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Evaluation of chemical composition and radioactivity of slags in terms of their potential for reuse for fertilizer purposes — a literature review

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Abstract
This article discusses the growing importance of using industrial waste, including furnace slag, in the production of agricultural fertilizer, recycling raw material for sustainable development and a closed-loop economy. Furnace slag, which is generated in coal combustion processes in industrial furnaces, is a valuable waste material, the yield of which depends on a number of factors, such as the type of fuel used, dust removal efficiency, and furnace type. In addition to furnace slag, other types of slag have been distinguished, such as metallurgical slags and those generated after burning municipal waste. Currently, the possibility of recovering metals from slags, especially steelmaking slags, and their use in processes such as cementing or geopolymerization is gaining importance. The potential use of these wastes as a fertilizer ingredient is also an important direction of management. Nonetheless, further research is needed concerning the safety of using these materials in agriculture, due to their high identified content of heavy metals and hazardous substances. Of great importance in terms of slag reuse is the monitoring of radioactivity parameters, especially in the context of slag's potential use in fertilizers.

1. INTRODUCTION

In recent years, the issue of using industrial waste in the production of agricultural fertilizers has been gaining attention, especially in the context of the growing need for sustainable development, recycling of raw materials and a closed-loop economy. One such material that has found wide application in this field is slag generated from the combustion of coal in industrial furnaces (furnace slag). The amount of combustion waste generated depends on the weight of the fuel used, its type and quality, the method of combustion (type of furnace), and the efficiency of the dust-collection elements installed in the system [Olszewski et al. 2012]. The amount of slag generated from coal combustion in thermal power plants and thermal waste conversion facilities is about 30% [Skoko et al. 2017, Poranek et al. 2021]. For example, in China, 244 million tons of municipal waste were generated in 2022, of which 195 million were thermally converted. China also produces huge amounts of phosphoric and steelmaking slags, 80 million tons/year of phosphoric slag, and 160 million tons/year of steelmaking slag, putting it at the forefront of these industries globally. It has a fairly low reuse rate of these resources, however, at less than 40% [Shi et al. 2022, Sai et al. 2024, Du et al. 2025].

It is worth mentioning slags produced from waste from the metal smelting industry, such as blast furnace slags (from the production of so-called pig iron) and converter slags (from the steel smelting process). Slags from metallurgical plants (including iron) have a high potential for metal recovery in reuse processes, with each ton of iron and steel producing about 0.10–0.23 tons of slag [Sitko 2014, Choi et al. 2021].

Slags have mainly been used as a sealing material, as an element of mortars and binders used in mining, and in landfills, road construction and geotechnical work, to improve soil structure and stability [Iwanek et al. 2008, Hycnar 2006, Koda et al. 2010, Gawlicki et al. 2013, Poranek et al. 2021, Vukanac et al. 2022, Zhang et al. 2025]. In the case of slags classified as hazardous substances (mainly from the incineration of municipal waste and sewage sludge), popular management methods include cementation, geopolymerization, or composite formation [Mikuła et al. 2017, Zhang et al. 2023, Sai et al. 2024, Kuranlı et al. 2024]. An important and developing direction of slag management (especially steelmaking slags) is their reprocessing during the recovery of elements from the waste material. As part of the expansion of knowledge and opportunities for the recovery of elements from slags, initiatives have been established, like the H2020 CHROMIC project in Europe, which focuses on the development of new technologies for the recovery of elements such as chromium or molybdenum. Slags subjected to recovery processes can also be an important source of rare earth elements [Jonczy 2018].

There are indications of the possibility of using slags as an ingredient in fertilizers and soil conditioners, but this management direction is controversial and requires further research to confirm the environmental safety of using these wastes. This is especially important in light of the potential radioactivity of slag, which depends on the origin of the incinerated substrate, among other factors [Hycnar et al. 2014, Skoko et al. 2017].

2. PURPOSE OF THE WORK

The purpose of this study is to evaluate the chemical composition and radioactivity of slags from various types of combustion and feedstock in terms of their fertilizer potential.

Physicochemical composition of slags by combustion source.

Table 1 above provides summary data on the chemical composition of slags by type of feedstock and source, according to Polish authors Sybilski et al. [2004], Giergiczny et al. [2004], Smarzewski et al. [2015], Jonczy [2013], Baran et al. [2017], Ostrowski [2018], Adamczyk et al. [2013], Soltys [2016], and Czop et al. [2022]. The table distinguishes slags from the combustion of hard coal, lignite, steel processing, iron, zinc, and municipal waste. Furnace slags from combustion in fluidized bed boilers (EC Żerań) were evaluated, and converter slags were taken directly from incineration plants and heaps.

There have been a number of studies in which slag composition is analysed with an eye toward its further use in construction (mainly for the production of cements). In addition to their physical properties relevant for construction use, the slags' chemical properties were also studied according to PN-EN 15167-1:2006. In most examples, the chemical composition is dominated by SiO_2, with the highest content for slag from municipal waste combustion, at 54.20%; CaO, which is most abundant in slag from ironworks (42.27–45.75%); and Al_2O_3, which is dominant in coal-combustion slag (23.60%).

Similar relationships were obtained by Jia et al. [2024] for slag from municipal waste incineration plants; Choi et al. [2021] and Bulut et al. [2022] for blast-furnace slag (steel industry); and Huang et al. [2025] for silico-manganese slag (smelter slag). Tao et al. (2024) and Feng et al. [2023] found this type of relationship in blast furnace slag for phosphogypsum production. Du et al. [2025] and Shi et al. [2022] found the highest CaO content for steelmaking slags, at 36.33–63.30%.

The composition of slags strictly depends on the substrates used in combustion and processing, in addition to the place and way in which the slags are produced. For example, Fe_2O_3 was found to have the highest content in slag obtained after the production of tin and coal, at 37.64%–42.30%, followed by SiO_2 and CaO [Zulkeplee et al. 2023; Lai et al. 2022]. The highest content of TiO_2 was found in titanium slag formed after the smelting of vandanium-titanium magnetite (21.46%), followed by CaO and SiO_2 [Wang et al. 2023], and manganese slag, where, in addition to a high proportion of SiO_2 and Al_2O_3, 11.63% MnO content was found [Hu et al. 2024].

Table 2 shows the results for the elemental composition of slags from the Ruda Śląska and Chorzów dumps, as well as granulated blast-furnace slag. The highest contents were recorded for Zn (62.70–83.70 mg/kg) and Pb (53.40–293.85 mg/kg) in slag from the Ruda Śląska dump. For slags from the Chorzów dump, the highest Mn was in the range of 87.30–866.00 mg/kg and Zn (1–108.00 mg/kg), and the lowest for Cd and Ni [Jonczy 2012, Król 2017].

In the granulated slag from metallurgical processes, the maximum values are much lower for Mn (19.78 mg/kg) and Zn (36 mg/kg), and the lowest for Pb and Ni. Jonczy et al. [2013] also examined the content of other metals (including lanthanides and actinides) in blast-furnace and converter slags. They found a high Cr content for converter slag (11.20–15.50 mg/kg), and a significant amount of As for blast furnace slags (11.80–16.00 mg/kg). By way of comparison, at HCM and Boleslaw smelters, 2.2 mg/kg of As was found in converter slags, and a trace amount, < 0.14%, for metallurgical slags [Jonczy 2018]. Also worth mentioning are the contents of Ni in blast-furnace slag (107–133 mg/kg), as well as Sr (239–240 mg/kg) and V (8.16–11.50 mg/kg) in converter slags [Jonczy, 2013].

Table 3 shows data on the elemental composition of slags from municipal waste incineration in different types of incinerators, from different locations, and metal leachability, according to authors Czop et al. [2022] and Martysz et al. [2021]. High zinc content (1621.00–2787,00 mg/kg) and particularly high copper content (21,608.00 mg/kg), as well as 766.00 mg/kg lead content, were found for slag from the waste incineration plant with a sliding grate. Also significant is the chromium content, at 277.00–605.00 mg/kg. However, the composition of municipal waste incineration slag is largely determined by the type of feedstock, and this is also the case in metallurgical slags. Kijowska et al. [2024], in a study of chromium content in steelmaking slags from municipal waste incineration and heaps, showed an average chromium concentration of < 440.00 µg/g, with an additional decrease in chromium concentration after the storage period. Adamczyk and Nowak (2012) found chromium content in the range of 80–190 mg/kg for furnace slag. Interestingly, in that study, the authors also found a upward trend in chromium concentration over 10 years after slag management for reclamation purposes. The cadmium concentration for municipal waste incineration slag is relatively low (0.96–5.80 mg/kg), comparable to the results for biomass incineration slag, which achieved concentrations of 0.95–2.57 mg/kg [Ma et al. 2023].

In addition to the elemental content of slag dry matter, elemental leachability studies are crucial for evaluating

Table 1. Chemical composition [% by weight] of slags by type of fuel used and type of combustion (examples from Poland)

Fuel and type of combustion	Hard coal		Lignite	Steel plant		Copper smelter	Steel mill (iron)	Zinc smelter	Steel plant	Municipal waste	
Source / Component	Combined heat and power plant – furnace slag	EC Żerań – slag from combustion in fluidized bed boilers	EC Żerań – slag from combustion in fluidized bed boilers	Dabrowa Gornicza heap – converter slags	Dabrowa Gornicza heap – blast furnace slags	Copper slag – shaft and granulated	Blast furnace slag (Katowice and Sandzimir Steelworks)	„Silesian Town”	Steel-making slag (converter slag)	Waste incineration plant with sliding grate (capacity: 210,000-220,000 t/year)	Waste incineration plant with reciprocating grate (capacity: 94,000 t/year)
SiO_2	50.10	31.00–46.00	47.50–52.00	10.80–14.41	39.57–45.03	35.24-42.76	36.84–39,66	24.82	9.40	54.20	54.20
Fe_2O_3	4.94	3.37–3.73	6.20–8.50	26.52–32.45	14.64–17.77	17.38–18.57	0.49–2.50	·	33.84	4.99	4.19
Al_2O_3	23.70	7.92–16.19	22.10–23.60	2.99–4.17	7.56-10.30	12.31–15.56	6.30–7.80	8.29	1.99	11.05	6.53
MnO	0.04	·	·	2.40–3.34	0.42–0.48	·	·	·	4.11	·	·
Mn_2O_3	·	·	·	·	·	·	0,17-0,24	·	·	0.12	0.13
TiO_2	1.22	·	·	0.45–0.55	0.42–0.59	-	0.42–0.80	·	·	0.73	0.66
CaO	2.13	4.20–48.20	6.30–33.80	35.81–37.53	19.24–20.58	11.88–21.27	42.27–45.75	17.43	37.64	14.50	16.30
MgO	1.46	1.00–3.10	0.70–2.30	7.01–7.82	5.33–5.63	7.29–7.77	4.57–8.03	2.68	9.06	1.75	1.80
SO_3	0.85	0.30–27.70	1.10–9.10	·	·	0.12–0.16	0.08–1.12	2.84	0.44	1.07	1.67
$P_{20}5$	0.64	·	·	0.99–1.37	0.06–0.09	·	·	·	·	0.93	0.99
Na_2O	0.45	·	·	< 0.02	0.25–0.28	·	0.42–0.55	·	·	5.39	5.62
K_2O	2.27	·	·	< 0.02	0.23–0.26	·	0.35–0.84	·	·	0.90	1.05
Cl	0.13	·	·	·	·	0.002–0.015	0.03-0.07	·	·	·	·
Source	[Smarzewski et al. 2015]	Sybilski et al. 2004]	[Sybilski et al. 2004]	[Jonczy et al. 2013]	[Jonczy et al. 2013]	[Kuterasińska et al. 2014]	[Baran et al. 2017], [Ostrowski 2018], [Giergiczny et al. 2004], [Różycka et al. 2008]	[Adamczyk 2013]	[Sołtys, 2016]	[Czop et al. 2022]	[Czop et al. 2022]

· = no data

Table 2. Elemental composition of heap slags compared to blast furnace slag

Element	Elemental composition [mg/kg]		
	Slag heap Ruda Śląska (after Zn-Pb, pre-metallurgy)	Slag heap Chorzow (steelmaking slags)	Granulated blast furnace slag
Mn	430-2223	873-86600	1978
Zn	6270-83700	1-10800	36-1580
Pb	5340-29385	6-3200	<83
Cd	32-262	<0.3-136	19-3
Cr	16-69	15-2920	12-372
Cu	66-1859	3-837	22
Ni	25-146	<1-102	<2,5
V	41-74	6-919	10-94
Mo	6-25	<1-8	2-4
Ag	55-140	<0.3-3.5	0.9

Table 3. Elemental composition of slags from municipal waste incineration by type and location of incineration plants

Slags from Municipal waste					
Source/ Element	Results on a dry weight basis [mg/kg]			Leachability [mg/l]	
	Waste incineration plant with sliding grate	Waste incineration plant with sliding grate	Waste incineration plant with reciprocating grate	Incinerator Bydgoszcz (0-8mm grain size)	Warsaw incineration plant (0-31.5mm grain size)
Zn	2787,00	1621,00	2337,00	0.06	0.03
Cu	21608,00	1918,00	867,00	0.03	0,04
Pb	766.00	687.00	437.00	0.03	0.02
Ni	73.60	81.00	211.00	< 0.01	< 0.01
Cr	277.00	342.00	605.00	0.01	0.05
Cd	5.80	3.35	0.96	< 0.01	< 0.01
As	5.30	16.50	6.07	-	-
V	31.80	30.00	30.70	-	-
Tl	< 1.00	< 1.00	-	-	-
Hg	0.04	0.24	< 0.01	-	-

- = no data

this material as a potential fertilizer additive. Kubiss et al. (2019) and Zhang et al. (2025) investigated the content of selected elements in copper slag — Cr(VI), Cd, Pb, Hg — as well as chloride, fluoride and sulphate in the aqueous extract. None of the parameters exceeded the permissible standard for national regulations (Journal of Laws 2015, item 1277), and hence it can be concluded that the introduction of copper slags into the environment would not pose a threat to aquatic organisms — provided that their chemical properties are checked each time. Czop et al. [2022] and Martysz et al. [2021] found similar results for municipal waste incineration slag (Table 3), as did Sai et al. [2024] for phosphate slag. Yu et al. [2024] obtained different results, investigating the leaching rate of heavy metals from silicate-manganese slag using the HVM method, along with TCLP, which stimulates the natural processes of element migration from landfill materials and leachate (as in the case of slag in landfills). In the analysed case, the TCLP method showed particularly high excesses of leached Mn and Cr, reaching the IV class of the Chinese standard for groundwater quality GB/T 14848, indicating a threat to the aquatic environment [Yu et al. 2024].

The above table shows the concentrations of natural radionuclides ^{40}K, ^{232}Th, ^{226}Ra, along with radioactivity indicators, where f_1 is the natural radioactive isotope content (taking into account potassium, radium and

Table 4. Results of γ-spectrometric analysis (Bq/kg) and radionuclide concentrations in different types of slag and other materials

Electric plant	^{40}K	^{232}Th	^{226}Ra	f_1	f_2
CHP plant Siekierki	254.00–731.00	57.30–124.00	52.90–113.00	0.47–1.12	57.30–124.00
CHP plant Żerań	364.00–691.00	44.20–113.00	39.10–89.70	0.46–1.01	44.20–113.00
Municipal waste incineration plant (Bydgoszcz and Warsaw)	·	·	·	< 0.61	< 75.3
Copper slags	749.00–961.02	40.10–50.47	320.19–400.00	1.62–1.65	320.19–344.08
Steel production (Croatia)	45.30–62.90	12.90–15.40	15.20–21.40	·	·
Ground granulated blast furnace slag	235.60	66.50	167.40	·	·
Non-ferrous Metal Slag	171.59	15.74	42.74	·	·
Slag (coal)	97.86	95.99	145.43	·	·
Phosphorus slag	221.60	23.48	153.08	·	·
Blast Furnace Slag (Mixed Material)	121.54	102.13	157.33	·	·
Slag (bituminous coal)	177.65	7.36	23.44	·	·
Solid Waste Contaminated Soil	663.95	47.84	33.77	·	·
Soil	269.00–561.00	26.20–73.30	33.20–120.00	·	·
River sand	404.30	28.10	26.70	·	·

· = no data

thorium) as a dimensionless indicator; f_2 is the radium content of ^{226}Ra in Bq/kg. In the case of f_1, a value of no more than 1.2 is considered acceptable, while the acceptable limit for the activity index f_2 is 240 Bq/kg according to the EU criteria adopted for constructed materials (OJ/L 157 of 27.5.2014, p.76) [Isajenko et al. 2014].

Analysing the above indicators, particularly high results were shown for post-copper slags, with f_1 in the range of 1.62–1.65 and f_2 ranging from 320.19–344.08 Bq/kg. These results would preclude the possibility of managing these slags in light of existing regulations. Radionuclides present in the environment can pose a threat as a type of external radiation, as the decay products of radium and thorium emitting γ-rays can damage the body's cells [Wang et al. 2025]. The results of radionuclide activity measurements for various types of slags can be compared with those for soils or naturally-occurring sands, as well as with averages of concentrations of global radionuclide activity available in the literature for granulated blast furnace slag. For ^{226}Ra, the average is 35 Bq/kg, and for ^{232}Th, it is 30 Bq/kg. Higher values were found in almost all cases analysed. Meanwhile, the global average for ^{40}K is 420 Bq/kg, with values higher than this average also found in CHP Siekierki and Żerań (furnace slag) and copper slags [Bulut et al. 2022].

Radionuclide concentrations obtained for slags are similar to or lower than those found in soils of various origins, including Croatia and China [Skoko et al. 2017, Wang et al. 2025]. In the context of using slags for fertilizer purposes in light of their potential radioactive properties, Skoko et al. [2019] used the ERICA tool to estimate an ash and slag storage site's radiological risk to flora and fauna. Several groups of plants, and all types of organisms present, were studied. The risk of impact on plants in the study area was considered negligible, with animals such as earthworms and small mammals hypothesized to have reduced reproductive capacity or higher mortality.

3. CONCLUSIONS

The chemical composition of slags varies depending on the source, combustion method and feedstock. The high content of alkali oxides in slags may determine their potential in regulating the pH of acidic soils, while their macronutrient content after thermal conversion processes is relatively low.

Most of the smelter and furnace slags analysed show unacceptable levels of heavy metals such as lead, zinc, copper and chromium, and thus cannot be used as substrates for the production of mineral-organic fertilizers or other soil improvers. The leachability of the above-mentioned elements depends on a number of factors, however, and this aspect should be studied more extensively in the context of the possibility of using slags for fertilizer purposes (especially since most of the available analyses refer to the use of slag in construction).

Slags, depending on their origin, can be successfully managed for the recovery of metals and other elements; metallurgical and potassium slags are particularly important sources.

The radioactive properties of most slags indicate no risks to the aforementioned wastes in terms of their radioactivity. The values of f_1 and f_2 are within the limits of the standard according to the criteria adopted for construction materials, although this aspect should be studied more extensively due to the low availability of data. The isotope content for the slags in this study is close to the values naturally occurring in the soil (except in the slags from municipal waste incineration). From this perspective, no negative environmental impact can thus be expected from using slag.

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