Incineration Bottom Ash from Municipal Solid Waste

Subjects: Area Studies
Contributor: Beatriz Bandarra, Joana Pereira, Rui Martins, Alex Maldonado, Josep Maria Chimenos, Margarida Quina

Incineration bottom ash (IBA) is the main residue from municipal solid waste (MSW) incineration and refers to the incombustible materials that remain in the furnace after combustion. IBA is a very heterogeneous material, comprising irregularly shaped particles and a wide particle size distribution. This material is a complex inorganic mixture generally composed of melt products, minerals, metallic compounds, ceramics, and glass [1]. The classification and the management practices of IBA differ worldwide and, particularly, among the EU Member States. However, different applications have been studied for this material.

Keywords: Incineration bottom ash ; IBA ; Residue ; Municipal Solid Waste

1. Production

Municipal solid waste (MSW) corresponds to household waste or similar waste, which can be processed through incineration. MSW incineration process allows the combustion of waste with energy recovery (waste-to-energy). Incineration bottom ash (IBA) is the main solid output from the incineration process, accounting for about 80 wt.% of all incineration residues [1]. IBA is highly produced worldwide and, particularly, in Europe [2][3]. Generally, 1 t of MSW incinerated produces 150-250 kg of IBA [4]. In the EU-28, Switzerland and Norway there are 465 operational MSW incineration plants that burn around 90 Mt/year of MSW and industrial waste of similar composition. This results in around 18 Mt/year of IBA, which accounts for nearly 20 wt% of the annual incinerated waste [5]. **Table 1** summarizes the number of incinerators, their capacity, and IBA generated in the EU-28, Switzerland and Norway in 2020.

Table 1. Number of incinerators, capacity, and IBA generated in the EU-28, Switzerland and Norway [5][6].

Country	Number of incinerators	Capacity (Mt/year)	IBA produced (Mt/year)	Country	Number of incinerators	Capacity (Mt/year)	IBA produced (Mt/year)
Austria	11	2.6	0.53	Lithuania	1	0.28	0.075
Belgium	15	3.3	0.47	Luxembourg	1	0.17	0.028
Czech Republic	4	0.65	0.2	Poland	6	0.97	0.21
Denmark	24	3.7	0.6	Portugal	4	1.2	0.24
Estonia	1	0.25	0.058	Spain	12	2.9	0.474
Finland	9	1.6	0.3	Slovakia	2	0.29	0.062
France	126	14.7	2.9	Sweden	34	5.4	0.99
Germany	68	19.8	4.8	Netherlands	12	7.6	1.9

Hungary	1	0.42	0.12	United Kingdom	45	12	1.5
Ireland	2	0.8	0.14	Norway	18	1.8	0.25
Italy	39	6.1	1.03	Switzerland	30	3.7	0.82

2. Characterization

The properties of IBA depend on the composition of the MSW feedstock, the combustion technology, and the operational conditions (e.g., incineration temperature) [7]. The moisture content in IBA represents from 7% to 30%, depending not only on the operational processes conditions but also on the post-combustion treatments and storage methods [8][9][10][11][12]. IBA is a very heterogeneous material and contains irregularly shaped particles with a porous microstructure. The average bulk density has been reported as 0.95–1.8 g/cm^3 and the average specific gravity as 1.1–2.7 [10][12][13][14]. IBA is a complex (mainly) inorganic mixture composed of melted products, minerals, metallic compounds, ceramics, and glass [1]. In Europe, IBA is generally composed of the material fractions presented in **Figure 1**.

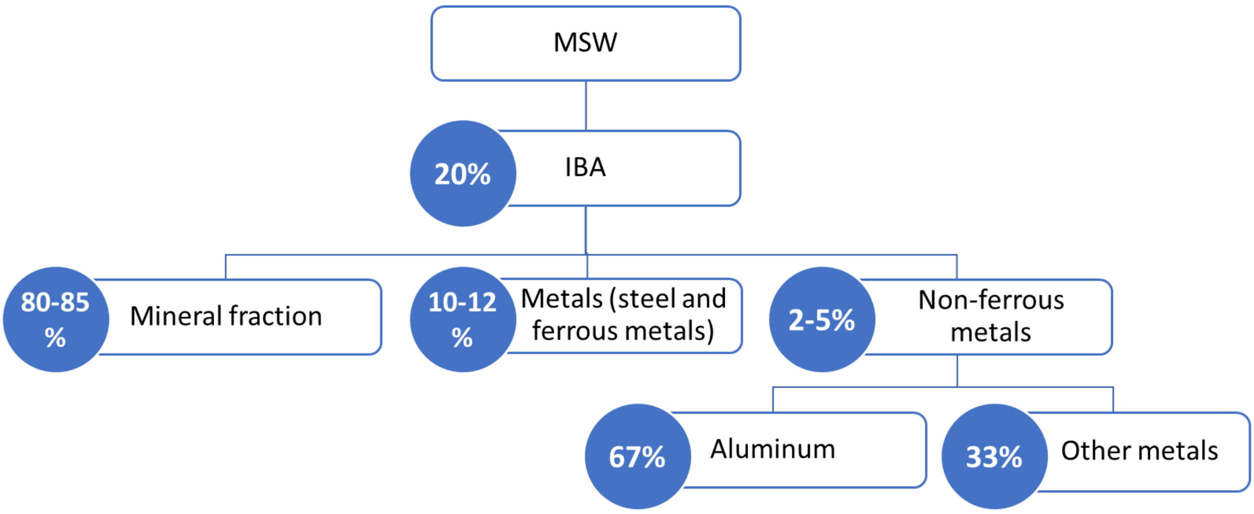

Figure 1 - Fractions of IBA in Europe, according to CEWEP (Confederation of European Waste-to-Energy Plants) [15]. Figure from Bandarra et al. (2021) [6].

In general, the particle size distribution of IBA covers a broad range, from a few μm to various cm [16]. According to Dou et al. [2], the main fraction of IBA has a particle size between 0.02 mm and 10 mm, accounting for 60-90 wt.%. Regarding the other fractions, 5 to 15% may contain a particle size below 0.02 mm, while < 30% can be higher than 10 mm. The larger particles normally include construction-type materials, pieces of glass, and ferrous and non-ferrous metals. While IBA finest fraction contains most of the soluble salts and the potentially leachable heavy metal(loid)s, the coarsest fractions mainly consist of synthetic ceramics (tiles, bricks, concrete blocks) and container glass. However, it should be noted that the particle size distribution depends on the technology used (grates or fluidized bed) and on the feed to the combustion chamber (MSW or refuse-derived fuel). The chemical composition may differ depending on the MSW input and the combustion conditions.

The main elements of IBA expressed as oxides are SiO_2, CaO, Fe_2O_3, Na_2O, Al_2O_3, P_2O_5, MgO, K_2O, TiO_2, and SO_3 (Table 2). Typically, fresh IBA is alkaline with a pH between 10 and 13 [9][17]. However, pH can vary as a function of the particle size fractions and composition: finer fractions tend to have a higher initial content of portlandite, and in the coarser fractions portlandite is scarcer and undergo carbonation faster [18].

Potentially toxic metals such as Cd, Cr, Cu, Ni, Pb, and Zn may be found in IBA (**Table 2**) due to their presence in MSW, and their leaching patterns may be linked to the presence of chlorides [19][20]. Thus, there are some environmental concerns regarding IBA [21][22] related to the potential contamination of vulnerable recipient compartments, such as water bodies and groundwaters, ultimately affecting the inhabiting biological communities [23][24][25][26]. However, as the chemical composition of IBA may vary significantly as a function of the particle size distribution [9][18][21][27], higher concentrations of chlorides and potentially toxic metals (e.g., Cr, Cu, Hg, Mo, Pb, Sb, Zn) have been detected for smaller IBA particles, namely fractions under 4 mm [1][17][27][28][29][30].

Furthermore, most di- and trivalent potentially toxic metal(loid)s are pH-dependent, and under natural weathering conditions, the leaching potential can decrease considerably due to pH decreasing [18][31]. Indeed, some of these metals can be retained in the neoformed mineral phases (calcite, ettringite, aluminosilicates, metal oxides, etc.). Therefore, the release of heavy metal(loid)s decreases during the aging period, and after 2-3 months in the open conditions, IBA may be classified as a non-hazardous material [31].

Table 2. Chemical composition of IBA from MSW based on the literature [a].

Constituents	Concentration (wt %)	Constituents	Concentration (mg/kg)	Constituents	Concentration (mg/kg)
Oxides		*Elements*		*Elements*	
SiO_2	22 - 64.84	Ag	0.28 - 38	Sb	10 - 86
CaO	10.45 - 42.9	As	0.12 - 189	Sn	2 - 960
Al_2O_3	5 - 31.31	Ba	400 - 3920	Sr	85 - 1000
Fe_2O_3	4. 64 - 15.13	Cd	0.3 - 146	V	20 - 122
MgO	1.18 - 4.62	Co	6 - 350	Zn	613 - 7770
Na_2O	1.53 -7.78	Cr	23 - 3170	Pb	98 - 13700
K_2O	0.83 - 1.66	Cu	190 - 12000		
P_2O_5	0.55 - 5.5	Hg	0.02 - 7.75		
TiO_2	0.5 - 2.17	Mn	465 - 3408		
SO_3	0.57-2.18	Mo	2.5 - 276		
Cl[b]	0.18 - 7	Ni	7 - 4280		

a [7][29][32][33][34][35][36][37][38][39][40][41][42][43][44]

b Chlorine content expressed as an element.

3. Management

The ferrous materials that are generally recovered from IBA are an absolute entry of non-hazardous waste in the European List of Waste (LoW, revised by EU Decision 2014/955/EU) with the code 19 01 02. Although generally classified as non-hazardous [32][45][46], the remaining material of bottom ashes appears as a mirror entry in the LoW (codes 19 01 11* and 19 01 12). This means that its classification relies on the evaluation of waste properties that render it hazardous in line with Regulation (EU) No 1357/2014, as well as on the assessment of persistent organic pollutants (POP) according to Regulation (EU) 2019/1021. As a result, there are different approaches for the management of IBA worldwide and, particularly, among the EU Member States [2][5]. According to Blasenbauer et al. (2020)[5], 16 out of 22 EU countries, plus Norway, and Switzerland allow the utilization of mineral IBA outside landfills. However, only 11 of them use it, at a rate varying from 20 to 100 wt%.

Given the large amounts of IBA produced, efforts have been made to valorize this material considering different applications instead of disposing of it in landfills. Indeed, IBA has the potential for the recovery of metals and minerals, contributing to decreasing the exploitation of natural resources and it has been largely recycled in different countries. Ferrous and non-ferrous metals are usually recovered through magnetic separation and Eddy current separation techniques, respectively [12][47]. Nearly 80% of the metals can be recovered from IBA, and metals such as aluminum, copper, steel, and zinc are frequently separated and applied as secondary raw materials [3]. The remaining ashes are generally landfilled (frequently after a solidification process with Portland cement) or used in different applications according to the policy of each country. Indeed, the rate of usage varies between 100 wt.% and 0 wt.% (i.e., 100 wt% disposed of in landfills) and the related regulations diverge among countries, particularly within the EU [2][3][5][16][26][33].

Before reuse, different treatments may be applied to reduce the mobility of potentially hazardous constituents from IBA. Depending on the intended IBA application, these treatments may include natural weathering, washing, heat treatment, particle density-based separation, and stabilization with the addition of hydraulic binders [26][48]. Natural weathering is the most used treatment. In this case, IBA is stored outdoors exposed to ambient conditions for 6 to 20 weeks to undergo an aging/weathering process [3][49]. This results in the neoformation and hydration of the mineral phases involving carbonation and oxidation reactions, which leads to a pH reduction into the range 8-10 [31][49]. The reactions of hydration originate mineral species that can encapsulate some potentially toxic metals, leading to an enhanced leaching behavior [26][50][51][52][53][54][55][56].

There are several potential applications of the mineral fraction of IBA. The main attraction of IBA is its particle size distribution and its composition rich in glass, ceramics, stone, brick, concrete, ash, and melting products. Indeed, the main application of the weathered bottom ash is found in the civil and building engineering field as a secondary aggregate material. The replacement of aggregates has been an appealing use for IBA due to its geotechnical properties [2]. Many European countries apply IBA as a secondary raw material to replace natural materials (e.g., gravel and sand). Belgium, Denmark, France, Germany, the Netherlands, the United Kingdom, Portugal, and Spain use IBA in road construction. IBA has been also applied in acoustic barriers for roads in Germany and the Netherlands [3]. Other common functions are the use in cement production [10][57], as aggregate for concrete [3][10][41][58], embankments [59], and as landfill cover [2][3]. Other constructive character applications are focused on the sintering of the IBA at high temperatures (above 1000 °C) to obtain ceramics [60], glass-ceramics [37], bricks [61], and tiles [62]. In the chemical engineering field, studies have been carried out for its use as an adsorbent for wastewater treatment processes and gas separation and purification through capturing hazardous elements [63][64]. It is also assessed the use of IBA in co-disposal and biogas production in landfills, as well as to protect wastes from pests and to avoid scattering of lightweight residues [65]. Finally, the alkali activation of IBA to produce alkali-activated binders is presented as a new alternative application [66].

4. Prospects for utilization

Proper and environmentally sound utilization of anthropogenic resources like IBA may contribute to the circular economy, decreasing the consumption of natural resources. Moreover, the utilization of IBA also allows to reduce the amount of waste landfilled and related impacts, pollution of groundwater and soil, odor emission, and loss of resources potentially recyclable [26][32][67][68]. Additionally, diverting waste from landfills provides economic benefits, since landfill costs, taxes, and costs of mining raw materials are prevented [69].

However, the classification of IBA as a “waste” leads to constraints in its management. Particularly, the classification as “mirror entry” in the LoW results itself in major differences in IBA management among countries. In this context, the proper assessment of the hazardous property HP 14 “ecotoxic”, related to potential environmental impacts, is of major importance to classify mirror entries since it is responsible for most of the hazardous entries in the LoW [67][70]. Currently, there is no consensus in the scientific community on the approach that should be followed, and there are different proposals in the literature [71][72][73][74][75][76][77][78][79][80]. However, it should be noted that a potential classification as “hazardous waste” is not necessarily directly linked to the environmental risks associated with its use as a product and should not automatically lead to valorization barriers. Raw waste and products thereof may not have the same environmental impact.

In fact, environmental contamination is one of the main concerns in using new materials. the technical feasibility of using IBA in different applications, its environmental performance is still being discussed and is not broadly known. The main concern in the IBA applications is the potential leaching of heavy metalloids, chlorides, and sulphates [81]. For example, IBA utilization in road construction is more beneficial than landfilling, but the benefits may not be verified for high amounts of elements released if the leaching behavior of IBA is not properly controlled [26]. Natural weathering/aging prior to IBA utilization is referred to as a form of enhancing the environmental performance since that process originates a more stable material.

Thus, it is foreseeable that more studies will be focused on this waste, particularly regarding finding alternatives for its application while ensuring environmental protection, pursuing a circular economy.

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