>
</tr>
<tr>
<td>NMG-C</td>
<td>-</td>
</tr>
<tr>
<td>YL-C</td>
<td>-</td>
</tr>
<tr>
<td>XJ-C</td>
<td>-</td>
</tr>
<tr>
<td>NX-C</td>
<td>-</td>
</tr>
<tr>
<td>NMG-X</td>
<td>-</td>
</tr>
<tr>
<td>YL-X</td>
<td>-</td>
</tr>
<tr>
<td>XJ-X</td>
<td>-</td>
</tr>
<tr>
<td>CGCS</td>
<td>4.31</td>
</tr>
<tr>
<td>CGFS</td>
<td>3.12</td>
</tr>
</tbody>
</table>

Note: "-" indicates that this heavy metal is not detected in the digestion solution.
**Leaching toxicity of heavy metals in CGS**

The leaching contents of heavy metals in CGS under different methods are shown in Fig. 7. There are differences in the test results of the two different leaching methods. By AM, the content of Cu in the leaching solution of each sample is generally not high, while it can be obviously detected by HM. On the contrary, Ag and Pb are generally detected by AM, but are relatively rare by HM. Ba, Cr, and Ni can be significantly detected in the leaching solution of the two leaching methods, while the contents of Be and Cd are low in the two leaching solutions and can only be detected in a few samples. This result indicates that CGS has different leaching characteristics under different leaching conditions, but there are also heavy metals such as Ba, Cr and Ni, which are easily leached under different conditions. In addition, the content distribution of each heavy metal in the leaching solution of CGCS and CGFS was summarized and compared. It was found that the content of Ag and Ba in the leaching solution of CGCS was higher than that of CGFS, while the content of Zn in the leaching solution of CGFS was higher than that of CGCS. This result can be explained in combination with the results of digestion experiments. The original content of Ag and Ba in CGCS are higher than that of CGFS, while Zn is more likely to occur in CGFS. Therefore, the same distribution law is also
presented in the leaching experiment. In general, the content of heavy metals in the leaching solution of CGCS is lower than that of CGFS. It is believed that most of heavy metals in CGCS are solidified in the gasifier, so they are not easy to precipitate during the leaching process.
Fig. 7 Leaching contents of heavy metals in CGS

In order to qualitatively evaluate the leaching toxicity of CGS, the contents of heavy metals in the leaching solution are compared with the relevant standards. The limit of each heavy metal content in the two standards is shown in Table 5. Since Be was not detected in the leaching solution of AM in all samples, it is obviously up to the standard. In addition, there is no limit value for Ba in the comprehensive sewage discharge standard, so it will not be shown in Table 5. Compare experimental data with the limit value, it can conclude that the content of each heavy metal in the solution of AM does not exceed the limit value, so it is considered that CGS does not belong to hazardous solid waste. On the other hand, for NMG-C and XJ-C, the content of Be in the solution of HM exceeds the limit value, so they belong to Class II general industrial solid waste. The rest of the samples do not contain heavy metals exceeding the standard and could be considered as Class I general industrial solid waste. The results indicate that although
most heavy metals in CGCS are solidified during gasification, there is still a pollution risk in the specific leaching environment due to its easy enrichment of non-volatile elements.

Table 5 The limit value of heavy metals in standards

<table>
<thead>
<tr>
<th>Heavy metals</th>
<th>Ba</th>
<th>Be</th>
<th>Cd</th>
<th>Cr</th>
<th>Cu</th>
<th>Ni</th>
<th>Pb</th>
<th>Zn</th>
<th>Ag</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM Standard</td>
<td>100</td>
<td>-</td>
<td>1</td>
<td>15</td>
<td>100</td>
<td>5</td>
<td>5</td>
<td>100</td>
<td>5</td>
</tr>
<tr>
<td>(mg/L)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>HM Standard</td>
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Conclusions

The above analysis demonstrates a detailed assessment of the potential ecological risks and leaching toxicity of CGS in China. The main conclusions are as following. CGS is mainly composed of SiO$_2$, Al$_2$O$_3$, and Fe$_2$O$_3$, and also contains a certain amount of alkaline earth metal and alkali metal. The results of XRF and XRD show that CGS contains abundant elements and has a certain activity. Through digestion experiments, it was found that the contents of Be and Pb in CGS are lower, while the contents of Cr and Cu are generally higher. The difference of CGS type and gasifier type all have influence on the content of heavy metals in CGS. The comprehensive potential ecological risk of all samples did not reach HR, and there are two kinds of CGCS and two kinds of CGFS reach MR. Through the leaching toxicity experiment, it was found that CGS has different leaching toxicity under different conditions. Overall, the content of heavy metals in the leaching solution of CGCS was lower than that of CGFS, probably due to heavy metals were solidified during the melting process. It was concluded that CGS is not hazardous solid waste. Most of samples in this study are Class I general industrial solid wastes, and a few are Class II general industrial solid wastes. Under different leaching conditions, except for Be, the precipitation amount of heavy metals in CGS is basically within the limited range of relevant standards, but its environmental risks cannot be ignored.
Acknowledgments

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