

Thermal valorization of sewage sludge through combustion in a fluidized bed unit

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Keywords: sewage sludge, combustion, fluidized bed, fly ash.

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Abstract

Combustion experiments in a bubbling fluid bed unit were carried out, in order to study the combustion performance of a bio-solid waste from a wastewater treatment plant, in terms of efficiency and gaseous emissions. The effects of excess air and fuel feeding rate were investigated and optimal values of process variables for minimizing emissions were provided. Fly and bottom ashes were characterized by mineralogical and chemical analyses.

The results showed that sewage sludge fuel burned uniformly along the reactor column. CO levels in flue gases were well below legislation limits. SO₂ emissions exceeded legislation limits, except when excess air was high (50%) and the temperature reduced, while NO_x emissions exceeded allowable values when excess air was low (30%). The optimum performance in terms of efficiency and emissions was accomplished when the feeding rate was 0.6 kg/h and the excess air 50%. Combustion efficiencies varied between 98.5 and 98.8%. Fly ashes were rich in Si and P and to a lesser extent in Ca and K. Also, they were enriched in trace elements Cu, Zn and Sr and contained elevated amounts of Pb and Cr. All heavy metal values measured in present samples were below the upper limit for disposal in landfills, according to EU directives. Overall, the combustion performance of sewage sludge was quite satisfactory and thermal treatment of this waste for energy production is an attractive solution.

Keywords: sewage sludge, combustion, fluidized bed, emissions, ash

1. Introduction

The Waste Framework Directive has set the hierarchy that energy exploitation precedes deposition in landfills, for the sustainable management of urban wastes, such as sewage sludge. In European Union, wastewater treatment plants produce up to ~30kg dry sludge per capita yearly [1]. In this context, thermal treatment for energy production is an attractive solution, by destroying hazardous constituents, reducing the disposal volume of this waste and increasing economic returns to urban communities.

Combustion is currently considered the most suitable process for the implementation of sewage sludge in power systems, contributing also to the net reduction of CO₂ emissions to the atmosphere, due to its biogenic nature. Among combustion technologies, fluidized bed is most promising, due to its inherent advantages, such as fuel flexibility, good mixing and relative low temperature, high efficiency, low pollutant emissions and destruction of pathogens [1,2].

Despite several sewage sludge combustion units already exist [3], there is still a lack of fundamental understanding of the basic mechanisms of sewage sludge conversion in fluid beds [4] and there is a need to study how the different characteristics of such waste fuels influence feeding, primary and secondary air required, temperature profiles, physico-chemical changes of sewage sludge particles during combustion, flue gas emissions, environmental impact of ashes and combustion efficiency.

The twofold nature of sewage sludge, a biogenic component associated with an inorganic component, the variable composition unlike other biomass materials, the high moisture and volatile matter contents, or the presence of problematic elements in ashes, imply a thorough investigation of its behaviour in thermal systems. Most researchers have focused on the co-combustion of sewage sludge with coal in fluidized bed systems and some in pulverized coal units [5-7].

Present work aimed at investigating the thermal valorization of sewage sludge from a wastewater treatment plant in the island of Crete, through combustion in a bubbling fluidized bed unit. Thermal behaviour, gaseous emissions and efficiency were determined as a function of excess air and reactor loading and fly and bottom ashes were analyzed.

2. Materials and methods

The raw material selected for this study was a bio-solid, sewage sludge (SS), from the wastewater treatment plant of the city of Chania, in Crete. After air drying, the material was ground and sieved to a particle size of 1-2.8 mm. Before being used in combustion tests, the fuel was pre-dried overnight in the oven. Fuel

characterization, i.e. proximate analysis, ultimate analysis and calorific value, were performed to a representative sample obtained by homogenization and riffing, according to the European standards CEN/TC335.

Combustion experiments were carried out in an atmospheric lab-scale bubbling fluidized bed reactor with an inner diameter of 70 mm and a total height of ~2 m (Fig. 1). The principal parts of the reactor are 2 silos with screw feeders, one dosimetric and one for delivering the fuel fast 2cm above the diffuser into the bed (equipped with a water jacket), reactor body equipped with controlled heating furnace, seven K-type thermocouples and a differential pressure transducer, a tangential flow type cyclone, a gas heat exchanger, a tar condenser and a multi-component gas analyzer with conditioning unit. The minimum fluidization velocity (0.12m/s) was determined by measuring the pressure drop across the bed and air diffuser plate versus the superficial air velocity, using a cold reactor model. The preheating temperature of air was ~550°C. For each fuel, feed rate and excess air were selected as the principal independent variables. Feed rates varied between 0.48kg/h and 0.6kg/h and excess air ratios between 1.3 and 1.5. At the end of each run, fly ash and bed material were drained, weighed and analyzed for unburned carbon, while the latter was sieved to remove ash and attrited particles and made up with fresh feldspar prior to be used in the following test. During the experiments no signs of agglomeration were observed. The results were the average of two replications. All data was displayed and logged on a computer via a data acquisition unit.

Mineralogical analysis of crystalline compounds was conducted with an X-ray diffractometer (XRD), model D8 Advance of Bruker AXS, with application of Cu K α radiation and nickel filter (U=35kV, I=35mA). The XRD scans were performed between 2 and 70 2 θ° , with increments of 0.02 $^\circ$ /s. A software system DIFFRAC plus Evaluation by Bruker AXS and the JCPDS database were used for data processing and identification of crystalline components. Chemical analysis of ashes in major and trace elements was performed by an inductive coupled plasma mass spectrometer type ICP-MS 7500cx, coupled with an Autosampler Series 3000, both by Agilent Technologies. Phosphorous and silicon measurements were conducted using a spectrophotometer type UV-VIS Hach 4000V and an atomic absorption spectrometer (AAS) Analyst-100 of Perkin Elmer, equipped with a graphite furnace assembly (model HGA 800) and a deuterium arc lamp background correction system. For sample preparation, the procedures of Li₂B₄O₇ fusion or acid digestion (HCl/HF/HNO₃) were used, depending on the element under determination.

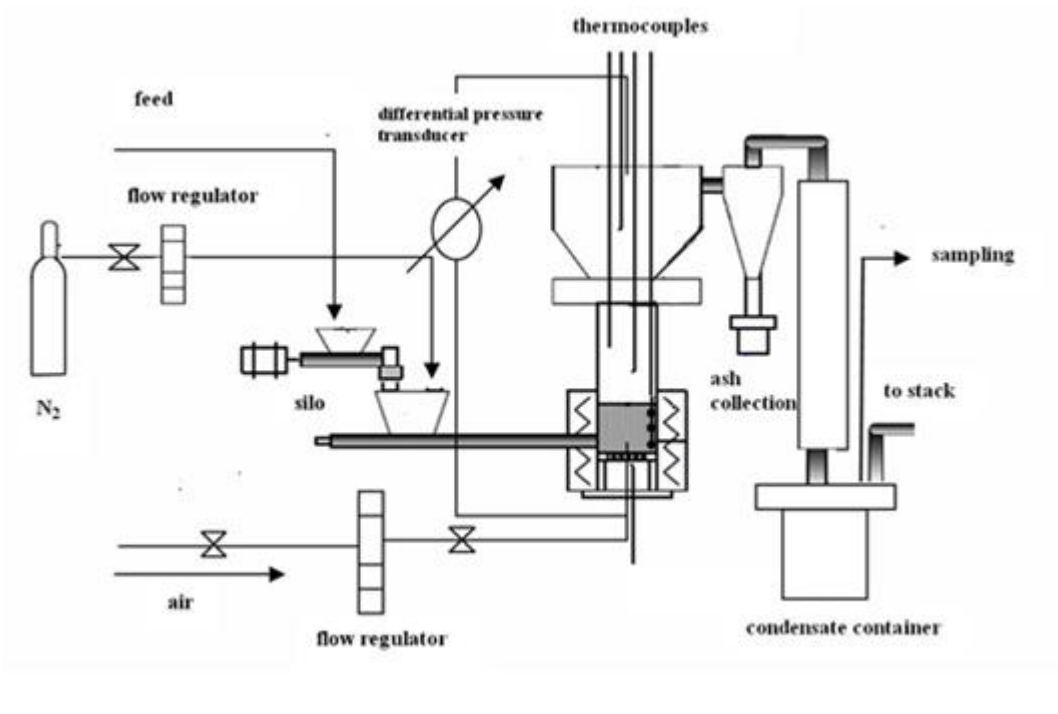


Figure 1 Schematic diagram of fluidized bed system

3. Results and discussion

3.1. Fuel characterization

Proximate and ultimate analyses of the fuel are presented in Table 1. Sewage sludge was rich in volatile matter and its ash content was quite high. However, the gross calorific value was comparable to the upper limit of low rank coals. Chlorine content, related to corrosion and fouling was low, in contrast to nitrogen and sulphur contents, which were high, revealing increased oxide emissions during combustion.

3.2. Temperature profiles under various operating conditions

Fig. 2 depicts the temperature profiles of the fuel inside the furnace as a function of air ratio λ at a feeding rate of 0.6kg/h. As can be observed, sewage sludge burned uniformly along the reactor column, indicating that volatiles were released at a low rate and burned together with char. The maximum temperature difference between the air diffuser and the upper part of the freeboard attained was 19°C. In the conical section of the reactor the temperature varied between 384 and 440°C.

When excess air ratio was increased from 1.3 to 1.5, combustion temperature at all locations inside the furnace was lowered, due to the dilution effect of excessive air, which caused flue gas cooling. The drop in temperature was up to 52°C. Thus, when air velocity was lower (at $\lambda=1.3$), the residence time within the bed was increased and the fuel burned at a higher temperature (836°C).

Table 1. Proximate and ultimate analysis (% dry weight)

Sample	Volatile matter	Fixed carbon	Ash	C	H	N	O	S	Cl	GCV ^a (MJ/kg)
Sewage sludge (SS)	67.2	15.6	17.2	42.4	6.7	8.1	23.9	1.7	0.01	18.8

^a Gross calorific value

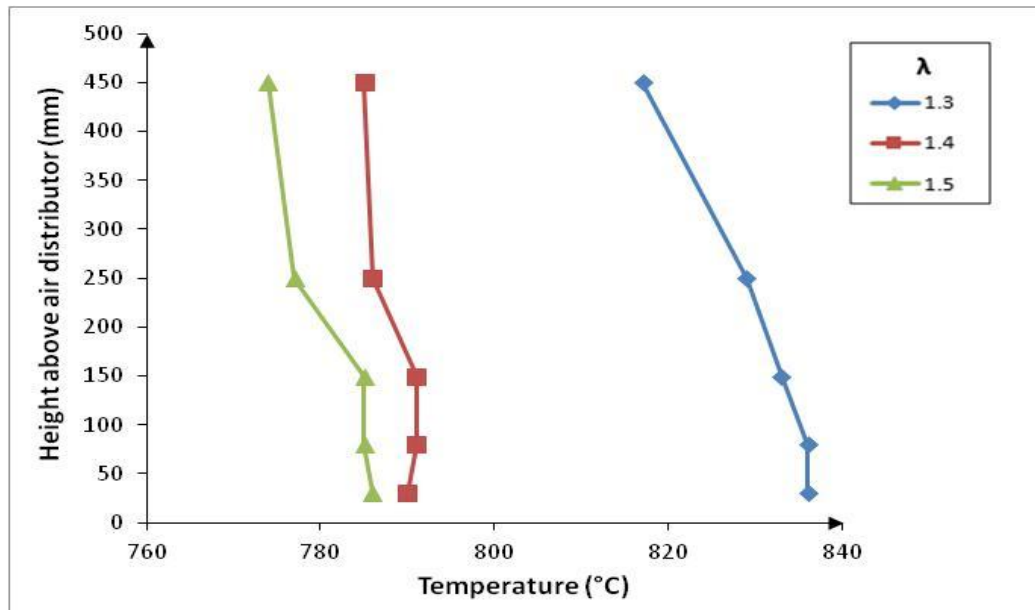


Figure 2 Temperature profiles inside the furnace as a function of air ratio λ at a feeding rate of 0.6kg/h

The effect of feed rate on the axial temperature profiles is shown in Table 2. It can be seen that when the excess air percentage was 30% and the feed rate was raised from 0.48 to 0.6 kg/h, the combustion temperature everywhere in the reactor was increased, as the heat of production was higher. On the other hand, for excess air 40% and 50% the temperature remained practically unchanged.

3.3. Flue gas emissions under various operating conditions

The emissions of pollutant gases (average values \pm standard error) at a feeding rate of 0.6 kg/h and as a function of air ratio λ are compared in Fig. 3. CO levels were below legislation limits for small units [8,9]. However, SO₂ emissions of sewage sludge exceeded emission guidelines [10], except when excess air was high (50%) and the temperature reduced. Consequently, several measures should be taken in this case, such as use of sulphur absorbent materials within the bed, or flue gas cleaning. Additionally, NO_x emissions at excess air ratio 1.3 exceeded allowable limits, suggesting that measures such as air staging, flue gas recirculation or treatment are required to meet legislation.

As concerns the influence of excess air on gaseous emissions, Fig. 3 illustrates that when this was raised from 30% to 50% the concentration of CO in the flue gas was increased, following the declining temperature trend inside the furnace. On the other hand, both SO₂ and NO_x concentrations in flue gases were reduced with excess air, due to the lower combustion temperatures attained, which counteracted the formation of sulphur and nitrogen oxides.

The effect of reactor loading on pollutant emissions is indicated in Table 2. As can be noticed, when more fuel was fed into the furnace, the higher amount of ash fed with it lowered oxygen penetration to the particles, resulting in higher CO levels in flue gases. Also, when feed loading was raised from 0.48 to 0.6 kg/h, SO₂ and NO_x emissions were generally higher, as they originated from the sulphur and nitrogen content of the fuel.

Table 2. Fluidized bed combustion performance at different excess air ratios and feed rates

Feed rate (kg/h)	Excess air ratio λ	Bed temperature (°C)	Flue gas emissions (ppm _v)			Heat losses (%)			Efficiency η (%)
			CO	SO ₂	NO _x	L _{CO}	L _{ba}	L _{fa}	
0.48	1.3	801-802	1069	263	181	1.17	0.04	0.01	98.8
	1.4	793-794	1151	221.5	139	1.23	0.05	0.02	98.7
	1.5	784-785	1216	166.3	104.9	1.33	0.06	0.02	98.6
0.6	1.3	833-836	1157	268.1	421.3	1.27	0.01	0.02	98.7
	1.4	790-791	1229	247.5	150.7	1.32	0.03	0.03	98.6
	1.5	785-786	1329	108	102.7	1.46	0.04	0.05	98.5

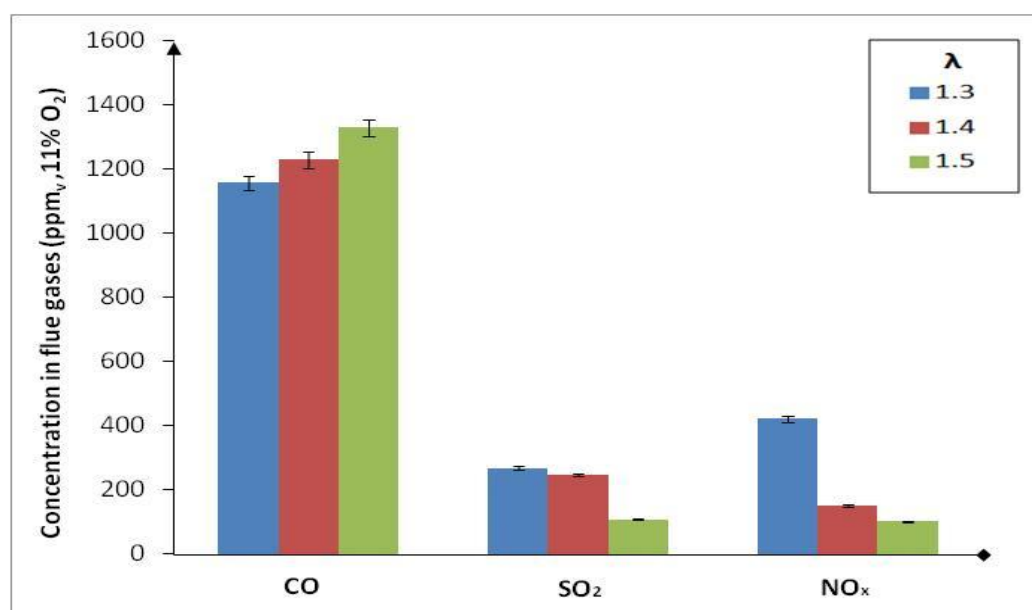


Figure 3 Emissions of pollutant gases at a feeding rate of 0.6 kg/h, as a function of air ratio λ

3.4. Combustion efficiency under various operating conditions

The combustion efficiencies presented in Table 2 are seen to be high, ranging between 98.5 and 98.8%. These values were controlled by the CO levels in flue gases, which represented the principal heat losses due to incomplete combustion of gases in the freeboard zone (L_{CO}). Variations with excess air or fuel feeding rate were small. Furthermore, it can be observed that combustion loss deduced from the fly ash (L_{fa}) had the largest portion in the total loss in ash (L_{ba} and L_{fa}). However, heat losses due to unburned carbon in ashes had a minor effect on efficiency.

3.5. Mineralogical and chemical analysis of ashes

The crystalline mineral phases of fly and bottom ashes, produced at a feed rate of 0.6kg/h and excess air ratio $\lambda=1.4$, are listed in Table 3. Both ashes were dominated by quartz, a great part of which was attributed to the bed material elutriated in the cyclone, together with albite, microcline and muscovite. Phosphorous was incorporated in whitlockite magnesian, while potassium was presented by sulphates or carbonates, in the form of apthitalite and fairchildite in fly and bottom ashes, respectively. Calcium was identified principally as calcite and in smaller amounts as whitlockite magnesian, srebrodolskite (in fly ash) and fairchildite (in bottom ash). Anhydrite was concentrated only in the bed material and was formed by dehydration of gypsum ($CaSO_4 \cdot 2H_2O \rightarrow CaSO_4 + H_2O$) and/or reactions between calcium and sulphur liberated during combustion ($CaO + SO_2 + 0.5O_2 \rightarrow CaSO_4$). Furthermore, small amounts of iron were detected in the form of hematite and srebrodolskite.

Table 3. Mineralogical analysis of ashes

Mineral phases	Sample		
	Bed material	Fly ash	Bottom ash
Quartz SiO_2	+	++	++
Calcite $CaCO_3$		+	+
Anhydrite $CaSO_4$			+
Albite $NaAlSi_3O_8$		++	+++
Muscovite $KAl_2(Si_3AlO_{10})(OH)_2$	+	+	+
Microcline $KAlSi_3O_8$	+	+	+
Whitlockite magnesian $Ca_{18}Mg_2H_2(PO_4)_{14}$		+	+
Fairchildite $K_2Ca(CO_3)_2$			+
Hematite Fe_2O_3		+	+
Srebrodolskite $Ca_2Fe_2O_5$		+	
Apthitalite $NaK_3(SO_4)_2$		+	

+++: high intensity ++: medium intensity +: low intensity

The chemical analysis of fly ash in major and trace elements is illustrated in Fig. 4. As can be observed, fly ash was rich in Si and P and to a lesser extent in Ca and K, in accordance with the XRD spectra. The higher proportion of P_2O_5 confirms the presence of whitlockite magnesian identified through XRD. Also, fly ash was enriched in trace elements Cu, Zn and Sr and contained elevated amounts of Pb and Cr. The latter was attributed to the operating parameters and furnace configuration, as reported in a previous investigation [11]. The concentrations of heavy metals of great environmental concern, such as As, Hg, Co and Cd, were below detection limits. All measured values were below the upper limit for disposal in landfills, according to EU directives [12]. However, the results cannot be extrapolated to full-scale units and leaching tests are further required to determine any potential environmental hazards from these ashes.

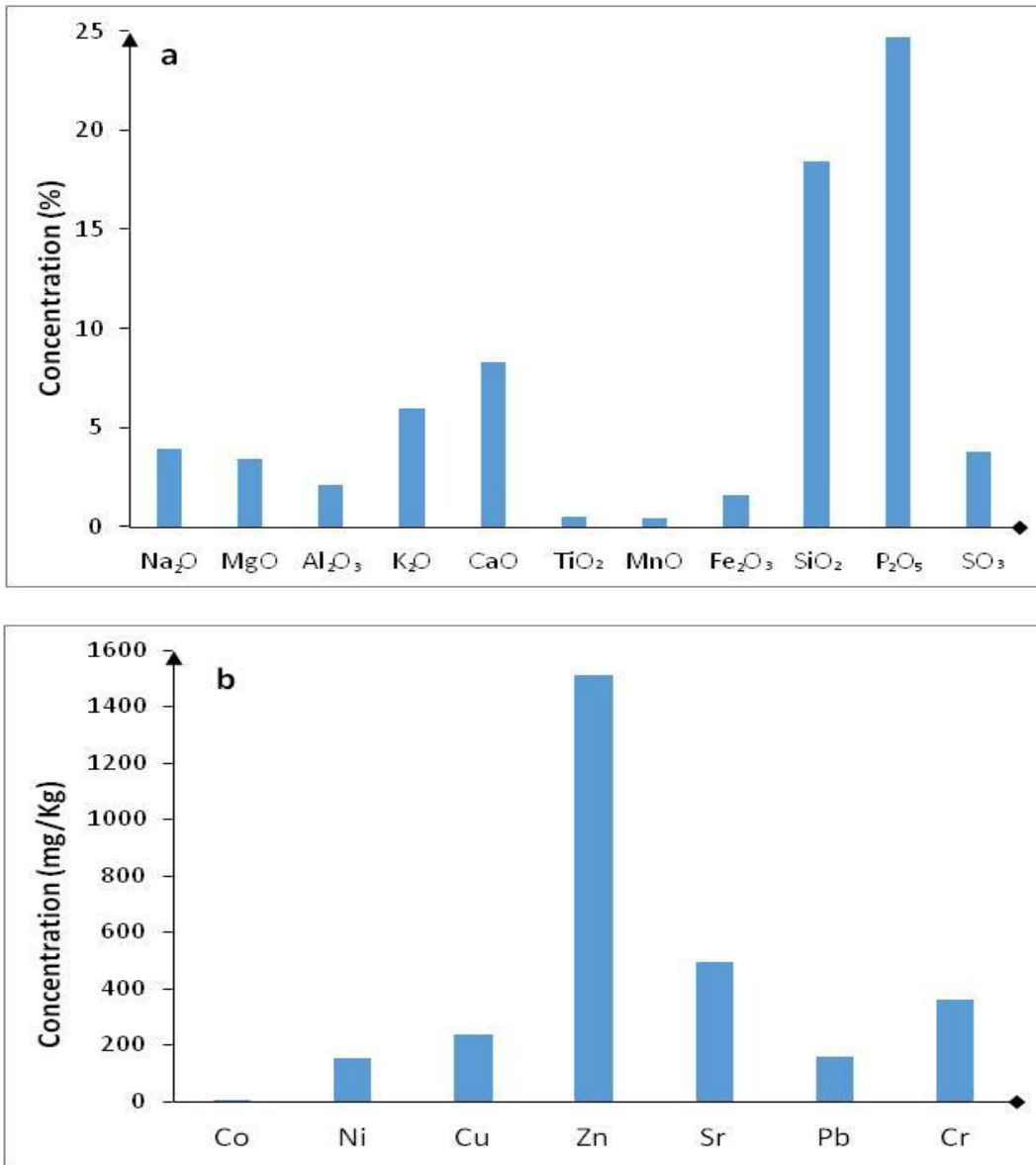


Figure 4 Chemical analysis of fly ash in major (a) and trace (b) elements

4. Conclusions

During fluidized bed combustion tests, sewage sludge fuel burned uniformly along the reactor column. CO levels in flue gases were well below legislation limits. SO₂ emissions of sewage sludge exceeded legislation limits, except when excess air was high (50%) and the temperature reduced, while NO_x emissions exceeded allowable values when excess air was low (30%).

CO levels in flue gases were strongly dependent on combustion temperature and increased with excess air, due to gas cooling. An increase of excess air from 30% to 50%, or a reduction of the feeding rate from 0.6 to 0.48kg/h resulted in lower SO₂ and NO_x emissions. Combustion efficiencies varied between 98.5 and 98.8%, as heat losses were very low. The optimum performance in terms of efficiency and emissions was accomplished when the feeding rate was 0.6 kg/h and the excess air 50%.

Fly ashes were rich in Si and P and to a lesser extent in Ca and K. Also, they were enriched in trace elements Cu, Zn and Sr and contained elevated amounts of Pb and Cr. All heavy metal values measured in present samples were below the upper limit for disposal in landfills, according to EU directives.

Overall, the combustion performance of sewage sludge in the fluidized bed system was quite satisfactory achieving high efficiencies. Thermal treatment of this waste for energy production is an attractive solution, reducing its disposal volume.

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