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Review

Legal situation and current practice of waste incineration bottom ash utilisation in Europe

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ABSTRACT

Almost 500 municipal solid waste incineration plants in the EU, Norway and Switzerland generate about 17.6 Mt/a of incinerator bottom ash (IBA). IBA contains minerals and metals. Metals are mostly separated and sold to the scrap market and minerals are either disposed of in landfills or utilised in the construction sector. Since there is no uniform regulation for IBA utilisation at EU level, countries developed own rules with varying requirements for utilisation. As a result from a cooperation network between European experts an up-to-date overview of documents regulating IBA utilisation is presented. Furthermore, this

Abbreviations: Al, aluminium; As, arsenic; Ba, barium; Be, beryllium; Cd, cadmium; Co, cobalt; Cr (total), total chromium; Cr (VI), hexavalent chromium; Cu, copper; Hg, Mercury; K, potassium; Mn, manganese; Mo, molybdenum; Na, sodium; Ni, nickel; Pb, lead; Sb, antimony; Se, selenium; Sn, tin; Ti, titanium; Tl, tellurium; V, vanadium; Zn, zinc; BTX, benzene, toluene, xylene; BTEX, benzene, toluene, ethylbenzene, xylene; EOX, extractable halogens inorganic bonding; PAH, polycyclic aromatic hydrocarbon; PCB, polychlorinated biphenyl; PCDD/PCDF, polychlorinated dibenzodioxins/-furans; cf., Latin: cōnfer (English: compare); COD, chemical oxygen demand; CPR, construction products regulation; C&D, construction and demolition; DM, dry matter; DOC, dissolved organic carbon; EoW, end of waste; EU, European union; FBC, fluidised bed combustion; GF, grate furnace; HP, hazardous properties; IBA, incinerator bottom ash; LNEC, laboratório nacional de engenharia civil; LOI, loss on ignition; LoW, list of waste; LV, limit value; MIBA, mineral fraction from incinerator bottom ash; MSWI, municipal solid waste incineration; perc., percolation test; POPs, persistent organic pollutants; RK, rotary kiln; TOC, total organic carbon; TEQ, toxic equivalent; VOC, volatile organic compounds; vol.%, volume-percent; wt.%, weight-percent.

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work highlights the different requirements that have to be considered. Overall, 51 different parameters for the total content and 36 different parameters for the emission by leaching are defined. An analysis of the defined parameter reveals that leaching parameters are significantly more to be considered compared to total content parameters. In order to assess the leaching behaviour nine different leaching tests, including batch tests, up-flow percolation tests and one diffusion test (monolithic materials) are in place. A further discussion of leaching parameters showed that certain countries took over limit values initially defined for landfills for inert waste and adopted them for IBA utilisation. The overall utilisation rate of IBA in construction works is approximately 54 wt%. It is revealed that the rate of utilisation does not necessarily depend on how well regulated IBA utilisation is, but rather seems to be a result of political commitment for IBA recycling and economically interesting circumstances.

1. Introduction

About 20–25 wt% of the waste input to incineration is transferred to so-called incinerator bottom ash (IBA), which represents the major solid residue from municipal solid waste incineration (MSWI) (Brunner and Rechberger, 2015; Morf et al., 2000). This secondary waste is roughly composed of a mineral fraction (80–85 wt%), metals (ferrous 7–10 wt%; non-ferrous 1–5 wt%) and a minor fraction of unburned material (<1 wt%) (CEWEP, 2016; Chandler et al., 1997; Chimenos et al., 1999; Holm and Simon, 2017; Huber et al., 2019). The term *metal* is to be understood in the present article as pieces of metals with an oxidation state of 0, which can be separated from the bulk of bottom ash. Chemical compounds like iron oxides present in the mineral fraction are not considered as *metals* in the present article. Due to their economic value (Verbinnen et al., 2017), metals are recovered and subsequently recycled in the metal industry (Allegrini et al., 2014; Bunge, 2018; Gökelma et al., 2019; Holm and Simon, 2017; Kahle et al., 2015; Lamers, 2015; Nørgaard et al., 2019; Van Caneghem et al., 2019; Vehlow and Bourtsalas, 2019). Conventional processes are able to recover about 85–95 wt% of the ferrous metals and 40–65 wt% of the non-ferrous metals present in IBA (Bunge, 2018). While the recycling of metals is common practice, the mineral fraction is either disposed of in landfills (including landfill construction) or utilised in the civil engineering sector as a secondary raw material (Silva et al., 2019; Verbinnen et al., 2017). Unless otherwise stated, in the subsequent text the term *IBA* always refers to unprocessed (*raw*) bottom ash. And in order to avoid confusion the term *MIBA* is introduced. *MIBA* stands for *mineral fraction from IBA.* While some countries utilise up to 100 wt% of MIBA in the civil engineering sector, other countries dispose of up to 100 wt% of this residue in landfills (Dou et al., 2017). Such different rates of utilisation may be a consequence of different barriers and/or drivers that can be of technical-, ecological-, economical- or legislative nature. The present work focuses on the latter, since legal aspects are most definitive for the utilisation of MIBA.

The European Union (EU) passed rules that form the legal basis for waste management operations. Even though these rules have to be applied by all member states, states can pass their own individual legislation within this framework as long as it is in accordance with EU law. These rules at EU level serve as a reference to minimise the effects on the environment and human health resulting from waste management activities. In the context of IBA handling the following EU rules have to be considered.

The incineration of waste in the EU is harmonised in *Directive 2010/75/EU* on industrial emissions (EU, 2010), which is due to its nature legally binding for all member states and therefore has to be implemented into national law (EU, 2019). If a waste incineration plant is operated in a member state it has to fulfil the minimum requirements set out in this directive. Such requirements are for example operating conditions that ensure a proper conversion of the waste in such a manner that the resulting bottom ashes show either total organic carbon contents lower than 3 wt% or their loss on ignition is less than 5 wt%. The directive furthermore requires the operator of such a plant to minimise the amount and harmfulness of the residues and to recycle them, where appropriate, on or off site. Prior to recycling, chemical and physical properties and the polluting potential shall be assessed including the determination of the total soluble fraction and soluble fraction of heavy metals. Besides these minimum requirements no more detailed parameters are defined in this directive.

Residues from waste incineration are themselves considered waste and are therefore subject to *Commission Decision 2014/955/EU* (EU, 2014a). In this decision a so-called List of Waste (LoW) is established that defines waste types and classifies waste as hazardous (marked with *) or non-hazardous. Regarding IBA, three entries in the LoW are of main importance: *19 01 02 – ferrous materials removed from bottom ash*, *19 01 11* – bottom ash and slag containing hazardous substances* and *19 01 12 – bottom ash and slag other than those mentioned in 19 01 11*. The last entry means, if it can be proven that it does not contain hazardous substances it can be classified non-hazardous waste. Therefore, IBA has to be tested if it shows any of the 15 hazardous properties (HP) laid down in *Commission Regulation (EU) No 1357/2014* (EU, 2014b) and it has to be assessed if persistent organic pollutants (POPs) are present or exceed concentration levels specified in *Regulation (EC) No 850/2004* (EU, 2004).

For the utilisation of MIBA as secondary raw material in the construction sector (either as non-hazardous or as hazardous waste), however, there is no harmonised test method and related limit values at EU level and countries have developed their own rules to regulate this matter. Hence, requirements for utilising vary significantly between countries. Van Gerven et al. (2005) and Crillesen and Skaarup (2006) observed the requirements for utilisation in several European countries and gave an overview on limit values for both total and leaching contents and addressed different leaching test methods. Both studies point out that a harmonisation of test standards, implementation of equal legal requirements for utilisation, development of EU treatment standards and equal standards for environmental protection are needed in order to incentivise MIBA utilisation. In a study by Saveyn et al. (2014) EoW criteria for waste derived aggregates (including aggregates from MIBA) are investigated for sixteen EU member states. The study summarises leaching limit values in the respective countries and the test methods for assessing them. Liu et al. (2015) focused on Denmark, the Netherlands, the USA, Taiwan and China and partially provides information on utilisation and disposal methods, the respective legal requirements and limit values for total and leaching content for utilisation and/or disposal. Dou et al. (2017) gave a broad overview on MIBA utilisation, MIBA properties, the environmental impact of MIBA utilisation and treatment methods in many EU countries, several Asian countries, the USA, Canada and Australia. For some of the countries leaching limit values and associated tests are presented. Huber and Fellner (2018) investigated nine European countries concerning legal requirements for MIBA utilisation and they presented limit values for total and leaching content and corresponding leaching tests. Vehlow and Bourtsalas (2019) showed several limit values and leaching test methods for Germany and Switzerland and quantities of annually generated IBA. The rates of metal recovery and utilisation of minerals are additionally shown for thirteen other EU countries.

These reviewed studies revealed a fragmented picture, highlighting the complex nature of MIBA utilisation in a supranational body of independent states like the EU and associated countries. All of these studies have in common that they are not covering the entire European Union, not all legal requirements are shown and relevant legal documents are not always presented. Furthermore, a comparison and discussion of differences in limit values is largely missing.

The aim of this paper is to provide a holistic view on regulations regarding MIBA utilisation outside of landfills, to aggregate the requirements that have to be met in order to utilise MIBA as secondary construction material and to discuss the similarities and differences of those requirements. Moreover, an outlook is to be given on future potential barriers and drivers which may complicate or facilitate utilisation of MIBA. The geographic system boundary is the entire EU and its neighbouring countries Norway and Switzerland.

Based on these aims the following research questions can be raised: (1) How is the utilisation of MIBA regulated in the observed countries and how much is utilised? (2) Which parameters and requirements have to be met for utilising MIBA and how do they differ between the countries? (3) Which future potential barriers and drivers may complicate or facilitate MIBA utilisation?

2. Methods

To answer questions related to policies in different countries, an expert survey is a suitable and widely applied method (Buchholz et al., 2009; Gabre-Madhin and Haggblade, 2004; Ray, 1999). According to Meuser and Nagel (2009), experts are defined by the knowledge they possess in the targeted field. This "expert knowledge [...] is defined as a special knowledge which the expert is clearly and distinctly aware of" (Meuser and Nagel, 2009). When carrying out a survey with experts, the interviewers should already have or build up a thorough knowledge in the expert's field, in order to present themselves as competent. This is usually dealt with by an in-depth review of literature in the expert's field, carried out before the expert survey is conducted (ibid.). Finally, the collected data from both, literature and expert survey, should be validated and discussed, in order to get a better understanding of possible future policy directions (Wood and Ford, 1993). Therefore, a focus group discussion (FGD) with the experts participating in the survey is carried out (Onwuegbuzie et al., 2009).

To follow these basic methodological steps, the article at hand applies a three-stage mixed methods approach, consisting of a policy review in the first stage, an expert survey in the second stage, and a focus group discussion with the experts in the third and last stage.

2.1. Policy review

The information on municipal solid waste incineration in the 28 EU member states was obtained from the online data base of the *Confederation of European Waste-to-Energy Plants (CEWEP)* (CEWEP, 2018). The result of this pre-scan indicates that 20 out of 28 EU members have implemented MSWI. Those countries are namely: Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Hungary, Ireland, Italy, Lithuania, Luxembourg, the Netherlands, Poland, Portugal, Slovakia, Spain, Sweden and the United Kingdom. Including Norway and Switzerland this makes in total 22 countries that are considered in this study. From these countries, information on the following topics was searched for in the literature databases Google Scholar and Scopus: (1) General questions about MSWI (number of plants, capacity, incineration types) – exemplary search terms: *municipal + solid + waste + incineration + in + 'country name' + capacity + number of MSWI plants*; (2) Policy related questions for MIBA handling – exemplary search terms: *legal + regulation + requirements + incinerator + bot tom + ash + utilisation + 'country name'*; (3) Requirements for utilisation of MIBA (limit values) – exemplary search terms: *chemical + composition + incinerator + bottom + ash + leaching + test + 'country name'*; (4) Fields of application for MIBA – exemplary search terms: *incinerator + bottom + ash + utilisation + application + road + cement + building + material + recycling + 'country name'*; (5) Current practice of MIBA utilisation (utilisation rate) – exemplary search terms: *incineration + bottom + ash + utilisation + rate + 'country name'*; By using Google Translator it was possible to extend the research to sources in all respective national languages from the investigated countries.

2.2. Questionnaire survey with experts

Based on the policy review, a questionnaire was designed and experts in each country under consideration were approached to participate in the survey. Where possible, these experts were selected from the COST action *Mining the European Anthroposphere* (*MINEA)* (MINEA, 2019). The MINEA project assesses anthropogenic resources like MIBA with respect to their potential to produce secondary raw materials by building up a network of competent persons (experts) for data collection and interpretation (Lederer et al., 2017). If a country was not represented in the MINEA expert group, additional experts were found (from scientific and policy literature) and added to the list. The final list of experts on MIBA utilisation, which included overall 29 specialists from scientific institutions, plant operators, waste management consultants, professionals from environmental agencies and experts on waste policy, is presented in Fig. 1.

2.3. Focus group discussion with survey participants

The questionnaires were analysed, compiled, and the results subsequently presented in a workshop on 26th and 27th November 2018 in Budapest, with a number of participants in the expert survey being present (Austria, Denmark, Czech Republic, Estonia, France, Germany, Lithuania, Portugal, Slovakia, Spain and the United Kingdom). Furthermore, additional experts participated in the presentation. These additional experts are affiliated to European scientific institutions, consultant firms and representatives from waste incineration plant operators. The presentation itself was used as a narrative-generating input for the focus group discussion that followed the presentation, aiming to get feedback and validation on the status of data collection and possible future directions of MIBA utilisation as construction material from a policy perspective.

2.4. Analysis of parameters and limit values

2.4.1. Determination of the utilisation rate

The utilisation rate u_n of MIBA outside of landfills in country n is determined in two different ways: (a) it is taken as reported in literature or by the participating experts or (b) it has to be calculated

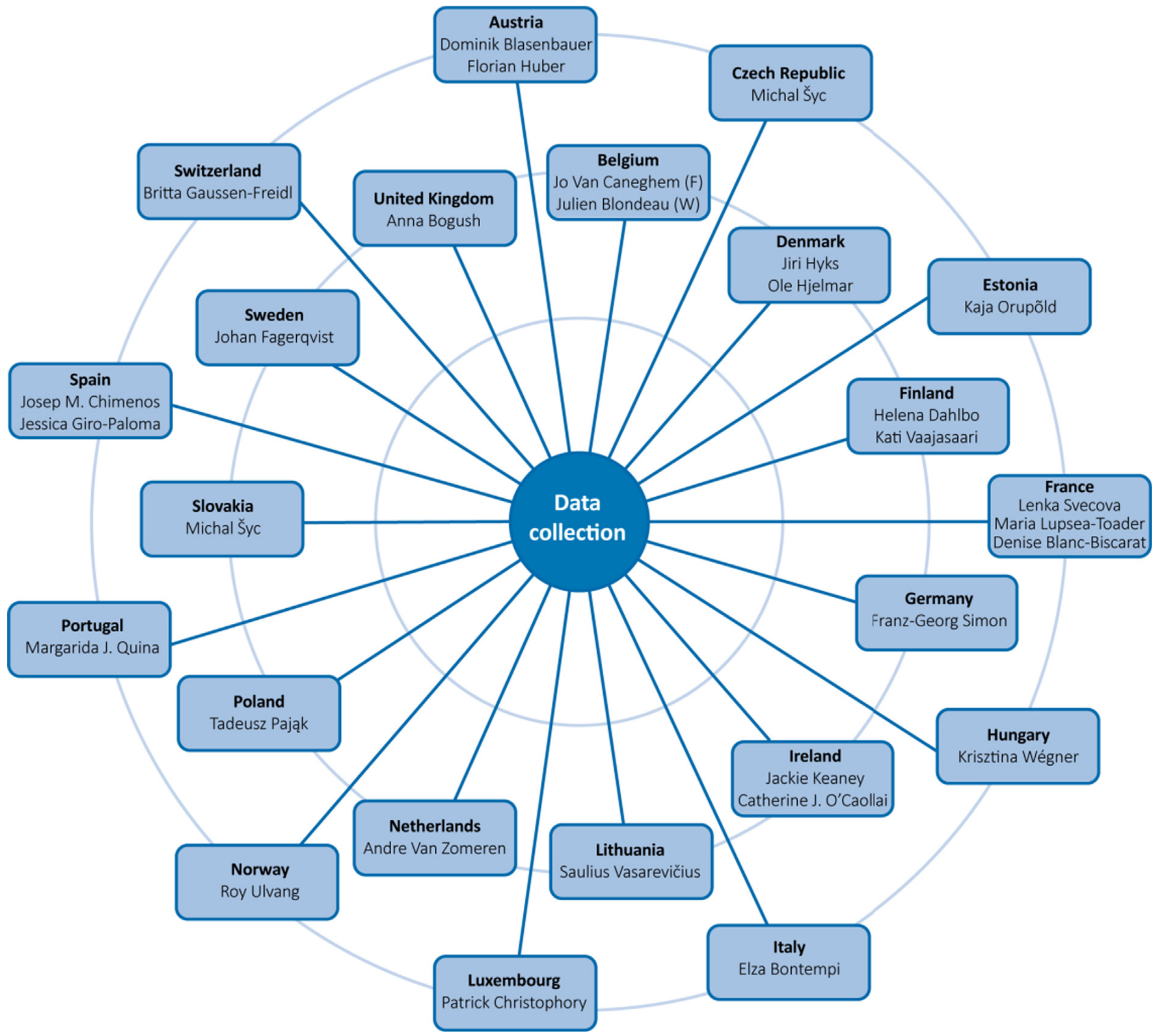

Fig. 1. Expert network of participating specialists from scientific institutions, plant operators, waste management consultants, professionals from environmental agencies and experts on waste policy.

from reported mass flows. Either way, u_n is a ratio between the mass of MIBA that is utilised outside of landfills $m_{u,n}$ and the total generated IBA mass $m_{g,n}$ in the respective country.

$$u_n = \frac{m_{u,n}}{m_{g,n}}[(Mt/a)/(Mt/a)] \tag{1}$$

It must be noted that $m_{g,n}$ is the mass of IBA reported for each country. However, it is not always clear whether the IBA mass reported is IBA as generated in the furnace or if some partial metal separation either directly in the MSWI plant or at other facilities has taken place. This leads to some uncertainty of the data.

2.4.2. Determination of relevance levels for parameters

For the determination of the relevance of a specific parameter x (e.g. elements, compounds, lumped parameters such as TOC), a so-called relevance level r_x is calculated. r_x (illustrated in Equation (2)) is defined as a ratio between $\sum y_{x,n}m_{g,n}$ and m_R. The numerator in Equation (2) is the sum of the IBA mass generated in all countries that defined a limit value for a particular parameter. For every country n, the mass of IBA generated (variable $m_{g,n}$) is multiplied by a factor $y_{x,n}$ that indicates if the observed parameter x is defined in country n. $y_{x,n}$ can be either 0 if the parameter is not defined or 1 if the parameter is defined. Finally, all these products from the single countries (being either 0 or $m_{g,n}$) are added. The denominator in Equation (2) represents the total generated mass m_R of IBA in all countries where MIBA utilisation is regulated and according requirements for utilisation are known.

$$r_x = \frac{\sum y_{x,n}m_{g,n}}{m_R}[(Mt/a)/(Mt/a)] \tag{2}$$

The calculation of the relevance level is carried out for all parameters defined in the observed countries.

2.4.3. Comparison of leaching limit values between countries

As it is not practical to compare leaching limit values directly due to their different testing methods, a common base line has to be found. This common base line is the EU leaching requirements for disposing of material in landfills for inert waste – Table 1. Although these types of landfills are (1) not intended for disposing of incineration residues and (2) criteria for landfilling material are based on completely different scenarios than using material in constructions (e.g. different protection levels, consideration of differ-

Table 1
Limit values for acceptance at landfills for inert waste (EU, 2003).

	EU landfill for inert waste		
	batch tests		percolation test
Liquid to solid ratio [l/kg]	2	10	0.1
Unit	mg/kg	mg/kg	mg/l
As	0.1	0.5	0.06
Ba	7	20	4
Cd	0.03	0.04	0.02
Cr (total)	0.2	0.5	0.1
Cu	0.9	2	0.6
Hg	0.003	0.01	0.002
Mo	0.3	0.5	0.2
Ni	0.2	0.4	0.12
Pb	0.2	0.5	0.15
Sb	0.02	0.06	0.1
Se	0.06	0.1	0.04
Zn	2	4	1.2
Chloride	550	800	460
Fluoride	4	10	2.5
Sulphate	560	1,000	1,500
Phenol index	0.5	1	0.3
DOC	240	500	160
TDS	2,500	4,000	–

ent time frames for landfilling and constructions), the following paragraphs will illustrate why this is still an appropriate choice. The compliance with limit values for inert waste landfills can be determined either by the test methods *batch test* at liquid to solid ratio 2 or 10 l/kg and *percolation test* at liquid to solid ratio 0.1 l/kg (EU, 2003). Hence, specific limit values for these three tests were established for inert waste landfills. These limit values were assumed to result in equal protection levels for soil and groundwater. The test methods correspond to the leaching test methods EN 12457/1-4 and EN 14405, which are in place in the investigated countries. This equivalence allows a normalisation of the leaching limit values for utilisation and makes it possible to compare utilisation limit values even when they have to be assessed with different liquid to solid ratios.

The normalised limit value is called *N*. *N* is defined as a ratio between the leaching limit value $c_{x,u,n}$ of a specific parameter *x* defined for utilisation in country *n* and the leaching limit value $c_{x,l,EU}$ defined for landfilling inert waste according to the EU landfill directive:

$$N = \frac{c_{x,u,n}}{c_{x,l,EU}} [(mg/kg)/(mg/kg)] \quad (3)$$

This procedure is illustrated by the following numerical example, using Eq. (3): Assuming the limit value for utilisation of MIBA for the element $x = As$ in the leachate in country $n = France$ is $c_{As,u,n}$ = 0.6 mg/kg. To assess the leaching behaviour of MIBA, *France* demands using testing procedure EN 12457-2 (batch test, liquid to solid ratio 10 l/kg). In Table 1, column two (batch test, 10 l/kg) the limit value for the element $x = As$ is 0.5 mg/kg. Hence, the ratio of *N* equals to 1.2 (0.6 mg/kg / 0.5 mg/kg). This means the limit value for *As* in *France* is a factor 1.2 higher than the limit for inert waste landfills (according to the EU landfill directive).

However, this does not imply that the environment is less protected in case of application as construction material due to the substantial differences in the scenarios of application (application in construction versus landfilling). The calculated values *N* can be used as an indicative comparison of limit values between investigated countries.

This calculation of *N* is only carried out for countries (and fields of application) that (a) defined leaching limit values, and (b) have leaching tests (including a liquid to solid ratio) in use that corresponds to the ones given in Table 1.

3. Results and discussion

3.1. How is the utilisation of MIBA regulated in the observed countries and how much is utilised?

In the EU, Norway and Switzerland 463 municipal solid waste incineration (MSWI) plants are operated (see Table 2). These plants can incinerate approximately 90 Mt/a municipal solid waste and industrial waste of similar composition. From this waste input 17.6 Mt/a are transferred into IBA. These correlate to approximately 20 wt% of the annual incineration capacity in these countries. It can be seen that the majority (16) of the 22 observed countries permit the utilisation of MIBA outside of landfills. But only eleven are making use of this permit and utilise MIBA in practice. In those countries where MIBA utilisation is practiced, the utilisation rate for MIBA varies between 20 and 100 wt%. Approximately 54 wt% of the entire generated MIBA in the EU, Norway and Switzerland has been utilised outside of landfills between 2015 and 2019.

Table 2 summarises relevant documents that regulate MIBA utilisation outside of landfills. The majority of countries regulate MIBA utilisation on the basis of legislation (decrees, regulations, and ordinances). Only Austria, Germany, Sweden and the United Kingdom published guidelines that address specific utilisation methods. Guidelines are unlike legislation usually not legally binding as they are considered to be so-called *soft law* (Eurofound, 2011; OECD, 2019). Portugal has an individual permit in place, issued by the independent national body *Laboratório Nacional de Engenharia Civil (LNEC),* for one IBA processing company. In six countries, namely Estonia, Hungary, Ireland, Luxembourg, Norway and Slovakia, the utilisation outside of landfills is not regulated. This is as well the case for the Brussels Capital Region in Belgium and sixteen out of seventeen Spanish autonomous communities (except Catalonia). In the case of Estonia, Hungary, Ireland, Luxembourg, Slovakia, Brussels Capital Region and Spain (except Catalonia) there is no regulation in place; in Norway utilisation outside of landfills is not allowed. All these countries (or regions) with no regulations regarding MIBA utilisation have in common, that the quantity of IBA is relatively small (ranging from 28,000 to 250,000 t/a). Although there are no regulations in place for MIBA utilisation inside Ireland and Luxembourg, both allow the export of the generated IBA. In Ireland one of the two plant operators exports its IBA to the Netherlands for utilisation, whereas the only plant operator in Luxembourg exports its IBA to Germany for utilisation. In Estonia, Hungary, Norway and Slovakia MIBA is disposed of in landfills.

Despite the fact that the utilisation is regulated in such different manner, it cannot be concluded that clear rules automatically results in high utilisation rates. On the one hand, in Lithuania and Switzerland the utilisation of MIBA outside of landfills is clearly regulated but the utilisation rate is still 0 wt%. In Portugal and the United Kingdom, on the other hand, no such clear regulations are in place, but both countries show utilisation rates of 56 wt% and 99 wt%, respectively. Low utilisation rates may be a result of different issues. Such issues can be if: (1) limit values are simply too strict, that IBA cannot comply with (e.g. Switzerland), (2) when the regulative has recently come into force that it takes some time until potential scepticism towards the material is decreased (e.g. Finland), (3) companies do not have experience in using a secondary raw material like MIBA for construction purposes (e.g. Lithuania) and (4) there is no scarcity of primary raw

Table 2
Overview on number and incineration capacity of MSWI plants, annually generated amount of IBA in the observed countries, information if utilisation is permitted and practiced, how much MIBA is utilised, respective documents regulating the utilisation of MIBA in the observed countries, type of legal document and references. (–)...no data available.

Country	MSWI plants		IBA mass	MIBA utilisation		MIBA utilisation rate outside landfills	Reference for utilisation rates	Original title of document regulating MIBA utilisation outside of landfills	Type	Reference for documents
	No [–]	Capacity [Mt/a]	[Mt/a]	permitted	practised	[wt.%]				
Austria	11	2.6	0.53	yes	no	0	(Republic of Austria, 2017a)	Bundesabfallwirtschaftsplan 2017; Technische Grundlagen für den Einsatz von Abfällen als Ersatzrohstoffe in Anlagen zur Zementerzeugung	guidance	(Republic of Austria, 2017a, b)
Belgium	15	3.3	0.47	Flanders: yes Wallonia: yes (mandatory) Brussels capital region: not regulated	yes	69	(Bogush, 2018)	VLAREMA-2012 (Flanders); Arrêté du Gouvernement wallon, 14/06/2001 (Wallonia)	legislation	(Flemish Government, 2012; Government of Wallonia, 2001)
Czech Republic	4	0.65	0.2	yes	no	0	(Šyc, 2018)	Vyhláška č. 294/2005 Sb.	legislation	(Czech Republic, 2005)
Denmark	24	3.7	0.6	yes	yes	99	(Hykš, 2016)	Order N.1672 (2016)	legislation	(Kingdom of Denmark, 2016)
Estonia	1	0.25	0.058	not regulated	–	0	–	–	–	–
Finland	9	1.6	0.3	yes	yes	20	(Rantsi, 2018)	Government Decree on the Recovery of Certain Wastes in Earth Construction (843/2017)	legislation	(Government of Finland, 2017)
France	126	14.7	2.9	yes	yes	80	(Tegelbeckers et al., 2015)	Arrêté du 18 novembre 2011 relatif au recyclage en technique routière des mâchefers d'incinération de déchets non dangereux NOR: DEVP1131516A	legislation	(French Republic, 2011)
Germany	68	19.8	4.8	yes	yes	30	(Alwast and Riemann, 2010; Mesters, 2018)	LAGA M19 (annex 6) and LAGA M20 (for leachates)	guidance	(LAGA, 1994, 1995)
Hungary	1	0.42	0.12	not regulated	no	0	–	–	–	–
Ireland	2	0.8	0.14	not regulated	no	0 (partial export)	–	–	–	–
Italy	39	6.1	1.03	yes	yes	85	(Utilitalia, 2019)	Decreto 5 febbraio 1998 including its amendment Decreto 5 aprile 2006, n. 186	legislation	(Italian Republic, 1998, 2006)
Lithuania	1	0.28	0.075	yes	no	0	–	Įsakymas 2016 November 25 No. D1-805	legislation	(Lithuanian Government, 2016)
Luxembourg	1	0.17	0.028	not regulated	no	0 (full export)	–	–	–	–
Netherlands	12	7.6	1.9	yes (mandatory)	yes	100	(Born, 2018)	Regeling van 13 december 2007, nr. DJZ2007124397, houdende regels voor de uitvoering van de kwaliteit van de bodem (Regeling bodemkwaliteit)	legislation	(Government of the Netherlands, 2007)
Norway	18	1.8	0.25	not permitted	no	0	–	–	–	–
Poland	6	0.97	0.21	yes	yes	60	(Pająk, 2019)	Poz. 796 – Rozporzadzenie Ministra Środowiska z dnia 11 maja 2015 r. w sprawie odzysku odpadów poza instalacjami i urządzeniami	legislation	(Republic of Poland, 2015)
Portugal	4	1.3	0.22	yes	yes	56	(Valorsul, 2017)	Individual permit issued by independent national body (LNEC – Laboratório Nacional de Engenharia Civil))	individual permit	(Valorsul, 2017)
Slovakia	2	0.29	0.062	not regulated	no	0	–	–	–	–
Spain	10	2.4	0.44	Catalonia: yes Rest of Spain: not regulated	yes	58	(Chimenos, 2018)	Ordre de 15 de febrer de 1996 (Catalonia)	legislation	(Generalitat de Catalunya, 1995)
Sweden	34	5.4	0.99	yes	no	0	(Fagerqvist, 2019; Van Praagh et al., 2018)	Återvinning av avfall i anläggningsarbeten Handbok	guidance	(Naturvårdsverket, 2010)
Switzerland	30	3.7	0.82	yes	no	0	(Holm and Simon, 2017)	Verordnung über die Vermeidung und Entsorgung von Abfällen (VVEA)	legislation	(Swiss Federal Council, 2015)
United Kingdom	45	12	1.5	yes	yes	99	(Lederer et al., 2018)	Guidance – Use of unbound municipal Incinerator Bottom Ash Aggregate (IBAA) in construction activities: RPS 206	guidance	(United Kingdom, 2019)
Total	463	90	17.6	16	11	54 (or 9.6 Mt/a)	–	–	–	–

Table 3
Parameters for total and leaching content and other requirements that have to be considered in order to utilise MIBA in the permitted fields of application. Related limit values are given in the supplementary information in Tables S1–S5. "non-hazardous waste" means only IBA classified as non-hazardous waste (EU waste code 19 01 12) is allowed to be used. Only countries where MIBA utilisation is regulated are considered in this table.

Country	Parameters specifically defined for MIBA	Permitted field of application	Requirements on		
			total content	leaching content	other requirements
Austria	yes	base layer in road construction (bound and unbound)	Cd, Cr (total), Ni, Pb, TOC	As, Cr (total), Cu, Mo, Ni, Pb, Sb, chloride, sulphate, pH	ferrous metals < 1 wt% DM, non-ferrous metals < 0.8 wt%;
	no	secondary raw material in cement production	As, Cd, Co, Cr (total), Hg, Ni, Pb, Sb, Tl	no requirements	Limitations regarding POPs according to (EU, 2004);
Belgium	no	Flanders: bound and unbound construction material	As, Cd, Cr (total), Cu, Hg, Ni, Pb, Zn, asbestos, benzene, ethylbenzene, styrene, toluene, xylene, benzo(a) anthracene, benzo(a)pyrene, benzo(ghi) perylene, benzo(b)fluoranthene, benzo (k)fluoranthene, chrysene, phenantrene, fluoranthene, indeno(1,2,3-cd)pyrene, naphthalene, hexane, heptane, petroleum, octane, PCB	As, Cd, Cr (total), Cu, Hg, Ni, Pb, Zn	floating contaminants < 5 cm^3/kg DM, non-floating contaminants < 1 wt% and glass content < 2 wt%;
	yes	Wallonia: Certification test (base layer and hydraulic bound material)	petroleum, PCB, BTEX, EOX, PAH	Al, As, Cd, Co, Cr (total), Cr (VI), Cu, Hg, K, Mo, Ni, Pb, Sb, Ti, Zn, chloride, cyanide, fluoride, sulphate	none
	yes	Wallonia: Regular quality assurance test (base layer and possibly hydraulic bound material)	petroleum, EOX	Al, As, Cd, Co, Cr (VI), Cu, Hg, Mo, Ni, Pb, Sb, Ti, Zn, chloride, cyanide, fluoride, sulphate, nitrate, ammonium, pH, electric conductivity	none
Czech Republic	no	application of waste on soil surface	As, Cd, Cr (total), Hg, Ni, Pb, V, hydrocarbons (C10-40), PCB, BTX, EOX, PAH	no requirements	none
Denmark	no	Category 1: unrestricted use in specific construction applications (no MIBA will meet Cat. 1 requirements), Category 2&3: subbase layer in road construction	As, Cd, Cr (total), Cr (VI), Cu, Ni, Pb, Zn	As, Ba, Cd, Cr (total), Cu, Hg, Mn, Na, Ni, Pb, Se, Zn, chloride, sulphate	non-hazardous waste
Finland	yes	road covered or paved, field covered or paved, subgrade filling in industrial and storage building	no requirements	As, Ba, Cd, Cr (total), Cu, Hg, Mo, Ni, Pb, Sb, Se, V, Zn, chloride, fluoride, sulphate, DOC	non-hazardous waste, particle size < 50 mm;
France	yes	Type 1: maximum 3 m high sublayers of pavements or shoulders of paved road structures, Type 2: maximum 6 m high road embankment or shoulder infrastructures, under the condition to be covered road structures	TOC, hydrocarbons (C10-40), PCB (sum of 28, 52, 101, 118, 138, 153, 180), BTEX, PAH, TEQ	As, Ba, Cd, Cr (total), Cu, Hg, Mo, Ni, Pb, Sb, Se, Zn, chloride, fluoride, sulphate, total dissolved solids	maturation, separation of unburnt material and large metals;
Germany	yes/no[a]	Z2: base course below non-permeable top layer, bound base course below low permeable top layer, bound top layer, anti-noise- and visual protection barriers and foundation of road dams with precipitation protection	Cd, Cr (total), Cu, Ni, Pb, Zn, TOC, PCDD/PCDF, EOX	Cd, Cr (total), Cu, Hg, Ni, Pb, Zn, chloride, sulphate, pH, electric conductivity	maturation > 3 months
Italy	yes	road foundation, cement process, construction of embankments, environmental recoveries	no requirements	As, Ba, Be, Cd, Co, Cr (total), Cu, Hg, Ni, Pb, Se, V, Zn, chloride, cyanide, fluoride, sulphate, nitrate, asbestos, chemical oxygen demand, pH	non-hazardous waste
Lithuania	yes	road, foundation of buildings	TOC, loss on ignition	Cd, Cr (total), Cu, Hg, Ni, Pb, Zn, chloride, cyanide, sulphate, pH, electric conductivity	non-hazardous waste
Netherlands	no	bound and unbound construction material,	benzene, ethylbenzene, toluene, xylene,	As, Ba, Cd, Co, Cr (total), Cu, Hg, Mo,	none

Table 3 (*continued*)

Country	Parameters specifically defined for MIBA	Permitted field of application	Requirements on total content	leaching content	other requirements
		IBC construction material	benzo(a)anthracene, benzo(a)pyrene, benzo(ghi)perylene, benzo(k) fluoranthene, indeno(1,2,3-cd)pyrene, petroleum, PCB (sum of 28, 52, 101, 118, 138, 153, 180), PAH, asbestos	Ni, Pb, Sb, Se, Sn, V, Zn, bromide, chloride, fluoride, sulphate	
Poland	yes	subbase layer in road construction	TOC, hydrocarbons (sum of C10-40), PCB, BTEX, PAH	As, Ba, Cd, Cr (total), Cu, Hg, Mo, Ni, Pb, Sb, Se, Zn, chloride, fluoride, sulphate, phenol index, dissolved organic carbon, total dissolved solids	non-hazardous waste, separation of light impurities, unburnt material, ferrous and non-ferrous metals and maturation, compliance with PL EN 13242 and Technical requirement WT4 "Unbound mixes for national roads" (Republic of Poland, 2015);
Portugal	no	aggregates for unbound and hydraulically bound materials for use in civil engineering work and road construction	Based on individual permit from LNEC: no requirements	Based on individual permit from LNEC [b]: As, Ba, Cd, Cr (total), Cu, Hg, Mo, Ni, Pb, Sb, Se, Zn, chloride, fluoride, sulphate, dissolved organic carbon, total dissolved solids	Based on individual permit from LNEC: compliance with NP EN 13242:2002 + A1:2010
Spain	yes	Catalonia: road subbase, levelling of terrain and embankments, filling and restoration of degradable areas from extractive activities, others	loss on ignition, unburnt material	As, Cd, Cr (VI), Cu, Pb, Zn, total dissolved solids	none
Sweden	no	general use – unbound material	As, Cd, Cr (total), Cu, Hg, Ni, Pb, Zn, PAH low ring number, PAH medium ring number, PAH high ring number	As, Cd, Cr (total), Cu, Hg, Ni, Pb, Zn, chloride, sulphate	none
Switzerland	no	use of waste as raw material and raw meal correction material in the cement industry	As, Cd, Co, Cr (total), Cu, Hg, Ni, Pb, Sb, Sn, Tl, Zn, TOC, hydrocarbons (sum of C5-10), hydrocarbons (sum C10-40), benzene, benzo(a)pyrene, PCB, BTEX, PAH, VOC	no requirements	none
	no	use of waste as grinding additives and aggregates in the cement industry	As, Cd, Cr (total), Cr (VI), Cu, Hg, Ni, Pb, Sb, Zn, TOC, hydrocarbons (sum of C5-10), hydrocarbons (sum C10-40), benzene, benzo(a)pyrene, PCB, BTEX, PAH, VOC	no requirements	none
United Kingdom	no	road, construction of structural platforms, pipe bedding	individual decision	individual decision	non-hazardous waste, compliance with BS EN 13242:2013;

[a] Total content limit values are not directly addressing MIBA utilisation, whereas the leaching limit values are specifically addressing MIBA utilisation.
[b] MIBA has to comply with leaching limit values for Portuguese non-hazardous waste landfill (Portuguese Republic, 2009).

materials, there is less need for secondary raw materials like MIBA (e.g. Austria).

3.2. Which parameters and requirements have to be met for utilising MIBA and how do they differ between the countries?

Table 3 summarises parameters defined in the documents shown in Table 2. It can be seen that in around half of these documents utilisation of IBA is directly addressed (or these documents were specifically created for that purpose) and therefore parameters are defined accordingly, whereas the others address the recycling of different materials in general. The latter do not differentiate between recycling of soil for example and recycling of MIBA; for both the same parameters and limit values apply. The most commonly permitted utilisation method is the application of MIBA in road construction, followed by different forms of earth works (anti-noise barriers, levelling of terrain, etc.), cement process, use in bound and unbound form and for foundations of structures. The requirements that have to be met in order to utilise MIBA are mainly chemical and/or physicochemical parameters and *other* requirements such as classification as non-hazardous waste, maximum particle size, maximum content of ferrous and non-ferrous metals etc. Overall 51 different chemical and physicochemical parameters for the total content and 36 for the leaching content are defined in the observed states. Each parameter is characterized by a limit value, which is given in the supplementary information (Tables S1–S5). A detailed view on the data shows that if a country allows the utilisation in road construction or some application where precipitation potentially may reach the layer where MIBA is applied, the focus is on the leaching behaviour of MIBA as soluble components can be released to the environment. If a country allows the use of MIBA in a more general application in bound or unbound form and is not just limiting it to road construction, requirements for the total content become additionally important. In order to limit the dispersion of pollutants (heavy metals, POPs etc.), Austria and Switzerland defined specific limit values for utilisation of IBA in the cement process. If MIBA serves as replacement of primary raw material in the cement kiln, leaching behaviour can be neglected and the total content of volatile components (such as Hg) comes into focus. This can be seen for instance in Italy where the leaching behaviour does not have to be assessed if MIBA is used in the cement manufacturing process. If MIBA is used as grinding additive or aggregate after the cement kiln and this material is used in constructions, potential pollutants are included in the cement matrix and their leaching is therefore as well significantly decreased. An issue which concerns all applications where MIBA is used is the demolition of such constructions. Even if all pollutants are bound in the material or due to technical measures leaching is suppressed; when the material becomes construction and demolition (C&D) waste it may become subject to legislation specifically addressing C&D waste. Therefore, pollutants from MIBA present in construction materials could prevent or limit the recycling of this material in a second life phase.

In order to assess the leaching behaviour, different standardised test methods are in place. Yet again, a big variation between countries can be observed. Table 4 shows all nine leaching tests which are in use in the countries investigated. Leaching tests differ in the test setup, liquid to solid ratio, the particle size of the tested material and the test duration. The setup can be a batch test (or sometimes as well referred to as shaking test) where both the tested material and the solution are in a bottle with fixed liquid to solid ratio and overhead rotated for a defined duration (usually 24 h). This type of test is defined within the standard EN 12457 parts 1, 2, 3 and 4 (EN, 2002a, b, c, 2003). The difference between these four parts lies within the number of leaching steps (one or two-stage batch test), the liquid to solid ratio (2, 8 and 10 l/kg) and/or the particle size of the tested material (<10 mm or < 4 mm). A second type of test setup is the percolation or column test, where the tested material is packed into a column and the leaching solution flows upwards through the packed material. Depending on the liquid to solid ratio, the leachate is collected in defined intervals. Liquid to solid ratios vary between 0.1 and 10 l/kg and 1–10 l/kg. The particle size of the tested material is sometimes not specified but mostly set to <4 mm. The test duration and particle size requirements of these types of tests often represent a compromise between the desire to obtain local equilibrium-like conditions and a wish to minimise testing time and avoid crushing. Recent standardisation developments under the Construction Products Regulation (CPR) have led to a similar percolation test that is suitable for construction products under this regulation (prEN 16637–3) (EN, 2016). A third type of test (NEN 7375:2004) for bound applications such as the use of MIBA as aggregate in concrete is in use in the Netherlands, where a monolith that contains the tested material is placed into water over a period of 64 days and the concentration of elements mobilised (due to diffusion) is measured (NEN, 2004). Samples are taken in defined time intervals, at which the water is changed after each sampling step. In this test the liquid to monolith surface area is relevant rather than the liquid to solid ratio. Also this tank leaching test is now standardised for construction products under the CPR (prEN 16637–2) (EN, 2014).

Table 4
Overview of leaching tests for MIBA utilisation and countries where those tests are in place.

Leaching test	Test setup	Liquid to solid ratio	Particle size	Test duration	Applying Countries
	[–]	[l/kg]	[mm]	[–]	[–]
EN 12457-1[a]	batch test	2	<4	24 h	Denmark, Poland
EN 12457-2[a]	batch test	10	<4	24 h	France, Italy, Lithuania, Portugal[b]
EN 12457-3[a]	batch test	2 & 8 (two-stage test)	<4	24 h	Finland
EN 12457-4[a]	batch test	10	<10	24 h	Austria, Belgium (Wallonia – regular quality assurance test), Germany, Spain (Catalonia)
CEN/TS 14405	percolation test	0.1–10	not specified	not specified	Finland, Sweden
CMA2/II/A.9.1.	percolation test	0.1–10	<4	not specified	Belgium (Flanders),
NEN 7343:1995	percolation test	0.1–10	<4	not specified	Belgium (Wallonia – certification test)
NEN 7383:2004	percolation test	1–10	<4	not specified	Netherlands
NEN 7375:2004	monolith in water containment	depending on surface area of monolith	not specified	64 days	Netherlands

[a] Note: Most countries translated the standard into national versions, e.g. Austria: *ÖNORM EN 12457-4*, Finland: *SFS-EN 12457-3*.
[b] Based on special permit from LNEC.

3.2.1. Relevance of specific parameters

Fig. 2 and Fig. 3 depict the results of the calculation of the relevance level described in section 2.4.2. It can be seen that the majority of total content parameters show relevance levels below 20 wt%. Levels above 40 wt% can be seen for Cd, Cr (total), Cu, Ni, Pb, Zn, TOC and PAH. The average relevance level for total content parameters is 19 wt%.

A view at the leaching content parameters reveals a different picture. First, the balance is significantly more on the side of inorganics regarding the number of defined parameters – in contrary to the total content. Second, these inorganic parameters show higher relevance levels with 13 being above 50 wt% and nine of them even close to or slightly above 90 wt%. Those nine parameters are Cd, Cr (total), Cu, Hg, Ni, Pb, Zn, chloride and sulphate. The average relevance level for leaching parameters is 42 wt%. This focus on leaching parameters is unsurprising, since it is more relevant to assess whether a substance is soluble/mobile and therefore more likely to affect environmentally sensitive areas such as (ground) waterbodies or soils.

It has to be noted, that this analysis does not imply that other defined parameters with lower relevance levels are less important, since it does not take into account the field of application and circumstances under which the parameters were defined. This analysis should only show how parameters are split up amongst countries and reveal parameters that are commonly used to evaluate MIBA utilisation. In addition, the limit values do in part have a much wider scope of application than only MIBA. For example, the limit values in the Netherlands cover all mineral materials used in construction, including primary construction materials.

3.2.2. Comparison of leaching limit values

From eighteen parameters defined at EU level for landfills for inert waste (cf. Table 1), twelve correspond to the most common parameters used for limiting the leaching behaviour discussed in the previous paragraphs. Consequently, the normalisation was applied to these twelve parameters. Based on the two criteria (a) and (b) defined in the last paragraph of section 2.4.3 the following countries and fields of application are left for comparison: Austria, Belgium (Wallonia – regular quality assurance test), Denmark (Category 1&2 and 3), Finland (roadway covered, roadway paved and subgrade filling in industrial or storage building, field covered, field paved), France (Type 1 and 2), Germany, Italy, Lithuania, Poland, Portugal, Spain and Sweden. The results of the normalisation procedure are summarised in Table 5.

It can be seen that many cells are coloured yellow, which means that limit values are closely related to the inert landfill limit values. This is specifically the case in Finland for the application "Field covered", where ten out of twelve parameters are equal to the limit

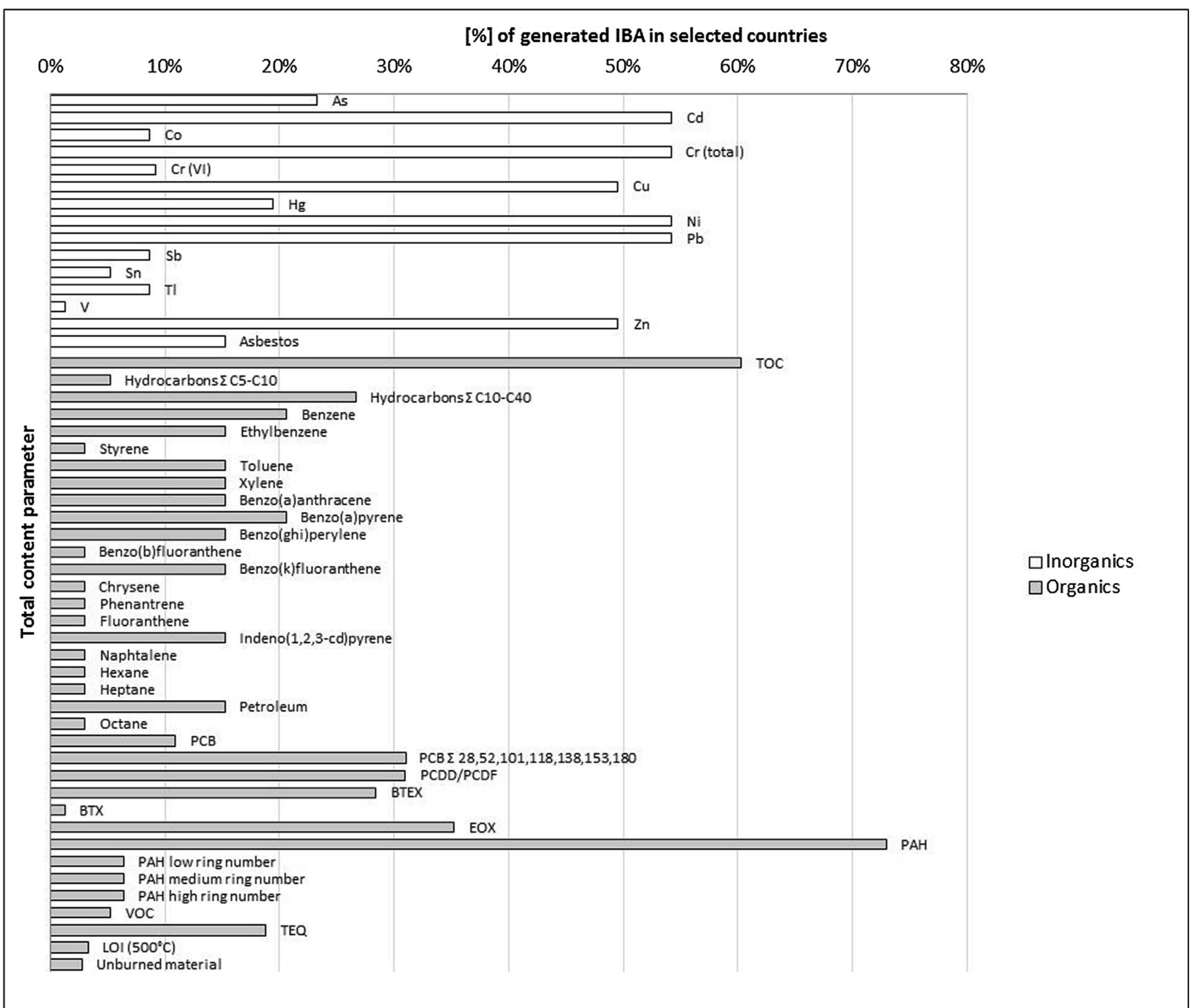

Fig. 2. Relevance of total content parameters relative to the overall generated amount of IBA in Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Italy, Lithuania, Netherlands, Poland, Portugal, Spain, Sweden and Switzerland.

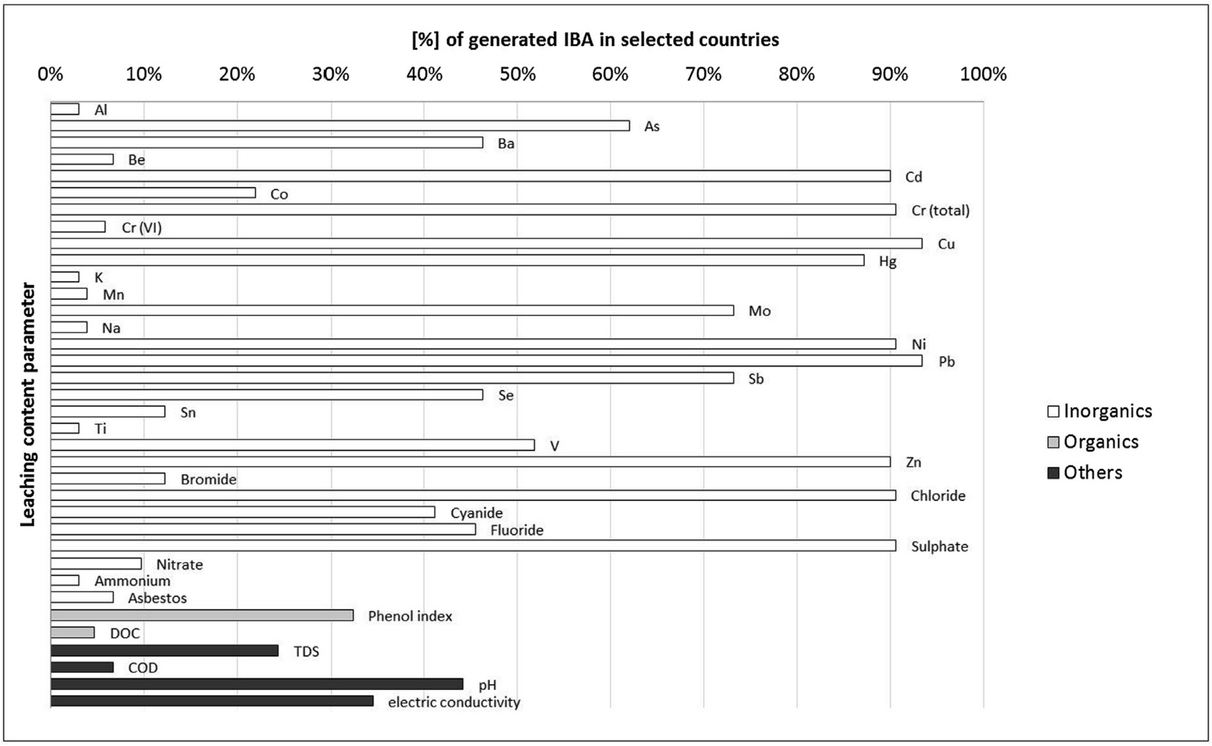

Fig. 3. Relevance of leaching content parameters relative to the overall generated amount of IBA in Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Italy, Lithuania, Netherlands, Poland, Portugal, Spain, Sweden and Switzerland.

values defined for inert landfills at EU level. It is assumed that Polish legislators have also been guided by the inert landfill limits, since eleven out of twelve parameters are exactly two times higher than the inert landfill limit value and the twelfth is equal to the inert landfill limit value. It also becomes obvious that countries that allow a general use as construction material also define the most stringent limit values. Those applications are represented by many green cells per category in the table and are in place in Denmark (Category 1&2) and Sweden (General use – unbound material). The individual permit issued by Portuguese authorities demands compliance with Portuguese non-hazardous waste landfill limit values, and since these limit values are higher than limit values for landfilling inert waste, relatively high factors were determined. Additionally, limit values for non-hazardous waste landfills in Portugal are higher than limit values for non-hazardous waste landfills defined in Council Decision (2003/33/EC) (EU, 2003). Overall, it was found that 16% of all defined leaching limit values for utilisation match exactly the leaching limit values for landfills for inert waste, 16% are stricter and therefore 68% of the values are less strict than the leaching limit values for landfills for inert waste. Breaking down this analysis to the different parameters reveals that in seven out of seventeen cases the limit value for the element Pb matches exactly the limit value for landfills for inert waste. It is followed by Hg (5/17), As and Ni (both 4/17), Cr (total) (3/17), Cd (2/17) and Cu, Mo, Sb, Zn and chloride (all 1/17). Only for sulphate all states defined own limit values. As the main field of application for MIBA is in the construction of roads, an analysis how different countries are defining limit values for that purpose is carried out. By taking into account only countries and applications that allow the use in road construction only and reducing the list of parameters to solely parameters where a value can be found in each category, it is possible to compare how strict values for utilisation in road construction are defined within the countries. This analysis reveals that in comparison Polish MIBA has to comply with the strictest leaching limit values, followed by Austria, Finland (roadway covered), Denmark (Category 3), France (Type 2), France (Type 1) and Finland (roadway paved).

Even though this analysis reveals a large variation between countries or applications regarding the magnitude of the limit values, one should not draw a conclusion that certain states are handling this matter more and others less carefully. Saveyn et al. (2014) already addressed the similarity between utilisation limit values and landfill limit values – even though the focus was on different waste derived aggregates and not only MIBA. Regardless, this report recommended to rather carry out risk or impact-based assessments for obtaining limit values for a specific field of application, than adopting limit values from other legislation. Such an approach was made by Denmark, Sweden or the Netherlands, for example. An assessment procedure that considers differences in national conditions like soil properties, infiltration, distance to groundwater or different climatic conditions, in combination with a standardised set of parameters and risk or impact-based models, linked to a specific application would create more equal and foreseeable environmental impacts of MIBA utilisation in the member states.

3.3. Which future potential barriers and drivers may complicate or facilitate MIBA utilisation?

Considering the huge amount of IBA produced in the EU (17.6 Mt/a) it would be very relevant to find ecologically suitable applications and avoid the landfill disposal. For this, the main barriers and drivers have to be addressed. A study by Klymko et al. (2017) found out that from 15 HP criteria laid down in Commission Regulation 1357/2014 (EU, 2014b), HP 10 (*Toxic for reproduction*) and HP 14 (*Ecotoxic*) potentially may lead to a classification of IBA as hazardous waste. IBA is seen to be classified hazardous by

Table 5

Comparison of leaching limit values for MIBA utilisation and EU leaching limit values for disposing of in landfill for inert waste. Values = 1: leaching limit value for MIBA utilisation matches exactly limit value for landfill for inert waste (cell colour yellow), values < 1: leaching limit value for MIBA utilisation is stricter than limit value for landfill for inert waste (cell colour yellowish to green), values > 1: leaching limit value for MIBA utilisation is less strict than limit value for landfill for inert waste (cell colour yellowish to red). Cells containing (-): no leaching limit value for MIBA utilisation is defined for the respective parameter. Factors determined for Portugal are based on an individual permit issued by Portuguese authorities. percolation test (perc.); limit value (LV).

		Austria	Belgium (Wallonia)	Denmark	Denmark	Finland	Finland	Finland	Finland	France	France	Germany	Italy	Lithuania	Poland	Portugal	Spain (Catalonia)	Sweden
		Base layer	Regular quality assurance test (base layer and possibly hydraulic bound material)	Category 1&2	Category 3	Roadway Covered	Roadway Paved and Subgrade filling in industrial or storage building	Field Covered	Field Paved	Type 1	Type 2	Z2	Utilisation	Civil Engineering purposes	Sub-base of roads and highways	Aggregates for unbound and hydraulically bound materials for use in civil engineering work and road construction	Road subbase, Levelling of terrain and embankments, Filling and restoration of degradable areas from extractive activities, others	Less than little risk (general use) - unbound material
LV utilisation / LV inert waste landfill	As	1	2	0.16	1	2	4	1	3	1.2	1.2	-	1	-	2	10	2	0.18
	Cd	-	25	0.13	2.7	1	1.5	1	1.5	1.3	1.25	13	1.3	0.75	2	50	25	0.5
	Cr (total)	1	-	0.1	5	4	20	1	10	4	2	4	1	4	2	40	-	2.4
	Cu	2	10	0.1	4.4	5	5	1	5	25	25	1.5	0.25	0.75	2	25	10	0.4
	Hg	-	20	0.067	0.67	3	3	1	3	1	1	1	1	0.1	2	50	-	0.5
	Mo	2	3	-	-	3	12	1	12	11	11	-	-	-	2	20	-	-
	Ni	1	5	0.1	0.7	5	5	1	3	1.3	1.3	1	0.25	1	2	25	-	0.92
	Pb	1	4	0.1	1	1	4	1	4	3.2	2	1	1	1	2	20	10	0.34
	Sb	5	33	-	-	12	12	5	12	12	10	-	-	-	1	12	-	-
	Zn	-	2.3	0.1	1.5	3.8	3.8	1	3	13	13	0.75	7.5	0.75	2	13	5	0.97
	Chloride	4	6.3	0.55	11	4	14	1	3	13	6.3	3.1	2.5	13	2	63	-	0.16
	Sulphate	5	10	0.89	14	5.9	18	1.2	10	10	5	6	2.5	20	2	20	-	0.046

HP 10 if the total content of Pb (neglecting its metallic form or as an alloy) exceeds 3,500 mg/kg. Special concern is raised regarding the HP 14 criterion since *Council Regulation (EU) 2017/997* came into force (EU, 2017). It is feared that great effort is necessary for assessing the HP 14 criterion and that certain waste types could suddenly be classified as hazardous waste under this criterion (Aldrian, 2018; Wahlström et al., 2016). Assessing HP 14 can be done using a summation (calculation) method and/or using bioavailability tests (Klymko et al., 2017; EU, 2017; Planchon et al., 2015). So far no harmonised standard is defined at EU level for carrying out these bio-tests (Republic of Austria, 2018).

The Waste Framework Directive presents an End-of-Waste (EoW) option for certain waste materials that have undergone a recovery operation and meet certain criteria to change status from being a waste to become a product (EU, 2008; EU, 2018). The intention of these EoW criteria is to incentivise recycling, ensure legal security when using such a material and to remove administrative burdens (EU, 2008). All of this under the premise of a high level of environmental protection and an economic benefit from commercialising this material. EoW status for a waste may be obtained at EU level, at national level and from case-to-case within EU member states. At EU level, EoW status has been given to certain scrap metals (EU, 2011, 2013) and glass cullet (EU, 2012). It has been suggested that, perhaps IBA could obtain EoW status, but this has not happened at EU level. A European EoW regulation for IBA might be unfeasible because of the rather complex discussions on how to fulfil the conditions mentioned in Article 6 of the Waste Framework Directive (2008/98/EC (EU, 2008) as amended by Directive (EU) 2018/851 (EU, 2018)), particularly those related to the protection of health and environment. A possible national EoW status for IBA should also not lead to the presumption that this material is inherently safe and that no further testing of the (leaching) properties would be needed. On the contrary, for any accepted application of a secondary material, testing is crucial to show acceptable emissions from this material. So far, none of the EU member states have implemented national EoW regulations specifically addressing IBA (Velzeboer and Van Zomeren, 2017). There would be obvious regulatory problems associated with IBA having EoW status in one country but still being classified as a waste in other countries. In addition, achievement of EoW status of aggregates such as MIBA would change the regulatory regime from waste legislation to product legislation which generally is much less developed in terms of environmental protection than waste legislation (with the Netherlands as the only exception). The UK Environment Agency has decided not to develop national EoW criteria for IBA, but several IBA processing companies in the UK have created a code of practice for reclassifying waste IBA to a secondary raw material by reaching the EoW status (MIBAA, 2017). Their approach is based on guidelines proposed by the UK Environment Agency (United Kingdom, 2014). This guidance can be applied if no EU EoW Regulation applies to this waste material.

4. Conclusion

The present study provides an overview of the legal framework for MIBA utilisation in the European Union, Norway and Switzerland. The hypothesis that these requirements vary significantly within Europe can be confirmed. Even though this issue was already addressed more than a decade ago, hardly anything changed since then and countries are still regulating the utilisation of MIBA individually. Some countries have guidelines in place; others passed laws (regulations, decrees, orders etc.) and in the case of Portugal, authorities decide individually case by case. Laws are legally binding, whereas guidelines or even individual decisions may leave more room for interpretation and could provide therefore less legal security when using MIBA as secondary construction material. Still, no correlation is found between the level of legal security and the utilisation rate.

As a result, it can be concluded that even though the legal security is an important point when it comes to recycling of MIBA, it does not seem to be the most crucial factor that influences the rate of utilisation. First, if policy is not only providing the possibility for MIBA utilisation, but restricts landfill, it will result in increased utilisation rates due to the recycling obligation. And second, if disposing of MIBA in landfills is economically more attractive than recycling this material, there is only little incentive for a company to first costly process this secondary material for improving its quality, in order to compete with cheap primary material. Therefore, restriction of landfilling can help to stimulate the recycling market.

Since this manuscript focuses on the legal framework of MIBA utilisation, the following main points for a uniform regulatory framework at EU level are proposed: (1) Definition of fields of application. Applications as road foundation layers, embankments etc.; (2) Definition of parameters and requirements that have to be tested with respect to the field of application; (3) A uniform assessment system for establishing limit values – both total and leaching content (e.g. a risk based assessment, rather than adopting existing limit values from other legislation). It is important to note that the limit values will probably differ between countries as a result of the local differences in soil types, groundwater depths and climatic conditions; (4) Standardised test methods – especially for determining the leaching behaviour;

A uniform regulatory framework ensures that the quality of this secondary raw material meets the same high level of environmental protection in all member states. To facilitate the acceptance of MIBA applications, end-of-waste criteria could in theory be defined either at national level or on EU level. However, the feasibility of European EoW criteria for MIBA is probably low due to the country specific situations. Instead European-wide conditions for the use of MIBA resembling those stipulated in Article 6 of the Waste Framework Directive could possibly be harmonised within the waste legislation. The eight EU member states in which waste incineration is not yet established can benefit from a clear regulation, as residue management is an important factor in the planning of an incinerator. If there are already clear rules on EU level, which qualities MIBA must meet for utilisation, this can already be taken into account during the planning phase of an installation. In terms of the HP 14 criterion, clarity should be achieved from the EU or from national governments. As long as there are no clear instructions for assessing HP 14 and chances are that MIBA is suddenly classified as hazardous, there will always be a certain reservation to use this material for construction purposes.

Assuming from 100 wt% of initial IBA, 80 wt% of MIBA is produced (cf. introduction) and these entire 80 wt% could theoretically be used as aggregates in the construction sector, only 0.6 wt% of the primary production of aggregates in the EU could be substituted (EU, 2017). Hence, the overall resource relevance of utilising minerals present in IBA is quite limited. Nonetheless, utilising the mineral fraction could reduce the overall volume of landfills for non-hazardous waste required in the EU by 5 million m^3 or 7–8 vol% each year (cf. chapter 3 in supplementary information). And even though the EU's action plan for the circular economy, does not explicitly address residues from waste incineration, using anthropogenic resources like IBA more efficiently in combination with high environmental standards, may contribute to reach the goals defined in this action plan and helps to close a gap in this circular economy loop.

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Appendix A. Supplementary material

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