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Evaluation of fly ash in terms of its suitability for fertilizer purposes by type of combustion and feedstock - literature review

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Abstract

Fly ash, as waste generated from the combustion of coal and other solid fuels, is an important topic in the context of a circular economy in any industry. There are many variables that affect the amount of waste generated, including the type and quality of fuel and the efficiency of dust collection systems. Statistics on the consumption of coal and lignite in Poland, as well as other sources of waste (such as municipal and sewage sludge) indicate a significant amount of fly ash produced.

According to the waste hierarchy, fly ash can be recycled or subjected to other recovery methods with the objective of using it as a sealing material, an ingredient in mortars and adhesives, and in geotechnics. For hazardous waste, the preferred recovery methods are cementation, geopolymerization and vitrification. The trace-element content of ash varies depending on the source and type of material burned. This is a key issue for determining the feasibility of further ash management.

Due to the content of macro- and micronutrients beneficial for plants and soil, fly ash can be used for fertilization purposes following the examination of its chemical properties, with particular attention to the concentration of heavy metals and other contaminants.

1. INTRODUCTION

In addition to heat, the combustion of coal and other solid fuels generates waste such as fly ash and slag. The amount of combustion waste generated depends on the mass of the fuel used; its type and quality; the method of combustion (type of furnace); and the efficiency of the dust-removal elements installed in the system [Olszewski et al. 2012]. According to some sources, ash from hard coal combustion can be estimated to comprise about 25% of the mass burned, and up to 40% of the mass in the case of lignite combustion [Luczak-Wilamowska 2011]. It is worth mentioning that the annual consumption of hard coal in Poland for energy purposes is about 57 million tons [forum-energii.eu]. Thermal conversion of municipal waste in installations for its combustion also generates fly ash qualified as hazardous waste [Poranek et al. 2021]. The amount of municipal waste generated per year is increasing all the time — over the past 5 years, according to GUS, it has increased from 12485.42 tons in 2018 to 13447.91 tons in 2023. Fly ash also results from waste after the thermal conversion process of sewage sludge. In 2023, the amount of incinerated sewage sludge in Poland after industrial processes amounted to 139,015 tons, accounting for about 35% of the total of 396,824 tons. In 2023, 89,800 tons of municipal sewage sludge were thermally transformed in

Poland, accounting for about 16% of the 549,702 total tons of municipal sewage sludge generated [GUS 2025].

The hierarchy of waste handling methods indicates that in addition to efforts to reduce the generation of waste, any waste generated should be recycled or otherwise recovered. Fly ash and slag have specific codes according to the Waste Catalogue [Regulation... 2020]. Among them are listed:

- 10 01 02: coal fly ash,
- 10 01 16*: fly ash from co-incineration containing hazardous substances.

The main uses for fly ash and slag are as a sealing material; in the mortars and binders used in mining; for landfills; for road construction and geotechnical work to improve soil structure and stability; and for cement mixes (especially for fluidized bed ash) [Iwanek et al. 2008; Hycnar 2006; Koda et al. 2010; Gawlicki et al. 2014; Poranek et al. 2021]. For ash and slag classified as hazardous substances (mainly from municipal waste incineration and sewage sludge), popular management methods include cementation or geopolymerization [Mikuła et al. 2017], as well as metal recovery processes (R12) for bottom ash. The rest, including flue gas cleaning products, are mostly stabilized and disposed of, mainly by landfilling [Poniatowska et al. 2018].

There is a growing interest in the management of ash for use in fertilizers, both as a direct additive to fertilizers and in the form of geopolymers and zeolites that improve the physical properties of soil conditioners [Szerement et al. 2021, Fan et al. 2023]. The properties of fertilizer with added fly ash depends on its chemical composition. The main advantage of fly ash is its alkalizing properties, which support plant growth and yield through macro and micronutrient content — through, for example, reducing the availability of heavy metals in the soil [Singh et al. 2013, Ram et al. 2014, Ma et al. 2023]. Fly ash can also be used as a raw material for potassium extraction, which reduces the need for synthetic fertilizers [Mehrez et al. 2017, Mayer et al. 2022]. Concerns raised about the use of ash in the environment may include its heterogeneous effects on heavy-metal leaching and its potential ecotoxicological

risks for animals and humans. There is thus a need for more extensive research on fly ash before it is reused in this way [Ukwattage et al. 2013, Yao et al. 2015, Chen et al. 2024]. The purpose of this study is thus to evaluate the chemical composition (and possible fertilizer potential) of fly ash from incineration plants in Poland by type of incineration and feedstock.

2. CHEMICAL COMPOSITION OF FLY ASHES, BASED ON COMBUSTION SOURCES

The results of fly ash oxide composition analyses were divided by fuel type and combustion type (Table 1). To more easily compare the results, the data throughout the article were standardised and converted into elemental

Table 1. Content of selected components of fly ash by type of fuel used and type of combustion

Fuel and type of combustion	Fly ash							
	Hard coal			Lignite			Co-firing of hard coal with biomass (10%–40%)	100% biomass (Wood and forest biomass)
	Boiler	Fluidized bed boiler	Dust boiler	Conventional boiler	Fluidized bed boiler	Dust boiler	Dust boiler	Fluidized bed boiler
Source	Element							
S	0.14–0.31	0.30–3.34	0.25	0.36–1.76	1.52–0.32	0.15–3.30	0.16–0.87	1.08–2.33
P	0.12–0.23	.	0.13–0.18	0.00	0.03	0.010–0.013	≥ 0.013	0.00–0.43
K	0.49–1.80	0.66–0.86	0.26–2.35	0.4–1.18	0.26–0.58	0.05–0.29	0.7–1.87	1.54–10.1
Ca	1.44–3.79	3.03–14.10	0.46–5.15	1.98–21.78	11.39–14.28	0.22–22.26	1.56–5.24	1.5–22.63
Mg	0.43–1.20	1.19–1.89	0.86–1.01	0.44–1.45	0.94–1.08	0.12–1.22	0.81–1.72	1.08–3.35
Na	0.19–0.47	0.27–0.59	0.13–0.52	0.07–0.86	0.39–0.61	0.06–0.94	0.38–0.47	0.14–0.36
Cl	0.002	0.12	0.16	0.008–0.01	0.025–0.03	> 0.01	0.003	1.06–1.19
Ti	0.68–0.88	0.45–0.55	0.47–2.05	0.98	1.02–2.30	0.12–0.48	0.75	0.18
Ba	0.05–0.12	.	.	0.03	.	.	.	.
Sr	0.08–0.12	.	.	0.07	.	.	.	0.03
Cr	0.01–0.013	.	.	.	.	.	.	.
Source	[Różycka et al. 2008], [Borowski 2010], [Ostrowski 2011], [Kosiar-Kazberuk et al. 2011], [Jóźwiak-Niedźwiec-ka et al. 2012], [Uliasz-Bocheńczyk et al. 2015], [Czar-na-Juskiewicz et al. 2018], [Cader et al. 2018]	[Różycka et al. 2008], [Łaskawiec et al. 2010], [Borowski et al. 2010], [Gawlicki 2014], [Uliasz-Bocheńczyk et al. 2015]	Haustein et al. 2012], [Kasprzyk et al. 2017], [Tkaczewska et al. 2019]	[Dąbrowska et al. 2014], [Cader et al. 2018]	[Sybilski et al. 2004], [Ostrowski 2011], [Jóźwiak-Niedźwiec-ka 2012], [Klędyński et al. 2016]	[Ostrowski 2011], [Garbacik et al. 2013], [Kasprzyk et al. 2017], [Hycnar et al. 2017]	[Kosior-Kazberuk 2011], [Giergiczny et al. 2012], [Haustein et al. 2012], [Poluszyńska et al. 2015], [Uliasz-Bocheńczyk et al. 2016]	[Rajczyk et al. 2013], [Poluszyńska 2013], [Uliasz-Bocheńczyk et al. 2015], [Poluszyńska et al. 2015], [Drózd et al. 2023]

Table 1. Content of selected components of fly ash by type of fuel used and type of combustion

Fuel and type of combustion	Fly ash			Bottom ash	
	100% biomass (80% forest biomass + 20% agricultural biomass)	Ash after flue gas desulphurization – Rybnik Power Plant and Ciech Thermal Power Plant	Combustion of municipal waste	Co-firing of coal and biomass	Combustion of municipal waste
Source	Fluidized bed boiler	.	Fluidized bed boiler	Fluidized bed boiler	Fluidized bed boiler
Element					
S	2.84–4.00	1.67–8.64	1.12–5.56	0.12–4.50	0.04–1.96
P	–	0.14	0.22–0.46	–	0.24–0.96
K	5.69–7.51	1.07	0.81–1.60	0.52–0.64	0.42–1.25
Ca	15.09–16.46	10.25–26.18	10.14–25.28	0.72–13.14	8.57–16.50
Mg	3.40–4.11	1.18	0.98–1.87	0.66–1.40	1.21–2.59
Na	0.12–0.22	0.22	.	0.18–0.29	.
Cl	.	.	0.93–8.1	.	0.1–5.9
Ti	.	0.49	0.65–1.34	.	0.54–1.4
Ba	.	0.13	0.09–0.20	.	.
Sr	.	0.05	0.04–0.06	.	.
Cr	.	.	.	.	.
Source	[Uliasz-Bocheńczyk et al. 2016]	[Sybilski et al. 2004], [Plaskacz-Dziuba et al. 2014]	[Nakano et al. 2007], [Czop 2020]	[Kasprzyk et al. 2017]	[Nakano et al. 2007]

* . = no data

forms. In the case of hard coal, a distinction was made between different types of combustion: conventional (the Kozienice, Opole, Lublin-Wrotkow, and Jaworzno thermal power plants), fluidized bed (the Katowice, Tychy, and Siersza thermal power plants), and pulverized coal boilers. The product of hard coal combustion is silica ash. Lignite is burned in conventional boilers, fluidized bed boilers (the Turów Power Plant) and pulverized coal boilers (e.g. the Bełchatów and Pątnów Power Plants). The product of lignite combustion is lime ash.

The most important distinguished macronutrients for fertilizers, according to the Ordinance on fertilisers and fertilisation [Regulation... 2024], are phosphorus and / or potassium, depending on the type of fertilizer. Phosphorus content was found in all the samples analysed and was highest in biomass combustion ash (ranging from 1.54–10.1%). The lowest phosphorus content was for lignite combustion in pulverized boilers (0.05–0.29%). The highest potassium content was found in ash from municipal waste combustion, ranging between 0.22–0.46% for fly ash and 0.24–0.96% for bottom ash. All the analysed examples of ash were also characterized by relatively high Ca content, particularly ash after flue gas desulphurization (10.25–26.18%) and ash after municipal waste combustion (10.14–25.28%).

The content of the aforementioned macronutrients confirms their suitability for use in fertilizers. In China,

they are used in the production of silicon-potassium mineral fertilizers from ash from coal-fired thermal power plants. This ash has an effective potassium content of 25.07% and a silicon oxide content of 34.56% [Li et al. 2014]. In Schönegger et al. (2018)'s study, which was conducted under greenhouse conditions, fly ash was added to acidic soil using wheat as a test crop until it reached a concentration of 2%. After an incubation period, the physical properties of the soil were found to have improved, and the available phosphorus for the plants increased, with higher recorded yields compared to the control trial.

The possibility of managing fly ash as a secondary waste is an opportunity to reduce the production of synthetic fertilizers and create alternative sources of phosphorus; Mayer et al. [2022] estimate the potential for macronutrient recovery from wood biomass combustion ash in Germany to be about 3.1% for phosphorus, 7.5% for potassium and 22.8% for calcium. On a global scale, this appears to be a significant result. Macronutrient recovery is also possible using fly ash from coal-fired power plants, which is abundant in Ca(II), as a sorbent to remove phosphorus from sewage sludge. This phosphorus is subsequently used for fertilizer purposes at a rate of up to 50 mg of recovered P-PO₄ per 1 g of ash applied [Hermassi et al. 2017].

Table 2 above presents a summary of the microelement contents in ashes of various origins. The regulation on

Table 2. Concentration of microelements (including heavy metals) in ashes after coal and lignite combustion (mg/kg)

Elements	Silica ash from hard coal – conventional boiler	Fluidized bed coal ash – fluidized bed boiler	Belchatow Power plant – lime ash	Ashes –biomass 100 % fluidized bed boilers	Ashes – co-firing 70% biomass + 30% hard coal	Ashes – co-firing 10% biomass + 90% hard coal
Cd	2.20	< 0.50	3.80–4.60	10.70–19.10	4.9	1.30
Cr	42	< 2	130–157	44.30–88.30	31.90	83.60
Pb	76	20	24–322	62.2–234	35.10	156
Zn	265	32	11–105	470–868	418	249
Hg	.	.	.	0.10–2.04	0.10	0.60
Co	41	< 0.50	11–12	.	.	.
Ni	56	1	36–46	32.70–60.80	18.40	117
Cu	86	5	34–55	89.50–342	65.20	83.80
As	.	.	.	7.2–16.20	2.70	31.50
Mn	745	42	.	.	.	.
V	240	2	.	.	.	.
Sr	110	40	.	.	.	.
Ba	410	36	349–754	.	.	.
Na	84	1	15–87	.	.	.
Be	20	< 2	.	.	.	.
B	960	1	.	.	.	.

* . - no data available

fertilizers and fertilisation [Regulation... 2024] regulates the permissible amounts of chromium, cadmium, nickel, lead, and mercury per kilogram of dry matter in organic and organic-mineral fertilizers. Particular attention should be paid to the lead content (24–322 mg/kg) and chromium content (130–157 mg/kg) of ashes from the combustion of lignite (Bełchatów), as well as the cadmium content of biomass combustion ash (100%), which ranges between 10.7 and 19.1 mg/kg. A relatively high zinc content was also found for biomass combustion ash (100%), at 470–868 mg/kg.

It is worth mentioning biomass ash's growing potential as a result of its increasing volume. For example, in Japan, 5.9–9.8×10⁵ tons of wood biomass ash are suitable for recycling and use as fertilizer [Ike et al., 2025]. Ashes have an enhanced bioavailability because of their physical properties, and potentially high reactivity due to their large surface area in relation to their volume. Due to the pH-regulating properties of ash (and consequently, the potential for immobilizing metals in the soil), a significant threat may be posed by the presence of trace elements such as vanadium and barium. The highest concentration of vanadium was found in ash from conventional hard coal combustion, at 240 mg/kg, with the highest concentration of barium in ash from lignite combustion, at 349–754 mg/kg.

However, it is worth emphasizing that the presence of these elements in ash does not preclude its use for fertilizer purposes through measures such as leaching or temporary storage. Examples of applications include rice

field cultivation, with ash applied at a rate of 120 t/ha, and rye cultivation on Mediterranean red soils, with an ash application rate of 40 t/ha. No boron toxicity was found in the soils or crops, thanks to the dilution effect [Uwattage et al. 2013]. According to the Regulation of the Minister of the Environment of July 20, 2016, when considering the availability of ash for a given fertilizer manufacturer, it is always important to pay attention to the amount of contaminants in the substrates (especially, for logistical reasons, those available locally). Ash may be used in waste recovery outside installations — for example, for the reclamation of degraded land — but not directly as an agricultural fertilizer. It must first be processed and officially approved for such use.

Table 3 presents further data regarding the elemental composition of ashes from Polish power plants. In addition to the characteristically high silicon content of fly ash, a high aluminium content was also observed, with the highest concentration being found in silica ash (15.52%). High aluminium content may limit crop growth because metals can inhibit cell division in roots, as Ansari et al. [2022] found with radish cultivation. However, it is worth noting that the risk of aluminium toxicity may be reduced in fly ash because it occurs in the form of an aluminio-silicate complex, which is difficult for plants to access [Uwattage et al. 2013]. Elements in silica ash, such as potassium (found at 3.29%) and iron (3.59%) — as well as magnesium, found in ash from the Pątnów Power Plant

Table 3. Elemental composition of ashes from coal and lignite combustion (% by weight)

Elemental composition	Silica ash: Power plants in Kozienice and Dolna Odra	Lime ash: Power plant in Belchatow	Limestone ash: Power Plant in Pątnów
Na	0.59	0.29–0.31	0.51
Mg	0.94	1.11–1.13	1.95
Al	15.52	11.30–12.80	8.72
Si	25.68	21.10–22.70	24.73
P	0.26	<0.01	0.03
S	0.10	0.42–0.46	0.56
K	3.29	0.21–0.24	1.65
Ca	0.18	18.70–23.80	20.16
Ti	1.21	1.00–1.10	0.80
Fe	3.59	3.56–3.59	2.13

(1.95%) — can increase crop yields and mineral content in plants, including radishes, spinach, and rapeseed, when the soil is enriched with a mixture of organic fertilizer and ash in a specific ratio of > 15% [Ansari et al. 2022, Taupedi et al. 2022].

The above summary in Table 4 shows the trace element content in fly ash from hard coal combustion (both with and without flue gas desulphurization) and lignite combustion (without flue gas desulphurization) [Ratajczak et al. 1999]. Each type of ash has unique characteristics resulting from the type of coal burned and the flue gas desulphurization processes. Hard coal ashes without desulphurization have higher trace element content, while lignite ashes are characterised by higher concentrations of rare earth elements. Attention should be paid to the high levels of barium, zinc, and lead, which can have adverse environmental impacts when present in excess. However, the content of many other rare earth elements can offer opportunities for soil enrichment, or for the recovery of these metals for other purposes.

3. RADIOACTIVITY INDICES FOR ASH FROM COAL AND LIGNITE COMBUSTION

The natural radioactivity coefficients of coal combustion ash, according to several authors, indicate that the highest F_1 and F_2 values were at the Siekierki power plant with hard coal ($F_1 = 1.09$ Bq/kg, $F_2 = 162.35$ Bq/kg). The lowest indices were found for Belchatow Power Plant with lignite, with $F_1 = 0.43$ – 0.85 Bq/kg and $F_2 = 69.60$ – 136.00 Bq/kg. For fly ash, the range of ratios is 0.09–2.74 [Sybilski et al. 2004, Garbacik et al. 2013, Górecka et al. 2024].

Based on the above results, the maximum natural radioactivity coefficients for the Dolna Odra power plant (hard coal) can be arranged in a descending-order series as follows: $^{40}\text{K} > ^{226}\text{Ra} > ^{228}\text{Th} > ^{224}\text{Ra} = ^{228}\text{Ra}$ [Sybilski et al. 2004].

4. PHYSICOCHEMICAL COMPOSITION OF ASH AFTER FLUE GAS DESULPHURIZATION AND CONTAMINANT LEACHABILITY RESULTS FOR ASH

Based on the results reproduced in Table 6, it can be concluded that the elements with the highest leachability from fly ash are potassium (9446.00 mg/l), sulphates (5745.80 mg/l), chlorides (1449.00 mg/l) and sodium (83.00 mg/l) in the case of biomass combustion in a fluidized bed boiler in natural circulation.

Bottom ash deposits are also produced as a result of fuel combustion in fluidized bed boilers, in addition to waste in the form of fly ash [Janecka et al. 2012]. Table 7 above presents the content, as a percentage, of leached metals from the aqueous extract of bottom ash deposits. Molybdenum was characterized by its particularly high leachability, at 69%, followed by strontium, at 16.4%. Other identified metals exhibited low leachability, at 1.7% or less. In the tested solution, only trace amounts of heavy metals such as Cr(VI) and Hg were detected, indicating no significant level of leachability for these. Studies on the leachability of elements from biomass combustion ash in China have, in most analysed cases, confirmed its safety for fertilization purposes due to the low leachability of contaminants, its high potassium and calcium content, and its alkalizing properties [Wang et al. 2020].

5. CHEMICAL COMPOSITION OF FLY ASH FROM MUNICIPAL WASTE INCINERATION

The physicochemical properties of the ashes from municipal waste incineration can vary considerably depending on the composition of the input material. Studies by Lewandowska et al. [2021] and Czop [2020] recorded results with both extensive ranges and

Table 4. Trace elements in fly ash from the combustion of selected hard and brown coals (mg/kg d.m.)

Element	Burning hard coal without flue gas desulphurization	Coal combustion with flue gas desulphurization	Coal combustion lignite without flue gas desulphurization
Be	7–21	5–16	< 2–4
Sc	18.30–18.31	19.90–26.10	16–19.10
V	129–459	183–270	130–194
Cr	87–230	131–170	130–157
Co	21–74	28–67	11–12
Ni	45–273	69–202	36–46
Cu	70–167	82–213	34–55
Zn	16–507	190–752	105–111
Na	2–120	15–95	16–85
Se	< 3–43	< 3–7	8–21
Br	7–21	9–28	5.1–7
Rb	120–176	71–139	< 15– < 20
Sr	543–1214	438–1183	662–728
Y	46–84	35–77	44–76
Zr	162–196	108–147	191
Mo	< 5–20	< 5–9	4–13
Ag	< 0.40–1.70	< 0.40–1.70	0.50–1
Cd	< 0.50–2.70	1.20–3.70	3.80–4.60
Sb	4.20–14	5.40–22	1.10–1.70
Cs	13–27.30	15.90–20.70	3.30–4.00
Ba	927–1600	879–1600	349–754
La	51.1–70	42.7–61	63–95.80
Ce	110–141	90–118	120–172
Nd	40–54	39–54	120–172
Sm	9.10–12.10	7.50–10.40	10–15
Eu	2–2.70	1.60–2.20	2.20–2.70
Tb	1.40–1.80	1.10–1.50	< 0.50–2.20
Yb	4.20–6.10	3.30–4.90	4.90–5.50
Lu	0.60–0.80	0.30–0.70	0.70–0.80
Hf	4.50–6	3.40–8	5–5.30
Ta	< 0.50–2	< 1–6	< 0.50– < 1
W	< 3–9	< 1–7	< 3
Hg	< 1	< 1	< 1
Pb	43–507	36–108	34–322
Bi	< 5–8	< 5–6	< 5
Th	20–25.10	15–22	17.20–26
U	7.60–13.70	5.70–10.90	8.40–13.80
Ir (ppb)	< 5	< 5	< 5
Au (ppb)	< 5–28	4–10	5–10

Table 5. Natural radioactivity coefficients for coal-combustion fly ash

Element	Belchatow power plant – lignite coal	Żerań power plant – hard coal	Siekierki CHP plant – hard coal	Dolna Odra power plant – hard coal
	(Bq/kg)			
⁴⁰ K	.	.	.	787–1045
²²⁶ Ra	.	.	.	102–149
²²⁸ Ra	.	.	.	104
²²⁴ Ra	.	.	.	104
²²⁸ Th	.	.	.	60–112
F ₂ ^{**}	69.60–136	101.03	162.35	102–149
	(-)			
F ₁ ^{**}	0.43–0.85	0.89	1.09	0.82–1.11

** radioactivity coefficients

*.= no data

Table 6. Leachability of selected compounds and elements from fly ash from co-firing and biomass combustion of different types of fluidized-bed boilers from aqueous solution, according to PN-G-11011 standard (mg/l)

Type of pollutant	Co-firing of hard coal with biomass in a pulverized coal boiler	Biomass combustion in a fluidized-bed boiler	Biomass combustion in a fluidized-bed boiler with natural circulation	Biomass combustion in a fluidized-bed boiler with a bubbling bed
Chlorides	150.30	445.60	1449.00	658.30
Sulphates	790.50	1436.90	5745.80	4779.70
K	223.00	604.00	9446.00	3161.00
Na	26.00	25.00	83.00	67.00
As	0.01	.	< 0.01	.
Cd	< 0.01	< 0.01	< 0.01	< 0.01
Cu	0.04	0.45	0.16	0.20
Cr	< 0.01	< 0.01	< 0.01	< 0.01
Hg	< 0.01	< 0.01	< 0.01	< 0.01
Pb	< 0.01	< 0.01	< 0.01	0.34
pH	11.96	12.25	12.79	12.46

Source: Uliasz-Bocheńczyk et al. [2016]

Table 7. Leachability of elements from bottom sludge from co-firing of biomass and hard coal (%)

Leachability from aqueous extract (%)																
Sb	Ba	Be	Cr	Zn	Cd	Co	Mn	Cu	Mo	Ni	Pb	Sr	Tl	V	Hg	Cr ⁺⁶
-	1.5	0.9	0.2	0.1	0.5	-	0.0	0.2	69.0	0.1	0.6	16.4	-	1.7	-	-

* - = leachability of < 0.1%.

Table 8. Content of selected elements in fly ash from combustion of municipal waste in fluidized-bed boilers

Parameter	Content (mg/kg)
Ca	8.60–170
K	0.66–16
Mg	0.24–26
Mn	> 3.20
Na	2.2–42
P	0.44–10.50
As	0.12–19.00
Ba	69–57.00
Cd	3–70
Cu	232–250.00
Cr	20–34000
Mo	2.50–28.00
Ni	7–43.00
Pb	74–1.56
Se	0.05–10
Sn	2–47.00
Ti	< 0.01–0.23
V	16–12.00
Zn	10–20.00
Hg	< 0.01–0.12

differences between the source data. The highest values were found for Cu (232,000–250,000 mg/kg), Sn (>47,000 mg/kg), As (with a particularly wide range of 0.12–19,000 mg/kg), and Cr (with a range of 20,000–34,000 mg/kg). Despite the relatively high content of macroelements relevant to fertilization, the high concentration of heavy metals might preclude any environmental use of these ashes in the environment.

The data in Table 9, which is based on Andrusikiewicz et al. [2023], indicates high variability in the physicochemical composition of waste from flue gas treatment, fly ash, as well as dust from boiler de-dusting after the incineration of municipal waste. Flue gas treatment waste is characterized by high levels of Zn (4,600–11,600 mg/kg dry matter), Pb (993–2,250 mg/kg), Cd (85–233 mg/kg), and Hg (6–24 mg/kg). This would preclude its use for fertilization purposes under Polish regulations regarding fertilizer composition. The arsenic (As) content in all types of ash is relatively low compared to the levels of other analysed elements at > 11.80 mg/kg dry matter. Beyond the heterogeneity of the feedstock, the significant variability in the results obtained (e.g., for ash from boiler de-dusting) may be linked to the specificity of ash collected from the de-dusting and the combustion process, in which heavy metals often volatilize and condense on the surface of fly ash [Dahl et al. 2010].

Table 9. Contents of selected compounds and elements in waste from waste gas treatment, fly ash and boiler dust removal ash from municipal waste incineration process

Parameter	Waste from waste gas cleaning 19 01 07*	Fly ash 19 01 13*	Dust from boiler dust removal 19 01 15*
CaSO ₄ [% d.m.]	6.16–14.13	9.82–23.82	10.11–28.54
CaCO ₃ [% d.m.]	3.89–10.96	4.07–8.77	2.05–5.10
CaCl ₂ [% d.m.]	11.31–14.87	.	.
CaO [% d.m.]	16.70–36.70	13.80–20.80	11.90–16.10
NaCl [% d.m.]	4.73–12.15	0.74–4.58	1.99–3.51
KCl [% d.m.]	4.46–6.52	1.60–4.86	2.52–3.95
SiO ₂ [% d.m.]	2.97–9.25	20.60–49.30	28.20–44.90
HCl (undissolved) [% d.m.]	0.63–3.47	5.34–10.57	4.41–5.98
Sb [mg/kg d.m.]	226–386	125–294	250–279
As [mg/kg d.m.]	6.80–16.40	5.74–8.71	8.57–11.80
Pb [mg/kg d.m.]	993–2250	121–571	408–637
Cd [mg/kg, d.m.]	85–223	13.00–34.60	35.30–48.50
Co [mg/kg d.m.]	4.27–9.66	25.80–49.70	22.50–29.70
Cu [mg/kg d.m.]	293–523	301–425	271–533
Ni [mg/kg d.m.]	12.80–28.60	53–244	45.40–67.50
Hg [mg/kg d.m.]	6–24	.	.
Zn [mg/kg d.m.]	4.60–11.60	3.58–6.36	4.58–7.72
pH (eluate)	12.20–12.30	12.30–12.50	12.00–12.60

*. = no data

Table 10. Contents of heavy metals in ashes from sewage sludge combustion depending on temperature and combustion time

No. of repetition	Cr [mg/kg d.m.]	Zn [mg/kg d.m.]	Cu [mg/kg d.m.]	Cd [mg/kg d.m.]	Ni [mg/kg d.m.]	Pb [mg/kg d.m.]	Combustion temp. (°C)	Burning time (min.)
S ₁	174.80	2755.23	553.51	1.09	53.76	170.28	600	11
S ₂	70.48	1430.76	351.79	0.81	38.40	0.32	980	11
S ₃	105.33	2479.30	383.80	0.90	42.22	108.82	655.60	4.60
S ₄	103.24	2730.79	433.90	-	52.47	93.83	790	20
S ₅	166.92	3091.66	462.88	0.70	57.27	156.01	655.60	17.40
S ₆	96.00	1620.01	314.94	0.06	46.59	0.25	924.40	17.40
S ₇	97.97	2542.87	388.93	0.18	47.88	87.37	790	11
S ₇ -bis	106.32	2616.96	387.36	0.16	51.68	97.65	790	11
S ₈	84.24	2844.42	401.13	-	54.22	75.55	790	2
S ₉	53.66	1398.53	326.37	-	40.25	-	924.40	4.60

* - = no data

Table 11. Contents of natural radioactive isotopes in ashes from municipal sewage sludge incineration

Type of ash	Isotopes	⁴⁰ K	²²⁶ Ra	²²⁸ Th (²²⁸ Ra)	F ₁	F ₂	Specific activity ²²⁶ Ra + ²²⁸ Ra
	Sample No.	[Bq/kg]	[Bq/kg]	[Bq/kg]	[-]	[Bq/kg]	[Bq/kg]
Fly ash	1	388 ± 20	52 ± 3	26 ± 2	0.43 ± 0.02	52 ± 3	78 ± 4
	2	512 ± 27	76 ± 4	32 ± 3	0.58 ± 0.02	76 ± 4	108 ± 5
	3	410 ± 25	94 ± 6	34 ± 2	0.62 ± 0.02	94 ± 6	190 ± 8
Waste from flue gas cleaning	4	175 ± 11	26 ± 2	12 ± 2	0.21 ± 0.01	26 ± 2	38 ± 3
	5	152 ± 11	42 ± 3	13 ± 2	0.26 ± 0.01	42 ± 3	83 ± 4

* F₁ = natural radioactive isotope content (with the contents of potassium, radium and thorium taken into account). This is a dimensionless indicator.

* F₂ = radium content, ²²⁶Ra, in Bq/kg.

6. PROPERTIES OF ASHES FROM SEWAGE SLUDGE COMBUSTION

The above table shows the concentrations of heavy metals in ashes from sewage sludge combustion with respect to temperature and combustion time [Latosińska, 2016]. Analysing this data reveals the relationships between the concentrations of individual metals, as well as the temperature and combustion duration, in the analysed samples.

Higher concentrations of chromium (Cr) do not show a clear correlation with combustion temperature and duration. For example, in sample S₁, the highest chromium concentration (174.80 mg/kg d.m.) was observed at the lowest combustion temperature (600°C) and at a combustion time of 11 minutes, whereas in sample S₂, a significantly lower chromium concentration (70.48 mg/kg d.m.) was recorded at the highest combustion temperature

(980°C) with the same combustion time as S₁. Cadmium concentrations were very low in all samples and did not exhibit a clear dependence on combustion temperature or duration. In all the cases analysed, a consistent pattern can, however, be observed, particularly for lead concentration: Combustion temperatures of > 600°C result in reduced concentrations of the analysed elements over the same amount of time, including an almost complete elimination of lead. This correlation is linked to the physical properties of the elements, such as their volatility [Wang et al. 2020]. Table 11 shows the natural radioactive isotope content of ashes from municipal sewage sludge incineration [Stempkowska et al. 2015]. Radioactivity measurement — i.e., determination of natural concentrations of ⁴⁰K, ²²⁶Ra and ²³²Th — was performed using scintillation and solid-state gamma-ray spectrometry. Samples 1, 2 and 3 were fly ash from multicyclones and electrostatic precipitators, and Samples 4 and 5 were of waste from flue-gas treatment

of acid gas pollutants (HCl , SO_x , HF , and NO_x) and heavy metals from bag filters.

For fly ash, the ^{40}K isotope was found to be most abundant, ranging from 388 ± 20 to 512 ± 27 Bq/kg, and the least abundant ^{228}Th (^{228}Ra), which ranged from 26 ± 2 to 34 ± 2 Bq/kg. The F_1 factor was recorded as being between 0.43 ± 0.02 and 0.62 ± 0.02 , while F_2 was found to be in the range of 52 ± 3 to 94 ± 6 Bq/kg.

For waste from flue gas cleaning, all the radioactivity parameters studied were lower than the results from the fly ash. For the ^{40}K isotope, the highest values were in the 152 ± 11 to 175 ± 1 Bq/kg range, and the lowest values were determined for ^{228}Th (^{228}Ra), which were in the 12 to 13 Bq/kg range. The F_1 coefficient ranged between 0.21 ± 0.01 and 0.26 ± 0.01 , while F_2 was recorded in the range of 26 ± 2 to 42 ± 3 Bq/kg. The acceptable values for the indicators are considered as follows: An acceptable value for F_1 did not exceed 1.2, while the threshold value for the activity indicator F_2 was 240 Bq/kg, according to the official criteria for building materials [Regulation... 2014].

7. SUMMARY

The chemical composition of ashes varies significantly depending on the source, combustion method, and feedstock material, with the greatest variability observed in ash from municipal waste incineration. The data analysed in this study for ashes produced in incineration, combined heat, and power plants in Poland indicate that these ashes could potentially be used for fertilization

purposes because they are rich in macronutrients like phosphorus and potassium, as well as micronutrients supporting proper plant growth. Ash has particularly high potential for use in the production of potassium fertilizers. According to literature data, adding ash to fertilizers in appropriate proportions improves both the quantity and quality of crops and positively affects soil properties.

The ashes' trace element content in this study reflect their overall concentrations. Based on total content, it is difficult to predict their mobile form concentrations, which pose particular environmental risks (e.g., leaching into groundwater). The proportion of mobile trace elements depends on the physical, chemical, and biological properties of the soil, including its grain composition, moisture, pH, and redox conditions. Therefore, further detailed chemical analysis of these ashes will be necessary before their environmental utilization.

The results of this study indicate that fertilizers or soil amendments produced with the addition of ashes from sewage sludge combustion may introduce potentially hazardous trace elements into the environment — but, on the other hand, natural radioactivity coefficients for ashes do not create any contraindications for their use in fertilization purposes.

Considering the increasing global production of fly ash, utilizing ashes for fertilization purposes could provide environmental benefits by reducing the production and consumption of synthetic substrates — and, in line with the concept of a circular economy, minimising ash landfilling as a management method.

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