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Pollution emission and heavy metal speciation from co-combustion of sedum plumbizincicola and sludge in fluidized bed

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ABSTRACT

The co-combustion of *sedum plumbizincicola* and sludge is becoming increasingly popular due to its environmental and economic benefits. Here, combustion experiments are performed in a large-scale fluidized bed at different temperatures. Results show that in flue gas, CO and NO_x exceed the emission standard and should be controlled by denitrification system before discharge. Three-ring polycyclic aromatic hydrocarbons (PAHs) are found to be the major organic pollutants, but no six-ring PAH is detected in the combustion process. The emission concentrations of Cd, Zn, and Pb are below the standard. With increased temperature from 700 °C to 1000 °C, the concentrations of total PAHs, NO_x, and Zn increase. The proportion of residual fraction in Cd for bottom ash increases from 16.82% to 44.03%. The proportion of exchangeable and carbonate-associated fractions in fly ash increases from 15.18% to 19.78%. The dominant phase in Zn and Pb is the residual fraction. With increased temperature, the leaching rates of Cd, Zn and Pb increase with different extents. Leaching rates in fly ash are less than those in bottom ash (except for Cd at 900 and 1000 °C). Cd and Zn show medium risk to environment in fly ash and bottom ash. Pb presents no risk to the ecosystem in fly ash and low risk in bottom ash. The co-combustion is suitable for the disposal of *S. plumbizincicola* and sludge in China.

1. Introduction

Phytoremediation is a green technology that utilizes the bioremediation of plants to remediate contaminated soil and water (Witters et al., 2012). Plants with this natural ability are called hyperaccumulators, among which *Sedum plumbizincicola* is one of the most widely used. Toxic heavy metals can be absorbed, accumulated and metabolized by *S. plumbizincicola*, which grow quickly in natural conditions (Arnamwong et al., 2015). With the growing popularity of phytoremediation technology, the production of *S. plumbizincicola* is also getting higher and higher. Therefore, the disposal of polluted *S. plumbizincicola* has become a hotspot.

At present, the treatment of contaminated plants contains composting, compaction, pyrolysis and combustion (Kovacs and Szemmelveisz, 2017). Combustion of heavy-metal-contaminated plants is a promising but not yet fully developed technology, which can achieve more than 90% volume reduction. As a treatment method option, combustion needs careful consideration because it not only results in SO_2, NO_x, and CO but also produces solid and gaseous metal compounds (Feng et al., 2015; Ren et al., 2017). Some studies on the combustion of *S. plumbizincicola* are available. However, most of them are carried out in the tube furnace, and a distance from the engineering application still remains. The incineration experiments with *S. plumbizincicola* in the tube furnace found that Cd, CO, NO_x and PAHs in flue gas can be removed effectively by kaolin and activated carbon (Wu et al., 2013). Thus incineration is a suitable way for the disposal of *S. plumbizincicola*. In accordance with the combustion of *S. plumbizincicola* by Zhong et al. in a tube furnace, the recovery rate of heavy metals in bottom ash decreased with increased temperature, while the recovery rate in fly ash increased (Zhong et al., 2015). By comparing trace metal emissions from hyperaccumulators in the tube furnace, Lu et al. demonstrated that combustion can promote the volatilization. The percentages of heavy metals in ash after incineration were lower than those after pyrolysis, especially for Cd, Pb and Zn (Lu et al., 2012). During the co-combustion of *S. plumbizincicola* and coal in the tube furnace, Guo et al. supposed that the high temperature was beneficial to the volatilization of heavy metals and that co-

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combustion was suitable for the disposal of waste (Guo et al., 2017).

Sewage sludge is the main waste produced in the process of wastewater treatment, and the continuous increase in sludge production is another urgent problem that we are now facing (Li et al., 2017). Many studied have proven that combustion or co-combustion is an effective method for sludge treatment in fluidized bed, which is a widely used combustion device (Guo and Zhong, 2017; Khiari et al., 2008; Leckner et al., 2004). During the combustion of sludge in fluidized bed, Shao et al. investigated the partitioning of heavy metals and PAHs emission. They (Shao et al., 2008) found that Co and Cu were mainly in the bottom ash, while Pb and Zn were in fly ash. The emission of PAHs was mainly in flue gas, and the total amount of emissions was related to the H/C ratio of sludge samples. Jiang et al. investigated the volatilization of heavy metals and demonstrated that it increased with increased temperature as the order of Zn > Cd > Cu > Mn > Pb > Cr (Jiang et al., 2010). During the combustion of coal with sludge, the emissions of NO_x and SO_2 reduced with increased sludge percentage, whereas the concentrations of heavy metals in fly and bottom ash increased (Jin et al., 2016). Olek conducted the combustion of sewage sludge and wood chips. Heavy metals were concentrated in ash and dust, whereas PAHs were concentrated in flue gases. With increased wood chips, the nitrogen content decreased (Olek, 2006).

Moreover, for the evaluation of the quality of the ash after combustion, toxicity characteristic leaching procedures (TCLP) and risk assessment code (RAC) of heavy metals have been widely used to evaluate the potential effects of waste disposal to the environment (Pan et al., 2013; Sano et al., 2013; Yuan et al., 2015). Xiao et al. conducted Community Bureau of Reference (BCR) sequential extraction and TCLP experiments. Results showed that heavy metals were mostly transformed into stable fractions and that the toxicity of heavy metals was greatly reduced after sludge combustion (Xiao et al., 2015). On the basis of RAC, Xiao et al. confirmed that the environmental risk of heavy metals in ash was decreased in comparison with raw sewage sludge. No risk to the environment was found after combustion besides As (Xiao et al., 2016). In Zhai et al.'s research, RAC assessment indicated that heavy metals at 350 °C pose lower risk than those at 400 °C (Zhai et al., 2016).

To the best of our knowledge, no study is available on the co-combustion of *S. plumbizincicola* and sludge in fluidized bed. In this study, we are assessing this co-combustion and exploring the feasibility in accordance with Chinese national standards. To understand the discharge of pollutants and potential ecological hazards, measuring the gaseous emissions and heavy-metal speciation is very important. This study aims (1) to analyze the gaseous emissions in flue gas and (2) to evaluate the potential risks of heavy metals by TCLP and RAC.

2. Experiment and method

2.1. Material

S. plumbizincicola is from a mine in Hangzhou, and it can effectively adsorb the heavy metals in soil. Sludge comes from a sewage treatment plant in Nanjing. Both *S. plumbizincicola* and sludge are dried for 18 h at 105 °C before being ground into powder (<5 mm) for combustion. Proximate and ultimate analyses of raw materials are given in Table 1. The volatile and fixed carbon of *S. plumbizincicola* is higher than that of sludge, while the ash content is lower. Trace element contents of raw materials illustrate that the heavy-metal concentrations of Zn, Cd, and Pb in plants are much higher than those in sludge. Therefore, they are selected as targeted heavy metals to discuss during the co-combustion process. Moreover, the concentrations of Al and Si in sludge are distinctly higher than those in *S. plumbizincicola*. In accordance with correlative reference (Liu et al., 2015), Oxides of Si and Al have excellent absorbability to capture heavy metals. The sludge selected in this study contains a large amount of Si and Al. Table S1 in the Supplementary Materials presents that the main composition of combustion ash is SiO_2 and Al_2O_3. Therefore, heavy metals can be well controlled by SiO_2 and Al_2O_3, which reflects the significance and necessity of this study on co-combustion. When the mixture ratio is over 30% (sludge content, w/w), it is not conducive to combustion because of the low calorific value (Kijo-Kleczkowska et al., 2016). However, if blending proportion is relatively small, the comprehensive utilization of *S. plumbizincicola* and sludge cannot be well realized. Hence, the maximum blending ratio of 30% is selected for combustion experiments and evaluation in our study.

Table 1
Properties of *S. plumbizincicola* and sludge.

Ultimate analysis (*wt* %, air dry basis)	*S. plumbizincicola*	sludge
C	38.8	28.2
H	5.5	6.5
O	30.4	15.48
N	1.5	3.3
S	0.1	0.2
Calorific value (J/g)	14,488	10,587
Proximate analysis (*wt* %, air dry basis)		
Ash	10.42	39.17
Moisture content	13.28	7.15
Volatile matter	61.61	41.10
Fixed carbon	14.69	12.58
Trace metal analysis (mg/kg)		
Zn	4810	702
Cd	387	6
Pb	101	50
Al	881	45,459
Si	850	36,209
Ca	36,229	34,007

2.2. Experimental apparatus

Fig. 1 presents the sketch map of a large-scale fluidized bed. The fluidized bed contains a fluidized bed reactor, heating system, gas supply device, and dust collector. The fluidized bed reactor is 4.5 m

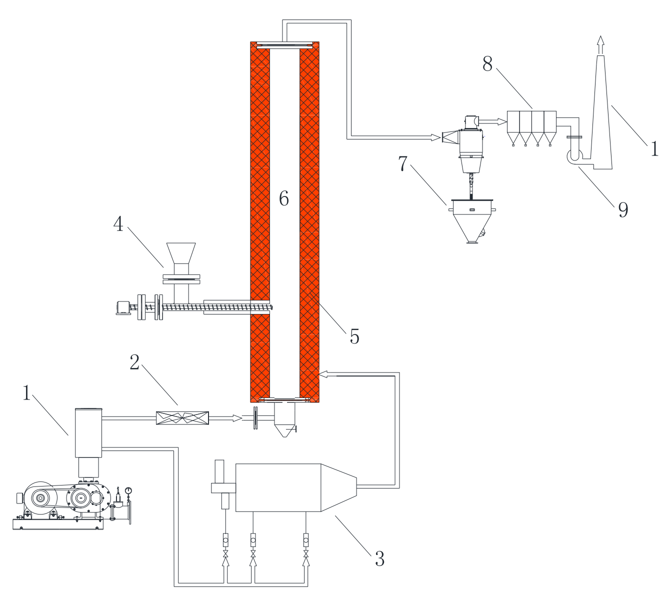

Fig. 1. Schematic diagram of the fluidized bed device. 1-air fan; 2-heat exchanger; 3-diesel combustion chamber; 4-hopper; 5- heating jacket; 6-fluidized bed reactor; 7-cyclone; 8-bag filter; 9-induced draft fan; 10-chimney.