JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2025, 26(12), 315–326
https://doi.org/10.12911/22998993/207580
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Received: 2025.05.30
Accepted: 2025.09.01
Published: 2025.10.01

Assessment of the suitability of energy waste for reclamation taking into account the risk to the soil and water environment

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ABSTRACT

The utilization of mineral wastes from a power plant, such as fly ash and bottom ash as well as from incineration a waste treatment plant, such as fly ash and air pollution control residue, is a challenge from the point of view of environmental engineering practice. This type of waste is used in mining, construction, road construction, as well as in agriculture, for example, as a raw material for mineral fertilizers. One of the uses of waste is reclamation. However, due to the physical and chemical properties of such waste, it may have a negative impact on the soil and water environment. The fly ash from the combustion of hard coal, lignite, agro and forest biomass as well as solid residues from the combustion of sewage sludge were studied. The chemical composition, leachability and phytotoxicity test were determined. The analysis of the tested ashes showed a high variability of the properties, depending on the type of fuel combusted. Fly ash contained macro- and micro-nutrients, indicating its fertilising properties and therefore its usefulness in the reclamation of degraded areas. On the other hand, the fly ash from agro biomass and flue gas desulphurisation products from the combustion of waste sludge showed a phytotoxic effect on the test plant *Lepidium sativum*, which is related to their high content of sulphates and chlorides.

Keywords: fly ash, air pollution control residue, ecotoxicity, soil-water environment, reclamation.

INTRODUCTION

The combustion of fuels such as coal and biomass, as well as waste, generates large amounts of combustion by-products, such as fly ash (FA), bottom ash (BA) and air pollution control residue (APCr). These wastes should be managed in an environmentally safe manner and as efficiently as possible, in accordance with the principles of a circular economy. The solid residues produced during fossil fuels, biomass and waste combustion are characterised by high variability of physicochemical properties, which depend on the type of fuel burned, the type of boiler (grate, rotary, fluidised), combustion parameters or the method of flue gas cleaning [Vassilev et al. 2005].

Waste and coal combustion processes cause an increase in the concentration of elements in the ash compared to the fuel content [Santos et al. 2022]. In addition, studies of ash from coal combustion have shown that there is a partitioning of trace elements, associated with boiling points of different phases present in the ash. For this reason, depending on the accumulation of trace elements, their division into three classes has been proposed [Klein et al. 1975]: Class I: trace elements with high boiling points (e.g. Al, Ba, Ca, Co, Fe, K, Mg, Si, Ti) which do not volatilise in the combustion chamber. These melt into the bottom ash and fly ash. Class II: trace elements, such as As, Cd, Cu, Pb, Sb, Se, Zn, which volatilise during thermal processes and then condense on the surface of fly ash particles due to a reduction in gas temperature. Class III: trace elements, such as Hg, Cl which remain in the gas phase throughout the thermal process and do not condense. Class IV: trace elements, such as Cr, Na, Ni, U, V which behave like the elements in Classes I and II.

The physicochemical and ecotoxic properties of the resulting FA, BA and APCr have a significant impact on the directions of their subsequent management [Horvatinec et al. 2025].

The ashes from hard coal and lignite are used, among other things, in the construction materials industry: in the production of cement, ceramics, artificial aggregates, in mining as a backfilling material, in agriculture as an additive improving soil properties, a neutraliser (alkaline reaction), in CO_2 mineral sequestration and for the production of mineral fertilisers [Uliasz-Bocheńczyk 2024; Uliasz-Bocheńczyk et al. 2023; Śliwka et al., 2017; Mishra et al. 2010; Ahmaruzzaman 2010; Pomykała et al. 2015; Kępys et al. 2014].

The use of biomass instead of coal has changed the physical and chemical properties of the resulting combustion by-products. This is the result of a change in the chemical composition of the fuel itself as well as an adaptation of the combustion technology. The main mineral components of the ashes from coal and biomass combustion are silica-clay enamel, quartz, alumina, iron oxide, mullite and calcium. In addition, they contain in their composition many trace elements, such as As, Ba, Cl, Cr, Cu, F, Mn, P, Pb, S, Ti, Zn, V, which may pose a risk to the environment. When comparing the properties of ashes from coal combustion in the power industry and biomass, however, it should be noted that qualitatively the basic elemental composition is the same. However, there are differences in the proportions of individual elements and chemical compounds [Tian et al., 2025; Ahmaruzzaman, 2010; Vassile et al., 2003; Williams, 2012]. This is because the fly ash from biomass combustion is not as widely used economically as the power plants generated during the combustion of coal. Due to the high content of valuable nutrients, they may constitute macro and micro elements that should be returned to the biogeochemical cycle, for example, an additive improving soil properties. The fly ash from biomass combustion can also potentially be used to deacidify soils due to their strongly alkaline nature. Regulation of soil acidity in the areas contaminated with heavy metals will additionally limit their bioavailability for plants [Saidy et al., 2025; Kępys, 2019; Markowski, 2018; Uliasz-Bocheńczyk et al., 2016].

Sewage sludge generated in municipal wastewater treatment plants should be managed in a manner that does not endanger the environment, with special attention to living organisms. The waste from wastewater treatment plants requires stabilisation or other methods of its neutralisation: biological, chemical or thermal [Szaja et al., 2023; Li et al., 2019; Neuwahl et al., 2019; Donatello et al., 2013; Hudziak et al., 2012; Świerczek et al., 2021]. The chemical composition of sewage sludge has been found to contain many trace elements, including heavy metals. Heavy metals include biogenic elements, essential for living organisms, such as: chromium, tin, zinc, cobalt, manganese, copper, molybdenum, vanadium, but also toxic metals, such as cadmium, lead, mercury, and arsenic [Rosik-Dulewska et al., 2016, Fialova et al. 2019]. Sewage sludge is most often used for agricultural purposes, in the reclamation of degraded areas and in thermal processes, it can be a valuable source of methane and phosphorus [Lag-Brotons et al. 2014; Martinez et al. 2014; Nghiem et al. 2014; Niu et al. 2013; Rodriguez et al. 2013, Rosik-Dulewska et al. 2016, Kępys et al. 2021, Fang et al. 2018, Iżewska et al., 2014]. Thermal processes consist of sludge incineration, co-incineration with other fuels, pyrolysis or gasification. The most commonly used method is to burn dewatered and dried sludge to a minimum dry matter content in a fluidised boiler [Donatello et al. 2013; Neuwahl et al. 2019]. Increasingly, incinerated sewage sludge ash (ISSA) is used in construction, road building, and as a source of phosphorus [Donatello et al., 2013]. The occurrence of phosphorus is also one of the reasons for research into the use of ISSA for reclamation or as a fertiliser ingredient [Rosik-Dulewska et al., 2016].

The aim of the research was to assess the physicochemical and ecotoxicological properties of ash from the combustion of hard coal, lignite, biomass and municipal sewage sludge, in terms of the possibility of their natural management as a material for land reclamation (improvement of soil properties) taking into account the risk to the soil and water environment.

MATERIALS AND METHODS

The fly ash generated in thermal power plants burning biomass or coal was used for the study. In addition, wastes in the form of solid residues from a sludge combustion plant with a heat recovery process were studied. In all installations, the combustion of fuels or waste is carried out in fluidised bed boilers. In the flue gas cleaning process, the fine mineral fraction is captured on electrostatic precipitators. In the case of a sewage sludge incineration plant, the flue gases are de-dusted in the first stage by an electrostatic precipitator and a multi-cyclone, followed by the removal of acidic pollutants and residual dust and heavy metals in the second stage. The solid residues from this process are removed on bag filters. The characteristics of the waste sampling source for the study, together with its designation, are shown in Table 1.

Waste was digested using a mixture of HNO_3/HCl in a microwave oven. The obtained solution was analysed after dilution by the Inductively Coupled Plasma Spectrometry/Atomic Emission Spectroscopy (ICP-AES) and by the Inductively Coupled Plasma Mass Spectrometry (ICP-MS) with the use of the Perkin Elmer Elan 6100 apparatus.

Leachability tests were conducted according to the EN 12457-2 standard. The distilled water, with a liquid-to-solid ratio (L/S) of 10, was used as a leaching solution. The suspension was agitated in a plastic flask for 24 hours, then the mixture was filtered through a 0.45 μm membrane filter. The resulting leachate was analysed for pH and trace elements using ICP-AES and ICP-MS methods. The amount of chlorides was analysed using the Volhard titration method.

The ecotoxicological properties of the tested fly ashes were analysed using a standard phytotoxicity test against garden cress (*Lepidium sativum*). For the phytotoxicity test, an aqueous extract of the test waste was prepared (following the standard procedure, PN-97/Z-15009). Then, a series of dilutions of the aqueous extract were prepared with distilled water at concentrations of: 6, 25%, 12.5%, 25%, 50%, and 100%. Afterwards, 5 ml of each of the prepared solutions was transferred (in three replicates each) to Petri dishes lined with filter paper and 10 seeds per each dish (*Lepidium sativum*) were introduced. Control subjects were prepared with distilled water instead of the waste aqueous extract solution.

All test objects were left to incubate in the incubator for biological tests. The tested plants were incubated in the dark in temperature 25 Celsius degrees for 72 hours. Afterwards, the number of germinated seeds and length of roots was determined.

RESULTS

The chemical composition of the tested wastes (main components and trace elements) is presented in Table 2.

The presence of quartz in fly ash from fluidised bed boilers is the result of using quartz sand as a deposit and entraining its particles with the flue gas. In addition, there is a mineral fraction (non-combustible fraction) in coals and sewage sludge, and biomass of forest origin is often mixed with sand and soil. Hence, in the fly ash from coal combustion (FA-HC and FA-L), the SiO_2 content is 43.54% and 33.20%, respectively, and from sewage sludge combustion FA-MSS is 37.80%. The fly ash from forest biomass combustion has the highest SiO_2 content (55.30%). In APCr-MSS, on the other hand, the SiO_2 content is 2.5%, which is the result of prior dedusting of the flue gas in the electrostatic precipitators and multicyclone (FA-MSS ash is produced) in the sewage sludge combustion plant.

Another characteristic of fuel combustion in fluidised bed boilers is the use of lime sorbents added to the boiler to remove sulphur oxides from the flue gas. As a result, flue gas desulphurisation products in the form of calcium sulphates and unreacted limestone sorbent are present in the fly ash. This is evident in the chemical composition of the tested fly ashes from both hard coal and lignite combustion.

The combustion of biomass, in addition to the benefits of obtaining green energy, is also

Table 1. Sources of the analysed waste

Source of origin	Fuel type	Place of sampling	Type and code of waste	Marking of waste samples
Heat and power plant	Hard coal	Electrostatic precipitator	Fly ash 10 01 82	FA - HC
Heat and power plant	Lignite	Electrostatic precipitator	Fly ash 10 01 82	FA - L
Heat and power plant	Forest biomass – wood chips	Electrostatic precipitator	Fly ash 10 01 03	FA - FOR
Heat and power plant	Agro biomass – sunflower husk and straw pellets	Electrostatic precipitator	Fly ash 10 01 03	FA - AGRO
Thermal waste treatment plant	Municipal sewage sludge	Multicyclone and electrostatic precipitator	Fly ash 19 01 14	FA - MSS
		Bag filter	Solid waste from flue gas treatment 19 01 07	APCr-MSS

Table 2. Chemical composition of waste

Elements	Content (wt %)					
	FA-HC	FA-L	FA-FOR	FA-AGRO	FA-MSS	APCr-MSS
Na_2O	0.87	1.04	0.52	0.25	0.59	34.28
K_2O	1.76	1.03	0.97	19.67	1.65	0.05
CaO	18.79	26.20	13.21	21.45	15.93	0.27
MgO	1.86	1.30	1.27	7.56	3.94	0.10
SO_3	4.13	5.90	3.58	17.09	2.07	54.53
P_2O_5	0.21	0.46	1.39	11.73	26.39	0.16
Al_2O_3	22.69	24.85	6.72	2.45	4.48	0.06
Fe_2O_3	5.25	5.67	8.54	2.38	5.53	0.10
SiO_2	43.54	33.20	55.30	16.10	37.80	2.50
Trace elements	Content (mg/kg)					
Ag	0.14	0.39	0.32	0.11	0.94	1.07
As	5.89	109.93	9.41	22.19	6.75	0.93
Ba	371.01	399.20	1605.56	725.10	785.52	18.29
Be	10.07	0.23	1.34	0.03	0.44	0.01
Cd	0.48	0.10	1.82	17.89	3.09	0.01
Co	12.19	31.37	26.12	6.16	18.00	0.06
Cr	74.59	170.79	101.69	49.50	471.50	6.10
Cu	61.85	71.09	92.47	186.80	838.01	25.24
Hg	0.26	0.01	0.58	0.01	0.09	6.29
Mn	323.28	296.15	1409.67	4528.70	778.96	13.05
Mo	1.51	0.71	3.84	4.53	15.65	0.30
Ni	36.57	99.41	80.95	28.87	108.64	0.41
Pb	74.86	22.22	39.85	257.90	109.67	1.39
Se	1.37	1.97	0.19	1.48	1.87	2.14
Sn	5.96	8.36	2.02	14.55	117.17	0.60
Sr	211.50	278.36	665.85	582.23	518.37	15.72
Ti	225.40	9.73	215.77	219.16	3080.22	1221.27
W	4.25	0.07	6.34	23.90	0.35	0.14
V	111.30	100.00	115.90	38.07	62.99	0.68
Zn	165.20	97.93	357.99	1443.51	3861.99	33.15

associated with the possibility of technical problems in boiler operation. Compared to coal, biomass has a higher content of alkaline compounds (K, Ca), phosphorus and chlorine [Nunes et al., 2017]. The presence of KCl results in the occurrence of increased high-temperature corrosion of the boiler heating surface and ash sintering in the boiler. To prevent these adverse phenomena, protective coatings are used and substances are added to the boiler to reduce these phenomena, e.g. sulphur or its compounds [Kępys, 2019]. The effect of sulphur introduction into the boiler is its high presence in the FA-AGRO fly ash (17.09% SO_3), in an amount higher than its content in the biomass itself. According to Vassilev [Vasisilev et al., 2010], the SO_3 content of ash from biomass combustion was 0.8–2.91% wt. and that from sunflower hulls was 4.07% wt. In contrast, the contents of the other components in biomass ash are typical for this type of fuel.

Noteworthy is the P_2O_5 content of the FA-MSS of more than 26%, converting this to a phosphorus content of approximately 115 g/kg. This is characteristic of the ashes from sewage sludge incineration, as treated domestic wastewater contains phosphorus compounds found in washing powders and detergents. The P_2O_5 content in ashes from sewage sludge incineration generally ranges from 10 to 26% [Rutkowska, 2023; Cyr et al., 2007]. This amount of phosphorus makes the waste an alternative source of this element for use in fertiliser or feed production (Fang et al., 2018). In contrast, APCr-MSS is dominated by two components, SO_3 (54.53%) and Na_2O (34.28%). Their presence is a result of cleaning the flue gas of acidic, gaseous pollutants, e.g. SOx, by adding acidic sodium carbonate to the flue gas as well as catching the cleaning products and unreacted sorbent on bag filters.

When comparing the content of minerals necessary for plant growth, clear differences are apparent between the FA fly ash and the solid waste from waste gas treatment at the APCr-MSS sludge incinerator. In fly ash, CaO occurs in the range of 13.21–26.20%, MgO (1.27–7.56%), K_2O (0.97–19.67%), P_2O_5 in biomass ash (1.39% and 11.73%) and sewage sludge incineration ash (26.39%) or Mn (296–4528 mg/kg). These components are practically absent in APCr-MSS waste.

Heavy metals (Cr, Cu, Ni, Pb, Zn, Cd) are present in varying amounts. In the fly ash from coal and biomass combustion, they are in higher quantities than in APCr-MSS. Only for mercury is the situation reversed. This is due to the relatively high temperature of the flue gas during its dedusting in the sewage sludge incinerator. As a result, mercury remains in a gaseous form and is removed in stage II by adding activated carbon and catching it on the bag filters from where the APCr-MSS waste originates.

One of the important characteristics of using waste in reclamation corresponds to the environmental aspects, in particular the impact of waste on the ground-water environment and vegetation. To this end, tests were carried out on the leachability of chemicals from the waste, the results of which are presented in Table 2. The table also includes the maximum contents of chemical pollutants in the wastewater that can be discharged into the ground-water environment according to the legislation.

The presence of SO_3 in the chemical composition of the waste results in sulphate entering the aqueous eluate in amounts exceeding the limit value (500 mg/l). The amount of sulphate is by far the highest in APCr-MSS (49375 mg.l) and in FA-AGRO (6980 mg/l), in the other ashes it occurs in amounts much lower 1517 mg/l and 1667 mg/l in FA-L and FA-FOR, respectively, and just over 800 mg/l in FA-HC and FA-MSS. Chloride leachability is exceeded in the case of FA-AGRO ash. Despite the presence of heavy metals in the tested wastes, their concentration in the eluates was well below the permissible amount in wastewater that may be introduced into water or the ground (Table 3).

To check whether aqueous extracts from the tested waste will have a negative impact on plants, a toxicity test against *Lepidium sativum* was performed. It was checked whether undiluted aqueous extracts showed an inhibiting effect on seed germination and what effect they had on root growth. For PCr-MSS waste, complete inhibition of germination was observed. For FA-AGRO waste, a PE (phytotoxicity effect) boundary value was observed, below which it is considered that no toxic effects are observed. In the case of the other waste, no inhibition of germination occurred (Figure 1).

It should be noted that in the case of the APCr-MSS waste, the seeds did not germinate in any concentration of the aqueous extract.

Comparing the lengths of plant roots in the control and the remaining tested samples, it was found that for two wastes (FA-AGRO and FA-FOR) the average values of root lengths in all concentrations of the tested samples are shorter than in the control. However, after conducting ANOVA analysis, it was found that these differences are statistically significant only for the FA-AGRO waste (except for the concentration of 6.25%). For the FA-FOR waste, no statistically significant differences in the lengths of roots in the control sample and the tested samples were noted. The results of ANOVA tests for these wastes are presented in Figures 2 and 3.

In the case of the FA-HC and FA-MSS wastes, the average values of root lengths in each of the aqueous extracts concentrations are greater than in the control, while for the FA-L waste they are smaller or larger, depending on the aqueous extracts concentration. On the basis of the ANOVA analysis results (Figures 4–6), it was found that for the FA-L waste these differences are not statistically significant. In the case of the FA-HC waste, it was found that the root lengths are significantly different (they are longer) at a concentration of 6.25%. Similarly, for the FA-MSS waste, it was observed that at a concentration of 12.5% the root lengths are significantly different (they are longer) from the root lengths in the control.

In order to compare the length of plant roots in undiluted aqueous extracts from individual wastes, statistical analysis was also performed. The results of ANOVA analysis (Figure 7)

Table 3. Leaching test

Kind of cations or anions	FA-HC	FA-L	FA-FOR	FA-AGRO	FA-MSS	APCr-MSS	Acceptable value according to (Polish Legal act) [mg/dm^3]
pH	12.4	12.1	9.0	12.9	8.45	10.6	6.5–9.0
Na^+	17.07	22.00	23.61	108.00	66.70	38608	800
K^+	15.15	8.05	81.88	10320.00	87.43	10.2	80
Li^+	0.261	0.201	0.264	0.248	0.152	0.0064	No requirements
Ca^{+2}	1163.00	939.10	768.00	458.60	237.50	11.43	No requirements
Mg^{+2}	0.02	< 0.1	64.18	0.02	86.72	6.66	No requirements
Ba^{+2}	0.234	0.243	0.371	0.399	0.084	0.078	2.0
Sr^{+2}	2.444	2.776	2.526	3.804	0.651	0.217	No requirements
Fe^{+2}	0.007	0.011	0.070	< 0.002	< 0.002	0.059	No requirements
Mn^{+2}	0.0002	< 0.001	0.194	0.002	0.0266	0.0056	No requirements
Ag^+	< 0.0004	< 0.0004	< 0.0004	< 0.0004	< 0.00002	< 0.00002	No requirements
Zn^{+2}	< 0.002	< 0.002	< 0.002	< 0.002	< 0.002	< 0.002	2
Cu^{+2}	0.0006	0.0007	0.0180	< 0.0002	0.0002	0.0026	0.5
Ni^{+2}	0.0140	0.0038	0.0270	0.0001	0.0011	0.0003	0.5
Co^{+2}	0.0021	0.0017	0.0150	0.0001	0.0002	0.0001	1
Pb^{+2}	0.0016	0.0002	0.0006	0.1280	0.0004	0.0004	0.5
Hg^{+2}	0.0019	0.0001	< 0.0002	< 0.0002	0.0020	0.0001	0.03
Cd^{2+}	0.0004	0.0004	0.0002	< 0.00003	0.0012	0.0001	0.2
Se^{+2}	< 0.01	< 0.01	< 0.01	< 0.01	< 0.02	< 0.02	1.0
Sb^{+3}	0.001	0.005	0.029	0.001	0.017	0.001	0.3
Al^{+3}	0.007	0.014	1.718	0.017	0.107	3.024	3.0
Cr^{3+}	0.0310	0.0490	0.0110	0.7910	0.0002	0.0003	0.5
Mo^{+6}	0.0900	0.1710	0.0910	0.3220	0.9520	0.0020	1.0
V^{+5}	0.0027	0.0008	0.1430	0.0050	0.1980	0.0150	2.0
Ti^{+4}	0.005	< 0.002	< 0.002	0.005	< 0.002	0.727	1.0
As^{3+}	0.0085	< 0.00002	0.007	0.0042	0.0136	0.002	0.1
W^{+6}	0.012	< 0.002	0.037	0.002	0.116	0.004	No requirements
Cl^-	196	240	242	1416	3.3	776	1000
Br^-	4.1	1.72	< 0.02	< 0.02	0.50	2.16	No requirements
SO_4^{-2}	805.1	1517	1667	6980	826.50	49375	500
HCO_3^{-2}	< 0.5	< 0.5	85	< 0.5	329.0	5700	No requirements
CO_3^{-2}	624	83	82	1650	< 0.5	18120	No requirements
OH^-	22.5	157	< 0.5	252	< 0.5	< 0.5	No requirements
PO_4^{-3}	< 0.05	< 0.05	0.3	< 0.05	4.80	0.4	No requirements

showed that there are no significant differences in the lengths of roots of plants germinating in aqueous extracts from the FA-FOR and FA-MSS wastes, as well as FA-HC and FA-L. For the remaining wastes, the root lengths showed significant differences, with the lowest mean value of root length occurring in the aqueous extract from FA-AGRO (excluding the APCr-MSS waste where the seeds did not germinate). The highest mean value occurred in an aqueous extract from FA-MSS.

DISCUSSION

Toxicity tests against *Lepidium sativum* were carried out for all tested wastes in order to check their potential toxic effects on living organisms. Conducting these tests was purposeful because the wastes used in remediation may indirectly affect the quality of groundwater and surface waters as well as the organisms living in them. Physicochemical tests of aqueous extracts from wastes showed exceedances of permissible levels in the

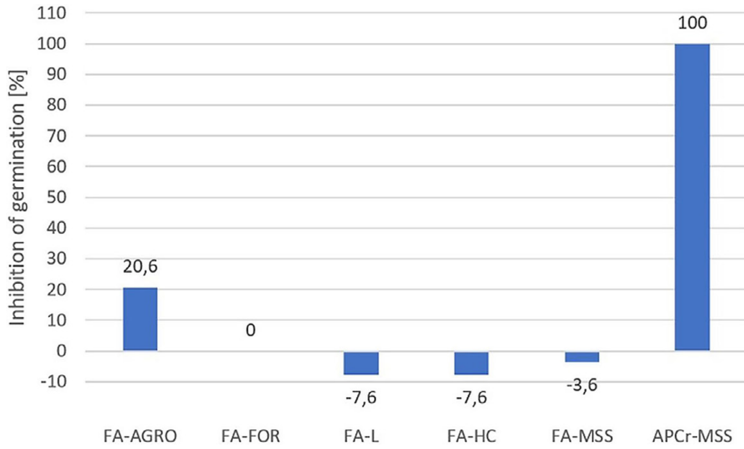

Figure 1. Inhibition of seed germination

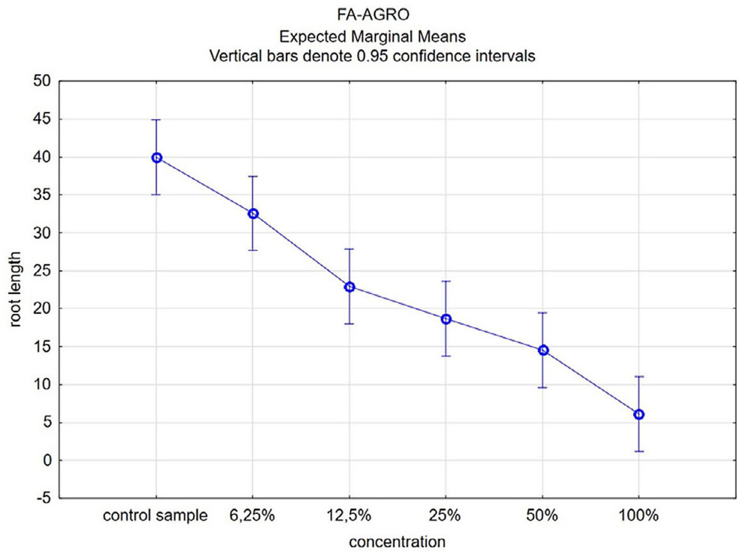

Figure 2. Expected marginal means for root lengths in aqueous extracts from the FA-AGRO waste (ANOVA analysis)

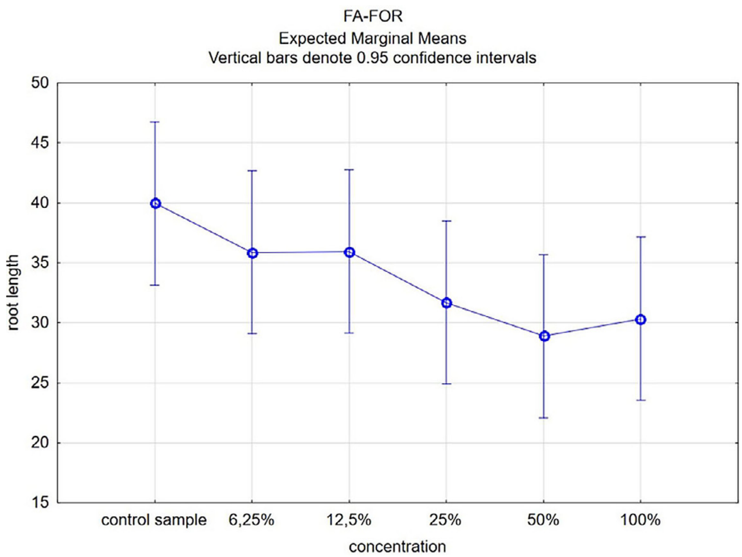

Figure 3. Expected marginal means for root lengths in aqueous extracts from the FA-FOR (ANOVA analysis)

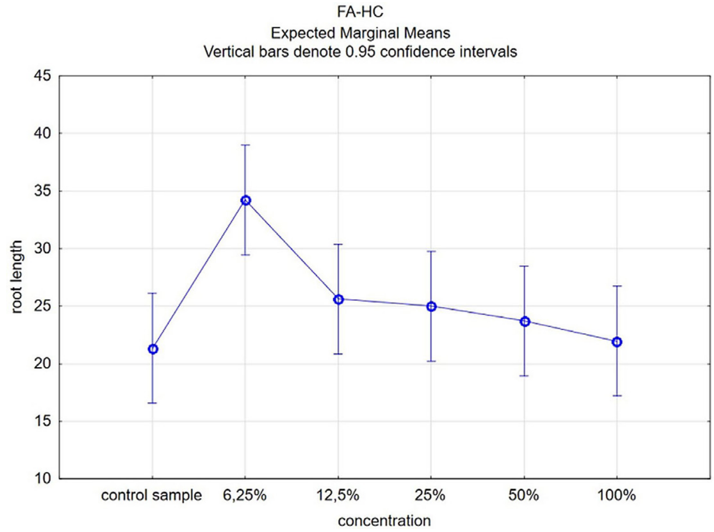

Figure 4. Expected marginal means for root lengths in aqueous extracts from FA-HC (ANOVA analysis)

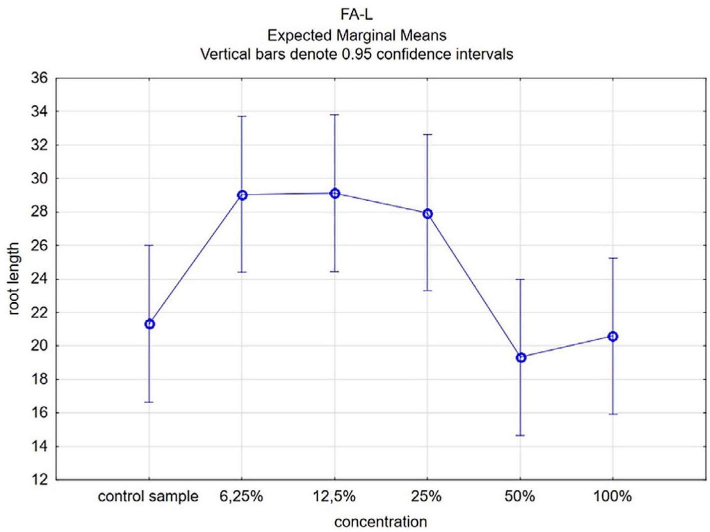

Figure 5. Expected marginal means for root lengths in aqueous extracts from FA-L (ANOVA analysis)

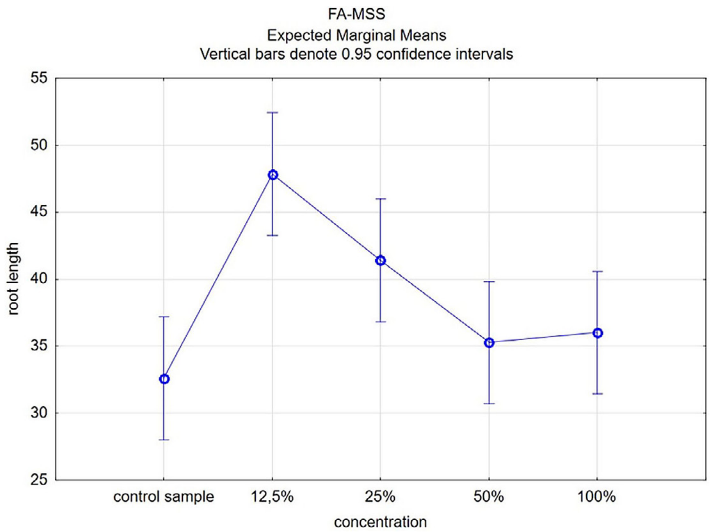

Figure 6. Expected marginal means for root lengths in aqueous extracts from FA-MSS (ANOVA analysis)

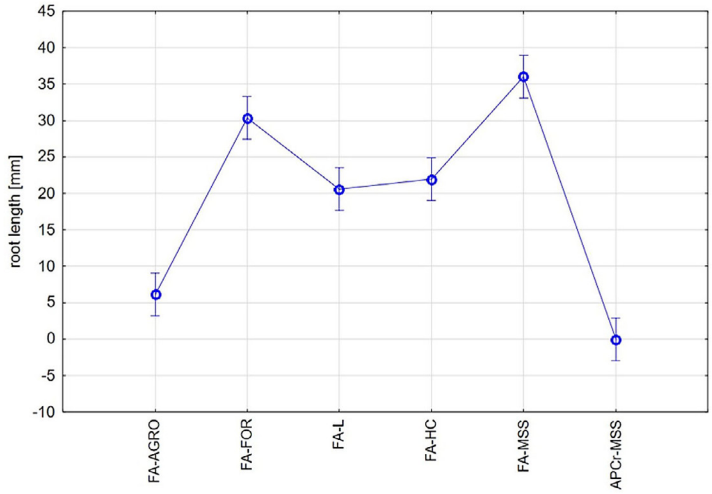

Figure 7. Expected marginal means for root lengths in undiluted aqueous extracts (ANOVA analysis)

sewage discharged into water or soil for some substances [Polish Legal Act, 2019], hence the need to check their toxicity towards living organisms.

On the basis of the conducted experiments, it was found that the aqueous extract from APCr-MSS waste completely inhibits the germination of the test plants. This effect was observed for all dilutions of the aqueous extract prepared from this waste. This indicates the high toxicity of this waste towards *Lepidium sativum*. For the FA-AGRO waste, PE reached the borderline value between no toxicity and low toxicity. Moreover, for the FA-AGRO waste, it was found that root lengths are statistically significantly shorter in aqueous extracts with concentrations of 12.5% and above than in the control. Therefore, this waste has a toxic effect on *Lepidium sativum*, but the toxicity is low. On the basis of the experiments and analyses conducted for the remaining waste, no inhibition of germination was demonstrated, nor was it found that the root lengths were significantly shorter than in the control sample. This waste did not show a toxic effect on the test plants. For the FA-HC waste, a significantly greater root growth was also observed for the aqueous extract concentration of 6.25%, compared to the control sample. This indicates that at this concentration, the aqueous extract had a stimulating effect on root growth. Similarly, for the FA-MSS waste, a stimulating effect on root growth was observed at a concentration of 12.5% (their lengths were significantly greater than in the control).

Comparing the results of toxicity tests with the results of physicochemical tests, it can be seen that undiluted aqueous extracts from waste having a toxic effect on the test plants (APCr-MSS i FA-AGRO) contain very high concentrations of sulphates (49375 mg/l and 6980 mg/l, respectively). In aqueous extracts from other waste, these values are also high (they exceed the permissible value in sewage discharged into water or soil), but these values are much lower than in the case of the waste classified as toxic on the basis of the biotests conducted.

Sulphur is a biogenic element, it has a structural function (a component of proteins, amino acids and fats, the structure of lignin) and a metabolic function. Sulphur deficiency in the soil causes disturbances in nitrogen metabolism, resulting in an increase in the content of unprocessed nitrates in the plant. Sulphur is a yield-forming element, it also increases plant resistance to pathogens. The content of sulphur in the soil, despite its global deficiency, should be controlled, due to the tendency of plants to absorb it luxuriously. Excess sulphur in plants can lead to disturbances in their metabolism, due to its antagonistic effect on the molybdenum anion. Excess sulphur in soil causes its acidification. The most active form of sulphur in soil is sulphate sulphur, which, due to its high solubility, is a direct source of this element for plants [Podleśna, 2013].

In addition to very high concentrations of sulphate ions, higher concentrations of chloride ions and sodium ions were found in aqueous extracts from the waste classified as toxic than in other extracts. Chlorine, which occurs in soluble forms in the soil, is passively absorbed by plants and transported to the above-ground parts of plants. Small amounts of it are needed for the proper course of photolysis and photosynthesis, so chlorine deficiency in plants practically does not occur. The reaction of plants to the presence of chloride ions in the soil solution varies and depends on the plant species. Species (e.g. beans, apple trees) will show limited growth at concentrations of 450–700 mg/l of soil solution. Resistant plants (e.g. tobacco, tomatoes) tolerate chloride concentrations of up to 3500 mg/l [Kabata-Pendias, Pendias, 1999]. Dry climate plants belonging to halophytes (salt plants) show a higher demand for chlorine and accumulate it in larger quantities, which is related to the water management of plants (osmoregulation).

Excessive amounts of chloride ions and sodium ions can lead to disturbances in the plant's ion balance, contributing to potassium deficiency, due to the competition of both ions for the same binding sites in plant roots. Excessive amounts of Na^+ ions can also cause calcium deficiency, because ion exchange can lead to the removal of Ca^{2+} from the rhizosphere [Kopcewicz, Lewak St., 2007].

In the case of the experiments presented in the article, toxicity for *Lepidium sativum* was observed when the concentration of Cl^- ions was 776 mg/l (this is not exceeding the permissible value) and more. For the wastes not showing toxicity, the concentration of chlorides does not exceed 242 mg/l.

The analysed wastes were found to contain small amounts of toxic metals, such as Cd, Ba, Hg and Pb. Despite the presence of these metals in the analysed wastes, they do not pose a threat to the soil and water environment, because they occur in insoluble or sparingly soluble forms, and therefore their contents in the analysed aqueous extracts are significantly below the permissible values in the sewage discharged into water or soil, specified in the relevant legal regulations.

CONCLUSIONS

Based on the results of the conducted research, it was found that:

1. A high variability of the UPS properties depending on the type of fuel.
2. APCr-MSS and FA-AGRO ashes affects the test plant *Lepidium sativum*, which is related to their high content of sulphates and chlorides at higher eluate concentrations.
3. The content of sulphates in the tested ashes may also have a beneficial effect. Due to the global deficiency of sulphur in the soil, related to its greater removal, the use of low-sulphur fertilisers and the reduction of SO_2 emissions into the atmospheric air, they may constitute a valuable source of this element in the environment.
4. Due to the strongly alkaline reaction of the tested ashes (8–12 pH), they can be used as an agent regulating the acidity of soils (the pH of CaO used to neutralize soil acidity is 12), also those contaminated with heavy metals (reduced bioavailability).
5. Fly ash in its chemical composition contains macro and micro nutrients, which also indicates its fertilising properties and thus its usefulness in the reclamation of degraded areas. These properties depend on the type of ash.
6. The tested ashes contained heavy metals, including those toxic to living organisms. The environmental risk is related to the bioavailability of these elements.
7. The natural use of fluidised fly ash from the combustion of various types of solid fuels (hard coal, brown coal, biomass, sewage sludge) is consistent with the assumptions of the circular economy. It allows the use of the beneficial properties of this type of waste in the reclamation of degraded areas and the return to the biogeochemical cycle of many valuable elements.

Acknowledgements

Research project partly supported by program "Excellence Initiative – Research University" for the AGH University, No. 501.696.7996, ID 8946.

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