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RADOSŁAW JĘDRUSIAK[1], BARBARA BIELOWICZ[2], AGNIESZKA DROBNIAK[3]

From waste to value: recovering critical raw materials from urban mines in the European Union and United States

Introduction

Modern human consumption, rapid urbanization and further increases in the world's population lead to the demand for more goods and materials. However, after utilization, only some of these materials are recovered or recycled, many are discarded due to a lkack of implemented recovery technologies and regulations, or due to the content of contaminants. Moreover, many of the potentially recoverable materials are deposited in landfills or shipped to less developed countries for disposal where they can cause environmental contamination. The new approach to waste management follows the hierarchy of waste prevention. First, waste is prepared for reuse and repair without the need for treatment processes, or it is recycled.

✉ Corresponding Author: Radosław Jędrusiak; e-mail: jedrusia@agh.edu.pl

[1] Krakowski Holding Komunalny Spółka Akcyjna w Krakowie; AGH University of Kraków, Poland; ORCID iD: 0000-0003-0008-4075; e-mail: jedrusia@agh.edu.pl

[2] AGH University of Kraków, Poland; ORCID iD: 0000-0002-8742-5890; e-mail: bbiel@agh.edu.pl

3 University of Silesia in Katowice, Poland; Indiana University, Indiana Geological and Water Survey; United States; ORCID iD: 0000-0003-2610-1128; e-mail: agdrobni@indiana.edu

If this is not possible, the waste is incinerated with energy recovery, or failing that, it is disposed of in landfills. This waste hierarchy has become one of the key factors in the transformation of a linear economy into a circular economy. Particularly noteworthy is waste containing raw materials of significant economic importance, especially those of a high supply risk due to the level of concentration in another country and import dependence. These critical raw materials (CRM) are an inherent part of our modern, technology-driven life. They are essential to national security and the economic development of every country. Their use is drastically increasing, and with it, the need to assure their reliable and unrestricted access along with lowering the environmental impact from their production and extraction. Currently, scientists and industry direct a lot of effort into finding new supplies of these materials, not only from traditional sources in nature but also from new sources like anthropogenic waste. The purpose of this study is to present the raw material potential which remains mostly unused in residues from municipal waste incineration in regions with highly developed economies – the United States and the European Union. These economies have shortages of their own raw material extraction capacity due to high levels of consumption and insufficient amounts of raw-material content in natural resources.

1. What are critical materials?

The term critical materials was introduced for the first time in 2008 and it defines materials (or minerals) as any substance essential to economic or national security for which the supply chain is vulnerable to disruptions and for which there are no substitutes (Bielowicz 2021; Nassar and Fortier 2021; TS 2015).

Until the nineteen-fifties, a limited number of elements were needed for technological development, and prior to the "Paley Report" publication in 1952, resources of these materials were not considered or discussed as limited. However, in the last decades, we have been reminded several times that the supply of critical materials are not guaranteed. In the nineteen-nineties, a civil war in the Democratic Republic of Congo caused a temporary but significant decrease in the amount of cobalt on the market and in 2010, a dispute between China and Japan led to supply chain issues and a drastic increase in the prices of rare earth minerals (Drobniak and Mastalerz 2022; Graedel et al. 2015; Offerman 2019).

Today, material criticality is an important assessment conducted by many countries and companies across the world. It requires the complex, short and long-term analysis of multi-dimensional factors which include supply risk, vulnerability to supply restrictions and environmental implications (Nassar and Fortier 2021; Graedel et al. 2015; IRT 2020). The European Union Commission published the first list of critical raw materials in 2011, and it has been updating it every three years since then. As of 2020, the EU Critical Raw Material List contains thirty metals, minerals and natural materials considered as economically essential for industrial growth and sustainability and as crucial components of Europe's transition to climate neutrality (European Commission 2020). Similarly, the United States

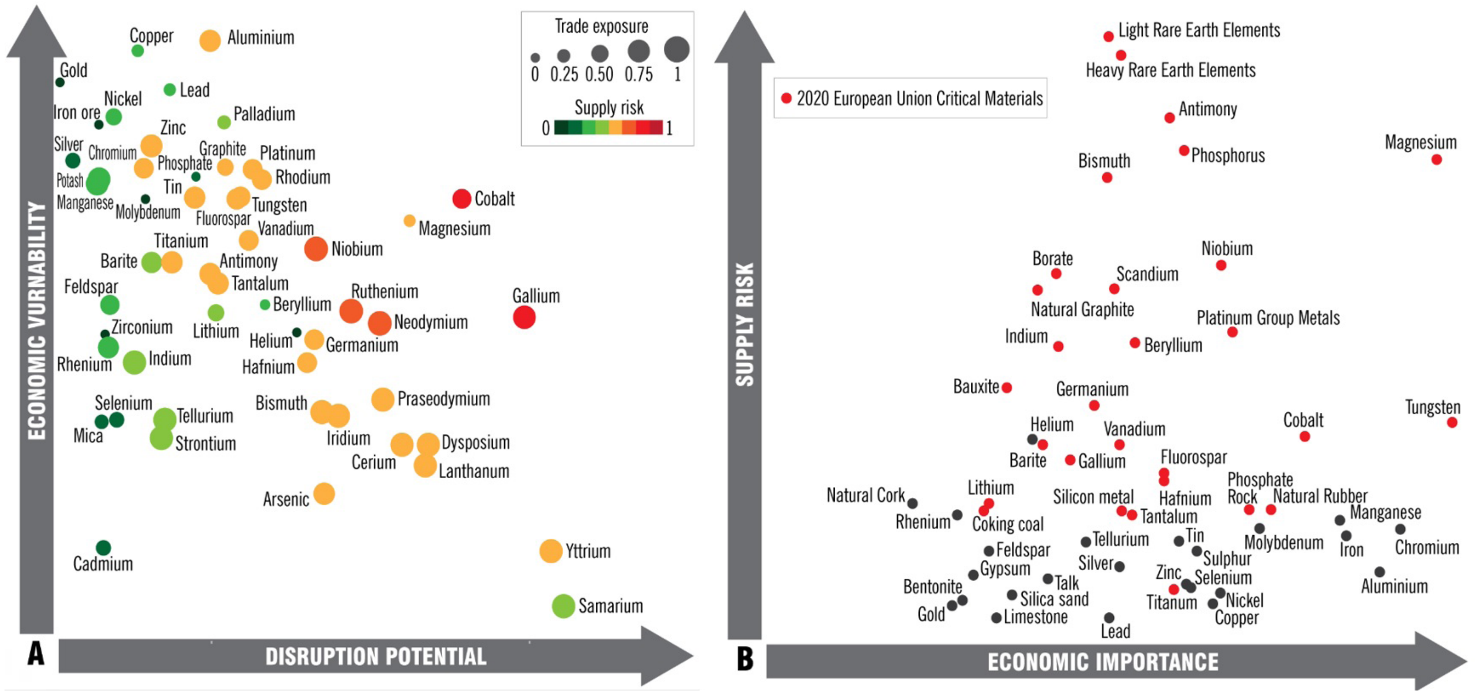

Fig. 1. Assessment of materials' criticality: A – 2021 United States Critical Minerals List (modified from Nassar and Fortier 2021), B – 2020 European Union Critical Materials List (modified from European Commission 2020; Al-Ghouti et al. 2020; Papadopoulos et al. 2019). Please note that the assessments are updated periodically and materials can be added or removed and change the criticality position

Rys. 1. Ocena krytyczności materiałów: A – Lista minerałów krytycznych Stanów Zjednoczonych 2021, B – Lista surowców krytycznych Unii Europejskiej 2020. Należy pamiętać, że oceny są okresowo aktualizowane, a surowce mogą zostać dodane lub usunięte oraz zmieniać swoją pozycję krytyczności has created its list of critical minerals, which as of 2021 contains fifty commodities, up from thirty-five listed in 2018 (Figure 1) (Nassar and Fortier 2021).

1.1. Waste management in the european union (EU)

Twenty-seven countries of the European Union generated 226 million Mg of municipal solid waste (MSW) in 2020. This means that each EU citizen generated 505 kilograms of MSW. To deal with the rising amounts of waste over the last two decades, EU countries have been increasingly focusing on the treatment of solid municipal waste through its recovery and recycling, while limiting depositing it in landfills from 50% in 2000 to 23% in 2020 (Eurostat 2021).

After waste recycling and composting, one of the most widespread methods of treating residual waste in the EU is thermal treatment with energy recovery in incineration plants (MSWI). In Europe, 516 MSWI were operated. Plants can be divided into three types based on the methods of energy recovery: heat recovery with electricity co-generation (251 MSWI), recovering only heat (94 MSWI) or recovering only electricity (161 MSWI) (Scarlat et al. 2019). Compared to waste disposal, this method of waste treatment includes a significant reduction of their volume by about 70–90% (Dou et al. 2017) and a significantly lower carbon footprint (Jeswani et al. 2013). As increasing pressure is placed on the efficient use of resources and reducing the negative impact on the natural environment, new EU MSW targets are aimed at increasing the share of the recycling and reuse of municipal solid wastes in 2035 to 65%, the incineration of waste to 25% and reducing the share of landfilled waste to 10% (EPC 2008).

Moreover, the waste incineration residue is becoming a reliable source of many materials that are important in the economies of the EU countries. This topic has become a subject of many studies and attempts to implement state-of-the-art technologies for the recovery of critical materials. The new EU climate Green Deal policy promotes the principles of sustainable development through the transition to a modern, resource efficient, competitive and environmentally neutral economy (Zhang et al. 2022). Therefore, the continuing EU waste management policy is aimed at transforming the linear economy into a circular economy by extracting high-quality resources from waste as much as possible. The planned legal regulations will introduce an obligation in the EU, where recycling capacity should be able to recover at least 15% of the EU's annual consumption of strategic raw materials (EPC 2023).

1.2. Waste management in the United States (USA)

United States in one of the largest producers of waste worldwide, generating nearly 816 kg of waste per person every year. This amount added to 265.3 million Mg of MSW in 2018 (about 12% of the global amount of waste), a drastic increase from 80 million Mg in 1960 (EPA 2020; Bradford et al. 2018).

Prior to 1976, the majority of waste in the United States was dumped in open pits, but enactment of the Resource Conservation and Recovery Act has fundamentally changed the landscape of waste management. The law described and enforced the proper governance and disposal of hazardous and non-hazardous solid waste and supported the development of facilities for resource and energy recovery promoting recycling programs (Code 1976). While the Act has transformed the approach to waste management, as of 2021, nearly two-thirds of the American trash (62%) is still primarily buried in landfills or combusted in incinerators, the rest is recycled, composted, and exported to other countries (EPA 2020; EPAa 2022; Bradford et al. 2018).

Although management of municipal solid waste is seen as a growing challenge, the MSW is also considered as a valuable and not fully tapped resource (Donahue 2018; He et al. 1995). The rates of recycling and composting increased from 6% of wastes generated in 1960 to over 32% in 2018, at the same time, the amount of combusted municipal waste with energy recovery raised from 0% in the nineteen-sixties to almost 12% in 2018 (EPAa 2022). Currently, there are seventy-five municipal waste incinerating facilities in twenty-five states generating on average 550 kilowatt hours (kWh) of energy per Mg of waste. In 2017, over 30 million Mg of MSW was combusted using waste to energy process, producing about 4.5–6 million Mg of ash (15–25% of trash weight) containing on average 2–3% of post-recycled waste metal scrap (EPA 2023). The operating waste-to-energy facilities use a variety of technologies to recover these valuable resources (mainly steel, aluminum, and copper), yet on average, 7.5 million Mg of metal scrap ends in the US landfills each year.

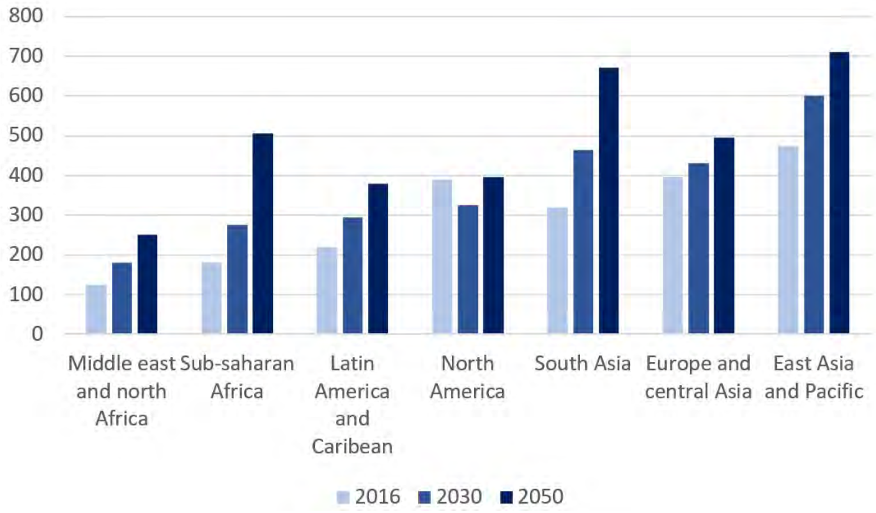

Fig. 2. Past and projected waste generation by region in million Mg per year (modified from Kaza et al. 2018)

Rys. 2. Historyczne i prognozowane ilości wytwarzanych odpadów według regionu w milionach Mg rocznie

The amount of generated residues could potentially contain significant amounts of fifty critical materials (including the rare earth elements) considered by the US Geological Survey as essential components necessary for technological development, energy independence and national security. However, while much research is presently conducted in the United States to assess critical-metal production from coal, coal waste, coal combustion products, fertilizer byproducts or electronic recycling, the concept of urban mining to recover critical metals from municipal waste is not as well-known and implemented as in Europe (Nassar and Fortier 2021; Drobniak and Mastalerz 2022; Balaram 2019; Gaustad et al. 2021; Funari et al. 2016).

In 2020, the US Department of Energy awarded a novel research project to look at the potential of REE recovery from MSW incinerated residues. While the initial results suggest the MSW might be a good source of critical elements, no data is publicly available due the pending patent application (Virginia Tech 2021).

2. Municipal soild waste and critical raw materials

Increasing demand, the geopolitical situation and the scarcity of the natural sources of critical metals pose a growing challenge for their production and extraction. To confront this challenge, a lot of attention is currently directed towards untapped resources, such as their recovery from waste. This is especially true in case of rare earth elements (REE) considered to be essential for technological development, energy independence and national security (Drobniak and Mastalerz 2022; Balaram 2019; Gaustad et al. 2021).

Much research is currently being conducted to assess CRM production not only from traditional sources and their byproducts, but also from "urban mines" – a general term defining the recovery of critical raw materials from anthropogenic sources like electronic waste, municipal landfills and waste-treatment plants. While many of these new techniques require refining and might not yet be economically viable on a large scale in many countries, they may become feasible in the future with technological innovations and government support (Balaram 2019; DOE 2021; Jowitt et al. 2018; Mastalerz et al. 2020; Mining 2021; Tesfaye et al. 2017; DARPA 2021). As the world generates over 2.1 billion Mg of municipal solid waste annually, anthropogenic waste can be a potentially vast resource of CRM. This resource is expected to grow as global waste production is predicted to reach 3.4 billion Mg by 2050 due to population and economic growth, urbanization, and shopping habits (Figure 2). While designing more recyclable products, effective waste collection and efficient processing technologies are key to a circular economy and environment protection, MSW can be also a critical raw materials resource of great potential (Tesfaye et al. 2017; Funari et al. 2016; Kaza et al. 2018; WWF 2023).

3. Methods

A flow assessment is performed in order to inventory the sources and proportions of the distribution of resources and materials. In waste management, mass flow can be used in reports on circular economy implementations in urban regions (Zeller et al. 2019). The estimation of the mass flow of elements available for recovery in the residues from municipal solid waste incineration process was calculated on the basis of the formula for material flow analysis (MFA) proposed by Brunner (Brunner and Rechberger 2016). Assumptions were made for the development of mass flow analysis. The equation has been transformed according to data collected in recent published articles. Mass (m_i) of waste generated in the US and EU has been taken from statistical data from EPAb (EPAb 2022) and Eurostat (Eurostat 2017). The chemical composition (c_i) of residues was determined by Funari et al. (Funari et al. 2015) and Bogush et al. (Bogush et al. 2015). Dry matter content (d_m) and the proportion of residues (r_c) to the mass of waste incinerated was defined by (Sabbas et al. 2003; Hykš and Hjelmar 2018).

$$X_i = m_i \cdot c_i \cdot dm_r \cdot rc_r \cdot 10^{-6}\ \text{(Mg/a)} \tag{1}$$

↳ X_i – is mass flow of "i" element in municipal solid waste incinerated residues (Mg/a);
m_i – mass of municipal solid waste incinerated in EU or USA (Mg/a);
c_i – concentration of "i" element in municipal solid waste incinerated residues (mg/kg);
dm – percentage dry mass content of "r" residue (in decimal form);
rc – percentage content of "r" residue [(decimal form);
r – residue type: IBA – incineration bottom ash, FA – fly ash,
APCr – air pollution control residues.

4. Critical raw materials in residues from municipal solid waste incineration

Although waste incineration is an optimal method for reducing the volume of waste, the remaining residues (by weight) remain around a quarter of incinerated waste. Typical incineration residues include: IBA – incineration bottom ash (20 to 30% of input weight), FA – fly ash (1 to 3% of input weight), APCr – air pollution control residues (2 to 5% of input weight) (Šyc et al. 2010), Fe – ferrous metal wastes (5 to 15% of IBA weight) and NFe – non-ferrous metals (1 to 5% of IBA weight) (Šyc et al. 2020).

Due to the high content of heavy metals, chlorides and sulfates FA as well as APCr are considered as hazardous waste for which state of the art treatment is necessary (Jung et al. 2004). On the other hand, unlike ash fraction, the IBA are rich in Fe and NFe scrap, and after metal recovery and ageing processes (usually lasting from two to several weeks), they are used as an aggregate (Mary Joseph et al. 2020; Lynn et al. 2017). Detailed studies of the

Table 1. Comparison of the estimated amounts of elements as summarized in MSWI residues with their mining in the US and the EU

Tabela 1. Porównanie szacunkowych ilości pierwiastków znajdujących się w pozostałościach z MSWI z ich wydobyciem w USA i UE

	Critical for USA – X, critical for UE – Y, candidates – Z	Mining output in USA	Mining output in EU	MFA content in MSWI Residues USA	MFA content in MSWI Residues UE
	Mg/a				
Ag	XZ	980	2,110	68	121
Au	XZ	200	23	4	7
Ba	XY	390,000	64,680	12,177	21,600
Be	XY	170	NM	5	9
Co	XY	500	21,648	314	557
Cu	XZ	1,300,000	861,925	28,773	51,041
Hf	XY	NM1	41	23	41
REE	XY	26,000[2]	NM	887	1,574
Li	XY	W3	23,185	226	401
Mo	XZ	44,000	1,210	156	276
Ni	XZ	14,000	49,239	1,874	3,325
Pb	XZ	280,000	146,062	15,878	28,166
Sb	XY	NM	NM	2,069	3,671
Sc	Y	NM	NM	87	154
Sn	XZ	NM	200	2,526	4,481
Sr	XZ	NM	121,920	4,180	7,416
Ta	XY	NM	399	10	17
V	XY	470	NM	1,585	2,812
W	XY	NM	1,615	170	302
Zn	XZ	780,000	645,623	44,069	78,175
Zr	XZ	100,000	NM	936	1,660

[1] NM – not mined.
[2] REE in USA – mined as bastnaesite concentrates.
[3] W – data withheld.
Data from (Brown 2020; USGS 2020).

composition of residual wastes have been conducted over the years (Shaub 1997; Bogush et al. 2015; Huber et al. 2020). Many of these studies have attempted to determine the level of the environmental impact of residues (Chen et al. 2020; Nikravan et al. 2020), other have focused on assessing the content of elements considered critical in maintaining supply chains in US and UE economies (Funari et al. 2015; Yao et al. 2014; Morf et al. 2013).

The analysis of the composition of waste in terms of the possibility of the recovery of valuable components should take into account both the concentration of the element in the waste and the total amount of waste available for recovery. If the element content and the amount of waste intended for recovery is low, the processing of waste proves to be unprofitable. On the other hand, in the case of the high availability of waste, elements recovery, even in a low concentration, may turn out to be profitable (Gaustad et al. 2021). The data collected in Table 1 was estimated on the basis of the formula proposed in this paper. Mining data was obtained from the United States Geological Survey and the British Geological Survey. Critical elements for the United States and the European Union as well as other elements present in large amounts in MSWI residues and which have significant economic importance were selected. For many raw materials, both the EU and the US are not present in the early stages of the value chain, which are related to the mining and processing of ores. The reason for this is both the lack of mineral deposits and the limited knowledge about the availability of these materials as well as the economic, environmental and social factors that negatively affect the research and mining stage (EC 2020). The analysis of the flow of elements shows that the share of elements found in MSWI residues is significant in terms of their mining both in the US and the EU. The content of hafnium in residues is comparable to its extraction in the European Union. The share of cobalt and vanadium is respectively, 63% and 37% of the mined volume of these elements in the United States. Rare earths are not mined in the EU, therefore their content at the level of 1,574 Mg/year is twice as high as in the case of mining in Brazil, which is the ninth largest producer of REE in the world. The amount of rare earths is also significant – note that REE mining in the US refers to bastnaesite concentrates where the REE oxides content is 60–70% (Cen et al. 2021). Due to the limited availability of elements, their enclosing into larger structures and morphological differentiation, possibilities for their recovery are limited (Blasenbauer et al. 2020). However, the development of research on recovery technology in urban mining promotes optimism and the first installations of this type are already operating on a technological scale in Europe (Quina et al. 2018).

5. Characteristics of some of the recovery methods of critical raw materials

Elements from MSWI residues can be recovered in several stages. These stages include the separation of different part sizes, and the leaching and recovery of coarse and fine metal fractions. The type of recovery technology depends on waste composition and the technology in which the waste is obtained. In the case of IBA, the recovery of elements can be performed in three ways: dry processing of wet bottom ash, wet processing of wet bottom ash, dry processing of dry bottom ash.

Magnetic and eddy current separation are the main methods of metal separation from bottom ashes. First, the recovery of ferrous and nonferrous metals from ashes take place with the use of electromagnetic and eddy current separation. Funari (Funari et al. 2016) demonstrated with magnetic methods and chemical analyses that iron rich FA and APCr contain the highest total concentration of REE. World class primary REE deposits are indeed found in sulfur-rich and iron-rich minerals. The use of magnetic separation (high field) to obtain a REE-rich concentrate facilitating further valorization can be used as a pretreatment in larger scale projects. Nonferrous metals are recovered in a conventional manner using an eddy current separator (ECS). However, this technology is not as effective in operation and with regard to the recovery rates of nonferrous metals (maximum of 40%). Therefore, many state-of-the-art technologies for the recovery of various types of raw materials are being implemented, including those critical from ashes and slags generated in the combustion process.

The first plant to comprehensively commence IBA treatment was an incineration plant of the Zweckverband Kehrichtverwertung Zürcher Oberland (KEZO) in Hinwil, Switzerland in 2016. The plant is based on the thermorecycling concept (ThermoRe process) (Mehr et al. 2021) and uses the dry processing of dry bottom ash. In the first stage of recovery, a system of eddy current separators is used, connected by crushers of decreasing fraction. ECS makes it possible to increase the metal recovery from the slag by 30 to 40% compared to the previous levels, as the plant can also separate out fine-grained metal residues. The process recovers iron, aluminum, copper, brass and even precious metals such as gold, silver and palladium. The benefits are twofold: first ecological, as small metal particles can cause considerable damage to the environment; second, financial, as the value of the metals recovered is so high that the dry slag processing plant brings sales revenues.

Precious metals are also recovered from ashes by magnetic density separation (MDS), for example, as employed in an incineration plant in Amsterdam, Netherlands (Muchova et al. 2009). This technology uses wet separation techniques. First, to recover precious metals, bottom ash must first be classified into different size fractions, then heavy nonferrous metals (HNF) should be concentrated by physical separation (eddy current separation, density separation etc.). Finally, MDS can separate gold from other HNF metals (copper, zinc). Precious metal concentrates must then be recovered in the smelter and the copper zinc fraction to a brass or copper smelter.

Another example of the IBA's metal removal is that which is used in the Afatek plant in Copenhagen, Denmark. Among the most important results of their development work is the semi-dry system, where bottom ash can be dried to a degree that makes it possible to sort out the very fine metals down to half a millimeter. When IBA arrives at Afatek's, it contains approximately 5% percent iron and 2% other metals, like nonmagnetic aluminum, copper, brass and zinc. Bottom ashes are initially aged for two to three months, and as the temperature rises in the heap, the bottom ash dries out. In the process, many of the heavy metals are bound to bottom ash; therefore, the metals are not washed out when slag gravel is subsequently used as aggregate. When IBA dries out sufficiently, iron and metals can be sorted out and the rest of the mineral material is used as aggregate. Magnetic iron is then separated using over-belt magnets, which are the first stage of IBA processing. Subsequently, metal droplets in grain sizes of half a millimeter are recognized and isolated from bottom ash. This is done with magnets for iron, with eddy currents for metals and with sensor technology combined with compressed air and nozzles that shoot stainless steel as well as residual metals out of the slag. The sorted metals are sold for processing Fe and NFe concentrates into a portfolio of pure fractions of iron, copper, brass, zinc, soft aluminum, hard aluminum and stainless steel. Some fractions can be sorted into several sizes to better meet the needs of the market. This applies, for example, to aluminum and copper (Nørgaard et al. 2019). Economic profitability of operated incineration bottom ash processing plants is achieved by most of the plants located in European countries with bottom ash mass flow exceeding 20,000 Mg per year. Average values of economic indicators are for net present value (NPV) 83 million Euro and return on investment (ROI) 20% with a payback time of eleven years (Bruno et al. 2021).

Mechanical operations such as grinding, classification, gravity separation, electrostatic separation, magnetic separation and flotation etc. have been widely used in the processing of waste from printed circuit boards (PCB). The release of Fe and NFe metals from the PCBs was achieved during size reduction. Crushers or impact crushers are used in the first stage, while in the second and third stages, mills and crushers produce the fine released particles (Yoo et al. 2009). The corresponding fine grained waste products obtained in this way are subjected to the separation of Fe and NFe metals (Sarvar et al. 2015) using the Harz instrument to separate particles based on differences in density.

Eswaraiah (Eswaraiah et al. 2008) conducted classification studies using a column air classifier to separate metals and plastics from crushed PCBs. The evaluation of the classifier's performance was analyzed in terms of various tested operating parameters. For example, Yue-Min (Yue-min et al. 2006) used the Falcon centrifugal concentrator, an advanced gravity unit to separate Fe and NFe metals. The test results show that the 76.9% metal concentrate obtained from the input raw material (feed) contained 5.42% metals. Li (Li et al. 2004) conducted studies on a corona electrostatic separator to concentrate metals from crushed PCB particles and Ghosh (Ghosh et al. 2015) investigated the use of an over-belt magnet to remove iron contamination prior to electrostatic separation.

Foam flotation is another method for the separation of physicochemical particles based on differences in the degree of hydrophobicity. Research shows that foam flotation is widely used to separate hydrophilic polymers of Fe and hydrophobic NFe metals from PCB EoL (Vidyadhar and Das 2013; Gallegos et al. 2014; He et al. 2017). The study by Vidyadhar and Das (Vidyadhar and Das 2013) on foam flotation show that particle sizes of less than 1 mm display an excellent separation of both ferrous and nonferrous metals. The results of one stage flotation studies show that the metal content of the input material (feed) containing 23% can be enriched to the value of 37%, of which 95% metal recovery can be obtained in further processes. In another study, Gallegos (Gallegos et al. 2014) investigated the separation of metals and nonmetals from waste PCBs using a conventional flotation cell proved that sing techniques and equipment designed for mineral processing can significantly aid the growing urban mining.

Chemical leaching of Zn, Cu, Cd and Pb from fly ash is performed in several plants, especially in Switzerland (Schlumberger et al. 2007; Quina et al. 2018). The extraction of metals such as Zn, Pb, Cu and Cd is mainly dependent on the properties of fly ash, the acidity of the rinse water, the redox potential, the temperature and the eluation time. Depending on these parameters, 60–80% of Zn, 80–95% of Cd and 50–85% of Pb and Cu can be recovered in the leaching process (Quina et al. 2018). This process was implemented at one of the MSWI plants in Zuchwil, Switzerland in 2012, where approximately 300 Mg of Zn are recovered per year. However, chemical leaching is a technology that is quite burdensome for the environment, especially the chemical leaching of critical elements, in particular REE. To lower the environmental impact, very intensive works are performed on the possibility of using the bioleaching of waste (Faramarzi et al. 2020).

Further methods of critical material recovery use the technologies of microfiltration, ultrafiltration, reverse osmosis and dialysis. Filtration methods transport water molecules through filters and membranes. These techniques are mainly used for pollution removal but can also be applied for light and heavy metals and even REE recovery (Elbashier et al. 2021). Before performing recovery, it is necessary to prepare the waste. The separation of the magnetic and non-magnetic fractions is required. Then, HNO_3 or HCl is used to wash out waste with a high content of calcium compounds. In the next step, ionic liquids are used to remove Si, Fe and Al. The last step of the separation involves the separation of the REE from the solution. For this, various solutions, like cyanex272, Trioctylphosphine oxide and di-nonyl phenyl phosphoric acid, are used to allow the REE to be washed out of the waste. Depending on the type of elements washed out from the waste, it is necessary to properly select the pressure and pH (Kose Mutlu et al. 2018). The filtration methods lead to the recovery of the elements contained in the solution at the level of 50–99% (Rybak and Rybak 2021).

A recent discovery by Rice University researchers is the use of flash joule heating to activate REE in coal fly ash and increase their leaching efficiency. Unlike other REE recovery methods characterized by long purification times, low extractability and high effluent volumes, the use of flash joule heating can activate REE in waste in about one second. The pulsed voltage brings the wastes to a temperature of 3,000°C within 1 second, leading to the thermal decomposition of the difficult-soluble REE phosphates to highly soluble REE oxides and then to the carbothermal reduction of REE components to highly reactive REE metals. REE leaching can then be performed with 1 M HCl or 15 M HNO_3. The extraction efficiency of activated REEs in coal fly ash ranges from 33 to 67% for individual REEs. The process has a low electricity consumption of 600 kWh ton^{-1} and costs of \$12 ton^{-1}. Costs are expected to be more than ten times lower compared to the direct leaching of raw materials. For further refining, however, it is necessary to remove dissolved impurities (Deng et al. 2022).

6. Discussion

The recovery of critical raw materials from the residues generated during municipal solid waste incineration has the potential to provide a domestic source of these materials, reducing the reliance on imports and enhancing the security of supply. The results of this study demonstrate that the recovery of critical raw materials from these residues is indeed feasible, as significant quantities of these materials are present in the residues. In 2020, 27% of MSW was incinerated in the European Union, 48% waste was recycled and composted, and about 25% of waste was placed in landfill. Despite the high share of waste subjected to recovery processes, incineration is still a very important component of the waste-management system. It reduces landfilling and a large proportion of non-recyclable waste due to the presence of pollutants, and it can be combined with energy recovery. Therefore, residues from waste incineration may be a stable and reliable source of many elements important for the economies of the EU and the USA for many years to come. The high variability of CRM in residues from waste incineration has become a subject of many studies and attempts to implement state of the art recovery technologies (EC 2020). Since China is the main supplier of most critical elements and many other important raw materials, the European Union countries and the United States try to diversify the source of these elements. Residues from MSWI are one of possible sources of CRM in urban mining. Recent trends by local initiatives promoting the circular economy are leading to the use of waste as a source of raw materials. Such actions certainly increase the security of supply.

Treating waste as a raw material can lead to an increase in the independence of poor countries in CRM in a new way. The municipal waste processing sector, despite the fact that it accounts for only 10% of total waste generated, is an important source of many raw materials. MFA has shown that the content of elements in residues from combustion can be comparable with the size of their extraction. The main limitation, however, may be the costly recovery techniques of these elements. The European Union places great emphasis on the waste to resources project. One such project was CEWASTE, which analyzed CRM recovery from electrical and electronic waste. The project report suggests that legislation should require the recovery of certain CRMs and additional market incentives should stimulate secondary use as much as possible CRM in new product. This approach should also be transferred to other sectors of the economy. Good examples can be found in the laws of the member states where information on the types, distribution and capacity of the existing ones and essential for the waste management system of recovery installations and waste disposal, including significant amounts of the most important economic raw materials the point of view of the deliveries of which are at high risk, is defined at nationals waste management plans (Ministry of the Environment 2023).

The estimated data in Figure 3 shows that waste is characterized by the presence of many elements recognized by the EU and the USA as critical raw materials. All waste consists of elements belonging to PGM, with LREE, HREE and precious metals also being present.

Precious metals are mostly represented by silver and gold. The content of REE is close to their concentration in the earth's crust. However, the high market prices combined with the low supply of REE, may make the recovery of these elements profitable, along with the processing of other valuable fractions like Zinc. The amount of the remaining elements in relation to their content in the Earth's crust is very diversified and is over 5,000 times higher in a case of Bi and Sb, over one hundred times higher for Ag, Au, Zn, Sn and fifty times

Critical materials below 2 %	Quantity [Mg]
Ni	1,874
V	1,585
Zr	936
REE	887
Co	314
Li	226
Ga	125
Nb	124
Ag	68
Au	4

Critical materials below 2 %	Quantity [Mg]
V	2,812
Zr	1,600
REE	1,574
Co	557
Li	401
Ga	223
Nb	220
Ag	121
Au	7

Fig. 3. Critical materials in residues from MSW incineration and their estimated annual quanti-ty in UE and USA

Rys. 3. Materiały krytyczne w pozostałościach ze spalania MSW i ich szacowana roczna ilość w pozostałościach w UE i USA higher for Cu. Heavy metals are represented mainly by copper and zinc. The estimated amounts of critical raw materials in the USA and EU residues indicate that their recovery could significantly reduce the reliance on primary mining activities. For example, the recovery of rare earth elements from the residues could exceed their mining from ores in the EU. Similarly, the cobalt content in USA residues accounts for a significant proportion of the amount mined in the country. This highlights the potential for significant resource recovery from these waste streams, which could contribute to a more circular economy and reduce the environmental impact of raw material extraction.

The recovery of zinc and copper from residues has been widely implemented in Switzerland using acid-leaching Fluwa technology. This process recovers up to 80% of the zinc and 40 to 80% of the copper in the waste, which confirms the effectiveness of this technology and the possibility of its implementation in other plants and countries (Zucha et al. 2020). However, the recovery of these critical raw materials from the residues presents several challenges. Firstly, the heterogeneous nature of the residues and the complex interactions between the different components can complicate the recovery processes. Secondly, the form in which these materials are present in the residues can limit their recovery potential. For example, some critical raw materials are present in the form of highly dispersed nanoparticles, which can make their separation and recovery difficult and costly. Despite partnership deals between countries, conflicts, disasters and diseases can cause months of breakdowns in supply chains. This makes it even more important to use the available raw materials as efficiently as possible, and anthropogenic sources such as municipal waste and residues from treatment processes can be a good alternative to natural sources of raw materials. The recovery of critical raw materials from municipal solid waste incineration residues should be pursued as part of a comprehensive strategy for the supply security of raw materials and the development of a circular economy. Advances in separation and recovery technologies and processes could enhance the efficiency of recovery operations and reduce the costs associated with these operations. Additionally, the development of policies and regulations that support the recovery of critical raw materials from waste streams could provide incentives for businesses and promote investment in these technologies.

Conclusions

The aim of this study was to present the potential for the recovery of critical materials contained in municipal waste and residues from municipal waste incineration. The paper presents the chemical composition of combustion residues with a particular emphasis on elements considered as critical by the United States and European Union. Mass flow analysis was used for the estimation of element content in MSWI residues in USA and UE.

- The analysis showed that the estimated amount of elements in residues from waste incineration in the USA is in the range from 1.4 Mg (Thallium) to 44,000 Mg (Zinc) and in the EU from 2.4 (Thallium) to 78,000 Mg (Zinc).

- The content of REE is 1,500 Mg and exceeds their mining from ores in the European Union.
- Cobalt content in USA residues accounts for 63 of the amount mined in this country.
- The share of other raw materials in residues correspond to 2% to over 2000% of their mining in the USA and the EU.
- Due to the form of occurrence of raw materials in MSWI residues, their recovery potential may be limited.
- Despite the implementation of circular-economy principles into waste management systems, there remain technical limitations for waste recycling processes. Therefore, waste incineration will probably remain the main method of processing residual waste in the nearest future, and attention should be paid to the possibility of element recovery that may be critical to economic growth.

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FROM WASTE TO VALUE: RECOVERING CRITICAL RAW MATERIALS FROM URBAN MINES IN THE EUROPEAN UNION AND UNITED STATES

Keywords

municipal solid waste, waste incineration,
critical raw materials, residue treatment, circular economy

Abstract

Municipal waste is a global issue and they are generated in all countries around the world. Both in the European Union and the United States, a common method of non-recyclable waste utilization is thermal incineration with energy recovery. As a result of this treatment, residual waste like bottom ash, air pollution control residues and fly ashes are generated. This research shows that residues from waste incineration can be a potential source of critical raw materials. The analysis of the available literature prove that the residues of municipal waste incinerators contain most of the elements important for the US and EU economies. Material flow analysis has shown that each year, the content of elemental copper in residues may be 29,000 Mg (USA) and 51,000 Mg (EU), and the amount of rare earth elements in residues exceeds their mining in the EU. In the case of other elements, their content may exceed their extraction by even over 300%. The recovery of elements is difficult due to their encapsulation in the aggregate matrix. The heterogeneous nature of residues and the many interactions between different components and incineration techniques can make the process of recovery complicated. Recovery plants should process as much of the residues as possible to make their recovery profitable. However, policy makers from the EU and the US are introducing new legal regulations to increase the availability of critical raw materials. In the EU, new regulations are planned that will require at least 15% of the annual consumption of critical raw materials to come from recycling. Therefore, innovative technologies for recovering critical raw materials from waste have a chance to receive subsidies for research and development.

OD ODPADU DO WARTOŚCI: ODZYSKIWANIE SUROWCÓW KRYTYCZNYCH Z MIEJSKICH KOPALNI W UNII EUROPEJSKIEJ I STANACH ZJEDNOCZONYCH

Słowa kluczowe

odpady komunalne, spalanie odpadów, surowce krytyczne,
przetwarzanie pozostałości, gospodarka o obiegu zamkniętym

Streszczenie

Odpady komunalne stanowią globalny problem i są wytwarzane we wszystkich krajach na całym świecie. W Unii Europejskiej i Stanach Zjednoczonych powszechną metodą utylizacji odpadów nienadających się do procesów recyklingu jest ich termiczne spalanie z odzyskiem energii. W wyniku tego procesu generowane są pozostałości procesowe, takie jak popioły denne, stałe pozostałości z oczyszczania spalin i popioły lotne. Badania wykazały, że te odpady mogą być potencjalnym źródłem surowców krytycznych. Analiza dostępnej literatury dowodzi, że pozostałości z instalacji termicznego przekształcania odpadów komunalnych zawierają większość surowców krytycznych ważnych dla gospodarki USA i UE. Analiza przepływu materiałów wykazała, że zawartość miedzi pierwiastkowej w pozostałościach może wynosić rocznie 29 000 Mg (USA) i 51 000 Mg (UE), a ilość metali ziem rzadkich w pozostałościach przewyższa ich wydobycie w UE. W przypadku innych pierwiastków, ich zawartość może przewyższać wydobycie nawet o ponad 300%. Odzyskiwanie pierwiastków jest jednak trudne ze względu na ich agregację. Heterogeniczna natura pozostałości i liczne interakcje między różnymi składnikami oraz technikami spalania mogą komplikować proces odzysku. Instalacje specjalizujące się w przetwarzaniu pozostałości muszą przetwarzać jak najwięcej odpadów aby ich odzysk był opłacalny. Jednak politycy z UE i USA wprowadzają nowe regulacje prawne w celu zwiększenia dostępności surowców krytycznych. W UE planowane są nowe przepisy wymagające, aby minimum 15% rocznego zużycia surowców krytycznych pochodziło z recyklingu. Dlatego innowacyjne technologie odzysku surowców krytycznych z odpadów mają szanse na uzyskanie dotacji na badania i rozwój.