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Research Paper

High voltage selective fragmentation on Swedish mineral fraction of incineration bottom ash (MIBA) – An exploratory study on metal and material recovery

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ABSTRACT

Waste-to-Energy (WtE) generates circa 1 Mt/y of Mineral fraction of Incineration Bottom Ash (MIBA) in Sweden, often used as construction material for landfills. Upcoming European Commission directives will limit landfilling and the demand for MIBA for landfill construction is predicted to decrease. Therefore, alternative utilisations of MIBA are required.

High Voltage Selective Fragmentation (HVSF) has been utilised in Switzerland to improve recovery from WtE bottom ash, yielding fractions of higher homogeneity: metals, minerals, iron oxide (FeO), and a sorting residue. Samples from two Swedish WtE plants were treated to test the effectiveness of HVSF on Swedish MIBA.

Applying HVSF to MIBA resulted in additional metal extraction of 2.2% and 1.2% for each sample, consisting of 1.2% and 0.6% ferrous metals and 1.0% and 0.6% non-ferrous metals, respectively. The minerals, FeO, and sorting residue were analysed for total elemental content and leaching. Potential utilisation in the clinker and brick industry is identified for FeO, while the mineral fraction exceeded guideline values for unlimited use in Sweden. The results indicate more research is required on how value recovery of MIBA can be increased to better align with circular principles, particularly concerning the chemical properties of the recovered fractions and appropriate legislation for use.

1. Introduction

Rising climate concerns along with warnings of resource scarcity, have triggered an increased demand for technologies to mitigate environmental impact and led to more advocation for a circular economy from key societal actors, including the European Union (European Commission & Directorate-General for Communication, 2020). ISO 59004 defines a circular economy as an "*economic system… which maintains a circular flow of resources by recovering, retaining, or adding to value…*". Circular economy principles are relevant for all economic

Abbreviations: Al, Aluminium; As, arsenic; Ba, barium; Ca, calcium; Cd, cadmium; Co, cobalt; Cr, chromium; Cu, copper; Fe, iron; Hg, mercury; K, potassium; Mg, magnesium; Mn, manganese; Mo, molybdenum; Na, sodium; Ni, nickel; P, phosphorus; Pb, lead; S, sulfur; Sb, antimony; Se, selenium; Si, silicon; Sn, tin; Sr, strontium; Ti, titanium; Tl, thallium; V, vanadium; Zn, zinc; Cl^-, chloride; F^-, fluoride; SO_4^{2-}, sulfate; HCl, hydrochloric acid; HF, hydrofluoric acid; HNO_3, nitric acid; CRM, critical raw materials; DOC, dissolved organic carbon; DS, dry substance; FE, ferrous; FeO, iron oxide; HNF, heavy non-ferrous; HV, high voltage; HVSF, high voltage selective fragmentation; IBA, incineration bottom ash; ICP-SFMS, inductively coupled plasma sector field mass spectrometry; LNF, light non-ferrous; MIBA, mineral fraction of incineration bottom ash; TOC, total organic carbon; wt.%, weight-percent; WtE, waste-to-energy.

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activities including Waste-to-Energy (WtE) plants, where Incineration Bottom Ash (IBA) is generated.

Approximately 18 Mt/y of IBA is generated within Europe (Blasenbauer et al., 2019). Conventional methods for treating the IBA are described by Šyc et al. (2020) and include, for example, crushing and separating the IBA into different particle size fractions before collecting metals through magnet and eddy current separation. Currently, in Sweden, IBA is often refined into a Mineral fraction of Incineration Bottom Ash (MIBA) by stabilising the material through carbonation after first extracting large metal pieces (above a few millimetres). MIBA is suitable for construction purposes (Hansson et al., 2017), but is classified as waste, leading to limited utilisation options. Regulation regarding utilisation options differ significantly between countries, even within the EU, mainly due to variations in the predicted risk of unwanted metal ions and anion leaching from the material. This has led to several different approaches for handling MIBA (Blasenbauer et al., 2019).

In some countries, e.g. Denmark and Finland, MIBA can be utilised outside landfills. In Finland, a general environmental regulation has been developed to enable the recycling of waste while maintaining environmental standards that are applicable for MIBA in, for example, road construction (Finlex, 2017). Similarly, Denmark has extensive regulations enabling utilisation outside of landfills (Blasenbauer et al., 2019; Liu et al., 2015) which is reflected in high MIBA utilisation outside landfills of 99 and 20 wt% respectively for Denmark and Finland (Blasenbauer et al., 2019). In Sweden, the corresponding value was close to 0 wt%, and the main utilisation of MIBA remains construction material within landfills (Blasenbauer et al., 2019). However, as the EU aims to reduce waste going to landfills (European Commission, 2023b), and newer landfill construction techniques require less construction material, the use of MIBA within landfills is predicted to decrease, and thus alternative handling and uses are needed.

When utilising secondary raw materials in conventional applications, total element/ion contents are often evaluated. Yet more important from an environmental perspective is the leaching properties of the material. Both total contents and leaching can relate to guidelines or limit values which vary between countries (see e.g. Blasenbauer et al. (2019)).

Switzerland is one of the more restrictive countries concerning the handling of IBA, where metal recycling is compulsory and any remaining MIBA must be sent to a landfill for hazardous waste (type D on a scale from A to E where E is the most hazardous waste (Swiss Federal Council, 2015)). Therefore, it is in both environmental and economic interest to decrease the amount of IBA going to landfill. One technology that can be utilised to improve recovery from waste material is High Voltage (HV) pulse power (Leißner et al., 2018). In Switzerland, the technology is used in WtE in conjunction with conventional IBA treatments to reduce the fraction of IBA sent to landfills. The HV pulse power is employed for HV Selective Fragmentation (HVSF) to liberate bound metals from the IBA, and the resulting ash residue is subsequently divided into three, more homogenous fractions (Selfrag, 2023a). This methodology of HVSF is explained in more detail in section 2.2.

The HVSF method described results in more efficient metal recovery compared to traditional IBA metal sorting (Weh & Mosaddeghi, 2016), and the remaining fractions can be partly reused which reduces the amount of material going to landfill in Switzerland (Selfrag, 2023b). The more homogenous fractions include an iron oxide-rich fraction and a mineral fraction. Iron oxide can be used in Swiss clinker production (Swiss Federal Council, 2015), while the minerals are considered secondary aggregates (Blasenbauer et al., 2019): both can, thereby, replace finite natural materials such as crushed stone. Furthermore, as the primary production of metals is energy-intensive, substantial amounts of greenhouse gas emissions can be avoided if metals are recycled efficiently while also reducing reliance on natural resources, as seen for secondary aluminium processing which requires only 5 % of the energy burden versus primary aluminium processing (Tabereaux & Peterson, 2014).

This laboratory study aims to identify if the HVSF method could improve the value recovery from, and utilisation of, MIBA in Sweden from enhanced purification through mechanical, electrical, and magnetic separation. To achieve this, the HVSF method at lab-scale is applied to MIBA sampled from two Swedish WtE plants. The results are compared to reference samples from Switzerland where HVSF is used for IBA processing commercially, and other references that are deemed relevant depending on fraction type. Challenges and opportunities with the material utilisation are evaluated in the Swedish context and the resulting purity of the new fractions recovered from MIBA are discussed.

2. Material and methods

2.1. Processing and sampling of Swedish MIBA

The current practice for refining fresh IBA into MIBA in Sweden involves several steps. Firstly, to cool the IBA after incineration, the IBA passes through a water bath before transportation to an outdoor storage area. The IBA is then placed in heaps where it is exposed to the environment and chemically reacts with the air, binding CO_2 from the atmosphere or rain to form $CaCO_3$ in a process known as carbonation. This results in less alkaline pH with lower metal mobility. After a few months of drying, the material is sorted into different particle size fractions and ferrous and non-ferrous metal pieces e.g. Cu, Zn, and Al, are recovered from the ash using magnetic sorting. Thereafter, the various size fractions are mixed into one sample and the material is stored for another couple of months for additional stabilisation through carbonation. In total, the drying and stabilisation processes take approximately 6 months. After these processes are completed, the resulting material is defined as MIBA and is the material used in this study.

The HVSF process is normally applied to fresh IBA in Switzerland. However, as the Swedish WtE processes currently result in MIBA production, for practical reasons and to evaluate how much additional metals could be recovered, MIBA was used in this study to be more relevant to the Swedish context. Further, using MIBA can indicate the efficiency of the HVSF method on IBA that has already undergone some treatment.

MIBA samples of circa 1 m^3 were collected from two Swedish full-scale WtE plants, denoted WtE-1, and WtE-2 respectively from hereon. Both plants, situated in the south of Sweden, are grate-fired boilers applied to municipal and industrial waste. The IBA generated from these plants accounts for approximately 20 % of all Swedish IBA. The treatment method for sorting the ash differs in the two sites; consequently, the MIBA sampling was conducted differently. The WtE-1 sample was collected by taking in excess of 20 sub-samples from the outdoor storage piles, while the WtE-2 sample was collected on one occasion while MIBA was free-falling after the sorting process. In both cases, the collected MIBA samples used in this work represent approximately 3,000 kg of waste.

2.2. Lab process for the HVSF method

The MIBA samples were treated with the HVSF method (Weh, 2018) at the SELFRAG lab in Kerzers, Switzerland. A riffle splitter was used before treatment, to gain more manageable sample sizes with limited impact on the sample representativeness. After splitting, the dry start weights of the samples used were 458.8 kg with a moisture content of 7.9 % for WtE-1, and 570.8 kg with a moisture content of 9.2 % for WtE-2.

The treatment of the Swedish MIBA samples was done according to the lab-scale HVSF method, which differs from the full-scale HVSF method in some respects. An overview of the lab-scale HVSF method is illustrated in Fig. 1. The full-scale HVSF method for the treatment of IBA is only commercial in Switzerland and is described in Weh (2018) as well as Glauser and Weh (2022). Weh (2018) also provides a simplified

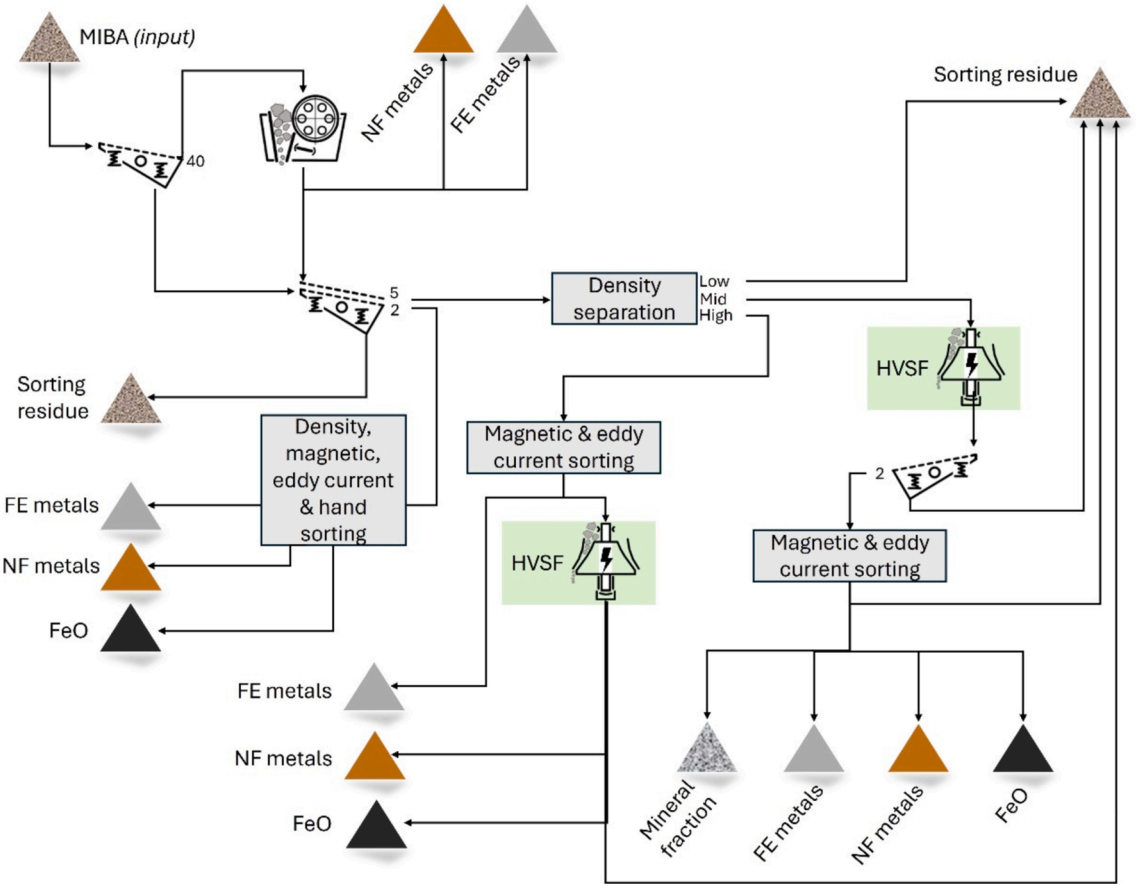

Fig. 1. A simplified flow sheet of the lab-scale HVSF treatment. All output flows of the same colour and naming have been grouped together for the results. Within the sorting residues, unburnt organics were selectively removed. Small numbers by screens indicate the sorting cut-off of each screen deck (mm). Particles that could not be crushed to below 40 mm were hand sorted into different metal fragments and sorting residues. FE = ferrous metals, HNF = heavy non-ferrous metals, LNF = light non-ferrous metals, FeO = iron oxide.

flow chart of the full-scale process.

The principle of HVSF is that HV pulses separate different materials from the feed material at their grain boundaries since they have different electrical properties (Seifert et al., 2014). HV induces breakage through pulses acting similarly to lightning or blasting. It generates shockwaves that fragment the heterogeneous feed material, crushing the material in a selective manner based on its conductivity (Weh & Mosaddeghi, 2016). As the IBA is crushed by the HV, increased material homogeneity and recovery are achieved, as more and cleaner metals are liberated which are then possible to separate through mechanical sorting methods.

As illustrated in Fig. 1, the material was first pre-sorted by removing fractions > 40 mm by sieving, which were then crushed with a jaw crusher and any large particles that could not be crushed were removed through manual sorting. Before treatment with HVSF, the remaining MIBA was divided into different density classes through jigging (Ramachandra Rao, 2006; Tao et al., 2023), to make the treatment more effective, as the material is crushed by HV due to the different conductive behaviour of the fractions present. Using density separation in the treatment of IBA is also described by Šyc et al. (2020) as a new technology trend, while the concept has been employed in the mining industry for hundreds of years (Ramachandra Rao, 2006). The intermediate density class was treated with HVSF and subsequently sieved before magnet and eddy current sorting to extract metals. Already liberated metals were removed from the heavy density class before treating with HVSF, as the treatment otherwise would be inefficient due to the high metal content present in the fraction. A fine residue (< 2 mm) is removed due to particle size screening in the process with a further residue removed after the density separation process. Coarse residue (> 2 mm) is removed after HVSF, magnetic and eddy current sorting.

The treatment resulted in six fractions: ferrous (FE) metals, heavy non-ferrous (HNF) metals, light non-ferrous (LNF) metals, iron oxide (FeO), minerals, and a sorting residue.

2.3. Chemical analyses

Samples of the mineral, FeO, and sorting residue were sent to an accredited external laboratory for chemical analyses of the total elemental contents and leaching according to the two-step leaching test (liquid-to-solid (L/S) of 2 and 8 L/kg) SS-EN-12457–3 (SIS, 2003). The leached concentrations were recalculated to mg/kg dry material. The total content analyses for selected elements (see Tables 1, 2 and 4 for a full list) were conducted using digestion in acid (HNO_3/HCl/HF) and lithium borate melt, followed by ICP-SFMS (inductively coupled plasma sector field mass spectrometry) analyses. Due to the sorting process, the mineral fraction consisted of two size fractions: 2 -< 5 mm, and 5 -< 40 mm, which were tested separately. Duplicates of each sample fraction were analysed for total elemental amounts, while the leaching tests were done as solitary samples on each fraction.

The total content results for WtE-1 and WtE-2 were compared with Swiss data collected from SELFRAG AG (denoted SF in tables and text). The Swiss data contains results for the minerals, FeO, and sorting residue fractions collected from treatment of different IBA samples with the lab-scale HVSF process. The Swiss samples were analysed using wavelength dispersive x-ray fluorescence for the major elements and aqua regia digestion for the minor and trace elements. The FeO was also compared

Table 1
Results in alphabetical order for total content analyses [mg/kg DS] of FeO from WtE-1, WtE-2 and a Swiss reference (SF) to the left. Swiss limit values to use waste in clinker production are included to the right, where the bold values specifically apply to waste that mainly consists of iron (Swiss Federal Council, 2015). Cadmium has one lower limit for general waste and one higher limit for waste incorporating mainly iron, bold in parenthesis.

Element [mg/kg DS]	FeO **WtE-1**	**WtE-2**	**SF**	Clinker production **Waste limit** (Swiss Federal Council, 2015)
Al	32,000	32,000	33,000	–[1]
As	31	27	16	30
Ba	2,100	3,500	na[2]	–
Ca	93,000	89,000	11,000	–
Cd	1.4	5.0	0.50	5 **(10)**
Co	250	89	76	–
Cr	1,100	1,300	850	–
Cu	4,900	4,600	3,000	–
Fe	400,000	350,000	330,000	–
Hg	< 0.05	< 0.05	na	**1**
K	5,100	5,700	3,500	–
Mg	11,000	10,000	7,900	–
Mn	2,500	2,500	2,600	–
Mo	54	69	na	–
Na	15,000	15,000	17,000	–
Ni	1,700	900	580	500
P	2,500	2,900	3,500	–
Pb	640	470	280	500
S	4,500	4,800	2,400	–
Sb	77	350	58	30
Se	< 8.0	< 4.0	na	–
Si	100,000	120,000	100,000	–
Sn	160	180	na	100
Sr	440	490	na	–
Tl[3]	0.06	< 0.05	na	**3**
Ti	7,400	7,100	8,200	–
V	63	140	na	–
Zn	2,600	2,800	2,100	2,000

[1] No limit value exists.
[2] Not analysed.
[3] Tested only in FeO fraction due to reference guideline limits.

with limit values for use as clinker corrective material in the cement industry (Swiss Federal Council, 2015). The minerals were further compared with an average of 23 crushed rock materials (Ekvall et al., 2006), crushed rock for road construction (Lidelöw et al., 2017), and guideline values for unlimited use in Sweden set by the Swedish Environmental Protection Agency (SEPA) (SEPA, 2010). The sorting residues from the HVSF process were compared with a reference MIBA sample consisting of an average of nine Nordic WtE ashes (i.e. MIBA) for insights into differences in composition between treated and original MIBA (Nordic Council of Ministers, 2022).

The leaching results of the minerals were compared with the average of 23 crushed rock materials (Ekvall et al., 2006), and crushed rock for road construction (Lidelöw & Lagerkvist, 2007), both based on SS-EN 12457–3. Guideline values from SEPA were also consulted while analysing the results of the minerals (SEPA, 2010). The leaching results of the sorting residue were compared with the Swiss data for sorting residue, analysed according to DIN EN 12457–4:2003–01. The difference between the Swedish and Swiss leaching analyses was that the Swedish samples were crushed to 4 mm, in contrast to the Swiss, which were crushed to 10 mm. However, the residues should theoretically only consist of fractions smaller than 5 mm, minimising the difference. Furthermore, the Swedish samples were analysed with two stages (L/S 2 and 10), while the Swiss sample was analysed with one stage, (L/S 10), both in L/kg. These differences could affect the comparability of the analyses and the leaching from the Swiss material can be lower as a result which is considered in the interpretation of the results. The sorting residues were also compared with limit values set by SEPA for different types of landfills in Sweden (SEPA, 2004), along with the reference MIBA sample.

2.4. Additional metal resource estimation

The HNF fraction from WtE-2 was sorted to determine valuable metal content, and thus the economic value. The sorting was done by washing the metals in weak acid to release the ash residues. Due to the low pH in the acid, impurities are released from the material. After washing, the low-magnetic metals were extracted. The remaining metals were then hand sorted into red metals, e.g., copper and brass, and white metals, e.g., stainless steel. All fractions were weighed after the test.

An estimation of the improved value recovery was conducted to determine the monetary value of indicative metal resources available in the Swedish MIBA from the application of HVSF. This was done using current metal scrap prices which are described in Appendix A (letsrecycle.com 2023a & letsrecycle.com, 2023b).

By using the weights for the different HNF metals of size 2 -< 40 mm obtained from the treatment of the WtE-2 HNF fraction, mass balance from the HVSF treatment, and the data on metal market prices, it was possible to estimate the monetary value of the metal resource that could be extracted using this technique. Assuming that all magnetic and white HNF metals were stainless steel and that all red were copper, the value from the HNF metals, I_{HNF}, was calculated by multiplying the scrap metal price with the corresponding weight of the metal to obtain the value in € retrieved from the MIBA samples.

Similarly, an estimation for the value from FE and LNF metals recovered of size 2 -< 40 mm, assumed to comprise steel scrap and aluminium scrap respectively, was calculated. The weights of each metal fraction were assumed to consist of 2 % dirt i.e. residual ash particles, as these samples had not been washed in acid. The same assumptions have been used in the mass balance.

The total monetary value for the additional metal resources €/t dry MIBA, I_{metals}, was then calculated and used to estimate the potential resource in Sweden considering the total amount of IBA generated in Sweden in one year, IBA_{yearly}, is estimated at 1 Mt/y (Avfall Sverige, 2023). From these ashes, around 80 % is assumed to end up as dry MIBA, with the assumption that around 10 % of the IBA consists of existing metal reserves that are extracted through current separation techniques, and 10 % is humidity, but this varies with different plants and treatment techniques. Thus, the total resource value, I_{yearly} due to recovering additional metals by shifting to the HVSF method has been estimated using Equation (1).

$$I_{yearly} = IBA_{yearly}\left[\frac{t_{ashes}}{y}\right] \times 0.8\left[\frac{t_{MIBA}}{t_{ashes}}\right] \times I_{metals}\left[\frac{€}{t_{MIBA}}\right] \quad (1)$$

3. Results

3.1. Results from HVSF treatment

The HVSF treatment resulted in a total of nine fractions for WtE-1 and WtE-2 respectively, as presented in Fig. 2 together with a percentage distribution between the non-metallic fractions FeO, minerals, and sorting residue. In further sections, the sorting residue is considered as only one fraction. Losses of 3.5 % and 2.9 % were seen for WtE-1 and WtE-2 after the HVSF method was applied, respectively, likely during the washing stages.

To further understand the resulting homogeneity of the recovered fractions from Swedish MIBA after applying the HVSF method, a Sankey diagram is presented in Fig. 3 for the normalised flows of six major elements. These have been calculated based on an average of the total content results from both WtE-1 and WtE-2, and normalised to 1 kg of MIBA, which was then used to estimate the original MIBA composition. The remaining elements analysed were grouped and represented as 'Other' in Fig. 2, with all untested elements, and unknown elements (i.e those in material lost during treatment and in the recovered unburnt

Table 2
Total contents [mg/kg DS] in alphabetical order for minerals 2 -< 5 mm and 5 -< 40 mm from WtE-1 and WtE-2, and analogous data for the Swiss mineral, SF, 5 -< 40 mm. For comparison, the total contents in crushed rocks (Ekvall et al., 2006; Lidelöw et al., 2017) are shown together with guideline values for free use in Sweden (SEPA, 2010).

	MINERALS 2-<5 mm		MINERALS 5-<40 mm			CRUSHED ROCKS		SEPA
Element [mg/kg DS]	**WtE-1**	**WtE-2**	**WtE-1**	**WtE-2**	**SF**	**Average of 23 samples** (Ekvall et al., 2006)	**Single sample** (Lidelöw et al., 2017)	**Guideline values** (SEPA, 2010)
Al	48,000	44,000	62,000	51,000	52,000	na[1]	77,000	–[2]
As	37	37	26	35	4.3	9.9	0.6	10
Ba	2,000	2,700	1,700	2,000	na[2]	420	670	–
Ca	120,000	120,000	89,000	99,000	140,000	na	21,000	–
Cd	1.1	0.79	0.86	0.56	2.1	0.36	0.1	0.2
Co	35	31	28	25	na	44	na	–
Cr	490	390	410	340	150	43	120	40
Cu	2,800	1,800	1,800	1,700	790	27	31	40
Fe	37,000	36,000	33,000	33,000	31,000	na	51,000	–
Hg	< 0.05	< 0.05	< 0.05	<0.05	na	< 0.01	< 0.04	0.1
K	10,250	10,900	13,250	13,800	11,305	na	30,000	–
Mg	15,150	13,300	13,800	12,000	11,830	na	19,000	–
Mn	1,500	1,200	710	860	1,100	1,000	700	–
Mo	46	18	14	13	na	2.1	< 6	–
Na	40,000	34,000	40,000	35,000	31,000	na	20,000	–
Ni	220	110	160	83	53	20	31	35
P	3,100	3,100	1,800	2,000	2,700	na	na	–
Pb	650	490	600	340	250	21	10	20
S	2,700	2,800	2,800	2,000	3,500	na	na	–
Sb	73	120	63	80	25	0.66	na	–
Se	< 6	< 2	< 7	< 3	na	< 5	na	–
Si	250,000	260,000	260,000	300,000	240,000	na	290,000	–
Sn	87	55	63	33	na	4.3	na	–
Sr	400	370	350	310	na	na	na	–
Ti	9,200	8,300	5,800	6,200	6,200	na	6,000	–
V	63	100	56	78	na	na	110	–
Zn	2,200	2,400	1,300	1,500	710	70	99	120

[1] Not analysed.
[2] No guideline value exists.

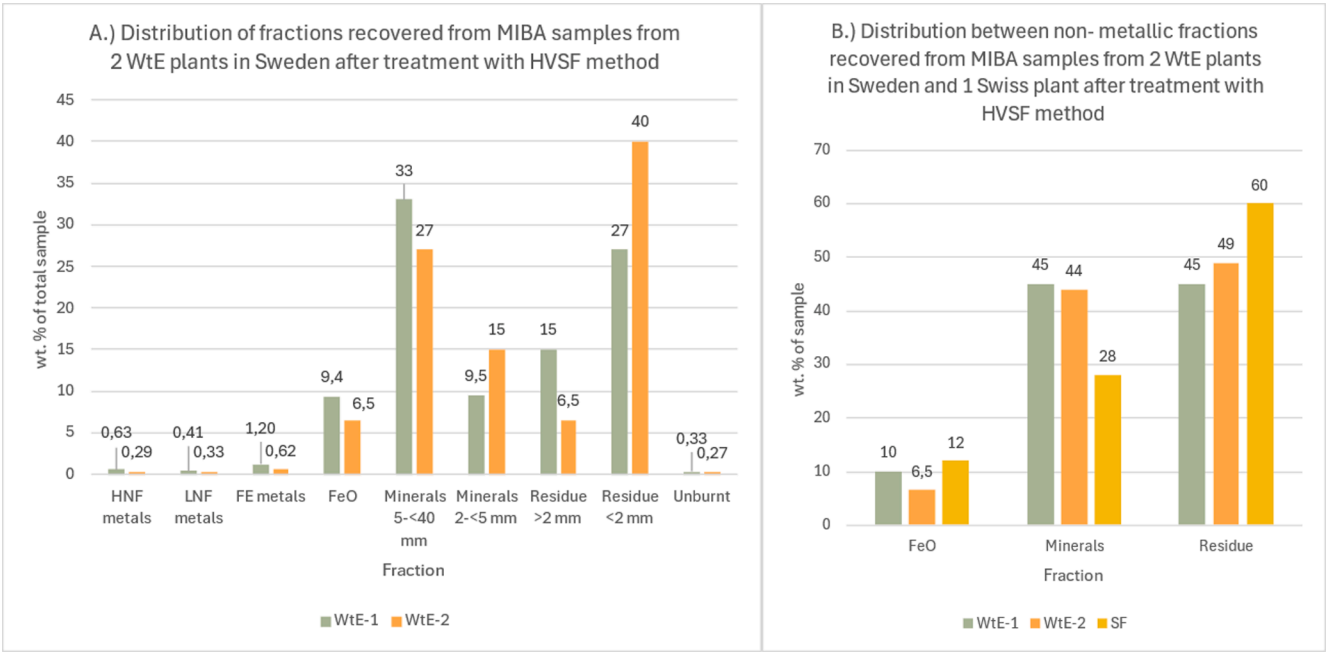

Fig. 2. A.) Resulting fractions (wt.%) from Swedish MIBA from WtE-1 and WtE-2 plants after treatment with HVSF method. For each sample, there are three metal categories: HNF, LNF and FE metals; an FeO fraction; two different sizes of minerals and residues with a final unburnt rest fraction. and B.) the distribution between FeO, minerals and residues without metals and unburnt material, compared between the Swedish WtE-1 and 2, and Swiss SF.

material) constituting the remaining weight denoted as 'Unknown' and likely consisting largely of oxygen in oxide compounds. The key fractions are discussed in more detail in the following subsections.

3.2. Metals

In total, 2.2 % and 1.2 % could be recovered as metals from WtE-1

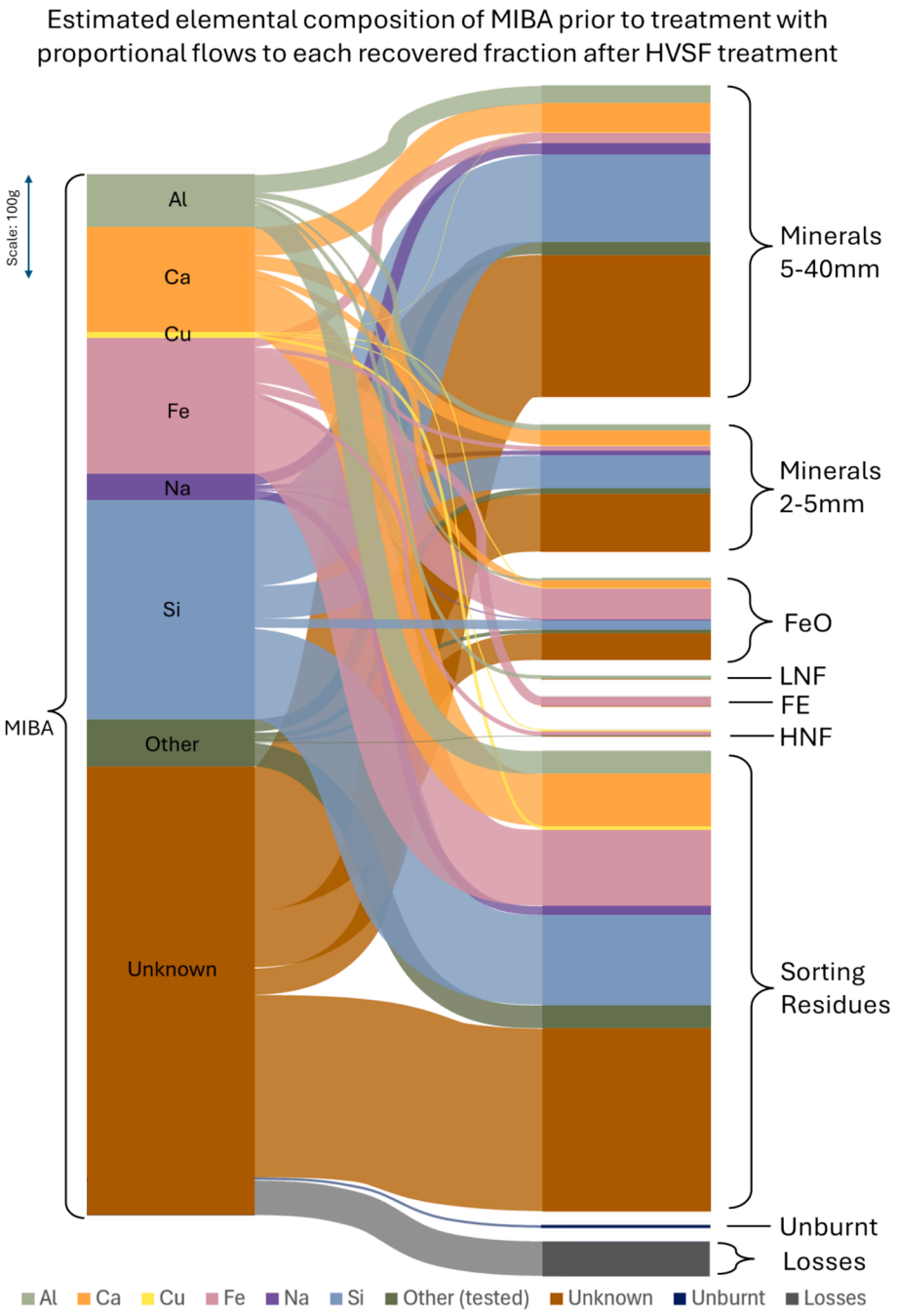

Fig. 3. Sankey diagram illustrating the estimated elemental flows normalised to 1 kg of MIBA to each of the fractions recovered by using the HVSF lab-scale method based on the content analysis results. A total of 27 elements were tested: six of the largest flows are shown with the further 21 elements grouped as 'Other'. The remaining elements which were not tested and consisted of the remaining sample, as well as the material lost during the treatment or recovered as unburnt combustible material, were labelled 'Unknown'. FE = ferrous metals, HNF = heavy non-ferrous metals, LNF = light non-ferrous metals, FeO = iron oxide.

and 2, respectively from the three considerably more homogenous metal fractions, LNF, FE, and HNF, with ferrous metals accounting for the largest portion. As the MIBA had already been metal sorted before the treatment, the results indicate the additional metals that could be obtained from the HVSF process. The most valuable metal fraction is the HNF e.g. copper and brass, however, less valuable metals, such as stainless steel, can also be present in this fraction due to low selectivity between metal types. To evaluate the distribution, the HNF fraction from WtE-2 was washed in weak acid and resulted in approximately 22 % copper and brass. A further 47 % was identified as magnetic white metals such as stainless steel, lead, and other low-magnetic metals. The last 32 % was white non-magnetic metals, consisting mainly of stainless

steel.[1]

Based on these experiments, the estimated value of metal resources gained by treating all Swedish IBA with HVSF, is between 9.6 M€/y (WtE-2) and 17.6 M€/y (WtE-1).

3.3. FeO

In Fig. 3, the FeO fraction can be seen to contain a higher proportion of Fe, where O is likely the main constituent of the 'Unknown' to form FeO, achieving a higher level of homogeneity than the reference MIBA. It also highlights that almost 30 % of Fe present in the MIBA was concentrated into the FeO and the FE fraction. To better understand the usability of the FeO fraction, the Swedish and Swiss FeO fractions are compared in Table 1 to limit values not to be exceeded to use waste as clinker corrective according to Annex 4 in the Swiss Waste Ordinance (Swiss Federal Council, 2015). However, the Waste Ordinance further states that waste consisting of mainly iron only needs to adhere to limits for Cd, Hg, Tl, and organic substances, as well as not exceeding 5 wt% of the total quantity of used raw meal corrective substances. The presence of organic substances is minimal in inorganic bottom ash with TOC usually around 1 wt% compared to the limit of 5 wt% (Karlfeldt Fedje et al., 2021). Additionally, unburnt i.e. organic material, is sorted out from this fraction. This means the FeO fraction would adhere to Swiss limit values for clinker corrective (no equivalent Swedish values could be found at the time of writing).

3.4. Minerals

The mineral fractions are not significantly different in composition to the reference MIBA in Fig. 3, showing little improvement in homogeneity. However, considering the potential use as aggregate replacement, the leaching properties are of higher interest than the homogeneity of this fraction. Therefore, the total elemental contents for Swedish and Swiss minerals and leaching from Swedish mineral fractions are presented in Tables 2 and 3, respectively. The values are compared with guidelines from the SEPA considering construction with material with less than minor risk i.e. free use (SEPA, 2010). Additionally for comparison, average values for total contents and leaching for 23 crushed rock materials (Ekvall et al., 2006) and crushed rock for road construction (Lidelöw & Lagerkvist, 2007; Lidelöw et al., 2017) are given. The mineral fractions do not meet guidelines for total content and fail to meet leaching guidelines for anions, but meet elemental leaching guidelines from SEPA.

3.5. Sorting residues

The total contents in the sorting residues from WtE-1 and WtE-2, together with a representative sorting residue from the HVSF process, SF, are shown in Table 4. These are compared with the reference MIBA sample handled according to typical IBA treatment (Nordic Council of Ministers, 2022). Table 5 summarises the leaching from the same samples, in addition to SEPA limit values for depositing waste in landfills for inert, non-hazardous, and hazardous waste (SEPA, 2004). Please note that the SF sample is tested according to another method i.e. DIN EN 12457–4:2003–01, than the one stated by SEPA, and why the results should be seen as indicative since the DIN method might result in somewhat lower leaching.

[1] Stainless steels can possess paramagnetic or ferromagnetic properties, depending on the presence of austenite, ferrite and martensite structure in the material (Bazri et al., 2024; Lyamkin et al., 2019; Vitos et al., 2003). The structure may also change upon material deformation, affecting the magnetic properties (Lyamkin et al., 2019).

4. Discussion

4.1. Metals

Additional metal recovery was achieved through utilising the HVSF method on Swedish MIBA which could lead to the realisation of metal reserves up to 17,600 t/y worth an estimated 18 M€, if the method could achieve the similar results on all Swedish MIBA as achieved in this lab scale experiment. This would align WtE practices more with circular economy principles by increasing the value recovery.

The recovered metal fractions were also more homogenous (cleaner) since contaminants and dust are removed from the surface by the HV pulse power, as well as due to the various wet treatments in the HVSF method which can reduce negative impacts during the refinement stages for the metals and thus increase the metal price. However, as can be seen from Fig. 3, a large amount of metallic elements are still lost in sorting residue and mineral fractions, but it is not known how much is in metallic form and, consequently, accessible, rather than bound in compounds. Therefore, determining the process's effectiveness, specifically the proportion of recovered metals relative to the total extractable metals in the MIBA, is challenging as it requires advanced analytical methods. A study by Tiberg et al. (2021) showed that between 10 and 40 % of all Cu in MIBA was metallic copper, but this Cu is likely difficult to recycle with mechanical methods, as Cu is present in very fine pieces. There are innovative methods for fine treatments, for example those described by Glauser and Weh (2022) and Mühl et al. (2024), that should be investigated to further increase the recovery of finer metals. As the focus of this study was to investigate the additional recovery of metals through HVSF, the effectiveness and treatment of fine material were not assessed further.

There is also the potential for environmental savings from replacing virgin materials with secondary materials. Tabereaux and Peterson (2014) state that 13.2 kWh/kg is needed for primary aluminium production. Assuming the LNF metals constitute only aluminium, approximately 51.9 kWh/t MIBA could be offset from virgin aluminium production due to the increased aluminium recovery from the application of the HVSF method. The estimated energy consumption of the HVSF is given as 5 kWh/t IBA by Weh and Mosaddeghi (2016), and the energy consumption of handling IBA in one Swedish plant in 2014 was 0.92 kWh/t IBA; although the energy consumption of treating IBA can vary greatly within Europe (Neuwahl et al., 2019). The HVSF alone is considerably more energy intensive than a Swedish plant; but with the potential offsets from virgin aluminium production, the method has the opportunity in saving more energy than it consumes at a societal level through additional metal recycling. Note that contributions from transportation to and from the sites are not included in the energy consumptions.

However, achieving the same efficiency observed in this lab-scale experiment in a commercial setting is unlikely. Further assessment is needed to determine the economic feasibility of implementing the HVSF method in Sweden, including potential impacts from economic factors such as metal prices or tax incentives. This evaluation is necessary to establish whether HVSF would be beneficial in the Swedish context.

4.2. FeO

As expected, the FeO consisted of a large share of iron at 30–40 wt%, as seen in Table 1 and Fig. 3. Furthermore, other metals including Co, Ni and Cr were enriched in the FeO fraction compared to the minerals. The total content analysis of FeO indicated that the Swedish and Swiss fractions were similar, but the Swedish fractions had a higher content of As, Cd, Pb and S than the Swiss fraction. WtE-1 had much higher values of Ni than WtE-2 and SF; and WtE-2 had much higher values of Sb than WtE-1 and SF. This could be due to differences in the waste incinerated which should be investigated in the future. However, all fractions were acceptable with regards to the limits set by Swiss law for waste

Table 3
Comparison of leaching according to SS-EN-12457–3 [mg/kg DS] from the Swedish minerals with crushed rocks (Ekvall et al., 2006; Lidelöw & Lagerkvist, 2007), and corresponding guideline values from SEPA (2010) to the right.

Element [mg/kg DS]	Minerals 2 -< 5 mm WtE-1	Minerals 2 -< 5 mm WtE-2	Minerals 5 < 40 mm WtE-1	Minerals 5 < 40 mm WtE-2	CRUSHED ROCKS Average of 23 samples (Ekvall et al., 2006)	Single sample (Lidelöw & Lagerkvist, 2007)	SEPA Guideline values (SEPA, 2010)
As	0.03	0.02	0.02	0.01	0.01	0.52	0.09
Ba	0.33	0.81	0.41	0.64	0.04	0.59	–[1]
Cd	< 0.0005	< 0.0005	< 0.0005	< 0.0006	0.0045	0.0016	0.02
Cr	0.05	0.06	0.06	0.07	0.08	< 0.01	1
Cu	0.42	0.38	0.60	0.48	< 0.05	0.02	0.8
Hg	< 0.0002	< 0.0002	< 0.0002	< 0.0002	<0 .015	na[2]	0.01
Mo	0.24	0.24	0.40	0.40	0.09	na	–
Ni	0.02	0.01	0.02	0.01	0.05	< 0.001	0.4
Pb	< 0.002	< 0.002	< 0.002	< 0.002	0.013	0.034	0.2
Sb	0.27	0.60	0.30	0.57	0.004	0.055	–
Se	< 0.02	< 0.02	< 0.02	< 0.02	0.05	na	–
Zn	< 0.02	< 0.02	< 0.02	0.03	0.06	0.02	4
Anions and pH [mg/kg DS]							
Cl^-	< 100	120	220	220	na	27	130
SO_4^{2-}	2,200	1,900	2,400	2,300	na	30	200
pH	10.4	10.6	11.0	11.0	na	na	–

[1] No guideline value exists.
[2] Not analysed.

Table 4
Total contents [mg/kg DS] in sorting residues from WtE-1, WtE-2, and a representative sample from Switzerland, SF. For comparison, average total contents in nine Nordic MIBA samples are given (Nordic Council of Ministers, 2022).

Element [mg/kg DS]	SORTING RESIDUES WtE-1	WtE-2	SF	MIBA samples for comparison (Nordic Council of Ministers, 2022)
Al	52,000	47,000	43,000	52,000
As	22	21	8.0	25
Ba	2,400	3,700	na[1]	2,100
Ca	120,000	110,000	220,000	110,000
Cd	1.0	2.4	9.0	5.2
Co	61	74	< 1	120
Cr	1,000	880	260	760
Cu	6,500	7,700	2,900	3,800
Fe	210,000	120,000	50,000	100,000
Hg	< 0.05	< 0.05	na	0.1
K	7,500	10,000	9,000	10,000
Mg	15,000	12,000	13,000	11,000
Mn	2,600	2,000	1,500	1,300
Mo	50	45	na	32
Na	20,000	20,000	12,000	22,000
Ni	390	350	180	300
P	3,000	3,400	12,000	4,400
Pb	872.5	700	860	860
S	4,700	5,000	21,000	4,900
Sb	67	240	120	83
Se	< 9	< 5	na	2.0
Si	170,000	220,000	130,000	190,000
Sn	140	150	na	150
Sr	440	420	na	370
Ti	9,300	8,300	11,000	8,000
V	76	130	na	52
Zn	3,300	3,500	3,900	4,000

[1] Not analysed.

consisting primarily of iron to be used in clinker production as raw meal corrective substances, but with the limitation to not exceed the total amount of 5 wt% (Swiss Federal Council, 2015).

It is possible to use mill scale, which is a rest product from iron manufacturing (Er et al., 2022), in clinker production according to Young and Norris (2002); and the mill scale should consist of 65–70 wt% Fe (Schmidt, 2003). This indicates that the FeO fraction could become more suitable for clinker production if it were further enriched with Fe to resemble mill scale.

Research has also been done on incorporating 10–30 wt% of mill scale in fired clay bricks, with findings that these bricks possess increased compressive strength and lower porosity compared to traditional bricks (Er et al., 2022). Bricks containing mill scale are concluded to be satisfactory as construction products since the obtained compressive strength comfortably passed specified minimum limits in building standards (Er et al., 2022). Furthermore, Er et al. (2022) found that incorporating the mill scale in bricks could mitigate the leaching of hazardous elements, such as metals, from the mill scale. Therefore, enriching the FeO fraction with more Fe could potentially make the fraction suitable for both clinker and brick production.

However, this must be evaluated to identify an enrichment technique compatible with the HVSF method. If such enrichment would be possible, the amount of FeO fraction diluted in the materials must be considered to ensure that the content of these materials is within acceptable limits and can be handled correctly throughout their life cycle. If the FeO fraction could be further refined or used directly in these industries, extra value could be recovered from the MIBA.

4.3. Minerals

Generally, it could be concluded that there was no distinct difference between the fine and coarse mineral fractions for WtE-1 and WtE-2, as seen in Table 2 and Fig. 3, while some noticeable differences were seen between the Swedish and Swiss minerals. The Swiss minerals contained less As, Sb, Cr, Cu, and Zn than the Swedish minerals. On the contrary, the Swiss minerals incorporated more Ca, Cd, and S. This could, again, be connected to differences in the feed material to the incineration plants, which should be investigated in the future to determine sources of variation. Additionally, the use of MIBA instead of fresh IBA could influence this.

Data for rock materials and crushed rock were included for comparison considering the use of MIBA as a construction material. Generally, the aggregate materials had lower shares of all elements compared to the minerals except for elements Al, Fe, K, and Mg for the crushed rock; and Co for the rock materials.

Table 5
Leaching [mg/kg DS] from sorting residues from WtE-1, WtE-2, and a representative sample from Switzerland, SF. For comparison, leaching from the original MIBA samples, WtE-1 and WtE-2 and the limit values for depositing waste into landfills are shown (SEPA, 2004). All leaching tests were done according to SS-EN-12457–3, except for the SF sample, which was done using the one-step leaching test DIN EN 12457–4:2003–01. Values exceeding the limit for inert waste are marked in bold, while values exceeding non-hazardous waste are marked in bold and italic.

	Sorting residues			Original MIBA		Landfill depositing limits (SEPA, 2004)		
Elements	WtE-1	WtE-2	SF	WtE-1	WtE-2	Inert	Non-hazardous	Hazardous
[mg/kg DS]								
As	0.02	0.01	< DL[1]	0.03	0.03	0.5	2	25
Ba	0.44	0.78	1.2	0.6	0.88	20	100	300
Cd	< 0.0005	< 0.0006	< DL	0.001	0.003	0.04	1	5
Cr	0.15	0.13	**2.4**	0.7	0.28	0.5	10	70
Cu	0.53	1.1	**12**	**4.2**	1.8	2	50	100
Hg	< 0.0002	< 0.0002	< DL	< 0.00005	0.0006	0.01	0.20	2
Mo	0.31	**0.63**	**1.7**	0.45	1.1	0.5	10	30
Ni	0.02	0.02	0.05	0.1	0.04	0.4	10	40
Pb	< 0.002	< 0.002	0.013	0.008	0.013	0.5	10	50
Sb	**0.35**	***1.6***	**0.19**	**0.3**	***0.73***	0.06	0.7	5
Se	< 0.02	< 0.02	< DL	0.04	0.04	0.1	0.5	7
Zn	< 0.02	< 0.02	0.13	0.02	0.12	4	50	200
Anions, DOC and pH [mg/kg DS]								
Cl^-	200	360	**1,400**	**5,300**	**3,200**	800	15,000	25,000
F^-	< 1	5.0	< DL	5.2	5.2	10	150	500
SO_4^{2-}	**2,800**	**5,200**	**3,800**	**9,800**	**7,800**	1,000	20,000	50,000
DOC	100	130	430	51	160	500	800	1,000
pH	10.2	10.1	10.9	10.1	10.0	–[2]	–	–

[1] Below detection limit.
[2] No guideline value exists.

The MIBA minerals exceeded guideline values set by SEPA for several elements. However, from an environmental perspective, the leaching is more important to evaluate than the total contents. If comparing the MIBA minerals with the rock materials, the MIBA material leached more of Ba, Mo, Cu and Sb, but less of elements like Cd and Pb (see Table 4). Despite this, all MIBA minerals passed SEPA leaching guideline values except for chloride and sulphate, where only the 2 -< 5 mm mineral fraction passed the limit for chloride. The material has undergone several washing steps, but additional washing steps would likely lower the chloride leachability further, yet it is unlikely to reduce sulphate mobility sufficiently, as the leaching is about ten times higher than the limit for unlimited use (see Table 3). Instead, stabilisation of the sulphates is an option e.g. by adding ground granulated blast furnace slag, which has been shown to reduce leaching from sulphate-rich soils by 90 % (Caselles et al., 2020) and is suggested as area of research in the future.

If the leaching cannot be reduced further, an alternative would be to use the minerals in a bound process or for road construction, where water access is limited. This must however be evaluated from legislation, environmental, and civil engineering perspectives. The content of e.g. crushed glass in the minerals should also be assessed, as it may affect the civil engineering properties, and be subject to recycling. The minerals could plausibly be used as raw material in the clinker industry, with the condition that they would pass all the waste limit values seen in Table 1. This is not fulfilled for the studied samples, as the contents of As, Pb, Sb, and Zn are near or above the limits.

4.4. Sorting residues

Generally, the total contents in the sorting residues WtE-1 and WtE-2 were lower or comparable to the amounts in the average MIBA sample, except for Cu, Mn, and Fe (see Table 4). These elements were also higher in the sorting residues compared to the SF sample. Contrarily, the amounts of Ca, P, and S were higher in the SF sample.

The releases of most elements from the sorting residues from WtE-1 and WtE-2 are comparable or lower relative to the general MIBA, and SF samples are indicatively below the limit for depositing waste in a non-hazardous landfill (see Table 5). However, the most important leaching difference is the mobility of Sb, which exceeds the limit for inert waste in both original and residual MIBA samples. For the WtE-2 residue, the leaching increases and exceeds the limit for non-hazardous waste.

The leachability of Sb is very complex and depends on both pH and oxidation state. The more mobile Sb(V) is the dominating state in IBA and at alkaline pH values the leaching is highest at pH around 10 (Simon & Scholz, 2023; Vogel et al., 2024), which is similar to the pH values observed in this work (Table 5). The bulk pH values are similar in both treated and original samples, but pore leachate pH values could differ from the bulk pH which could influence the Sb leaching. This has, however, not been evaluated in the present study. In addition to pH and oxidation state, the increased mobility of Sb is suggested to be due to the dissolution of Fe- and Ca- antimonate, where high Sb concentrations in the leachate correlate with low Ca concentrations (Kalbe & Simon, 2020; Simon et al., 2021; Simon & Scholz, 2023; Verbinnen et al., 2017). The Ca concentration was not analysed in the leachates in this study but water-soluble Ca compounds like $CaCl_2$ are likely washed out during the HVSF process and thus enhance Sb leaching from the residues. Additional washing might decrease the Sb leaching, but more research is needed to better understand this complex process (Staffas et al., 2016; Tian et al., 2024).

The anion leaching is significantly lower in the treated residues, which is likely due to the washing steps included in the HVSF method. However, the release of SO_4^{2-} still exceeds the limit for inert landfills (see Table 5). The total contents of S in the Swedish MIBAs are comparable before and after treatment and significantly lower than in the SF sample, but the sulphate leaching is higher in the original MIBA samples. This shows that the HVSF process efficiently reduces the sulphate mobility, but not enough to pass the limit for inert waste. Studies on MIBA have shown that the sulphate leachability decreases with time (Kalbe & Simon, 2020; Simon et al., 2021) but stabilisation, as discussed in 4.3, is likely more efficient if the leaching should be reduced quickly (Caselles et al., 2020).

The sorting residue from WtE-2 also exceeded the inert limit for Mo. This was also the case for the SF sample, which also exceeded limits for inert waste for e.g. Cr and Cu. The reason for the higher leaching from the SF residue could be natural variations in the waste, but is more likely

caused by the fact that the SF residue originates from fresh IBA while MIBA was used for the Swedish samples. The latter is also confirmed by the higher pH in the SF residue, as seen in Table 5. During storage of the ash, i.e. carbonation, new compounds that influence metal leachability and recovery potentials are formed. Tests on fresh IBA are suggested to evaluate this. However, the leaching of ions from ash is very complex and to fully understand the processes, detailed work is needed which is not in the scope of this study.

From a leaching point of view, the MIBA residues from the HVSF method could be treated the same way as the MIBA is treated today (SEPA, 2004). However, the construction qualities are different as the washing steps reduce both the pozzolanic properties as well as the particle size; and experiments must be compiled to evaluate these effects of the treatment.

4.5. General Discussion

Despite the increase in metal recovery, the likely reduction in performance of the remaining fractions as construction materials could lead to a decrease in the utilisation of MIBA in the Swedish context. To investigate the applicability of the different fractions for other uses, the results of chemical composition and leaching were compared with the guideline values given by SEPA regarding recycling of waste (SEPA, 2010), where the results must be lower than the guideline values for the waste to be considered recycled and be usable without limitation in Sweden. None of the sorting fractions achieved the limits set by SEPA, and it is unlikely that these materials can be refined to reach these limits. From a Swedish perspective, the regulations would need to be revised to promote the utilisation of waste in different construction uses i.e. increased limit values or specific applications where waste materials not fulfilling the limits set by SEPA (2010) could be used; and is a suggested area of investigation for the future.

It is noticeable that virgin crushed rock used for road construction in Sweden, also exceeded the SEPA limits for some elements (Lidelöw & Lagerkvist, 2007; Lidelöw et al., 2017) along with the average 23 crushed rock materials (Ekvall et al., 2006). This highlights that the requirements are different depending on whether the material is considered waste or a product, even though the application does not distinguish between them. It indicates that a conflict between striving for a more circular society and reducing hazardous elements exists where trade-offs may need to be established in future legislation.

The results from the total content analyses showed that several elements on the Critical Raw Materials (CRM) list are present, e.g. Mg, Co, V, Cr, Cu, and Ni (European Commission, 2023a). The current study did not investigate the potential of recovery for CRM but this could be of interest in the future to help reach goals set by the EU to acquire 25 % CRM from recycled materials (European Commission, 2023a).

The overall results indicate that to enable the use of the separated fractions from chemical, civil engineering, and legislation perspectives, more work is needed. Additionally, if HVSF is implemented in full-scale, the more reactive IBA should be used instead of MIBA, which would result in somewhat different properties of the sorting fractions and thus tests are needed.

This study used two samples from large-scale plants in Southern Sweden with a lab-scale version of the HVSF method, reflecting the study's exploratory nature. Further research is needed to determine how representative these results are for Sweden in general. As noted in Section 4.1, an assessment of the full-scale HVSF method's efficiency and economic feasibility in the Swedish context is necessary. Additionally, since the HVSF method involves extra sorting steps that overlap with existing IBA processing to produce MIBA, it would be valuable to test IBA samples from Sweden to explore efficiency improvements as well as property improvements, particularly as some metal recovery in the study occurs through only additional sorting and do not require the HVSF. Both plants are among the larger plants in Sweden, so it would also be beneficial to include samples from smaller plants in less urban areas to enhance generalisability, along with variations in waste streams into the systems. Finally, due to the limited sample size, further sampling and application of the HVSF method are recommended to verify the results' consistency.

5. Conclusion

This laboratory study investigating the potential to increase value recovery and utilisation of MIBA in the Swedish context indicates more value can be recovered from the MIBA from increased metal recovery using the HVSF method. This identifies a potential metal resource of 9,600 to 17,600 t/y within MIBA across the country and further research is recommended to investigate if this technology could be used to identify new metal reserves in the Swedish waste industry i.e. if the technology is commercially feasible.

Differences in chemical composition and leaching behaviour were determined and showed noticeable variations between Swedish and Swiss waste compositions. When analysing the further fractions recovered using the HVSF method, no use cases could be found in the current Swedish context and further research is needed to investigate if these fractions could be utilised through further treatment for better enrichment, or in new use cases under appropriate updates to regulations in the future. The most promising potential utilisation was identified in clinker production for the FeO fraction which is recommended to be investigated further. For the mineral fractions, future research is encouraged to determine the civil engineering characteristics of the material for its applicability as an aggregate replacement before work is done on whether further treatment can be conducted to bring the material within SEPA limits.

From a broader perspective, this explorative study has also highlighted differences in regulation for virgin and secondary materials which may limit the use cases for secondary materials, and more research is encouraged into how regulations can stimulate the use of secondary materials for a more circular economy without increasing risk to the environment and human health. The potential for exceptions for certain use cases, like that of aggregates, is one possibility that could be investigated. In conclusion, further research is essential to develop new methods for enhancing metal recovery and optimising IBA/MIBA use in line with circular economy principles for the future.

CRediT authorship contribution statement

Lisa Dacklin: Writing – review &, editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Christina Lee:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Conceptualization. **Karin Karlfeldt Fedje:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Alexander Weh:** Visualization, Validation, Resources, Methodology, Investigation, Data curation. **Andreas Glauser:** Visualization, Validation, Resources, Methodology, Investigation, Data curation. **Raul Grönholm:** Writing – review & editing, Validation, Resources, Methodology, Investigation, Funding acquisition, Conceptualization. **Fredrik Björckebaum:** Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Magnus Evertsson:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2025.01.015.

Data availability

Data will be made available on request.

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