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Research article

Physicochemical characterization and resource recovery potential of hazardous municipal solid waste incineration (MSWI) fly ash and air pollution control (APC) residues in the Netherlands

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ABSTRACT

The growing incineration of municipal solid waste results in hazardous byproducts, particularly municipal solid waste incineration (MSWI) fly ash and air pollution control (APC) residues. The high toxicity of these residues limits their potential for recycling, leading to their direct disposal in landfills. This landfilling poses a significant environmental risk and presents a major challenge in countries with limited availability of land, such as the Netherlands. In this study, the physicochemical properties of Dutch MSWI fly ash and APC residues were evaluated, including, for the first time, an assessment of trace metal concentrations. High concentrations of heavy metals such as Zn, Pb, Cu, and Cd were identified in most MSWI fly ash and APC residues, along with notable concentrations of trace metals like Bi, suggesting new opportunities for resource recovery. The most hazardous residues were characterized by high contents of chloride, sulfate, alkali oxides, or carbonates, along with low calcium content in their chemical composition. These findings provide valuable insights for the targeted treatment and potential recycling of hazardous MSWI fly ash and APC residues currently being landfilled in the Netherlands.

1. Introduction

The growing generation of municipal solid waste (MSW) is driving a higher demand for waste incineration, especially in countries where land capacity is limited (Chen et al., 2024). Incinerating MSW effectively reduces the mass and volume of waste while generating energy (Chen et al., 2024; Chen and Ye, 2024; Tang et al., 2016). This trend is evident across the 27 European Union countries, where incineration rates have risen significantly, from 15 % in 1997 to 27 % in 2020 (B. Chen et al., 2023). The Netherlands, in particular, stands out with one of the highest annual capacities for waste incineration in Europe, producing over 400 kt/year in waste-to-energy plants - significantly higher than the European average of 170 kt/year (Shah et al., 2023). According to Eurostat data, the recycling rate of municipal waste in the Netherlands has been around 50 % (Chioatto et al., 2023), which needs to be further increased to 60 % by 2030 and 65 % by 2035 (Chioatto and Sospiro, 2023). As a result, implementing effective and sustainable waste management strategies in the Netherlands is essential, not only due to limited land availability but also to comply with future recycling targets.

Despite the benefits of MSW incineration, the hazardous residues generate a significant environmental concern (Marieta et al., 2021). These hazardous byproducts are primarily municipal solid waste incineration (MSWI) fly ash and air pollution control (APC) residues (Phua et al., 2019). MSWI fly ashes originate from untreated flue gas, while APC residues result from various flue gas treatment methods, such as dry, semi-dry, or wet scrubbing (Nedkvitne et al., 2021). Although these MSWI residues are produced through different processes, they are often grouped together as “MSWI fly ash” in the literature (De Boom and Degrez, 2012; Khalid, 2019), primarily due to the common mixing of these residues at the incineration plants (Margallo et al., 2015). However, oversimplified definitions in some review papers may also contribute to this grouping (Khalid, 2019). Consequently, much of the literature focuses on MSWI fly ash and bottom ash, neglecting the physicochemical differences and leaching toxicity between MSWI fly ash

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and APC residues, which complicates the development of effective treatment and management strategies.

The main sources of toxicity within MSWI fly ash and APC residues are high contents of heavy metals, toxic organic pollutants, and soluble salts (Nikravan et al., 2020; Quina et al., 2014). However, their leaching behaviour can vary. According to Boom (De Boom and Degrez, 2012), separating MSWI fly ash from APC residues is crucial for adapting suitable treatments, reducing treatment costs, and facilitating valorization. Studies have explored the difference in leaching toxicity between these residues by examining the chemical composition and mineralogy (De Boom and Degrez, 2012; Tian et al., 2023). Findings suggest that the leachability of heavy metals such as Zn, Cd, and Pb is influenced by the presence of alkaline or acidic components in MSWI fly ash and APC residues. Other studies have assessed the impact of physical properties, such as particle size distribution or specific surface area, on leaching behavior (Ni et al., 2017; Nikravan et al., 2020). Finer particle size distribution was associated with higher leachability of heavy metals. However, only a few have compared the leaching behavior of MSWI fly ash and APC residues in relation to total metal content (Yin et al., 2018, 2020). The total metal concentration not only affects heavy metal leaching but also plays a key role in evaluating the potential for metal recovery (Yin et al., 2020). Therefore, further studies are needed to fully understand the relationship between the physicochemical properties of MSWI fly ash and APC residues and their leaching behavior.

Although MSWI fly ash and APC residues are highly toxic, they have demonstrated potential for various industrial applications, including use as supplementary cementitious materials (SCMs) (Liu et al., 2021; Ren et al., 2022), metal recovery (Bakalár et al., 2021; Tang et al., 2020), soil stabilization (Liang et al., 2020), and lightweight aggregates (Han et al., 2022; Quina et al., 2014). However, in the Netherlands, their use is primarily limited to filler materials in asphalt, with about 30 % of MSWI fly ash and APC residues replacing limestone (Margallo et al., 2015). Compared to other European countries, the recycling of these residues in the Netherlands remains limited (Cho et al., 2020). To promote greater recycling and reuse, it is essential to fully understand the limitations of current practices by investigating the physicochemical properties of hazardous MSWI fly ash and APC residues. This knowledge can help to develop targeted treatment strategies depending on the intended application.

Based on the existing literature, there is a lack of in-depth understanding of the physicochemical characteristics of hazardous MSWI fly ash and APC residues in the Netherlands. The primary objective of this study is to provide a comprehensive characterization of these residues, in order to support targeted treatment strategies and evaluate their recycling potential. Accordingly, this paper aims to: (a) compare the properties of MSWI fly ash and APC residues and assess their potential leaching risks; (b) evaluate the correlation between the physicochemical properties and leaching behavior in these residues; and (c) investigate the influence of different purification systems on the physical and chemical properties of APC residues. Ultimately, this research seeks to mitigate the environmental impact associated with the disposal of MSWI fly ash and APC residues.

2. Materials and methods

2.1. Materials collection

The MSWI fly ashes were collected from eight different incineration plants at different locations in the Netherlands. Given that the Netherlands has a total of 12 waste-to-energy plants (Shah et al., 2023), this research provides comprehensive insights into the physicochemical properties of MSWI fly ashes, encompassing two-thirds of the national facilities.

For MSWI APC residues, the collection was based on different flue gas treatment processes employed in the Netherlands. These treatment processes are neutralization with sodium bicarbonate and lime-based treatments as the most common approaches. The use of sodium bicarbonate scrubbers is popular in Europe as it provides ease of operation and maintenance (Dal Pozzo et al., 2016), while limestone and its derivatives are more commonly used because they are cheaper and more abundant (Shareefdeen, 2022).

The collected samples were named FA1 to FA8 for MSWI fly ash samples and APC 6, APC 7a, and APC 7b for the air pollution control residues. The samples were labeled based on the numbers to keep the plant names anonymous. MSWI APC residues and MSWI fly ash with identical numbers are sourced from the same plants.

Acid gas neutralization methods varied between plants. In Plant 6, limestone (calcium carbonate) was applied as a dry absorbent via filter systems. Plant 7 employed two distinct neutralization techniques: APC7a represents the residue from sodium bicarbonate scrubbing, while APC7b corresponds to the residue from calcium hydroxide-based neutralization. Moreover, baghouse filters (BFs) and electrostatic precipitators (ESPs) are most commonly used for dust removal in Dutch MSWI plants. In addition, in the Netherlands, nitrogen oxide (NO_x) emissions are typically reduced through either selective catalytic reduction (SCR) or selective non-catalytic reduction (SNCR), depending on the specific plant design and operational conditions (Neuwahl et al., 2010). Although the specific emission control techniques of the facilities involved in this study were considered confidential and were not disclosed to us, the samples were likely collected from plants employing these standard technologies commonly used in the Netherlands.

All the plants utilize the Grate technology for incineration, which is among the most widely used technologies for municipal solid waste incineration (Wang et al., 2023). The primary source of fuel in these plants comprises a combination of household and commercial waste. Incineration temperatures differ between plants, with Plants 5 and 6 capable of reaching up to 1200 °C, while the remaining facilities maintain consistent temperatures around 1000 °C.

2.2. Characterization techniques

To examine the characteristics of MSWI ashes, both physical and chemical properties were assessed. The selected properties can determine the toxicity and the potential application of hazardous residues.

2.2.1. Chemical analysis

The chemical composition of samples was investigated using the X-ray fluorescence (XRF) measurement. The test samples were ground to a particle size of below 63 μm and then dried at 105 °C for 24h before XRF characterization. The grinding machine used for the sample preparation was a planetary ball mill (Retsch® PM 100). In addition to XRF, loss on ignition (LOI) tests were performed at two temperatures: 550 °C and 950 °C. The lower temperature (550 °C) was used to assess the unburned organic content, while the higher temperature (950 °C) provided information on the carbonate content. For XRF measurements, the samples were dried at 105 °C before the LOI analysis. The mineralogical composition of the samples was determined using X-ray powder diffraction (XRD). To determine the concentrations of heavy metals and mercury (Hg), inductively coupled plasma emission/mass spectrometry (ICP-ES/MS) was employed. The following elements were of particular interest: Strontium (Sr), Manganese (Mn), Tin (Sn), Antimony (Sb), Copper (Cu), Lead (Pb), Zinc (Zn), Molybdenum (Mo), Arsenic (As), Nickel (Ni), Bismuth (Bi), Chromium (Cr), Cadmium (Cd), Silver (Ag), Vanadium (V), Barium (Ba), Tungsten (W), Thallium (Tl), Uranium (U), Mercury (Hg), and Thorium (Th). For mercury analysis, acid digestion was performed using a solution of concentrated HCl, HNO_3, and deionized water in equal parts. For the analysis of other elements, the digestion process used a mixture of H_2O, HF, $HClO_4$, and HNO_3 in a 2:2:1:1 ratio. Leaching tests were conducted to evaluate the environmental risks associated with the leachability of heavy metals including Zn, Cr Ba, Cu, Cd, Pb, and Ni following the NEN 6966 standard (EN-ISO 11885). For the leachability of trace metals such as Sn and Sb, the ISO

17294-02 standard was applied, using ICP-MS for its superior sensitivity and ability to detect lower concentrations. The batch leaching tests followed the EN 12457-4 standard, with a constant liquid-to-solid ratio (L/S) of 10 for all experiments.

2.2.2. Physical analysis

Bulk density and particle size distribution (PSD) were determined for physical properties. The bulk density serves as an indicator to assess the densification of fly ash, providing insights into the amount of ash that can be accumulated within a specific volume (Yan et al., 2021). In this study, the bulk density analysis was performed in accordance with the EN 1097–3:1998 standard. Moreover, particle size distribution is one of the key factors in assessing MSWI fly ash and APC residues, as it offers valuable insights into the potential health risks to the environment (De Boom and Degrez, 2012; Takaoka et al., 2016). To analyze the particle size distribution, a laser diffraction (Malvern Mastersizer) was employed. For this test, the samples were dried at 105 °C and sieved to particles smaller than 250 μm.

3. Results

3.1. MSWI fly ash

3.1.1. Physical properties

The physical properties of MSWI fly ashes, including the particle size distribution and bulk density are provided in this section.

3.1.1.1. Particle size distribution. The distribution of particle sizes is represented as cumulative volume percentages in micrometers (μm) for the eight distinct MSWI fly ash samples in Table. A.1, Appendix A. The median particle diameter (d_{50}) predominantly falls within the 60–70 μm range for most samples. According to the literature, the d_{50} values of MSWI fly ashes are typically in the range of 10–200 μm (Z. Z. Chen et al., 2023; Zhang et al., 2023; Weibel et al., 2017) which aligns with the d_{50} values observed in this work. Among the samples, FA5 stands out with the largest particle sizes, measuring 133.64 μm, 80.17 μm, and 41.71 μm, for d_{90}, d_{50}, and d_{10} values, respectively.

3.1.1.2. Bulk density. Table. A.1, Appendix A, also illustrates the bulk density data for MSWI fly ashes presented in Kg/m^3. As can be seen, the bulk density in MSWI fly ashes varies from 300 kg/m^3 to about 600 kg/m^3 for most of the fly ashes. However, the highest density is recorded for FA4 at 727.97 kg/m^3, whereas the lowest density is observed in Plant 7, measuring 247.81 kg/m^3 for FA7. A comparison with literature values reveals a range of bulk densities between 295 and 1010 kg/m^3 across various studies (Tan et al., 2013; Yan et al., 2021; Polettini et al., 2004), aligning well with the results of this study.

3.1.2. Chemical properties

This section presents the key chemical properties of MSWI fly ashes, including elemental composition, loss on ignition, mineralogical composition, heavy metals concentration, and leaching.

3.1.2.1. Chemical composition. The chemical composition of the raw MSWI fly ashes was determined by XRF and is illustrated in Table 1. As shown in Table 1, CaO is the predominant oxide in most MSWI fly ashes, varying from 11.03 wt% in FA3 to 34.23 wt% in FA4. The other major components are Cl^-, SO_3, Na_2O, K_2O, and SiO_2, comparable to the MSWI fly ashes in other studies. Table 1 also highlights that FA3 and FA7 have noticeably different chemical compositions from the other samples. These two fly ashes contain considerably higher amounts of total alkali oxides and Cl^- content. Conversely, FA3 and FA7 have much lower SiO_2 and Al_2O_3. Moreover, among all the fly ashes, the highest SO_3 content can be observed in FA7 at 14.71 wt%. Additionally, heavy metals such as ZnO, PbO, CuO, Sb_2O_3, SnO_2, BaO, CdO, NiO, and Bi_2O_3 are more abundant in FA3 and FA7, with ZnO particularly elevated in FA7 at 9.11 wt% compared to the other fly ashes. A comparison of the LOI content is also provided in Table 1. Overall, the average carbonate content (4.42 wt%) is much higher than the average organic content (1.77 wt%) in MSWI fly ashes, according to LOI_{950}, and LOI_{550} values, respectively. Among MSWI fly ashes, FA7 stands out with the highest carbonate content (7.89 wt%) while having the least amount of organic content

Table 1
Chemical composition of Dutch MSWI fly ashes (normalized values based on $LOI_{550°C}$).

Oxide (wt. %)	Sample name								Min (wt. %)	Max (wt. %)	Mean (wt. %)	Median (wt. %)	SD (wt. %)	Range in literature (wt.%) (Lan et al., 2022; Ma et al., 2021; Xing et al., 2023; Ebert et al., 2020; Marieta et al., 2021; R. Zhang et al., 2020)
	FA1	FA2	FA3	FA4	FA5	FA6	FA7	FA8						
SiO_2	9.48	8.58	7.22	7.54	10.28	10.32	6.88	9.69	6.88	10.32	8.75	9.03	1.39	2.4–33.4
Al_2O_3	3.59	3.00	1.37	4.19	3.70	3.97	1.32	3.87	1.32	4.19	3.13	3.64	1.15	0.5–15.4
CaO	25.41	20.35	10.95	34.18	23.92	31.26	11.50	25.78	10.95	34.18	22.92	24.66	8.38	12.6–58.4
Na_2O	11.79	15.03	21.75	5.25	13.02	6.27	14.02	13.32	5.25	21.75	12.55	13.17	5.17	2.0–24.9
K_2O	5.38	7.20	12.86	4.92	5.23	4.61	11.13	5.49	4.61	12.86	7.10	5.43	3.15	0.6–21.7
Fe_2O_3	2.19	2.17	1.52	2.48	2.71	3.58	1.89	2.11	1.52	3.58	2.33	2.18	0.62	0.3–9.4
Cl^-	18.97	17.86	22.04	20.33	14.99	15.34	22.56	19.21	14.99	22.56	18.91	19.09	2.79	3.1–42.0
MgO	1.29	1.10	0.65	0.78	1.71	1.39	0.57	1.62	0.57	1.71	1.14	1.20	0.44	0.1–8.1
SO_3	9.20	10.67	9.12	10.34	11.80	9.95	14.71	8.35	8.35	14.71	10.52	10.15	2.00	2.2–20.5
P_2O_5	1.86	1.65	0.96	1.44	1.51	1.66	1.34	1.50	0.96	1.86	1.49	1.51	0.27	0.2–3.6
TiO_2	1.34	1.81	1.09	1.49	2.01	2.42	1.00	1.68	1.00	2.42	1.60	1.58	0.48	0.8–2.8
MnO	0.08	0.09	0.05	0.10	0.11	0.12	0.07	0.09	0.05	0.12	0.09	0.09	0.02	0.04–0.09
ZnO	4.15	4.71	6.32	3.74	4.33	4.67	9.11	3.12	3.12	9.11	5.02	4.50	1.89	–
PbO	0.67	0.78	0.89	0.42	0.61	0.52	1.11	0.47	0.42	1.11	0.68	0.64	0.23	–
CuO	0.32	0.34	0.70	0.27	0.34	0.26	0.31	0.25	0.25	0.70	0.35	0.31	0.15	–
Sb_2O_3	0.28	0.28	0.25	0.29	0.28	0.37	0.59	0.24	0.24	0.59	0.32	0.28	0.11	–
SnO_2	0.15	0.23	0.24	0.14	0.17	0.16	0.31	0.12	0.12	0.31	0.19	0.17	0.06	–
BaO	0.08	0.15	0.14	0.12	0.19	0.23	0.11	0.11	0.08	0.23	0.14	0.13	0.05	–
CdO	0.54	1.03	0.05	0.02	0.75	0.53	0.07	0.50	0.02	1.03	0.44	0.52	0.37	–
NiO	0.01	0.03	0.01	0.01	0.02	0.02	0.01	0.01	0.01	0.03	0.02	0.01	0.01	–
Bi_2O_3	0.02	0.06	0.08	0.01	0.03	0.01	0.02	0.01	0.01	0.08	0.03	0.02	0.02	–
Other oxides	0.42	0.52	0.38	0.40	0.42	0.70	0.67	0.52	0.38	0.70	0.50	0.47	0.12	–
$LOI_{550°C}$	2.79	2.36	1.35	1.52	1.87	1.63	0.71	1.94	0.71	2.79	1.77	1.75	0.63	–
$LOI_{950°C}$	5.11	4.95	3.22	3.02	3.70	4.18	7.89	3.30	3.01	7.89	4.42	3.94	1.61	–

(0.71 wt%).

3.1.2.2. Mineralogical composition. The main crystalline phases are illustrated in Fig. 1, which were determined by XRD. According to the diffraction pattern, the most intense peaks correspond to halite (NaCl) and the other major crystalline phases include sylvite (KCl), anhydrite ($Ca(SO)_4$), and quartz (SiO_2). Calcium-based phases were also identified as compounds like calcite ($CaCO_3$), lime (CaO), andradite ($Ca_3Fe_2(SiO_4)_3$), and calcium hydroxychloride (CaClOH).

As indicated in Fig. 1, except for low-calcium-based fly ashes (FA3 and FA7), the mineralogy of the other samples is similar. The formation of calcium hydroxychloride was only detected in these samples. Furthermore, the intensity of NaCl phases in FA3 is significantly higher than in the other MSWI fly ashes. This is consistent with the XRF results, showing the highest alkali oxides in FA3 at 34.61 wt%.

Consistent with the elemental composition, the identified phases in the mineralogical composition of MSWI fly ashes were mainly soluble salts such as NaCl, KCl, and CaClOH, along with other silicon and calcium-containing minerals, which have been frequently reported in previous studies (Lan et al., 2022; Fan et al., 2022; Duan et al., 2024; Weibel et al., 2017; Marieta et al., 2021).

3.1.2.3. Total concentration of heavy/trace metals. The heavy and trace metals concentrations were analyzed using ultra-trace ICP-ES/MS, with the results presented in Fig. 2. To enhance clarity, elemental concentrations are categorized by the magnitude and shown in Fig. 2(a–d). The raw data is provided in Table. A.2 in Appendix A. As shown in Fig. 2 (a–d), the values range from less than 0.05 mg/kg to over 10,000 mg/kg. Notably, Zn consistently exhibits concentrations exceeding 10,000 mg/kg in all fly ash samples, making it the most abundant heavy metal. Pb and Cu also show significant concentrations, following a general trend of Zn > Pb > Cu across samples FA1 to FA8. A similar distribution pattern has been reported in previous studies on MSWI fly ashes (Pan et al., 2013)(Zucha et al., 2020)(Fan et al., 2021). However, considering the other toxic metals such as Hg, the concentration range of Hg in this study is considerably lower than those reported for MSWI fly ashes in other countries such as China (1–24 mg/kg), Japan (0.03–41 mg/kg), or Taiwan (0.90–73 mg/kg)(Zhou et al., 2015), highlighting the effective management of Hg in the Netherlands. Among all the samples, FA3 and FA7 stand out as the most toxic MSWI fly ashes with considerably higher heavy metal concentrations such as Pb. This high heavy metal concentration in these fly ashes could pose significant environmental risks due to the increased potential for leaching (Chen et al., 2024). Interestingly, FA3 also contains higher concentrations of critical elements such as Ag and W (Fig. 2(c)). The higher Ag content (46.32 mg/kg) in FA3 is likely due to the formation of stable complexes with chloride present in its chemical composition (Fabricius et al., 2020). Other technology-critical elements, such as Mo and Sb, are found in higher concentrations with about 196 mg/kg and 2111 mg/kg, in FA2 and FA6, respectively.

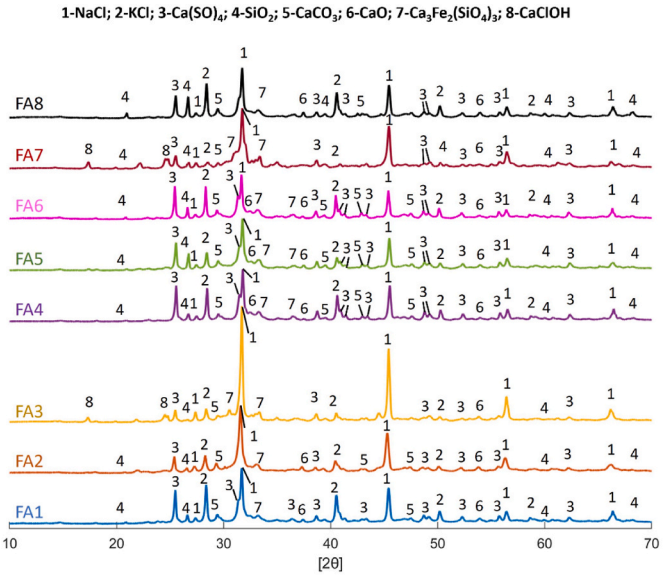

Fig. 1. Mineralogical composition of Dutch MSWI fly ashes. Identified crystalline phases include 1- NaCl, 2- KCl, 3- $CaSO_4$, 4- SiO_2, 5- $CaCO_3$, 6- CaO, 7- $Ca_3Fe_2(SiO_4)_3$, and 8- CaClOH.

Table 2 shows the minimum, maximum, and mean concentrations of the elements in mg/kg. Additionally, the table includes typical concentration ranges found in MSWI fly ash and the elemental abundance in the Earth's crust. As illustrated in Table 2, the max concentration of several elements, including Cu (4307.40 mg/kg), Sb (2111.68 mg/kg), Ni (268.20 mg/kg), Cd (492.83 mg/kg), and Mo (196.09 mg/kg), exceed the typical concentration ranges reported for MSWI fly ash. Additionally, the Dutch MSWI fly ashes analyzed in this study display lower concentrations of Tl, Th, and U compared to their natural abundances, whereas the W and Bi concentrations are significantly higher. Notably, the maximum Bi content in the MSWI fly ashes is more than 40,000 times greater than its natural concentration.

3.1.2.4. Leachability of heavy metals. The leaching behavior of heavy metals from MSWI fly ashes is shown in Fig. 3. Moreover, the limit values for landfilling of hazardous wastes (named as DLM) and the requirements for recycling as construction material (named as RLM) in the Netherlands are provided for each element.

According to Fig. 3, FA3 and FA7 exhibit significantly higher leachability of heavy metals, particularly Zn, Cd, Sb, and Cu. The leaching risk of Zn is especially concerning, with the highest concentrations reaching 4300 mg/kg for FA7 and 3600 mg/kg for FA3. When comparing the total heavy metal concentrations shown in Fig. 2, the most prominent leaching potential is observed for Cd in FA3 and FA7. While Pb leaching remains below 100 mg/kg for most fly ashes, FA8 presents an exception, with a maximum Pb leaching of 240 mg/kg.

In addition, FA3 and FA7 exceed the landfilling limits of 0.2 mg/kg, 25 mg/kg, 40 mg/kg, and 0.8 mg/kg for the leaching of Cd, Pb, Zn, and Sb, respectively. Furthermore, the landfilling limit for Pb is not met in FA8. In the other MSWI fly ashes, the leaching of toxic heavy metals is within the safe range. However, considering the recycling requirement as a construction material, no sample meets all the requirements. In FA3 and FA7, the limit values for Cd, Pb, Zn, and Sb are exceeded, while in the other fly ashes, the requirement for Cr is not met. Nevertheless, FA4 and FA5 show the highest potential for recycling as construction materials after the treatment for Cr and Sn.

3.2. MSWI APC

3.2.1. Physical properties

Similar to MSWI fly ash, this section offers insights into the physical characteristics of MSWI APC samples, including particle size distribution and bulk density. Table. A.3, Appendix A, presents a summary of these findings.

3.2.1.1. Particle size distribution. The particle size distribution of MSWI APC samples is illustrated in Table A. 3 as a cumulative volume percentage. As illustrated, the MSWI APC residues are distributed in an average particle size of 63.34 μm, 20.05 μm, and 27.65 μm, for APC6, APC7a, and APC7b, respectively. A comparison of the particle size distribution in MSWI APC residues suggests that the particles in APC6 are distributed in much coarser sizes than in APC7a and APC7b. The finer particles in APC residues from plant 7 increase the risk of heavy metals accumulating on particle surfaces(Yang et al., 2017). It is noteworthy that the d_{10} (21.27 μm) and d_{50} (70.66 μm) values for the APC6 residue exceed the typical range for MSWI APC particle size distribution, as

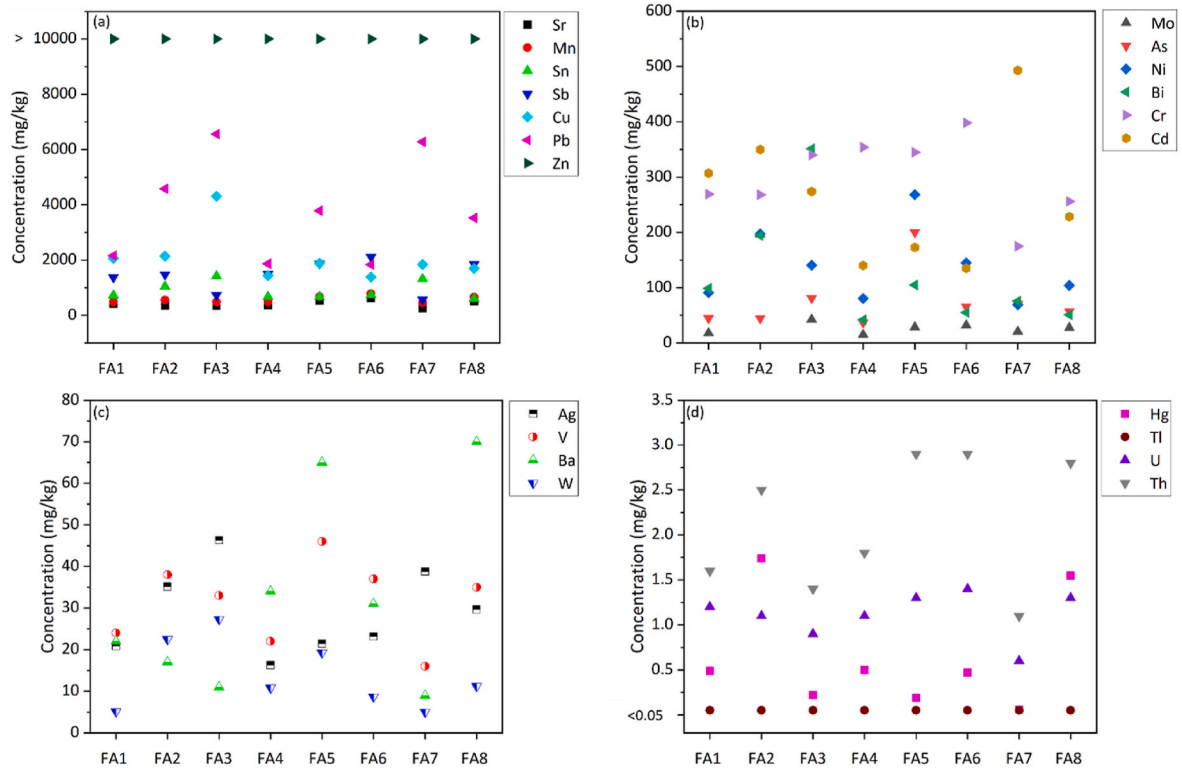

Fig. 2. Concentration of heavy and trace metals in MSWI fly ashes in four different groups. Values are expressed in mg/Kg.

Table 2
The heavy/trace metal concentration of Dutch MSWI fly ashes in this study compared with the typical range and the Earth's crust abundance (values are in mg/kg).

Element	Min	Max	Mean	Typical range in MSWI fly ash (J. Chandler et al., 1997)	Abundance in the Earth's crust (Alekseenko and Alekseenko, 2014; Haynes, 2016)
Sr	259.00	618.00	430.13	40–640	340
Mn	462.00	789.00	576.50	800–1900	1000
Sn	610.70	1421.40	901.64	550–2000	2.50
Sb	570.09	2111.68	1435.82	260–1100	0.50
Cu	1387.40	4307.40	2096.40	600–3200	47
Pb	1836.75	6560.56	3824.00	5300–26000	16
Zn	>10,000			9000–70000	83
Mo	15.01	196.09	47.49	15–150	1.10
As	36.90	200.20	75.14	37–320	1.70
Ni	69.40	268.20	137.06	60–260	58
Bi	42.01	351.13	121.64	–	0.0085
Cr	175.00	398.00	300.63	140–1100	83
Cd	135.15	492.83	262.52	50–450	0.13
Ag	16.3	46.32	29.0	2.3–100	0.07
V	16.00	46.00	31.38	29–150	90
Ba	9.00	70.00	32.38	330–3100	650
W	5.00	27.30	13.74	–	1.30
Hg	0.06	1.74	0.65	0.70–30	0.08
Tl	<0.05			–	1
U	0.60	1.40	1.11	–	2.70
Th	1.10	2.90	2.13	–	9.60

summarized by Phua (Phua et al., 2019), where d_{10} ranges from 0.15 to 17.51 μm and d_{50} from 0.5 to 48.71 μm.

3.2.1.2. Bulk density. The analysis of bulk density in MSWI APC residues is reported in Table A.3, Appendix A. Consistent with the results of particle size distribution, the APC7 residues with finer particle sizes

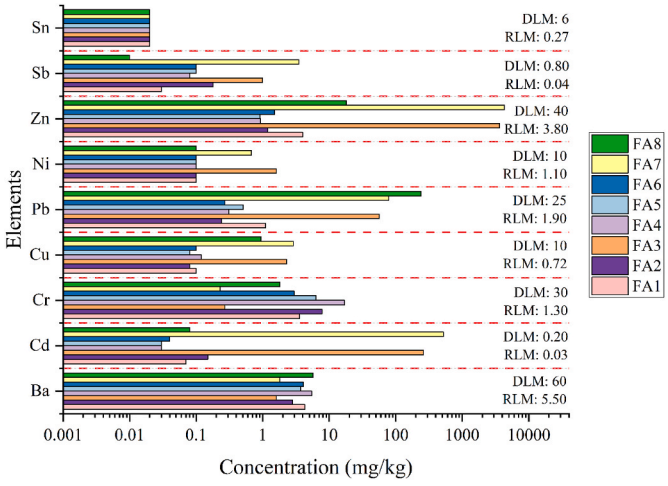

Fig. 3. Leaching concentrations of heavy metals in Dutch MSWI fly ashes (L/S ratio = 10). DLM: Disposal limit values of hazardous wastes in the Netherlands (mg/kg); RLM: Recycling limit values as construction materials in the Netherlands (mg/kg) (Van Gerven et al., 2005).

have higher bulk densities compared to APC6. The APC6 residue exhibited the lowest bulk density, at approximately 351.59 kg/m3, which is below the range of 422.68 kg/m^3 to 682.8 kg/m^3 reported in the literature for MSWI APC residues(Heng et al., 2018; Fernández Bertos et al., 2004).

3.2.2. Chemical properties

The MSWI APCs' chemical properties are provided in this section, including elemental composition, loss on ignition, mineralogical composition, heavy metals concentration, and leaching.

3.2.2.1. Chemical composition. Table 3 shows the chemical composition of MSWI APC samples from Plant 6 and Plant 7. As shown in Table 3, the major oxides in MSWI APC residues vary significantly. In APC6, CaO is the predominant component, followed by Na_2O, Cl^-, and SO_3 accounting for approximately 65 % of the total composition. On the other hand, APC residues from plant 7 have higher Cl^- content. Over 80 wt% of APC7a is composed of only Na_2O and Cl^- contents. APC7b, however, mostly consists of Cl^- and CaO, comprising approximately 40 wt% and 36 wt% of the total composition, respectively. The differences in the chemical composition of MSWI APC residues can be attributed to their different neutralization processes.

In addition to the major oxides, the MSWI APC residues show differences in their minor oxide contents. For instance, APC7a and APC7b have lower amounts of SiO_2, Al_2O_3, and K_2O compared to APC6. Additionally, the total heavy metals content in APC7a and APC7b is lower than 0.5 wt% in each residue, whereas APC6 has about 5.8 wt% heavy metals, with ZnO comprising 3.94 wt% of the composition.

According to the literature, the highest reported Na_2O and Cl^- contents in MSWI APC residues are 39.10 wt% and 29.30 wt%, respectively (Table 3). However, APC7a has a notably higher Na_2O content of 49.35 wt%. Additionally, the Cl^- content in Plant 7's APC residues exceeds 30 wt%, which is significantly higher than those reported in previous studies.

Similar to MSWI fly ash characterization, the determination of LOI for APC residues was carried out at temperatures of 550 °C and 950 °C (Table 3). As shown in Table 3, APC6 residue presents higher LOI values, which indicates more organic compounds, unburnt carbon, and volatile species within this residue (Nikravan et al., 2020).

3.2.2.2. Mineralogical composition. The XRD patterns of MSWI APC residues from Plant 6 and Plant 7 are compared in Fig. 4. The crystalline phases detected in APC6 residue include potassium and sodium soluble salts, such as KCl, NaCl, $NaK_3(SO_4)_2$, and along with calcium-bearing, such as $CaCO_3$ and $CaSO_4$. The mineralogy of APC6 reveals a more complex composition compared to the residues from Plant 7. As indicated in Fig. 4, APC7a is predominantly comprised of inorganic sodium salts which is in good agreement with the high Na_2O content determined by XRF analysis. While inorganic sodium salts are present in all three residues, the strong intensity of NaCl in APC7a correlates with its significantly higher Na_2O content. On the other hand, the high Ca and Cl^- contents, observed in the XRF characterization of APC7b can be found in some mineral phases such as NaCl, $CaCl(H_2O)_2$, and $CaSO_4$.

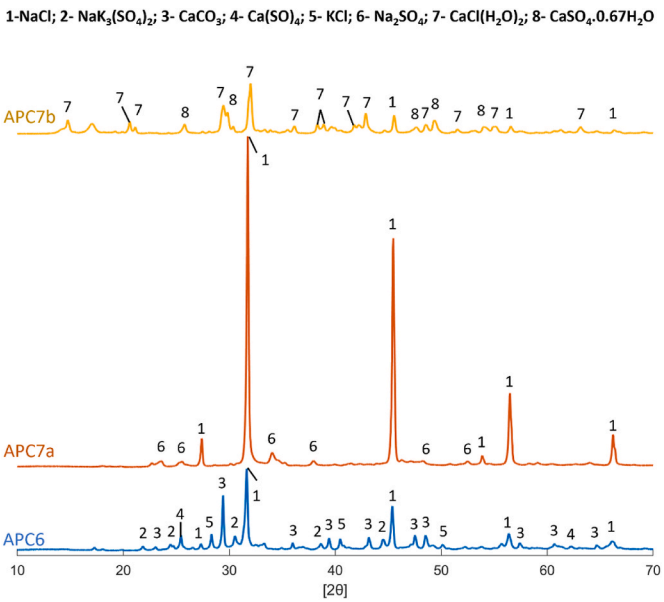

Fig. 4. XRD patterns of MSWI APC residues. Identified mineral phases include 1- NaCl, 2-$NaK_3(SO_4)_2$, 3- $CaCO_3$, 4- $CaSO_4$, 5- KCl, 6- Na_2SO_4, 7- $CaCl(H_2O)_2$, and 8- $CaSO_4{\cdot}0.67H_2O$.

3.2.2.3. Total concentration of heavy/trace elements. Fig. B.1 in Appendix B shows the concentrations of MSWI APC residues in mg/kg and Table 4 compares these elemental concentrations to the typical ranges reported for MSWI APC residues from dry/semi-dry purification systems and their natural abundance in the Earth's crust. For elements like Bi, W,

Table 3
Chemical composition of Dutch MSWI APC residues (normalized values based on $LOI_{550°C}$).

Oxide (wt. %)	Sample name			Min (wt. %)	Max (wt. %)	Mean (wt. %)	Median (wt. %)	SD (wt. %)	Range in literature (wt.%) (Bogush et al., 2020; Cao et al., 2024; Ahmad et al., 2023)(S. Zhang et al., 2020; Dontriros et al., 2020; Alba et al., 1997; Phua et al., 2019; Yang et al., 2017)
	APC6	APC7a	APC7b						
SiO_2	6.57	0.41	0.44	0.41	6.57	2.47	0.44	3.55	0.78–25.68
Al_2O_3	1.71	0.13	0.13	0.13	1.71	0.66	0.13	0.91	0.00–15.69
CaO	19.76	2.25	36.32	2.25	36.32	19.44	19.76	17.04	3.27–60.27
Na_2O	17.73	49.35	6.89	6.89	49.35	24.66	17.73	22.06	0.00–39.10
K_2O	7.49	0.25	0.33	0.25	7.49	2.69	0.33	4.16	0.21–6.52
Fe_2O_3	1.04	0.10	0.16	0.1	1.04	0.43	0.16	0.53	0.19–5.69
Cl	17.64	34.44	39.99	17.64	39.99	30.69	34.44	11.64	6.36–29.30
MgO	0.96	0.17	0.44	0.17	0.96	0.52	0.44	0.40	0.32–2.77
SO_3	10.71	8.33	6.02	6.02	10.71	8.35	8.33	2.35	3.43–31.90
P_2O_5	0.79	0.05	0.02	0.02	0.79	0.29	0.05	0.44	0.39–3.02
TiO_2	0.67	0.01	0.00	0.00	0.67	0.23	0.01	0.38	0.12–0.95
MnO	0.04	0.00	0.01	0.00	0.04	0.02	0.01	0.02	0.02–4.95
ZnO	3.94	0.34	0.22	0.22	3.94	1.50	0.34	2.11	–
PbO	0.55	0.06	0.03	0.03	0.55	0.21	0.06	0.29	–
CuO	0.82	0.02	0.09	0.02	0.82	0.31	0.09	0.44	–
Sb_2O_3	0.21	0.01	0.00	0.00	0.21	0.07	0.01	0.12	–
SnO_2	0.14	0.04	0.00	0.00	0.14	0.06	0.04	0.07	–
BaO	0.08	0.00	0.00	0.00	0.08	0.03	0.00	0.05	–
CdO	0.04	0.00	0.00	0.00	0.04	0.01	0.00	0.02	–
NiO	0.02	0.00	0.00	0.00	0.02	0.01	0.00	0.01	–
Bi_2O_3	0.02	0.00	0.00	0.00	0.02	0.01	0.00	0.01	–
Other oxides	0.44	0.20	0.64	0.2	0.64	0.43	0.44	0.22	–
$LOI_{550°C}$	8.53	3.84	7.83	3.84	8.53	6.73	7.83	2.53	–
$LOI_{950°C}$	15.18	7.62	8.99	7.62	15.18	10.60	8.99	4.03	–

Table 4
The heavy/trace metal content of Dutch MSWI APC in this study compared with the typical range in MSWI APC residues and abundance in the Earth's crust (values are in mg/kg).

Element	APC6	APC7a	APC7b	Typical range in MSWI APC residues with dry/semi-dry purification system (J. Chandler et al., 1997)	Abundance in the Earth's crust (Alekseenko and Alekseenko, 2014; Haynes, 2016)
Sr	315.00	19.00	207.00	400–500	340
Mn	334.00	28.00	104.00	200–900	1000
Sn	705.90	94.30	48.20	620–1400	2.5
Sb	598.10	86.54	82.89	300–1100	0.5
Cu	2222.00	104.70	74.80	16–1700	47
Pb	4842.14	506.71	111.83	2500–10000	16
Zn	>10,000	2236.80	1043.80	7000–20000	83
Mo	17.65	0.39	0.88	9.3–29	1.1
As	32.50	2.50	1.60	18–530	1.7
Ni	169.30	1.80	1.70	19–710	58
Bi	97.15	18.98	8.05	–	0.0085
Cr	185.00	4.00	5.00	73–570	83
Cd	316.29	20.36	11.56	140–300	0.13
Ag	33.97	0.97	1.20	0.9–60	0.07
V	15.00	<2	<2	8–62	90
Ba	20.00	21.00	26.00	51–14000	650
W	18.60	0.10	0.20	–	1.3
Hg	12.69	6.92	8.24	0.1–51	0.08
Tl	<0.05	<0.05	<0.05	–	1
U	1.00	<0.1	0.30	–	2.7
Th	0.90	<0.1	<0.1	–	9.6

Tl, U, and Th, typical ranges are not reported for MSWI APC residues from dry/semi-dry purification systems. Thus, their concentrations are compared solely to their abundance in the Earth's crust.

According to Fig. B. 1, a significant variation in the concentration of heavy and trace metals among different MSWI APC residues can be seen. The concentration of potentially toxic heavy metals reveals the dominance of Zn, Pb, Cu, and Cd within APC residues. Among APC residues, the concentration of the toxic heavy metals is significantly higher in APC6 than in the other residues, following the order of APC6 > APC7a > APC7b. The other moderately concentrated elements are Sn, Sb, Mn, and Sr, ranging from 10 to 1000 mg/kg, with notably higher concentrations in APC6. In addition, elements such as Mo, As, Ni, Cr, Cd, Ag, W, and Hg were observed in concentrations below 10 mg/kg in APC7a and APC7b, which are considerably lower than APC6. However, Tl, U, V, and Th are present at minimal levels, with no significant variation between different residues.

As shown in Table 4, several elements in the APC residues deviate significantly from the typical ranges reported for MSWI APC residues with dry/semi-dry purification systems. In APC7a and APC7b, except for Hg and Ag, the concentrations of all heavy and trace metals are substantially lower than the expected ranges for APC residues in such systems. Among the trace and radioactive elements not commonly reported for APC residues, Bi exhibits significant enrichment in APC7a, APC7b, and APC6 compared to its crustal abundance, with APC6 showing the highest concentration at 97.15 mg/kg. Unlike the residues from Plant 7, most elemental concentrations in APC6 align with the typical ranges for APC residues. However, notable exceptions include Ba and Sr, which are present at lower concentrations, while Cu and Cd exceed the upper limits of their respective ranges.

3.2.2.4. Leachability of heavy metals. The leaching toxicity of heavy metals, including Zn, Pb, Cu, Cd, Cr, Ba, Ni, Sn, and Sb, in MSWI APC residues is presented in Fig. B.2, Appendix B. Similar to MSWI fly ash, the Dutch standard limits for landfilling and recycling of hazardous waste are provided for comparison.

Fig. B.2, illustrates that the concentration of leachable heavy metals in APC7a is notably higher than in APC6 and APC7b, with the leaching amounts of 17 mg/kg, 22 mg/kg, 11 mg/kg, and 9.60 mg/kg, for Pb, Zn, Sb, and Sn, respectively. The leaching sequence in APC7a follows this order: Zn > Pb > Sb > Sn > Cu > Ba > Cr > Ni > Cd, which shows the highest risk of leaching. Nevertheless, APC6 has a higher leaching of Cr with 6.22 mg/kg, and the leaching of Cd (0.46 mg/kg) is higher in APC7b. Additionally, a comparison of heavy metal concentrations for APC6 and APC7b (Fig. B.1) with leaching results indicates that Ba leaches more readily than other elements, while Sb and Sn show greater leachability in APC7a.

The Dutch standard limits for disposal and recycling hazardous wastes indicate that all APC residues present a high risk, considering the leaching of Sb. Besides Sb, in APC7b, the high leachability of Cd (0.46 mg/kg) is another challenge for the disposal or recycling of this residue. In APC6, the leaching concentrations of Cd (0.15 mg/kg), Cr (6.20 mg/kg), and Pb (2.90 mg/kg) exceed the threshold values for recycling as construction material. For APC7a, the leachability of Sn poses a risk for both landfilling and recycling. However, the concentrations of Pb (17 mg/kg) and Zn (22 mg/kg) in this residue meet the requirements for landfilling but exceed the recycling limits.

4. Discussion

This discussion addresses key factors influencing hazardous MSWI fly ash and APC residues. First, the impact of waste inputs and neutralization methods on the chemical composition of MSWI fly ash and APC residues is discussed. Then, the physicochemical properties driving the leaching behavior of heavy metals are explored. Finally, current challenges are discussed, along with potential strategies for the sustainable utilization of these residues.

4.1. Influence of waste inputs and neutralization techniques on the chemical properties of hazardous MSWI residues

The elemental concentrations in MSWI fly ashes showed considerable variations due to the diversity of waste input composition. The source of the abundant chloride content can be traced back to the incineration of polyvinyl chloride within plastics or the burning of paper, leather, and kitchen wastes (Fan et al., 2022). In addition, vegetables and seasonings, present in kitchen wastes, also contribute to high amounts of alkali oxides (Ohbuchi et al., 2019). According to the IAWG (J. Chandler et al., 1997), 30 % of the sulfur in MSW comes from organic sources, whereas 70 % is present in paper or plastics. Thus, the incineration of paper and plastic fractions not only increases the chloride content but also influences the sulfur content in the incinerated ash. Accordingly, a higher proportion of plastic, paper, and kitchen wastes is likely present in the waste inputs of Plant 3 and Plant 7, where MSWI fly ashes with high amounts of alkali oxides, chloride, and sulfates are generated. This suggests a need for further attention to the separation efficiency of plastic, paper, and kitchen wastes in these plants.

In addition, the significant concentrations of Sb, Cu, Ni, Cd, and Mo, which were found to be out of the typical range in MSWI fly ashes, could be attributed to some waste inputs such as electronic waste (Mama and Nnaji, 2025) or batteries (Hu et al., 2021), which needs further attention. However, the percentage of Al in the chemical composition of Dutch MSWI fly ashes is relatively low (<5 wt%), indicating the effective recycling of aluminum cans in this country.

The differences in chemical properties, including chemical composition and mineralogy of MSWI APC residues, are mainly influenced by the specific gas neutralization systems employed. For example, in Plant 7, despite identical waste input for APC7a and APC7b, their chemical compositions differ significantly. APC7a residue, neutralized with sodium bicarbonate, has a considerably high Na_2O content, while CaO was found to be the major oxide in APC7b, where calcium hydroxide was injected. The significant quantity of Na_2O in the composition of APC7a,

which is higher than the range in the literature, suggests that the injection of sodium bicarbonate in the Netherlands is considerably higher than in other countries.

Additionally, different neutralization techniques significantly impact the mineralogical composition of APC residues. Residues treated with lime, such as APC6 and APC7b, contain more calcium-bearing minerals, while those treated with sodium bicarbonate (e.g., APC7a) are dominated by inorganic sodium salts due to the sodium bicarbonate used in gas neutralization (see Fig. 4). The identified crystalline phases in MSWI APC residues of this study have also been detected in previous studies (Bogush et al., 2015; Sun et al., 2023; Kitamura et al., 2022; Alba et al., 1997; Phua et al., 2019). However, in the literature, calcium chloride hydroxide has been predominantly reported as a hydrated calcium chloride mineral (sinjarite). This could be attributed to the highly metastable condition of sinjarite, which has been observed to crystallize at approximately 50 % mass concentration of calcium chloride (Baumgartner and Bakker, 2009). This aligns well with the chemical composition of APC7b, which primarily consists of calcium and chloride (Table 3).

4.2. Chemical and physical properties influencing the leaching behavior in hazardous MSWI residues

The leaching risk of hazardous MSWI fly ash and APC residues can be attributed to their physicochemical properties. According to the results of this study, the MSWI fly ashes with the highest leaching of heavy metals (FA3 and FA7), as well as the most leachable APC residue (APC7a), were found to have the lowest Ca contents, along with considerable amounts of chloride, sulfate, alkali oxides, or carbonates in their composition.

Higher amounts of calcium in the chemical composition of MSWI residues can mitigate the leaching risks. Calcium promotes the formation of $CaSO_4$ and $CaCO_3$, which are thermodynamically stable and poorly soluble, thereby preventing the formation of more soluble metallic compounds from sulfates and carbonates (Jiao et al., 2016; Cao et al., 2021). Some researchers also argue that the formation of C-S-H gel from the reaction of Ca-bearing silicates with water can immobilize the heavy metals and reduce their leaching toxicity in MSWI fly ashes due to the pH buffering mechanism of C-S-H gels (Tian et al., 2023).

High chloride content causes greater concentrations of heavy metals due to the formation and volatilization of unstable metallic chlorides, such as $PbCl_2$ and $ZnCl_2$ (Ma et al., 2021; Verbinnen et al., 2018). As the generated metallic chlorides are unstable and have high solubility, their formation increases leaching toxicity (Ni et al., 2017; Ferraro et al., 2019; Jiao et al., 2016).

Carbonates and sulfates can form soluble compounds with toxic elements such as Zn, Pb, Cu, and Cd, increasing their leaching risk through dissolution and precipitation (Zhang et al., 2016).

High amounts of alkali oxides in the elemental composition increase the alkalinity nature of ashes, resulting in their high solubility and greater release of cationic metals such as Pb, Zn, Cd, or Cr (Zhang et al., 2016).

Therefore, while high contents of chlorides, carbonates, sulfates, and alkali oxides tend to increase leaching toxicity, higher calcium content can be advantageous in mitigating the leaching risk. This is consistent with the experimental results of this study.

Furthermore, it is known that the physical properties, including bulk density and particle size distribution, also contribute to the leaching behavior (De Boom and Degrez, 2012),(Ni et al., 2017). A higher bulk density can be attributed to a lower risk of heavy metals leaching by providing denser particles and solidified heavy metals (Yan et al., 2021). In addition, finer particle size distribution leads to an increase in the dispersion of ashes in the air and a higher potential for the release of heavy metals by leaching (Chuai et al., 2022; Ni et al., 2017). It is noteworthy that, as baghouse filters and electrostatic precipitators are commonly used as dust removal techniques in the Netherlands, the residues collected from these sites may have a higher leaching risk of Pb and Zn than those collected from furnace or boilers, due to their finer particle size (De Boom and Degrez, 2012). The influence of physical properties on the leaching toxicity of heavy metals is consistent with the experimental results of this study. The overall higher leachability of APC7a can be attributed to its finer particle size, and the high leaching risk of FA7 is in line with its lower bulk density as well as the smaller average particle sizes.

4.3. Current challenges and potential utilizations

In order to properly manage MSWI fly ash and APC residues, some challenges need to be first addressed:

The diversity of waste inputs significantly influences the chemical characteristics of hazardous MSWI residues. As discussed in Section 4.1, current waste streams in some facilities may contain increased levels of plastics, paper, or kitchen waste, leading to higher concentrations of chlorides, alkali oxides, and sulfates. This, in turn, elevates the leaching risks associated with heavy metals. Enhancing the separation of waste inputs prior to incineration could help reduce treatment costs by minimizing the hazardous components in the resulting residues. Furthermore, different acid gas neutralization methods used in treating MSWI APC residues result in varying chemical compositions and distinct leaching behaviors for heavy metals. Although sodium bicarbonate is favored for its ease of operation and low maintenance, it is less effective in reducing the leachability of Pb, Zn, Sn, and Sb compared to calcium hydroxide or calcium carbonate-based methods. Consequently, the use of sodium bicarbonate requires consistent monitoring of heavy metal leachability in treated flue gases to ensure safety and compliance.

Despite the current challenges, some potential utilizations can be considered for MSWI fly ash and APC residues. For instance, FA5 could be promising as a supplementary cementitious material in concrete mix designs thanks to its high silica, alumina, and iron oxide content (a total of 17.88 wt%). Additionally, extracting valuable metals such as Zn, Pb, and Cu from MSWI fly ashes could provide economic benefits and reduce environmental impacts, particularly in FA3 and FA7. Moreover, extraction of some trace elements, such as Bi, found in extreme concentrations in hazardous residues from Plant 3 and Plant 7, can be advantageous.

5. Conclusions

This study comprehensively evaluates the physicochemical properties of MSWI fly ash and APC residues in the Netherlands, focusing on the leaching risk of heavy metals and resource recovery potential. Eight plants across various locations were selected to analyze MSWI fly ash, with three of these plants further studied for MSWI APC residues to assess the impact of different acid gas purification systems. The key findings of this study are as follows:

Leaching risks in MSWI fly ash and APC residues are influenced by a mix of stabilizing factors (e.g., calcium) and destabilizing factors (e.g., chlorides, carbonates, and alkali oxides), as well as physical properties such as particle size and density. Effective management strategies should focus on optimizing these factors to reduce leaching risks and stabilize hazardous components.

MSWI fly ashes have more complex chemical and mineralogical compositions compared to APC residues. The composition of APC residues is more predictable due to the influence of acid gas neutralization techniques. This makes the management, treatment, and disposal of APC residues simpler and less dependent on variations in waste input.

Except for mercury, heavy metal concentrations are generally higher in MSWI fly ashes than in APC residues, posing greater environmental challenges. The most toxic residues—both fly ash and APC—were characterized by higher contents of chlorides, sulfates, alkali oxides, or carbonates, alongside notably lower calcium content. This suggests that classifying hazardous residues based on their chemical composition may

improve assessments of heavy metal concentrations and leaching toxicity.

This study emphasizes the opportunity to recover valuable trace elements, such as Bi, from MSWI fly ash and APC residues. In addition to high concentrations of metals like Zn, Pb, and Cu, resource recovery offers an alternative to landfilling these residues, supporting sustainable waste management.

Further studies should investigate the impact of diverse waste inputs on the leaching behavior and physicochemical properties of hazardous MSWI residues. Additionally, it is recommended to explore alternative purification systems, such as wet purification with sodium hydroxide, to compare the leaching risks in APC residues. Future research should also consider analyzing concentrations of other valuable elements, particularly rare earth elements (REEs) and precious metals (e.g., Au, Pt, and Pd), to fully assess the resource recovery potential of MSWI fly ash and APC residues. Moreover, due to the relatively high LOI values observed in the MSWI fly ash and APC residues, the investigation of organic pollutants (e.g., dioxins, furans, PAHs) and macropollutants (e.g., CO, NO_x, etc.) is highly recommended for future research to enable a more comprehensive toxicity evaluation.

CRediT authorship contribution statement

Farnaz Aghabeyk: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Boyu Chen:** Writing – review & editing, Supervision, Conceptualization. **Marc Brito van Zijl:** Writing – review & editing, Resources. **Guang Ye:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT-4o in order to improve the readability of the text. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Farnaz Aghabeyk, Boyu Chen, Marc Brito van Zijl, Guang Ye reports financial support was provided by European Commission. If there are other authors, they 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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Appendix A. Table of Contents

Table. A.1
Summary of particle size distribution (μm) and bulk density (kg/m^3) of MSWI fly ash residues. Bulk density values are reported as mean ± standard deviation based on triplicate measurements.

	Particle size distribution (μm)			Bulk density (Kg/m^3)
	d_{10}	d_{50}	d_{90}	
FA1	23.2	69.1	101.88	492.16 ± 24.42
FA2	22.47	67.06	94.16	494.27 ± 2.76
FA3	14.68	62.27	96.39	301.05 ± 4.24
FA4	24.2	64.76	106.79	727.97 ± 14.03
FA5	41.71	80.17	133.64	386.67 ± 22.64
FA6	37.96	78.38	103.71	588.93 ± 4.80
FA7	12.34	70.76	96.83	247.81 ± 11.38
FA8	25.68	64.29	90.37	620.92 ± 8.37

Table. A.2
Concentrations of the heavy and trace metals in MSWI fly ashes (values are in mg/kg)

	Sr	Mn	Sn	Sb	Cu	Pb	Zn	Mo	As	Ni	Bi	Cr	Cd	Ag	V	Ba	W	Hg	Tl	U	Th
	1*	1*	0.1*	0.02*	0.1*	0.02*	0.2*	0.05*	0.2*	0.1*	0.04*	1*	0.02*	0.02*	2*	1*	0.1*	0.01*	0.05*	0.1*	0.1*
FA1	424	488	724.3	1378.4	2065.7	2157.54	>10,000	17.91	44.9	91.1	99.06	269.00	307.02	20.897	24	22	5.1	0.49	<0.05	1.2	1.6
FA2	362	552	1047.1	1478.97	2141.2	4583.16	>10,000	196.09	44.50	197.10	194.10	268.00	349.80	35.157	38	17	22.5	1.74	<0.05	1.1	2.5
FA3	350	487	1421.4	731	4307.4	6560.56	>10,000	42.22	81.20	140.80	351.13	340.00	273.92	46.317	33	11	27.3	0.22	<0.05	0.9	1.4
FA4	368	494	673.3	1493.61	1442.9	1866.33	>10,000	15.01	36.90	80.70	42.01	354.00	140.05	16.335	22	34	10.8	0.5	<0.05	1.1	1.8
FA5	541	678	675	1872.62	1885.6	3784.19	>10,000	28.52	200.20	268.20	105.03	345.00	172.89	21.418	46	65	19.3	0.19	<0.05	1.3	2.9
FA6	618	789	741.8	2111.68	1387.4	1836.75	>10,000	32.05	65.70	145.00	55.09	398.00	135.15	23.175	37	31	8.7	0.47	<0.05	1.4	2.9
FA7	259	462	1319.5	570.09	1839	6278.95	>10,000	20.63	70.60	69.40	75.77	175.00	492.83	38.782	16	9	5	0.06	<0.05	0.6	1.1
FA8	519	662	610.7	1850.15	1702	3524.5	>10,000	27.51	57.10	104.20	50.94	256.00	228.50	29.662	35	70	11.2	1.55	<0.05	1.3	2.8
Blank	<1	<1	0.1	0.07	<0.1	0.13	1.2	<0.05	0.2	<0.1	<0.04	<1	<0.02	<0.02	<2	<1	<0.1	<0.01	<0.05	<0.1	<0.1
Preparation blank	4	28	0.3	0.15	2.6	1.99	2.0	0.29	0.3	1.3	<0.04	3	<0.02	<0.02	3	8	<0.1	<0.01	<0.05	0.3	1.8

*Method detection limit.

Table. A.3
Summary of particle size distribution (μm) and bulk density (kg/m^3) of MSWI APC residues. Bulk density values are reported as mean ± standard deviation based on triplicate measurements.

	Particle size distribution (μm)			Bulk density (Kg/m^3)
	d_{10}	d_{50}	d_{90}	
APC6	21.27	70.66	88.73	351.59 ± 8.78
APC7a	8.38	19.36	31.37	380.66 ± 12.61
APC7b	7.06	31.08	45.87	675.82 ± 9.71

Appendix B. Figures

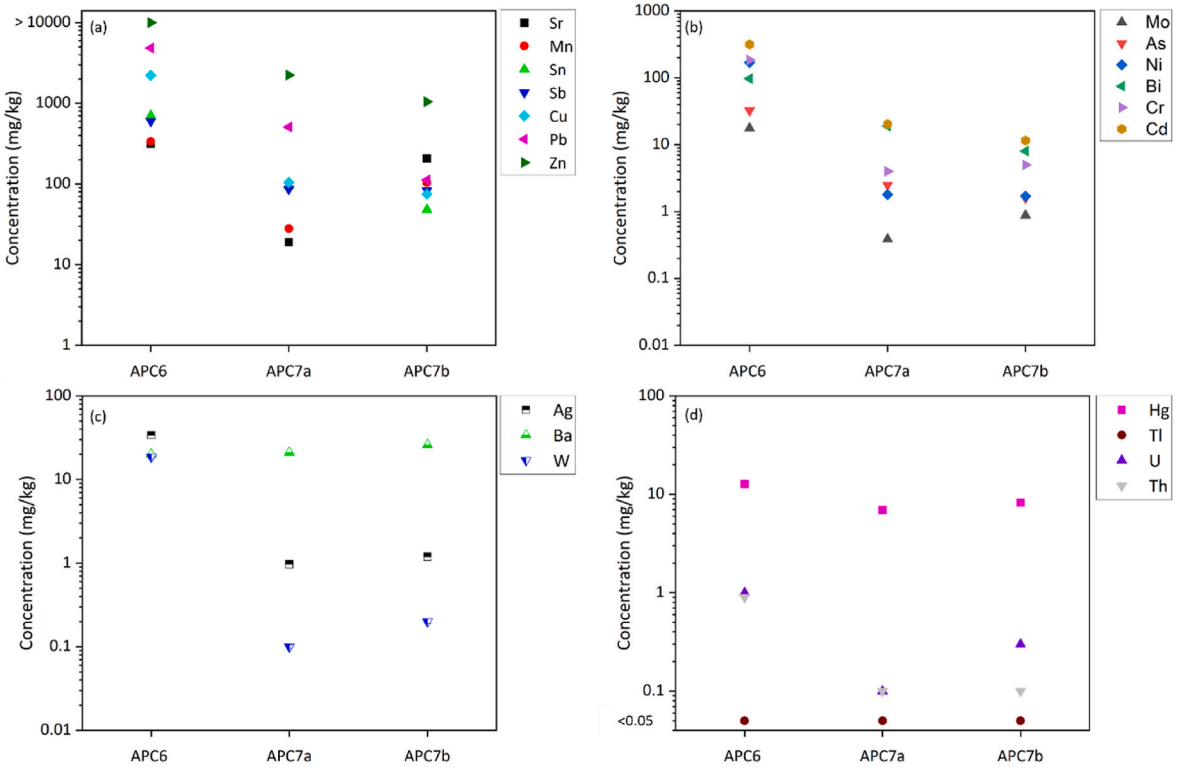

Fig. B.1. Concentration of heavy/trace metals in MSWI APC. Values are expressed in mg/Kg.

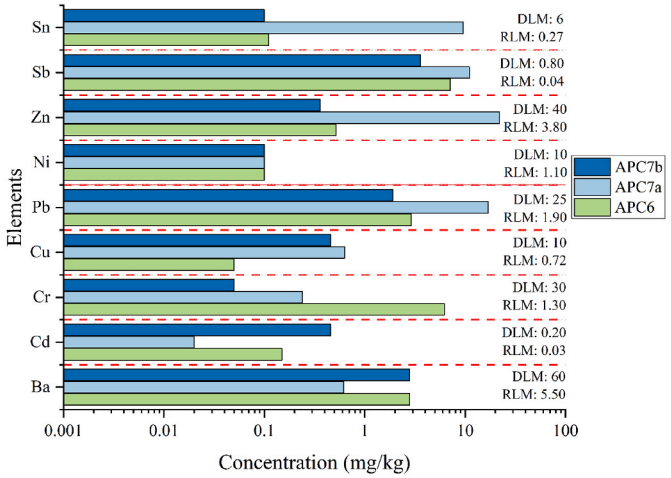

Fig. B.2. Leaching concentrations of heavy metals in MSWI APC residues (L/S ratio = 10). DLM: Disposal limit values of hazardous waste in the Netherlands; RLM: Recycling limit values as construction materials in the Netherlands (Van Gerven et al., 2005)

Data availability

Data will be made available on request.

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