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Assessing the Metal Recovery Value of Municipal Solid Waste Incineration Residues: Impact of Pretreatment on Fly Ash and Bottom Ash

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Abstract

This paper focuses on evaluating the metal recovery potential of Municipal Solid Waste Incineration (MSWI) residues, with particular emphasis on the influence of pretreatment methods on MSWI fly ash and bottom ash. We assess the effectiveness of these pretreatments in enhancing the concentration of valuable metals and compare the metal content before and after treatment. Our findings reveal that water washing significantly enhances fly ash's zinc and copper content, surpassing the minimum industrial-grade requirements. Mechanical sieving is an efficient pretreatment method for bottom ash, with the zinc concentration inversely related to particle size. Additionally, copper content peaks in the 1 - 2 mm particle size range for both bottom ash samples. These results provide valuable insights into the potential for metal recovery from MSWI residues. They hold significance for relevant research, engineering practices, and policy formulation.

Keywords

Water-Washing, Mechanical Sieving, Zinc, Copper, Lead

1. Introduction

The municipal solid waste disposal incineration method is widely employed in Japan and other countries. The advantages of incineration are evident as it effectively reduces the mass and volume of waste while also recovering energy (Hjelmar, 1996). However, this method is accompanied by a significant drawback. During the incineration process, two residues are generated: fly ash and bottom ash.

MSWI fly ash is typically considered hazardous waste and requires special treatment before being safely disposed of in landfills (Lin et al., 2022; Zhang et al., 2021). In contrast, bottom ash can be directly sent to municipal waste landfills. These residues also contain valuable metal resources such as zinc, copper, lead, antimony, and potassium (Tang et al., 2018, 2019, 2022; Tang & Steenari, 2016). However, traditional landfilling methods cannot achieve the recovery of these resources. Consequently, the recovery of these metal resources has become a crucial topic in waste incineration, with relevant engineering practices in various countries. For instance, Switzerland employs an acid-leaching method to recover zinc from 60% of its fly ash, while China utilizes a water-washing method to retrieve potassium chloride and sodium chloride (Weibel et al., 2018).

However, despite the considerable potential for metal resource recovery from MSWI residues, the metal content in both fly ash and bottom ash often falls significantly below the minimum industrial grade thresholds and, in some cases, even below the cut-off grades, which hinders their direct economic viability for recovery (Tang et al., 2018, 2019, 2022; Tang & Steenari, 2016; Asad, Qureshi, & Jang, 2016; Thompson & Barr, 2014; Hagni, Hagni, & Demars, 1991). It's crucial to note that materials meeting or exceeding the cut-off grade for metal content are typically classified as ores. In the current economic context, such materials cover the costs associated with mining, processing, and refining and yield a profit (Asad, Qureshi, & Jang, 2016; Thompson & Barr, 2014).

Furthermore, the minimum industrial grade of ore denotes the minimum concentration or quality of valuable minerals or elements within the ore, making it economically feasible for industrial extraction and subsequent processing (Hagni, Hagni, & Demars, 1991). A notable advantage of utilizing MSWI residues over traditional ores is eliminating mining operations and the need for long-distance transportation. This aspect enhances the overall environmental sustainability and cost-effectiveness of metal recovery efforts from these waste streams.

Thus, proper pretreatment is necessary to enrich the metal content in fly ash and bottom ash before efficient metal recovery can be achieved. In the case of fly ash, due to its high soluble salt content, using a water washing method is essential for chloride salt recovery and aids in enriching the valuable metals present (Wang et al., 2001). Additionally, it has been observed that the heavy metal content in bottom ash is closely related to its particle size (Chimenos et al., 1999). In this case, mechanical sieving was used as a pretreatment method for bottom ash.

The primary objective of this paper is to delve into the crucial issue of metal resource recovery from incinerated waste, with a specific focus on the pretreatment methods for fly ash and bottom ash. Through comprehensive research and experimentation, we will evaluate the effectiveness of these pretreatment methods in enriching valuable metals in fly ash and bottom ash and compare the recovery value of the waste before and after treatment. We believe this study will contribute to addressing the environmental and resource challenges in waste incineration management and provide valuable insights and guidance for relevant industries and policy formulation.

2. Materials and Methods

2.1. Materials

The MSWI fly ash samples (referred to as fly ash A and fly ash B), and MSWI bottom ash samples (referred to as bottom ash A and bottom ash B) from two stoker grate incineration facilities in Japan were utilized in this study. These samples were collected using established protocols. Subsequently, the fly ash samples were meticulously preserved in hermetically sealed containers against contamination before analysis.

2.2. Water-Washing Experiment

A plastic bottle with a volume of 250 mL was used for the experiment. Initially, 30 grams of fly ash were placed inside the bottle, and this was followed by the addition of 180 mL of deionized water. To facilitate mixing, a magnetic stir bar was introduced into the bottle, and the mixture was stirred for a duration of 10 minutes at a speed of 200 rpm. After this stirring period, the sample was subjected to centrifugation at 3000 rpm for 20 minutes. This washing procedure was repeated once for thorough purification. Subsequently, the solid phase obtained from the centrifugation was carefully dried at 105˚C for a period of 12 hours before undergoing further measurements and analysis.

2.3. Mechanical Sieving Experiment

A specific quantity of bottom ash, approximately 1000 grams, was placed in a tray and dried at 105˚C for 24 hours. After drying, the bottom ash was subjected to sieving using screens with apertures of 2 mm, 1 mm, 0.5 mm, and 0.25 mm. Following the sieving process, the mass of bottom ash at each particle size was measured to calculate its mass distribution.

2.4. Sample Characterization

The elemental composition of both samples was determined using Energy Dispersive X-ray Fluorescence Analysis (ED-XRF), employing a Spectro Xepos spectrometer with matrix-adjusted calibration. The measurements were conducted on pressed powder pellets with a diameter of 32 mm.

3. Results and Discussion

3.1. Characterization of the Fly Ash Samples

3.1.1. Characteristics of the Raw Fly Ash Samples

In Table 1, it is shown that the content of Cl, Na, and K in fly ash decreases significantly after washing. As indicated in Table 2, the fly ash samples A and B exhibit distinct elemental compositions. Specifically, fly ash A contains 1.58%

Table 1. The chemical composition of fly ash samples.

Element	Concentration (mg/kg)			
	Fly ash A	Fly ash B	Washed ash A	Washed ash B
Ca	283,010	179,470	452,757	370,477
Cl	246,880	252,420	16,417	14,187
Si	47,910	38,280	248,967	172,450
Na	47,480	93,570	16,083	32,960
K	20,080	52,760	5320	5190
S	18,530	21,630	23,503	17,837
Zn	15,807	50,888	36,124	77,479
Mg	14,620	17,350	21,640	28,607
Al	9720	19,120	51,963	92,913
Fe	5360	7630	17,437	18,583
Cu	3601	3962	7185	6049
Pb	3575	11,136	3385	16,128
Ti	2750	6750	11343	22,183
P	2600	6260	15637	29,280
Sb	1750	9461	4939	14,482
Ba	461	1126	582	2690
F	370	570	913	1757
Cd	286	443	536	545
Mn	160	530	540	1230
Cr	158	251	326	421
Sr	153	283	245	366
Ni	70	61	147	88
As	24	74	23	107

Zn, 0.36% Cu, 0.36% Pb, 0.18% Sb, and 2.00% K. In contrast, fly ash B demonstrates significantly higher levels of Zn at 5.09%, with 0.40% Cu, 1.11% Pb, and 5.28% K.

By Chinese geological and mineral industry standards, the Zn content in fly ash A falls within the prescribed cut-off grade range of 1.5% - 2.0%, while the Zn content in fly ash B comfortably exceeds the minimum industrial grade range of 3.0% - 6.0% (DZ/T 0214-2020). Additionally, the Pb content in fly ash B meets the specified cut-off grade range of 0.5% - 1.0%, and the Sb content in fly ash B also conforms to the prescribed cut-off grade range of 0.5% - 0.7% (DZ/T 0214-2020; DZ/T 0201-2020). It is worth noting that the Cu contents in both fly ash samples closely approach the cut-off grade of 0.5% (DZ/T 0214-2020).

Table 2. The concentration of valuable metals in fly ash samples.

Sample	The concentration of valuable metals (wt%)				
	Zn	Cu	Pb	Sb	K
Fly ash A	1.58	0.36	0.36	0.18	2.01
Fly ash B	5.09	0.40	1.11	0.95	5.28
Washed ash A	3.61	0.72	0.34	0.49	0.53
Washed ash B	7.75	0.60	1.61	1.45	0.52
Cut-off grade	1.5 - 2.0[a]	0.5[a]	0.5 - 1.0[a]	0.5 - 0.7[b]	0.5[c]
Minimum industrial grade	3.0 - 6.0[a]	0.7[a]	1.5 - 2.0[a]	1.0 - 1.5[b]	2.0[c]

a: DZ/T 0214-2020: Specifications for copper, lead, zinc, silver, nickel, and molybdenum mineral exploration. b: DZ/T 0201-2020: Specifications for tungsten, tin, mercury, and antimony mineral exploration. c: DZ/T 0212.2-2020: Specifications for salt mineral exploration—Part 2: Present saline lake mineral.

Furthermore, the K contents in both fly ash samples surpass the minimum industrial grade threshold of 2% (DZ/T 0212.2-2020).

3.1.2. Characteristics of the Raw Fly Ash Samples

The mass of washed fly ash A and B constitutes 37.87% and 48.47% of the raw fly ash, as indicated in **Table 2**. The pH of the leachate for fly ash A is about 11.8, and for fly ash B, it is about 10.3. After water-washing, the concentration of zinc in washed fly ash A and washed fly ash B reached 3.61% and 7.75%, respectively, meeting the minimum industrial-grade requirements. In the case of copper, the content increased to 0.72% in washed fly ash A and 0.60% in washed fly ash B. The copper content in washed fly ash A exceeded the minimum industrial grade, while in washed fly ash B, it reached the cutoff grade. Comparatively, there was no significant change in Pb content in washed fly ash A compared to the original ash. This could be attributed to its higher pH value, as under high pH conditions, Pb forms complex ions and dissolves in the leachate (Zhang, Jiang, & Chen 2008). In contrast, washed fly ash B showed an increased Pb concentration, reaching 1.61%, meeting the minimum industrial grade. After water washing, both washed fly ash samples exhibited increased Sb content. In washed fly ash A, the Sb content approached the cutoff grade, while in washed fly ash B, it reached the minimum industrial grade.

3.2. Relationship between Particle Size and Heavy Metal Concentrations in Bottom Ash

Figure 1 depicts the mass distribution of two bottom ash samples as it varies with particle size. As shown in **Figure 2**, the zinc concentration in both bottom ash samples increases as the particle size decreases. However, in bottom ash A, the zinc content does not reach the cutoff grade. In bottom ash B, the portion with a particle size less than 0.25 mm has a zinc concentration that meets the cutoff grade (DZ/T 0214-2020).

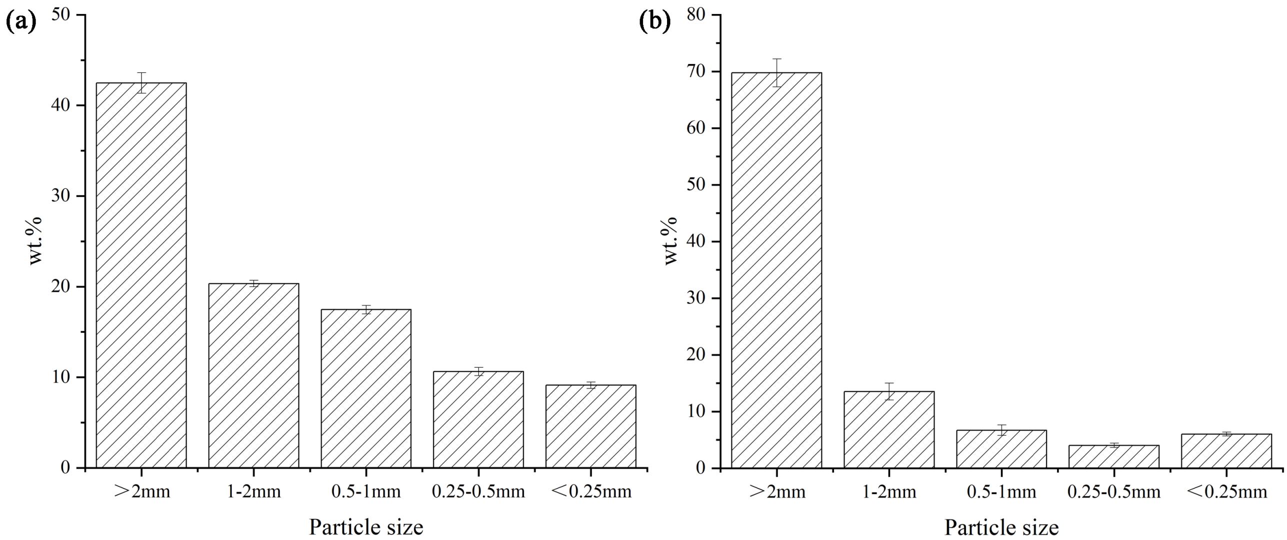

Figure 1. The distribution of bottom ash mass with particle size after sieving: (a) Bottom ash A; (b) Bottom ash B.

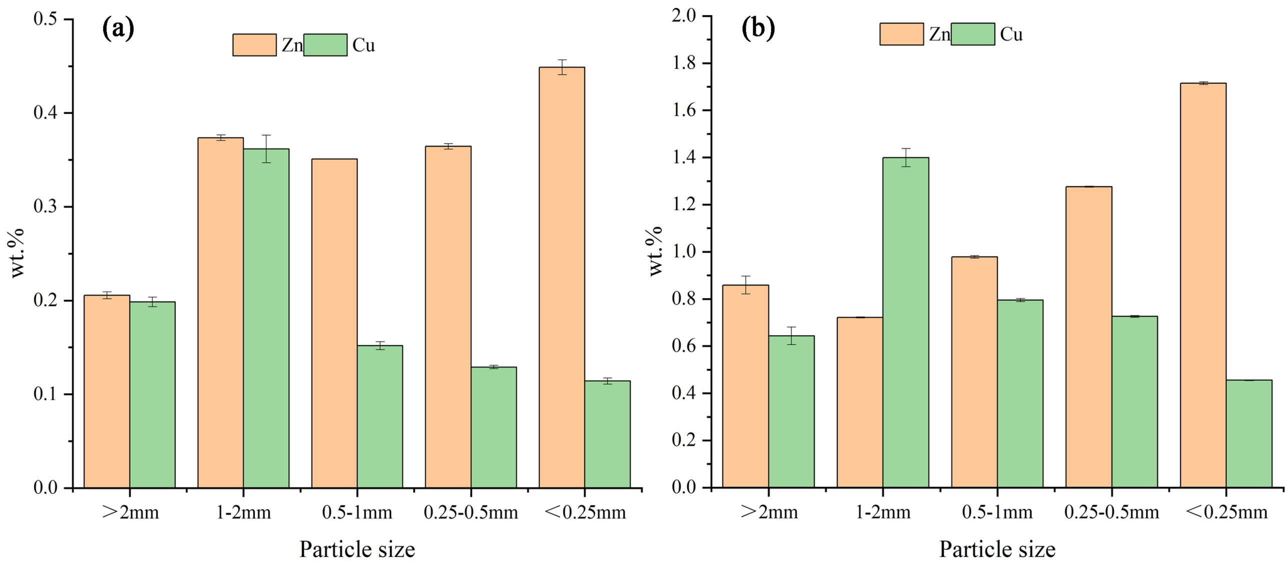

Figure 2. Variation of Zn and Cu content in bottom ash after sieving with particle size: (a) Bottom ash A; (b) Bottom ash B.

In both samples, the copper concentration reaches its highest values in the bottom ash with particle sizes between 1-2mm and decreases with decreasing particle size. In bottom ash A, none of the samples at different particle sizes meet the cutoff grade for copper 14. In bottom ash B, the ash with particle sizes greater than 2 mm meets the cutoff grade, and the samples with particle sizes in the ranges of 1 - 2 mm, 0.5 - 1 mm, and 0.25 - 0.5 mm all have copper concentrations exceeding the minimum industrial grade. 14 However, the concentration falls below the cutoff grade when the particle size is less than 0.25 mm (DZ/T 0214-2020).

4. Conclusion

Water washing is an effective method for increasing the concentration of heavy metals in fly ash. After water washing pre-treatment, the zinc and copper content in both fly ash samples significantly increased and exceeded the corresponding industrial grades.

Mechanical sieving is an effective pre-treatment method for bottom ash. In bottom ash, the zinc content increases as the particle size decreases, and in Sample B, it reaches the boundary grade when the particle size is less than 0.25 mm. The copper content in bottom ash is highest in the 1 - 2 mm range and decreases as the particle size decreases. In Sample B, copper in samples with particle sizes of 1 - 2 mm, 0.5 - 1 mm, and 0.25 - 0.5 mm exceeds the industrial grade, whereas in Sample A, the copper content does not meet the cut-off grade.

However, it is crucial to acknowledge that the relationship between heavy metal content and particle size in bottom ash still lacks a definitive explanation in the existing body of research. This intriguing knowledge gap presents an exciting opportunity for future investigations in this field. Further studies could delve into the underlying mechanisms that govern these metal-particle size interactions, potentially offering insights that could inform more efficient and targeted strategies for bottom ash treatment and recycling.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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