



## Research Paper

# Substance flows of heavy metals in industrial-scale municipal solid waste incineration bottom ash treatment: A case study from Austria

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## ABSTRACT

While standard municipal solid waste incineration bottom ash (IBA) treatment aims to recover only ferrous and non-ferrous metals, enhanced treatment of IBA also promotes a recovery of glass and the mineral fraction. In this study, an enhanced dry-wet IBA treatment plant consisting of commonly applied dry process units, including several screens, a crusher, magnetic and eddy current separators and rarely applied wet process units, including a wet jigger, falcon concentrators and a wet shaking table, was evaluated for its ability to treat IBA from grate (G) and fluidized bed (FB) incineration. The process was examined on a material and substance flow level with regard to Ag, Cd, Co, Cr, Cu, Mn, Ni, Pb, Sb and Zn. It was found that the wet process units separated 52% of the total substance load of the aforementioned substances from G-IBA, while only 28% were separated from FB-IBA. The dry process units separated 57% from FB-IBA, while only 21% from G-IBA. The balance was found to remain in the mineral fraction of G-IBA (27%) or to be split between glass (7%) and mineral fraction (7%) of FB-IBA. While FB-IBA treatment was described for the first time on a substance flow level, transfer coefficients of 57–73% into the mineral fraction were reported for other G-IBA treatment plants for the substances investigated. Gravity separation was found to be able to promote the conservation of metallic resources and to deplete the total contents of heavy metals in the mineral fraction, which is favorable in terms of utilization.

## 1. Introduction

## 1.1. Resource recovery from waste incineration bottom ash

Municipal solid waste incineration (MSWI) is the most important treatment technology for non-recyclable mixed municipal solid waste (mMSW) in the EU 27 (Pomberger et al., 2017). While combustible materials leave MSWI plants through the off-gas, unburnable materials like minerals and metals end up either in the air pollution control residues or in the MSW incineration bottom ash (IBA) (Hellweg et al., 2001; Quina et al., 2018). The latter, which accounts for the quantitatively most important solid output of MSWI, contains materials having the potential to be used as secondary raw materials. While the recovery of metals, which account for 6–20 % in untreated IBA, has a long tradition in many countries (Syc et al., 2020), utilization of the mineral fraction is

not yet very common. The main reason for this is the remaining content of unwanted substances in the mineral fraction after standard IBA treatment (Verbinnen et al., 2017).

## 1.2. Enhanced IBA treatment

Enhanced IBA treatment aims to minimize the entry of unwanted substances like heavy metals into the mineral fraction to develop its potential as a secondary resource in the construction sector (Blasenbauer et al., 2020). This can be accomplished by directing those substances into metal fractions, where they can potentially be recycled, or by separating them into landfilling fractions that are disposed of in safe final sinks. There are a large number of studies that have investigated different technologies for enhanced IBA treatment on a laboratory or pilot scale (Abis et al., 2020; Alam et al., 2017; Glauser et al., 2021; Kalbe and Simon, 2020; Mühl et al., 2023; Pfandl et al., 2020; Poranek

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|                                 |                                                  |                                                            |                                                                                     |
|---------------------------------|--------------------------------------------------|------------------------------------------------------------|-------------------------------------------------------------------------------------|
| <b>Nomenclature</b>             |                                                  | $x$                                                        | mass fraction of a sub-good in a sample                                             |
| <b>Abbreviations</b>            |                                                  | $\omega$                                                   | mass fraction of a size class of a sample                                           |
| MSWI                            | municipal solid waste incineration               | $\dot{x}$                                                  | substance flow                                                                      |
| mMSW                            | mixed municipal solid waste                      | $\dot{m}$                                                  | mass flow                                                                           |
| IBA                             | incineration bottom ash                          | TC                                                         | transfer coefficient                                                                |
| FB-MSWI                         | fluidized bed municipal solid waste incineration | <b>Index and Description (possible values in brackets)</b> |                                                                                     |
| G-MSWI                          | grate municipal solid waste incineration         | i                                                          | substance (Ag, Cd, Co, Cr, Cu, Mn, Ni, Pb, Sb, Zn)                                  |
| FB-IBA                          | fluidized bed incineration bottom ash            | j output                                                   | output flows of IBA treatment plant (1,...,16)                                      |
| G-IBA                           | grate incineration bottom ash                    | j 1                                                        | first subset of output flows (Fe >50, Fe crusher, Fe <50, MS met >50, MS unb >50)   |
| MFA                             | material flow analysis                           | j 2                                                        | second subset of output flows (Sludge SB, Sludge C, Fstp Fe, Fstp NFe, ECS 2, MIN)  |
| SFA                             | substance flow analysis                          | j 3                                                        | third subset of output flows (HF jigger, Unb jigger, ECS 1 Al, ECS 1 mix, Glass >9) |
| TC                              | transfer coefficient                             | p                                                          | considered sub-goods containing a specific substance (1, ...,11)                    |
| ECS                             | eddy current separator                           | > 4                                                        | size class greater than 4 mm of sieved sample                                       |
| DM                              | dry matter                                       | < 4                                                        | size class smaller than 4 mm of sieved sample                                       |
| Fe                              | ferrous metals                                   | input                                                      | input material (untreated IBA) into IBA treatment plant during experiment           |
| NFe                             | non-ferrous metals                               | output                                                     | output material within output flows of treatment plant during experiment            |
| sSD                             | sample standard deviation                        |                                                            |                                                                                     |
| n.a.                            | not analysed                                     |                                                            |                                                                                     |
| n.d.                            | not detected                                     |                                                            |                                                                                     |
| n.p.                            | not produced                                     |                                                            |                                                                                     |
| <b>Variable and Description</b> |                                                  |                                                            |                                                                                     |
| c                               | substance content                                |                                                            |                                                                                     |

et al., 2022; Santos et al., 2013). In contrast, few studies have also conducted their investigations on an industrial scale (Holm and Simon, 2017; Mehr et al., 2021; Muchova, 2010; van der Wegen et al., 2013). Such latter studies are, however, important to determine whether the desired results achieved in laboratory or pilot experiments can be realized on an industrial scale.

1.3. Substance flows in IBA treatment

When it comes to measuring the success of diverting unwanted substances from the mineral fraction of IBA, the fate of those substances during IBA treatment must be known (Huber, 2020). A useful tool for determining this is Substance Flow Analysis (SFA). As part of Material Flow Analysis (MFA), SFA uses material flow and substance content data to determine the distribution of substances to different material flows (Brunner and Rechberger, 2016). This distribution is described by transfer coefficients (TCs), which are strong indicators for evaluating the performance of waste treatment processes (Arena and Di Gregorio, 2014). While there is a large number of such SFA studies on other waste treatment processes (Andersen et al., 2011; Arena and Di Gregorio, 2013; Funari et al., 2015; Jensen et al., 2017; Jung et al., 2006; Morf et al., 2013; Rotter et al., 2004), a surprisingly small number of SFA studies are available on IBA treatment. Mehr et al. (2021) and Glauser et al. (2021) used SFA to compare different IBA treatment plants in Switzerland. However, they focused on sparingly applied dry discharge technology (Šyc et al., 2020). By contrast, Huber (2020) performed a SFA for treatment of wet-discharged IBA using secondary data from Allegrini et al. (2014), Holm and Simon (2017), Pfandl et al. (2020). Although various IBA treatment processes were investigated in these studies, all of them deal with grate incineration bottom ash (G-IBA). According to the best knowledge of the authors of this study, no SFA has yet been performed on the enhanced treatment of fluidized-bed incineration bottom ash (FB-IBA), despite its relevance in countries like Austria, China and the US (Leckner and Lind, 2020).

1.4. Research questions and objectives

Against this background, it becomes obvious that too little is known

about the fate of substances in enhanced IBA treatment, taking different types of IBA from grate and fluidized bed incineration into consideration. In order to minimize this research gap, the present study asks the following research questions: (i) What are the material flows of IBA from grate and fluidized bed MSWI in a dry-wet IBA treatment process on an industrial scale? (ii) What are the total contents of the substances Ag, Cd, Co, Cr, Cu, Mn, Ni, Pb, Sb and Zn in the output flows of this process for both types of IBA? (iii) What are the recalculated total contents of these substances in both IBAs and do they accord with previous studies on the same IBAs? (iv) What are the substance flows in this process for both types of IBA and which process units remove the bulk of these substances? (v) How does this plant perform in comparison to other plants described in the literature?

Based on these research questions, the objectives of this study were to describe an enhanced dry-wet treatment process on a material and substance flow level and to identify distinctions in G-IBA and FB-IBA treatment. This included determining the material flows of goods, substance contents and flows and transfer coefficients.

2. Materials and methods

2.1. Experimental determination of material flows in IBA treatment

2.1.1. IBAs used for the experiments

The IBAs of two different MSW incinerators were investigated. Both incinerators are located in an area with a uniform waste management system in Austria. One incinerator is a bubbling FB incineration plant that incinerates 100,000 t/yr of mechanically pretreated mMSW together with 20,000 t/yr of municipal sewage sludge. The pre-treatment includes shredding and screening and is applied to obtain a particle size suitable for FB incineration (Blasenbauer et al., 2023). The bed temperature is kept intentionally below 660 °C by under-stoichiometric air staging to prevent ash sintering and fouling, while the Waste Incineration Directive is fulfilled in the free board (gas zone) above the bed where the temperature reaches 930 °C (Kirnbauer & Kraft). Discharge of solid IBA is conducted at the bottom of the reactor. IBA is air-cooled and screened at 2 mm to recover the bed material (Krobath and Thomé-Kozmiensky, 2004). Only coarse IBA is collected

and discharged directly, while the bed material and the fine fraction of IBA is recirculated several times before being discharged (Kellner et al., 2022). The other MSWI plant is a grate incinerator with an annual capacity of 250,000 t/a. The waste input is mMSW, bulky and commercial waste (Huber et al., 2020). The temperature in the fuel bed of grate incinerators is reported to reach 1100 °C, while the flue gas temperature lies above 900 °C (Bunge, 2018; Leckner and Lind, 2020). The IBA is discharged into a water bath followed by magnetic ferrous metal separation when the IBA is conveyed into piles for temporal storage (Huber et al., 2020).

### 2.1.2. IBA treatment plant used for the experiments

The IBA treatment plant used is also located in Austria. The treatment process includes dry and wet process units (see Fig. 1). A short overview on the process is given in the following paragraph and a description of the material flows, which are given in short names, can be found in Table 1.

The dry process units include several screens, a crusher, several overbelt magnets, one drum magnet and two eddy current separators (ECS). The first ECS has two splits to obtain three material fractions: concentrate (ECS 1 Al), middling (ECS 1 mix), and treated IBA. The drum magnet and the second ECS at the end of the process chain aim to extract as many small metallic particles as possible in order to minimize their entry into the mineral fraction. When FB-IBAs are treated, the material stream >9 mm passes a sensor-based sorter to recover glass cullet >9 mm, while the separation of cullet in the fraction <9 mm is not economical for the plant operator. In G-IBA treatment, cullet separation is not economical at all due to the lower glass quality and the amount that can be obtained (Blasenbauer et al., 2023; Mühl et al., 2024), and the material stream >9 mm is recirculated into the crusher. The wet process units include a jigger that combines classification by particle size and density, a hydrocyclone to remove the suspended particles <0.1 mm with the process water flow, and a fine slag treatment plant (Fstp), which is a module from Sepro Urban Mining for the IBA fine fraction

0.1–4 mm to recover heavy non-ferrous metals by gravity separation with falcon concentrators and a wet-shaking table. A ferro-magnetic fraction is also separated in the Fstp by a drum magnet, while the 0.1–4 mm light fraction is recombined with the 4–50 mm light fraction. The process water with suspended ultrafine particles is passed through a sedimentation basin which allows the particles to settle before entering a dewatering centrifuge. The clear process water is recirculated in the process, while particulate matter is separated and landfilled as sludge.

### 2.1.3. Experiments

Two experiments on an industrial scale were carried out in the IBA treatment plant, described in Section 2.1.2.: one with FB-IBA and one with G-IBA, treating a total of 190 t (dry matter DM) of each IBA for 8 h during the experiment. The preparation of the experiments included discharging the plant and operating it with the IBA to be analyzed in a ramp-up phase of 2 h to enable constant process parameters before the experiments started.

### 2.1.4. Sampling

For G-IBA 15 and for FB-IBA 16 output flows were sampled. Two aspects were addressed to archive representative sampling. First, the aspired sample size, respectively the mass, was calculated in advance. The minimum sample mass depends on the particle size, the abundance and the distribution of the particles that carry a characteristic feature of interest (e.g., content of a specific substance) and the desired precision for the determination of this characteristic feature (accepted sampling error) (Bunge and Bunge, 1999; Esbensen, 2019; Gy, 1998). Such particles are denoted as sub-goods in this study. An equation that considers all these attributes was proposed by Skutan and Brunner (2005) (Eq. (1)) and represents a modified version of the equation for minimum sampling mass by Bunge and Bunge (1999). It was used to calculate the minimum sampling mass with a relative standard deviation (rsd) of 10 % for each output flow. Since IBA is a very heterogenous material, a variety of sub-goods are present for each substance. Since the minimum

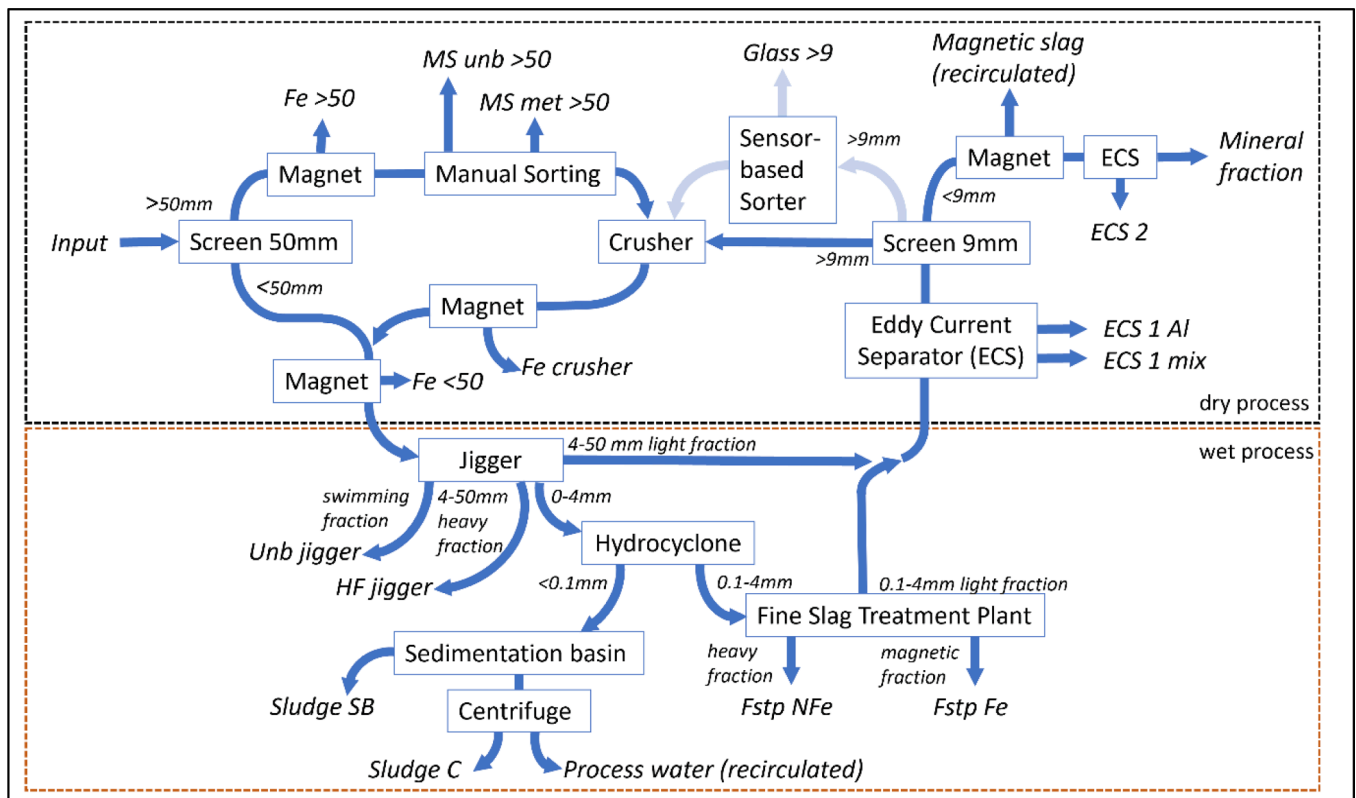


Fig. 1. Process scheme of dry-wet IBA treatment plant in Austria; material flows given in italics; process units shown in blue boxes.

**Table 1**

Definition of the IBA treatment plant output flows determined in this study; short names and descriptions were harmonized with Mühl et al. (2024).

| Output flow<br>j <sub>output</sub> | Short name | Sub-fraction               | Description of Output flow                                                                                      | Output flow Category     |
|------------------------------------|------------|----------------------------|-----------------------------------------------------------------------------------------------------------------|--------------------------|
| 1                                  | Fe >50     |                            | Magnetic ferrous metals >50 mm                                                                                  | Metals (Fe scrap)        |
| 2                                  | MS met >50 |                            | Manually sorted non-ferrous metals and stainless steel >50 mm                                                   | Metals (NFe scrap)       |
| 3                                  | MS unb >50 |                            | Manually sorted unburnt material >50 mm                                                                         | Residues                 |
| 4                                  | Fe crusher |                            | Magnetic ferrous metals after crusher                                                                           | Metals (Fe scrap)        |
| 5                                  | Fe <50     |                            | Magnetic metals fraction separated prior to jigger                                                              | Metals (Fe scrap)        |
| 6                                  | HF jigger  |                            | Jigger output: heavy fraction (material with high-density)                                                      | Metals (NFe concentrate) |
| 6.1                                | HF jigger  | metallic >4                | Heavy non-ferrous metals >4 mm                                                                                  | Metals (NFe scrap)       |
| 6.2                                | HF jigger  | metallic <4 & non-metallic | Metallic grains <4 mm and non-metallic fraction                                                                 | Metals (NFe concentrate) |
| 7                                  | Unb jigger |                            | Jigger output: floating material                                                                                | Residues                 |
| 8                                  | Fstp Fe    |                            | Magnetic ferrous material fraction <4 mm                                                                        | Metals (Fe scrap)        |
| 9                                  | Fstp NFe   |                            | Non-magnetic material fraction <4 mm                                                                            | Metals (NFe scrap)       |
| 10                                 | Sludge SB  |                            | Sludge from sedimentation basin                                                                                 | Residues                 |
| 11                                 | Sludge C   |                            | Sludge from dewatering centrifuge                                                                               | Residues                 |
| 12                                 | ECS 1 Al   |                            | Light non-ferrous metals from first ECS (concentrate fraction)                                                  | Metals (NFe concentrate) |
| 12.1                               | ECS 1 Al   | metallic >4                | Al scrap >4 mm                                                                                                  | Metals (NFe scrap)       |
| 12.2                               | ECS 1 Al   | metallic <4 & non-metallic | Metallic grains <4 mm and non-metallic fraction                                                                 | Metals (NFe concentrate) |
| 13                                 | ECS 1 mix  |                            | Mixture of Aluminum, non-ferrous metals, stainless steel, minerals and glass from first ECS (middling fraction) | Metals (NFe concentrate) |
| 13.1                               | ECS 1 mix  | metallic >4                | Aluminum, non-ferrous metals, stainless steel >4 mm                                                             | Metals (NFe scrap)       |
| 13.2                               | ECS 1 mix  | metallic <4 & non-metallic | Metallic grains <4 mm and non-metallic fraction                                                                 | Metals (NFe concentrate) |
| 14                                 | Glass >9   |                            | Glass fraction >9 mm                                                                                            | Glass >9                 |
| 15                                 | ECS 2      |                            | Non-magnetic metals from second ECS                                                                             | Metals (NFe concentrate) |
| 16                                 | MIN        |                            | Mineral fraction <9 mm                                                                                          | Mineral fraction         |

sampling masses depend on the abundancies of the sub-goods p ( $p = 1 \dots 11$ ) that carry the substances i ( $i = 1 \dots 10$ ), Eq. (1) had to be calculated separately for each combination of sub-good and substance and for each output flow j ( $j = 1 \dots 16$ ) individually. A list of the considered sub-goods p can be found in Table S1 in the supplementary material while the substances i are described in Section 2.3 and the output flows j in Section 2.2. After that, the highest value for the minimum sampling mass was selected for each output flow, ensuring that even the lowest abundant sub-good will be determined with a rsd value of 10 %.

$$M_{i,j,p} = \frac{1}{\omega_{i,j,p}} \cdot \frac{\bar{c}_i^2}{s_i^2} \cdot \frac{1}{1 + 3 \log \left( \sqrt[3]{\frac{m_{i,j,pmax}}{m_{i,j,p10\%}}} \right)} \cdot m_{i,j,pmax} \quad (1)$$

In Eq. (1),  $M_{i,j,p}$  is the minimum sampling mass for the sub-good p carrying the substance i in an output flow j in kg and  $\omega_{i,j,p}$  is the mass fraction (abundancy) of the sub-good p carrying the substance i in an output flow j in wt-%. The mean content of the substance i is denoted as  $\bar{c}_i$  in Eq. (1) and given in mg/kg, while  $s_i^2$  is the corresponding variance in  $\text{mg}^2/\text{kg}^2$ . For the calculation, the following relation was considered:  $\frac{\bar{c}_i^2}{s_i^2} = \frac{1}{\text{rsd}^2}$ . This allows to insert a target rsd value that can be arbitrarily selected ( $\text{rsd} = 10 \%$  this study). When the mass distribution of an individual sub-good p that carries a specific substance i in an output flow j is considered,  $m_{i,j,pmax}$  is the maximum value in Eq. (1) and  $m_{i,j,p10\%}$  is the 10th percentile value of this distribution. These values were estimated from experience (Blasenbauer et al., 2023; Huber et al., 2020). However, the calculated sampling masses were only used to plan and carry out the sampling campaign, while the actual uncertainty values from the actually analyzed test sample masses were evaluated as part of the data analysis (see Section 2.3.4).

The second aspect applies to the practice of sampling itself. According to Gy (1992), incremental sampling should be preferred over grab sampling and sampling from a moving lot (e.g. from conveyed material) over sampling from a stationary lot (e.g. material in a pile or container). Both aspects were addressed in this study. A few output flows could not be sampled from a moving lot due to safety reasons (Fe >50, MS met >50) or accessibility (Sludge SB). For the former, the material was collected, inspected and parts of it were hand-sorted as obtained, while the latter was incrementally sampled from a stationary lot. The other output flows were sampled every 10–15 min with a minimum of 30 increments over a period of 8 h from moving lots. The sampling tools varied from tailor-build hand-devices to a wheel loader for the residual mineral fraction. Attention was paid to ensure sampling of the whole cross section of these moving lots. To obtain sub-samples for further characterization, incremental sampling (Gerlach and Nocerino, 2003; Skutan et al., 2018) was performed and repeated until the desired test sample masses were obtained. The sampling procedure is also described in Mühl et al. (2024).

## 2.2. Material flows of goods

In SFA, first the material flows of goods have to be determined (Brunner and Rechberger, 2016). These were the mass flows of the IBA treatment plant outputs (Fig. 1). A brief description of each output flow is given in Table 1.

The output flows 6, 12 and 13 represent concentrates of light and heavy non-ferrous metals. Hand-sorting was performed to separate each of these concentrates into two subfractions. One subfraction comprised only metallic particles >4 mm and was given the suffix “metallic >4 mm” (Output flows 6.1, 12.1 and 13.1). The other one represented the residual material, which was a mixture of mineral particles and metallic particles <4 mm and was given the suffix “metallic <4 mm & non-metallic” (Output flows 6.2, 12.2 and 13.2). Hand-sorting below 4 mm was not performed. The output flows were then subsequently allocated into four categories. One category was “Residues”, comprising output flows that are either landfilled (sludge SB, sludge C) or are directed back to the incinerator (MS unb >50, Unb jigger). Another category was the “Mineral fraction” and yet another one was “Glass >9”, which was only produced from FB-IBA, as mentioned previously. The fourth category was named “Metals” and comprised all output flows designed for the recovery of ferrous and non-ferrous metals (Fe >50, Fe crusher, MS met >50, Fe <50, HF jigger, ECS 1 Al, ECS 1 mix, ECS 2, Fstp Fe, Fstp NFe). It is important to note that some of these “Metals” output flows are obtained as scrap fraction that can be used in metallurgical recycling as obtained, while others are obtained only as metal concentrates which contain considerable amounts of mineral impurities that must be removed prior to recycling. This distinction is shown in brackets in Table 1.



### 2.3. Determination of total substance contents in the material flows of goods

To perform an SFA, according to Brunner and Rechberger (2016), the contents of substances in the material flows of goods need to be determined. In this study the material flows of goods are represented by the output flows of the IBA treatment plant. Although the term “concentration” was initially used by Brunner and Rechberger (2016) to express the amount of a substance within a good, the term “content” will be used instead in this study, which is a more common term in chemistry to express the mass fraction of a substance within a solid material, having the unit mg/kg or wt-%. Other terms that will be used are substance flow (substance mass per time unit) and substance load (absolute substance mass within a material flow in unit of mass). The substances (chemical elements) selected for the SFA were Ag, Cd, Co, Cr, Cu, Mn, Ni, Pb, Sb and Zn.

To determine the total substance contents in the material flows of goods, three different approaches with different data sources were used. The three approaches will be presented briefly in the subsequent paragraphs. More details on each approach can be found in Section 1 in the supplementary material, while details on the sampling of each output flow are described in Mühl et al. (2024).

#### 2.3.1. Substance contents determined by hand-sorting and literature data

The first approach was used for the subset  $j_1$  of the output flows, which are composed only of sub-goods with particle size  $>4$  mm: Fe  $>50$ , Fe crusher, Fe  $<50$ , MS met  $>50$  and MS unb  $>50$ . Either the primary samples (MS unb  $>50$  from G-IBA; Fe  $>50$  and Fe crusher from FB-IBA) or the sub-samples (Fe  $<50$  and MS met  $>50$  from both IBAs) were hand-sorted into their compositional sub-goods  $p$  ( $p = 1, \dots, 11$ ). MS unb  $>50$  was not obtained from FB-IBA treatment. The whole material of Fe  $>50$  and Fe crusher from G-IBA was collected in separate scrap piles and was only visually inspected for the content of electromagnetic coils, but not sorted into sub-goods. The total substance content  $c_i$  in the output flows  $j_1$  was then obtained from the sum of substance loads within the sub-goods (Eq. (2)):

$$c_{ij1, \text{total}} = \sum_{p=1}^{11} x_p \cdot c_{i,p} \quad (2)$$

In Eq. (2),  $c_{ij1, \text{total}}$  is the total content of substance  $i$  ( $i = \text{Ag, Cd, Co, Cr, Cu, Mn, Ni, Pb, Sb, Zn}$ ) in the output flows  $j_1 \dots$  ( $j_1 = \text{Fe } >50, \text{ Fe crusher, Fe } <50, \text{ MS met } >50, \text{ MS unb } >50$ ) in mg/kg.  $x_p$  in Eq. (2) is the mass fraction of a sub-good  $p$  in the hand-sorted sample ( $p = 1, \dots, 11$ ) in wt-% and  $c_{i,p}$  is the content of substance  $i$  in the sub-good  $p$  in mg/kg. A list on all the sub-goods and their substance contents is shown in Table S1 of the supplementary material.

The sub-goods from G-IBA were partially coated with a mineral layer from wet-discharge (see Figs. S1 and S2 in the supplementary material). To obtain the net weight of these sub-goods, the mineral coatings had to be removed. This was accomplished by spreading the samples on a metal plate, crushing them with a vibrating roller (BOMAG BW 65S) and sieving the material afterwards. Metallic sub-goods were differentiated by metal type: Steel was identified by its characteristic rusty surface and strong ferromagnetism, while stainless steel was characterized by weak magnetism, the presence of rusty stains and a high resistance to scratches from a metal file. Copper and brass were characterized by their color after filing the surface layer. Lead was moldable by hand and very soft when filed. Aluminum and zinc were differentiated via dense media separation. Metal-metal/mineral-composites were not dismantled, but the masses of the constituents of a composite were calculated and taken into account (see Section 1.1 in the supplementary material). The output flow MS unb  $>50$  from G-IBA, which is obtained by manual sorting in the treatment plant (Fig. 1), was not chemically analyzed and the substance contents determined originated only from missorted metals. Because of the very low mass flow of MS  $>50$ , the impact of this on the

overall results was negligible and the data obtained were used without correcting them.

#### 2.3.2. Substance contents determined by total digestion and chemical analysis

The second approach was applied to the output flows  $j_2$ , which either could not be sorted by hand due to the small particle size ( $<4$ mm) or were composed mainly of mineral material. Those output flows were chemically analyzed for total substance contents. This included: Sludge SB, Sludge C, Fstp Fe, Fstp NFe, ECS 2 and MIN. After sub-sampling of the primary samples by fractionate shoveling, laboratory samples of these output flows were first dried and then pulverized to  $<0.1$  mm in a disc mill (Essa LM201 from FLSmidth). Those samples that could not be entirely pulverized to  $<0.1$  mm were fractionally milled, as described in the literature (Back and Sakanakura, 2022; Mehr et al., 2021; Morf et al., 2013; Skutan and Brunner, 2012). For chemical analysis, microwave-assisted acid digestion (Multiwave 5000 from Anton Paar) with mixtures of hydrofluoric, hydrochloric and nitric acid (Merck, p.a.) was performed on two test samples. If fractionate milling was applied, chemical assays were done for all size classes individually and weighted averages were calculated from the results. All measurements were accomplished with ICP-OES (Perkin Elmer Optima 8300). Single-element standards (Merck, Roth) were used for calibration. A detailed description of the analytical procedure can be found in Section 1.4 in the supplementary material.

#### 2.3.3. Substance contents determined by hand-sorting and chemical analysis

The third approach was used for output flows  $j_3$ , which contained hand-sortable sub-goods  $>4$  mm as well as material unsuitable for hand-sorting. These were HF jigger, Unb jigger, ECS 1 Al, ECS1 mix, Glass  $>9$ . The following combination of the two approaches was used. After sub-sampling of the primary samples by fractionate shoveling, the laboratory samples were sieved at 4 mm. For G-IBA, it was necessary to crush the samples prior to sieving to remove mineral coatings and to liberate metallic particles encapsulated in mineral agglomerates. The material greater than 4 mm was then hand-sorted into sub-goods, as described in the first approach, and that below 4 mm was chemically analyzed according to the second approach. Only the output flow Unb jigger from G-IBA was comminuted with a rotor mill (Retsch ZM200) instead of the disc mill because unburnt plastics were present in the sample. Since FB-IBA is dry-discharged and molten agglomerates are not present due to the low bed temperatures, it was not necessary to crush the samples prior to sieving. Otherwise, the sample preparation was done according to the described procedure for G-IBA samples. Only Glass  $>9$  was treated differently: first, batteries were hand-picked from the laboratory sample. Then the material was crushed in a laboratory crusher (LiTech RC200) to below 1 mm. By sieving, metallic particles  $>1$  mm were separated. After splitting in a riffle splitter, it was entirely pulverized to  $<0.1$  mm in a disc mill (Essa LM201 from FLSmidth) before two test samples were chemically analyzed. To calculate the overall substance content, weighted averages were calculated from the determined substance contents in each size class (Eq. (3)):

$$c_{ij3, \text{total}} = \omega_{>4} \cdot \sum_{p=1}^{11} x_p \cdot c_{i,p} + \omega_{<4} \cdot c_{i,<4} \quad (3)$$

$c_{ij3, \text{total}}$  in Eq. (3) is the total content of substance  $i$  in the output flows  $j_3 \dots$  ( $j_3 = \text{HF jigger, Unb jigger, ECS 1 Al, ECS1 mix, Glass } >9$ ) in mg/kg.  $\omega_{>4}$  in Eq. (3) is the mass fraction of the material greater than 4 mm and  $\omega_{<4}$  of the material below 4 mm of the sample, while  $c_{i,<4}$  is the content of substance  $i$  in the material below 4 mm in mg/kg and  $x_p$  and  $c_{i,p}$  were already specified in Eq. (2).

#### 2.3.4. Uncertainty assessment

The experiments described were single experiments without

replication. To calculate sample standard deviations (sSD or s) for the obtained substance contents in a statistically correct way, repetition of the experiments several times would be necessary. The workload of such detailed studies on industrial-scale IBA treatment is excessive and hence not practically feasible. For this reason, methods to accurately estimate the sSD values are more feasible. Skutan and Brunner (2005) proposed calculating the variances ( $s^2$ ) based on the material characteristics of only one primary sample with respect to the heterogeneity of the material. This method was based on the equation for the minimum sampling mass by Bunge and Bunge (1999) (Eq. (1)). It was used in this study to calculate the variances of the output flows  $j_1$  of the first approach. Additionally, it was assumed that any values for substance contents taken from the scientific literature have a coefficient of variation (CV) of 13.5 % if not stated otherwise, as suggested by Laner et al. (2015) for SFA studies. The variances, deriving from the heterogeneity of the material, in the output flows  $j_2$  had to be calculated using a different equation because these samples could not be sorted into subgoods. Gerlach and Nocerino (2003) suggested using a simplification of “Gy’s formula” to calculate the CV depending on the sample mass, particle diameter and substance content. For the output flows  $j_3$ , a combination of both methods was used. Details on the uncertainty assessment of the three approaches are described in the supplementary material in Section 1.5.

## 2.4. Modelling of substance flows in SFA

The spatial system boundary of the SFA was the IBA treatment plant on a DM basis and the temporal system boundary was the experimental observation time, which was an 8-hour working day. The SFs were normalized to 1 t input IBA per day ( $t_{\text{input}} \cdot d$ ) in this study. The SFA equations applied according to Brunner and Rechberger (2016) are briefly described.

After determination of the material flows of goods (Section 2.2) and their substance contents (Section 2.3), the first equation of SFA (Eq. (4)) was used to determine the SFs within the output flows of the IBA treatment plant.

$$\dot{x}_{i,j,\text{output}} = \dot{m}_j \cdot c_{i,j} \quad (4)$$

In Eq. (4)  $\dot{x}_{i,j}$  is the SF of substance  $i$  in an output flow  $j \dots (j = 1, \dots, 16)$  in  $\text{kg}/t_{\text{input}} \cdot d$ , while  $\dot{m}_j$  is the mass flow of the output flow  $j$  in  $\text{kg}/t_{\text{input}} \cdot d$  and  $c_{i,j,\text{output}}$  is the content of substance  $i$  in output flow  $j$  in  $\text{mg}/\text{kg}$ .

The second equation (Eq. (5)) in SFA according to Brunner and Rechberger (2016) relates the input mass flows to the sum of output mass flows and, accordingly, the input SFs to the sum of output SFs. In the present study it was used to determine the SFs within the input IBAs:

$$\dot{x}_{i,\text{input}} = \dot{m}_{\text{input}} \cdot c_{i,\text{input}} = \sum_{j=1}^{16} \dot{x}_{i,j,\text{output}} \quad (5)$$

Eq. (5)  $\dot{x}_{i,\text{input}}$  is the substance flow of substance  $i$  within the input IBA in  $\text{kg}/t_{\text{input}} \cdot d$ .  $\dot{m}_{\text{input}}$  in Eq. (5) is the material flow of the input IBA in  $t_{\text{input}}/d$ , while  $c_{i,\text{input}}$  is the total content of substance  $i$  in the input IBA in  $\text{mg}/\text{kg}$  and  $\dot{x}_{i,j,\text{output}}$  is the SF of substance  $i$  in an output flow  $j \dots (j = 1, \dots, 16)$  in  $\text{kg}/t_{\text{input}} \cdot d$ .

To calculate the total content of a substance  $i$  in the input IBA, Eq. (5) was rearranged and solved for  $c_{i,\text{input}}$ . The reason to use this approach for the determination of the overall total substance contents in the IBA was twofold. First, the determination of total contents from sampling and analyzing the untreated IBAs had already been carried out in prior studies with large sample sizes and triplicate experiments to calculate mean values and standard deviations. (Blasenbauer et al., 2023; Huber et al., 2020; Huber et al., 2021). Second, the output flows of a treatment plant are more homogenous than the input flow and thus much better results can be achieved with smaller sample sizes (Morf and Brunner, 1998; Morf et al., 2013). Following the second approach and

determining the uncertainty ranges based on the material heterogeneity in a single experiment as described in Section 2.3.4 has not yet been carried out for Austrian IBAs. A comparison of the results with the previous studies should help to develop new sample strategies in the future.

The mean values and the standard errors of the SFs within the output flows obtained in this study were processed with the software STAN 2.7. These values, representing random variables, were assumed to be normally distributed in order to be able to apply a standard data reconciliation algorithm and to perform uncertainty propagation, two main features of software STAN (Cencic, 2016; Cencic and Rechberger, 2008).

## 2.5. Determination of transfer coefficients in IBA treatment and evaluation of the performance of different IBA treatment plants

The transfer coefficients (TCs) describe the partitioning of a good or a substance contained in the sum of input flows among the output flows of a process. By definition, the sum of all TCs is one. The TC is calculated by the transfer equation according to Brunner and Rechberger (2016) and is usually given as a percentage of the input mass (Eq. (6)). In the present study, the input IBA on a DM basis was the only input mass flow considered.

$$TC_{i,j,\text{output}} = \frac{\dot{x}_{i,j,\text{output}}}{\dot{x}_{i,\text{input}}} \cdot 100\% \quad (6)$$

$TC_{i,j,\text{output}}$  in Eq. (6) is the TC of the substance  $i$  into the output flow  $j$  in wt-%, while  $\dot{x}_{i,j}$  is the SF of substance  $i$  in an output flow  $j \dots (j = 1, \dots, 16)$  and  $\dot{x}_{i,\text{input}}$  the respective SF within the input IBA, both having the unit  $\text{kg}/t_{\text{input}} \cdot d$ .

The TC can be used to compare the ability of different IBA treatment plants to decrease the share of unwanted substances entering the mineral fraction by directing them into metal or landfilling fractions instead (Huber, 2020). As already mentioned at the beginning, a lack of empirical SF data on IBA treatment was recognized in the scientific literature and therefore the mathematically modelled SFs published by Huber (2020) were used for such a comparison. The output flows of the various treatment plants described therein were also categorized into “Metals”, “Mineral fraction”, “Glass >9” and “Residues”.

## 3. Results and Discussion

### 3.1. Material flows of goods

Fig. 2 displays the material flows of goods determined of both IBAs on a DM basis. The mass distribution in wt-% of each IBA is additionally given in the supplementary material in Section 3.

The output flow Glass >9 was only produced from FB-IBA, as already explained in Section 2.1.2. MS unb >50 mm was only obtained in G-IBA treatment and missorted metals contributed the most to the mass flow, while the output flow was not detected at all in FB-IBA. A considerable difference between both types of IBA could be observed for the output flows Fstp Fe, Fstp NFe, Sludge SB and Sludge C. This originates from two intrinsic technological features of FB-MSWI. The first one is the screening of the dry-discharged IBA at 2 mm to recover and recirculate the bed material, which also recirculates the IBA fraction <2 mm that includes small ferrous- and non-ferrous metals. The second feature is the constant air flow from the fluidization of the bed material, which transports ultrafine particles into the cyclone and the baghouse filter, which leads to a lower amount of ultrafine particles in the IBA and accordingly to a lower amount of sludge in dry-wet IBA treatment.

### 3.2. Total substance contents in output flows of G- and FB-IBA treatment

A complete list of the determined substance contents in the output flows of the IBA treatment plant for G-IBA and FB-IBA is given in Section

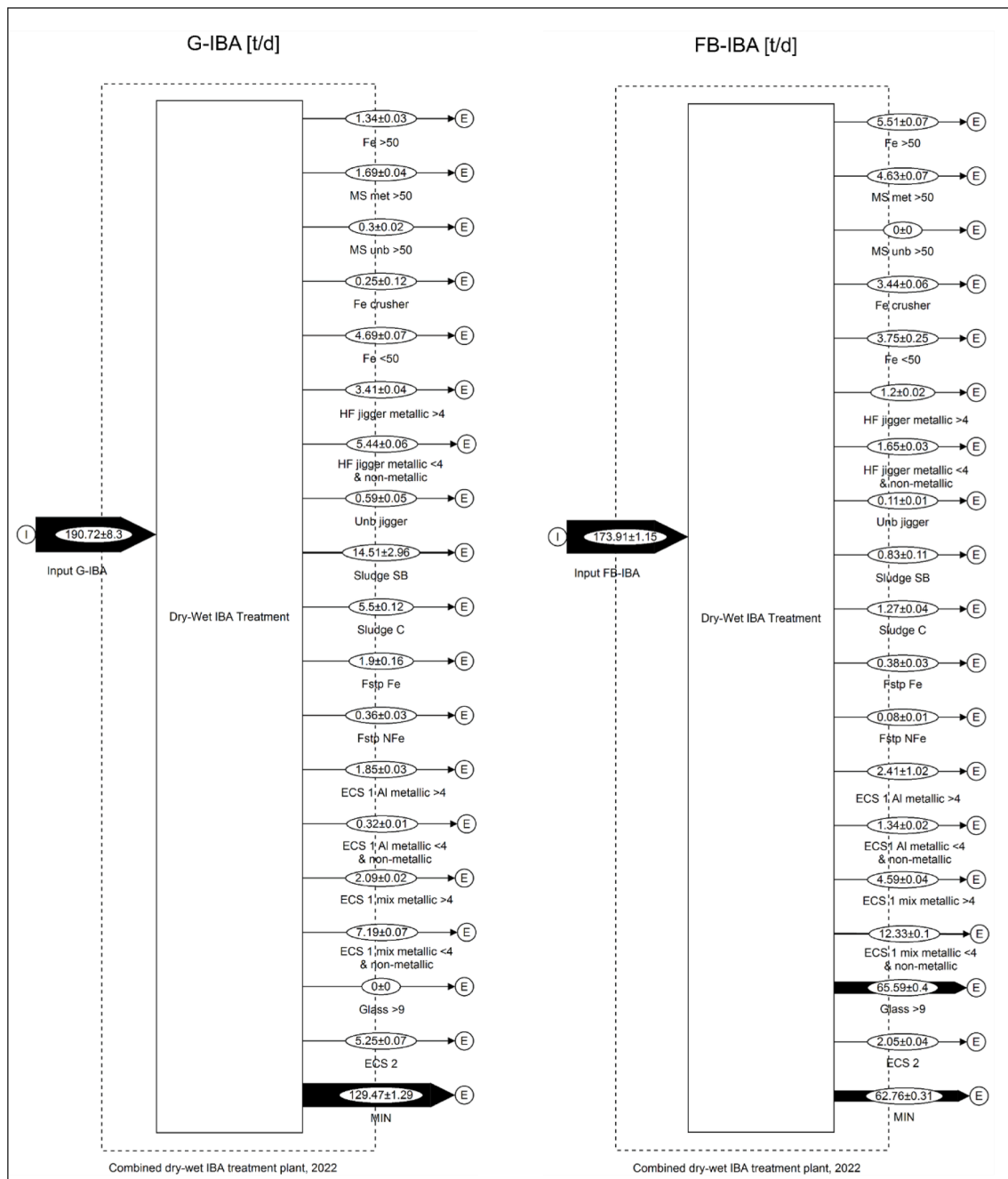


Fig. 2. Determined material flows of goods of G-IBA (left) and FB-IBA (right) in t/d DM.

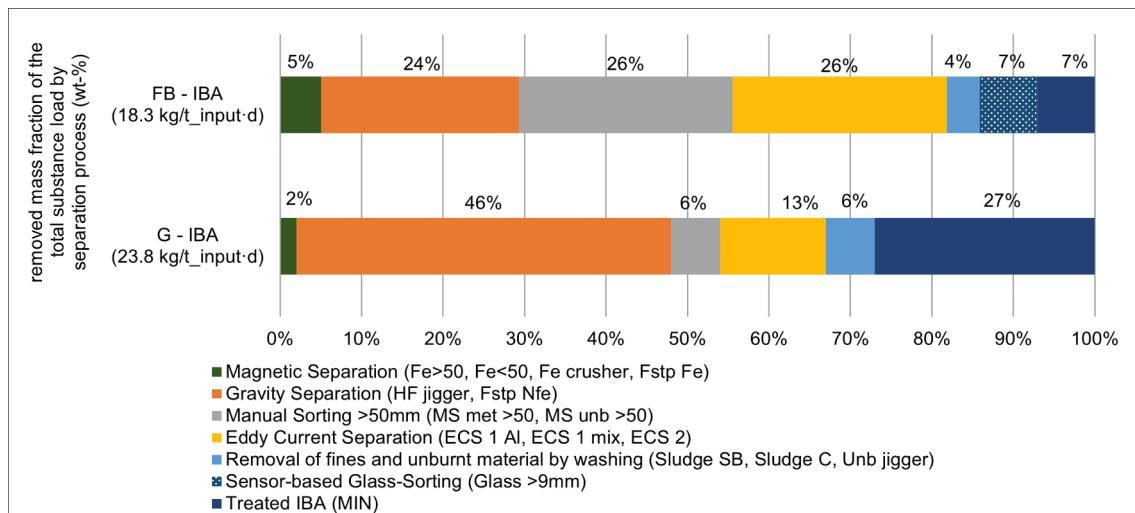
2 of the supplementary material. Those output flows, designed to target light and heavy non-ferrous metals (MS met >50, HF jigger, ECS1 Al, ECS1 mix, Fstp NFe) showed high contents of Cu and Zn, which are also indicators for an enrichment of other non-ferrous metals. ECS2 is installed at the very end of the process chain to extract remaining metallic aluminum, while other non-ferrous metals have already been extracted by previous process units. The success of this could be seen from the decrease in the substance contents along the process chain (HF jigger > ECS1 > ECS 2). The high contents of Cu and Zn in the output flow Fstp NFe showed distinctly that the IBA fraction <4 mm carries a significant load of metallic particles and that their recovery contributes to an overall depletion of metallic particles and, accordingly, the total substance contents in the mineral fraction (MIN). High substance contents were also determined in the output flows Sludge SB and C, showing that separation of ultrafine particles <0.1 mm is an important measure

to decrease the total substance contents entering the MIN. This observation was also previously reported in other studies (Alam et al., 2017; Mehr et al., 2021).

### 3.3. Substance flows within the material flows of goods

#### 3.3.1. Calculated substance flows in IBA treatment output flows

By summation of all determined substance loads over all the output flows, the total substance load was determined to be 23.8 kg/t<sub>input</sub>·d for G-IBA and 18.3 kg/t<sub>input</sub>·d for FB-IBA. Fig. 3 shows the different types of separation processes and their ability to remove the substances from the IBA. Data on individual elements and output flows can be found in Section 4 of the supplementary material. Concerning Fig. 3, both types of IBA clearly showed a different behavior. While gravity separation (HF jigger and Fstp NFe) was very effective in extracting the substances



**Fig. 3.** Mass fraction of total substance load removed from IBA by separation process in wt-%: magnetic separation (Fe >50, Fe crusher, Fe <50, Fstp Fe), gravity separation (HF jig, Fstp Nfe), manual sorting >50 mm (MS met >50, MS unb >50), eddy current separation (ECS 1 Al, ECS 1 mix, ECS 2), removal of ultrafine particles and unburnt material by washing (Sludge SB, Sludge C, Unb jig), sensor-based glass-sorting (Glass >9) and treated IBA (MIN).

investigated from G-IBA (46 % removal), this effect was much weaker for FB-IBA (24 %), where the majority of the substances investigated (52 %) were separated by means of manual sorting of particles >50 mm and ECS. This is in agreement with [Blasenbauer et al. \(2023\)](#), who observed that non-ferrous metals occur in larger particle sizes in FB-IBA compared to G-IBA. Additionally, in G-MSWI most of the glass contained in the mMSW was molten and solidified again as mineral agglomerates ([Wei et al., 2011](#)). This also transfers the substances within the glass into the mineral fraction. The mass fraction of substances in the treated IBA is four times higher for G-IBA (27 %) than for FB-IBA (7 %) and still twice as high if sensor-based glass-sorting (7 %) and treated IBA (7 %) are considered together. These observations show that by applying wet process units in IBA treatment, significant improvements in substance removal can be made, especially for G-IBA, while for FB-IBA the dry process units already remove the majority of the substances concerned.

In [Table 2](#) the substance contents in the input G- and FB-IBA, which were recalculated from the output flows of the treatment plant according to Eq. (5) in [Section 2.3](#), were compared with the total substance contents determined in previous studies via direct sampling of the untreated IBAs ([Blasenbauer et al., 2023](#); [Huber et al., 2020](#)). The total contents shown in [Table 2](#) were received from [Blasenbauer \(2024\)](#) with permission to be published. Additionally, the percentage of metallic content of each substance is shown in brackets, which was exclusively determined in this study.

The total contents of Cd, Cr, Cu, Ni, Pb, Zn determined for G-IBA and Co, Cr, Cu, Pb, Zn determined for FB-IBA were in agreement with previous studies. Higher total contents for Ag, Co, Mn and Sb were found for G-IBA and for Ag, Mn and Sb for FB-IBA. Lower contents than reported in previous studies were only found for Cd and Ni in FB-IBA. Interestingly, the metallic contents were found to be slightly higher in FB-IBA, making this IBA type more valuable for recycling. At the same time, this shows that the substance load in the mineral fraction can be reduced by efficiently separating metallic particles from FB-IBA. The Ag contents determined showed a strong discrepancy relative to previous studies. The reason is that the main Ag found originated from jewelry detected by hand-sorting. It was assumed all jewelry pieces have an average Ag content, but they were not chemically analyzed. While even filigree jewelry like ear rings were identifiable in FB-IBA, it is likely that some jewelry is encapsulated in molten agglomerates or are even molten at the fuel bed temperatures in G-MSWI. Additionally, the high sSD values indicate that a larger laboratory sample mass should have been hand-sorted for a more significant determination. [Blasenbauer et al. \(2023\)](#)

**Table 2**

Total contents determined by recalculation from substance flows in IBA treatment (this study) in comparison to total contents determined in previous studies by sampling of untreated IBA.

|      | This study                                | <a href="#">Huber et al. (2019)</a> | This study                      | <a href="#">Blasenbauer et al. (2023)</a> |
|------|-------------------------------------------|-------------------------------------|---------------------------------|-------------------------------------------|
| Year | 2022                                      | 2017/2018                           | 2022                            | 2017/2018                                 |
| Type | G-IBA                                     |                                     | FB-IBA                          |                                           |
| Ag   | mg/kg<br>61±120<br>(metallic: 84 %)       | 12±10                               | 460±420<br>(metallic: 99 %)     | 58±10                                     |
| Cd   | mg/kg<br>8±4 (metallic: 7 %)              | 5±3                                 | 9±4 (metallic: 11 %)            | 28±12                                     |
| Co   | mg/kg<br>45±10<br>(metallic: 14 %)        | 12±5                                | 36±7<br>(metallic: 16 %)        | 32±10                                     |
| Cr   | mg/kg<br>1,660±260<br>(metallic: 57 %)    | 1,310<br>±380                       | 1,780±160<br>(metallic: 76 %)   | 2,950±2,040                               |
| Cu   | mg/kg<br>12,870±2,620<br>(metallic: 67 %) | 12,000<br>±2,000                    | 8,000±1,260<br>(metallic: 88 %) | 7,580±2,510                               |
| Mn   | mg/kg<br>1,520±76<br>(metallic: 22 %)     | 750±590                             | 1,730±200<br>(metallic: 69 %)   | 900±90                                    |
| Ni   | mg/kg<br>550±88<br>(metallic: 71 %)       | 709±98                              | 880±85<br>(metallic: 93 %)      | 1,340±980                                 |
| Pb   | mg/kg<br>950±110<br>(metallic: 39 %)      | 1,100<br>±390                       | 620±160<br>(metallic: 47 %)     | 500±40                                    |
| Sb   | mg/kg<br>38±15<br>(metallic: 8 %)         | 10±4                                | 28±10<br>(metallic: 1 %)        | 0.35±0.05                                 |
| Zn   | mg/kg<br>6,140±580<br>(metallic: 38 %)    | 5,600<br>±2,100                     | 4,760±720<br>(metallic: 87 %)   | 3,370±720                                 |

reported higher values for Cd in FB-IBA than found in this study. In general, the main pathway for Cd is the flue gas due to its volatility ([Morf et al., 2013](#)) and only a few Cd carriers were reported for IBA ([Viccek et al., 2020](#)). The only one considered in this study was NiCd batteries, although sales have declined strongly in the last decade in Europe ([Friege et al., 2018](#)). While it was assumed that NiCd batteries have a share of 0.3 % of all batteries in the waste ([Bigum et al., 2013](#)) in this study, [Blasenbauer et al. \(2023\)](#) chemically analyzed batteries from



IBA, which showed higher contents. The determined Sb contents of both IBAs in this study indicate that the total contents are higher than previously reported.

### 3.4. Determination of transfer coefficients

#### 3.4.1. Determined transfer coefficients of the substances into the output flows

Fig. 4 shows the TC of each substance to the individual output flows of the treatment plant for FB- and G-IBA treatment. A list of the TCs can be found in Section 5 in the supplementary material. Fig. 5.

The treatment of FB-IBA exhibited a significant share of Cd, Co, Pb and Sb to the output flow Glass >9. In G-IBA, the glass is contained in the output flow MIN, and this also applies for the SFs within the glass. This indicates that glass is an important substance carrier for these elements. Sensor-based sorting technologies, which are already applied to separate leaded glass from waste glass, might enable new possibilities to further separate these elements from the glass and the mineral fraction of IBA (Weiss, 2012). While most of the substances showed more or less similar TCs to “Metals” for FB- and G-IBA, there were remarkably big differences for Mn and Zn. One major type of substance carriers for Mn are aluminum sub-goods, which have a melting point of 660 °C (Vollmer et al., 2019). It was already reported by Hu et al. (2011) that exposure to high temperatures leads to oxidation and loss of metallic properties, especially of thin-sheeted Al-packaging items. For Zn, brass is an important sub-good, which has a melting range starting from 900 °C (DKI, 2007). It was reported from metallurgical recycling that Zn evaporates from brass melts (Ma and Qiu, 2014; Wilk et al., 2023) and it is likely that this also occurs in MSWI. Formation of ZnO might explain the high transfer into the mineral fraction. Cd and Sb were the only substances showing a higher transfer to “Metals” for G-IBA than for FB-IBA. Examining the data in detail showed that the output flows HF jigger metallic <4 & non-metallic as well as Fstp NFe were primarily responsible for this effect. Both mass flows of goods were determined to be higher in G-IBA than in FB-IBA, for the latter by as much as a factor of ten. This results in higher substance flows and transfer coefficients. It is

reasonable to assume that the exceedance of the melting points of aluminum, brass and other copper alloys leads to a decrease in the average particle size of these sub-goods in G-MSWI. Small metallic droplets from splashing of molten metals are formed and encapsulated in molten agglomerates (Wei et al., 2011). Besides that, FB-IBA is dry discharged and screened at 2 mm to recover the bed material. This leads to an accumulation of metallic particles <2 mm in the bed material. Metallic Cd and Sb do not withstand the bed temperatures due to their high volatility (Chemical Rubber Company, 1977), but they can accumulate if they are present as alloy or tramp elements of other non-ferrous metals. The G-IBA, on the other hand, is wet-discharged. Rapid quenching can lead to inclusions of small metallic particles in mineral agglomerates (Glauser, 2021; Mantovani et al., 2021). Both types of agglomerates are likely to be recovered by gravity separation due to an increase in the particle density compared to pure mineral particles.

#### 3.4.2. Transfer coefficients in comparison to other studies

In Fig. 5 the TCs of IBAs from this study are compared to Plants B, C and D from Huber (2020) on the basis of the four pre-defined output flow categories “Glass >9”, “Mineral Fraction”, “Metals” and “Residues” (see Section 2.2). A major characteristic of Plant 1 is the high mass share of “Metals” compared to the other plants. This is due to the high scrap metal recovery yield, but also due to the mineral impurities in some of the metal concentrates. Those metal concentrates demand further cleaning before the metals can be sold as scrap, which produces secondary residues that have to be landfilled. Plant 2 represents Plant 1 in a previous plant configuration. The differences between the previous (Plant 2) and the latest process chain (Plant 1) are a screen at 9 mm, the crusher, the sensor-based glass-sorter, a drum magnet and a second ECS (ECS 2) (Huber, 2020; Mühl et al., 2024; Pfandl et al., 2020). It can be seen that the plant performance further increased, but the plant was already directing much higher substance loads into “Metals” than at any other plant. Plant 3 represents a conventional dry IBA treatment plant, which seems to perform well in terms of transferring Cr, Cu, Ni and Zn to “Metals”, with an even higher load for Ni than dry-wet treatment (Plant 1 and 2) because Plant 3 is the only plant which operates a stainless-steel

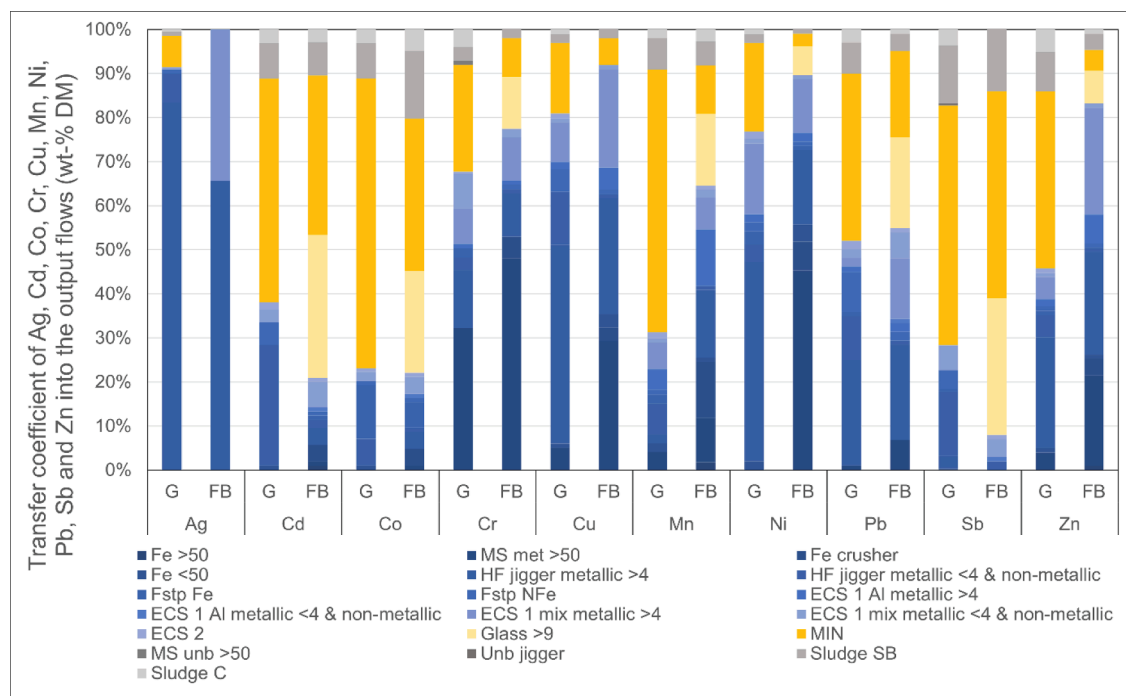
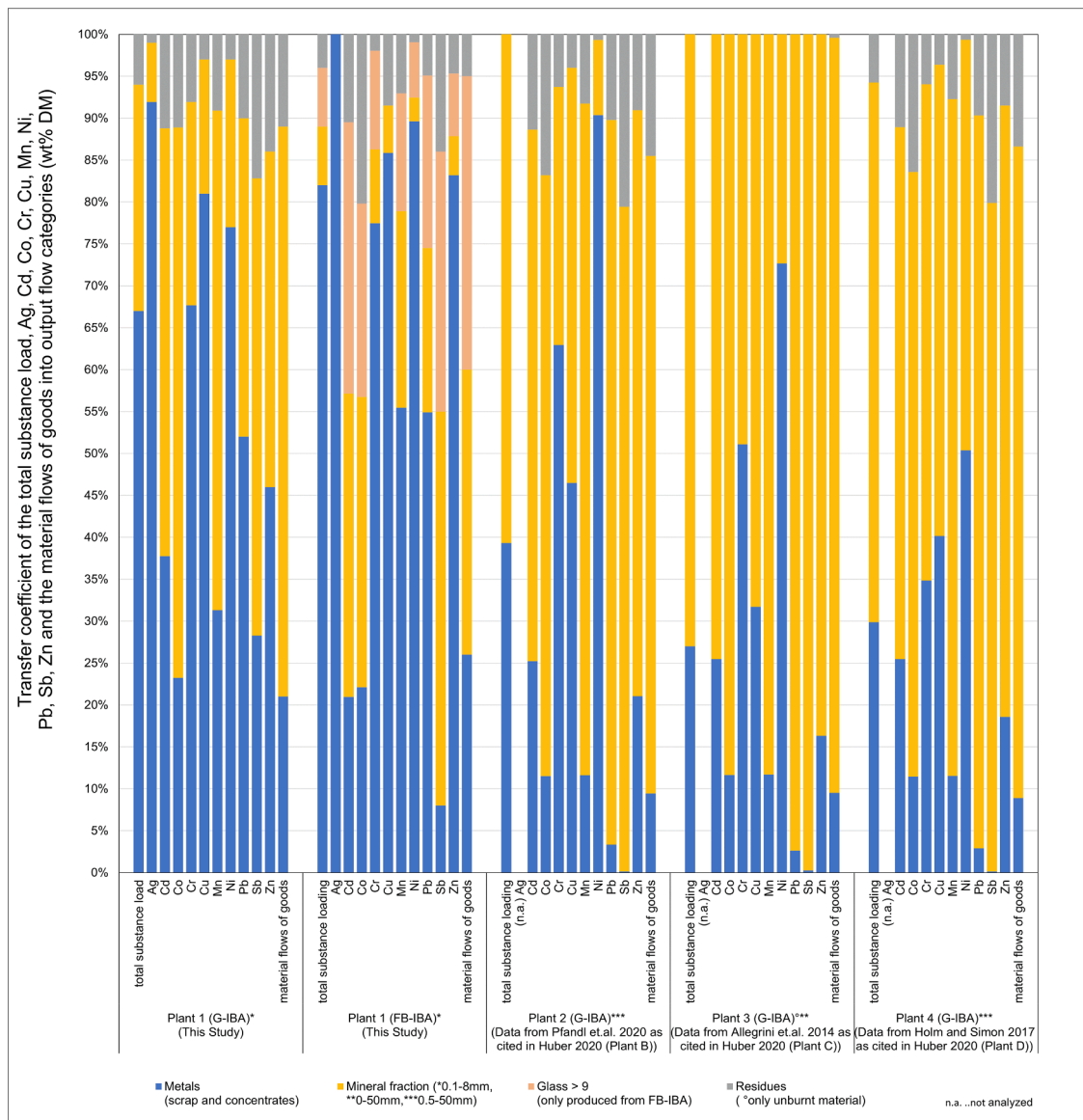


Fig. 4. Transfer coefficients of substances into the output flows (wt-%): G = G-IBA, FB = FB-IBA, blue shaded = Metals, yellow shaded = Mineral fraction and Glass >9, grey shaded = Residues.



**Fig. 5.** Comparison of transfer coefficients into output flow categories of the dry-wet IBA treatment plant investigated with different IBA treatment plants described in the literature.

separator. Plant 4 uses a washing stage to improve the quality of the “Mineral fraction” by separating salts and ultrafine particles. The mass share of “Residues” was found to be similar to Plant 1. Although removal of the ultrafine fraction removes a significant substance load, it is evident from the data that another process feature is crucial for the much lower transfer coefficient to the “Mineral fraction” in Plant 1.

Apparently, gravity separation not only targets metallic particles, but also heavy minerals. These are reported to be especially molten agglomerates with high Cu, Fe, Pb and Zn contents (Huber et al., 2021). Also, several mineralogical investigations found inclusions of small metallic particles in molten agglomerates of G-IBA, increasing the particle density (Alam et al., 2019; Glauser, 2021; Wei et al., 2011). These observations are in agreement with Back and Sakanakura (2022), who found gravity separation to be an effective way to reduce heavy metal contents in dry- and wet-discharged G-IBA in lab-scale experiments. The fact that Plant 1 crushes the mineral material to 8 mm is presumably another strength of the plant since this increases the probability of either liberating the encapsulated metallic particles entirely from their mineral shell or separating them into light and heavy fragments. Since FB-IBA does not contain such molten agglomerates, the removal of substances

by means of gravity separation is not as distinctive as for G-IBA, as seen in Fig. 3. A surprisingly big difference between Plant 1 and 2 could be seen for the TC of Pb to “Metals” and the “Mineral fraction”, although both plant configurations already carried out gravity separation. This seems to show the discrepancy between real and modelled data rather than reflecting any enormous improvement in plant performance. This underlines the need to carry out such detailed studies on industrial processes.

#### 4. Conclusion

A substance flow analysis on a dry-wet IBA treatment process was performed, evaluating IBAs from FB- and G-MSWI. By determination of the material flows of goods and substance contents in the individual output flows, it was possible to recalculate the total substance contents in the IBAs. The results were in agreement with previous studies on untreated IBAs, while the work load to access this valuable data could be reduced. The recalculation method was found to be more advantageous for trace-element analysis because the treatment process classifies the IBA by size and other material characteristics like magnetism, electric

conductivity (ECS) and density, which reduces the heterogeneity in output flows. This obtained higher Ag, Co and Sb contents than previously reported.

The detailed investigation of FB-IBA and G-IBA brought to light substantial differences between these incineration residues, which originate in the incineration technologies and IBA discharge types. While the grate incinerator represents a very common type of waste incineration plant with untreated waste feed, moving grate and wet IBA discharge, the fluidized bed incinerator discussed in this study represents an incineration plant with completely different operational features. This particularly includes the low bed temperature and the dry-discharge of IBA with integrated screening at 2 mm for bed material recovery. Keeping the bed temperature low is important in bubbling fluidized bed MSWI because it decreases inorganic fouling and sand agglomeration that can cause damage or even de-fluidization (Kirnbauer and Kraft, 2017; Pettersson et al., 2013). This results in a situation where aluminum alloys, brass and other copper alloys as well as glass do not reach their melt ranges in FB-MSWI, while they are at least partially molten at a fuel bed temperature of 900–1000 °C in grate incineration. Therefore, neither molten agglomerates nor mineral agglomerates, from wet IBA discharge, which both tend to encapsulate small metallic particles, are formed in FB-IBA, in contrast to G-IBA. While another study on FB-MSWI has already been able to show the operational benefits of a low bed temperature, which was prevention of glass melting and bed sand agglomeration and also lower heavy metal release to the gas phase (Jones et al., 2013), this study on FB-IBA showed that the mild conditions also enable the recovery of non-ferrous metals in the IBA with a very high yield, unmolten glass cullet and a mineral fraction with a low total heavy metal load. Additionally, it was found that the dry process units extract the main substance fractions from the FB-IBA. On the other hand, it was found that mechanical gravity separation by means of a jigger and a fine slag treatment plant is especially advantageous for G-IBA to separate metals as well as heavy metal bearing minerals from coarse (4–50 mm) and fine (0.1–4 mm) IBA fractions. While this was already indicated in lab-scale experiments in other studies (Back and Sakanakura, 2022; Huber et al., 2021), its successful realization on an industrial-scale could be shown in this study. Therefore, gravity separation is simultaneously capable of promoting the conservation of metallic resources and depleting the total heavy metal contents in the mineral fraction, which is favorable regarding its utilization. Together with removal of the sludge fraction <0.1 mm, the share of heavy metals entering the mineral fraction could be reduced tremendously in comparison to selected G-IBA treatment plants described in the literature, which provide standard and enhanced treatment (Huber, 2020). For FB-IBA, it was observed that the dry process units of the treatment plant extracted a higher substance load than the wet process units, while at the same time a higher share of the substance load was found to be in metallic form in FB-IBA than in G-IBA. These aspects should be considered in future operational planning of MSWI.

#### CRediT authorship contribution statement

**Simon Mika:** Writing – original draft, Methodology, Investigation, Formal analysis. **Julia Mühl:** Writing – review & editing, Methodology, Investigation. **Stefan Skutan:** Writing – review & editing, Methodology, Formal analysis. **Philipp Aschenbrenner:** Formal analysis. **Andreas Limbeck:** Methodology, Formal analysis. **Jakob Lederer:** Writing – review & editing, Supervision, Project administration, Methodology, 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.2025.02.011>.

#### Data availability

Data will be made available on request.

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