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Elementary analysis and energetic potential of the municipal sewage sludges from the Gdańsk and Kościerzyna WWTPs

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Abstract. This paper aims to present municipal sewage sludge (MSS) elementary analysis and energetic potential based on measurement of heat of combustion (higher heating value HHV) and calculation of calorific values (lower heating value LHV). The analysis takes into the consideration water content in sewage sludge, at different utilization stages, in wastewater treatment plants in Gdańsk Wschód and Kościerzyna – Pomeranian Voivodeship. The study yielded the following results (in % dry matter): ash 19÷31 %, C - 31÷36 %, H - 5÷6 %, N - 4÷6 %, O - 28÷32 %, S – 1 %. Calorific value of stabilized sludges in Gdańsk was on average 13.8÷15 MJ/kg. In case of sludges not undergoing digestion from Kościerzyna WWTP, the calorific value was at the level of 17.5 MJ/kg. Thus, sewage sludges are good energy carriers. High water content though is the problem, as it lowers the useful effect of heat. There is no alternative for thermal sewage sludge neutralization, which is in conformity with valid Polish National Waste Management Plan (KPGO 2022).

1 Introduction

Sludge production is directly connected to the sewage treatment. Both, primary and secondary sludges, easily become putrescent. They contain bacteria, pathogenic parasites and exhibit a distinctive feature in the form of repulsive odour. Esthetic, epidemiological, and legal issues make their safe management necessary. Possibilities of sludge processing (management) are the result of:

• physical properties (humidity, dehydration susceptibility, calorific value, heat of combustion), chemical properties (heavy metal contents, dioxins, furans) and sanitary properties;

• economical aspects – accepted cost level of processing and utilization;

• legal aspects.

The basic assumption in waste management, apart from the overriding occurrence prevention or minimization of their quantities, should be resource recirculation. In case of sludges the principle can be fulfilled in two ways: by mass or energy recirculation.

In the first instance it means repeated utilization of organic matter and mineral elements (mostly phosphorus) contained in sludges, which can be achieved by their use in fertilization or land reclamation. Whereas energy recirculation can be carried out by sewage sludge combustion.

According to Polish law and the directive of the European Parliament and Council 2006/12/EEC dated April 5 2006 dealing with waste, waste storage is the last and the least required way of waste processing [1]. The effect of Poland's accession to the EU is the systematic reduction of quantities of sewage sludges utilized in this way (Table 1).

According to regulations of Polish Minister of Economy dated from July 16th 2015 dealing with criteria and procedures permitting wastes to be disposed in given type landfill sites [16] municipal waste exceeding the following values can not be stored from January 1st 2016:

• total organic carbon (TOC) > 5% d.m.,

• ignition losses > 8% d.m.,

• heat of combustion > 6MJ/kg d.m.

Table 1. MSS produced in years 2011-2014 in Poland [5], 2015 [11].

Years	Sludge produced and management within a year in thousands Mg d.m.							
	Total	used				landfilled		sludge accumulated in WWTP
		in land reclamation	in agriculture	in plants cultivation, production of compost	thermally transformed (incineration)	totally	% produced	
2011	519.2	54.4	116.2	31.0	41.6	51.4	9.89	212.4
2012	533.3	50.3	115.0	33.3	56.6	46.8	8.77	208.1
2013	540.3	29.4	105.4	32.6	72.9	31.4	5.81	219.8
2014	556.0	22.0	107.2	46.3	84.2	31.5	5.67	226.0
2015	568.0	19.2	107.5	47.1	79.3	40.5	7.13	246.9

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To improve waste management operation in Poland the National Waste Management Plan is prepared every four years (KPGO). The latest National Waste Management Plan 2022 was prepared in 2016 in accordance with the new framework directive 2008/98/EEC dealing with waste [2], which replaced the directive 2006/12/EEC. The plan KPGO 2022 in context of sewage sludges underlines '*limited possibilities of prevention in occurrence of municipal sewage sludges'* at the same time anticipating the rise of produced sludges. Among the basic assumptions of sludge management for the coming years there are: restrictions in their storage, increased quantities of municipal sewage sludges, which will be thermally processed, maximal utilization of biogenic substances contained in sludges with fulfillment of all requirements referring to sanitary, chemical and environmental safety conditions.

Quality requirements, in particular related with low concentration of heavy metals in non-industrious sludge use in treatment plants for agricultural use, are very strict and difficult to achieve in municipal and industrial catchment areas. Yet, the basic obstacle in agricultural use results from quantity restrictions of applied annual sludge doses. The order of Minister of Environment dated from February 6th 2015 dealing with municipal sewage sludge [15] limits the annual dose of municipal sewage sludge in agriculture to 3 tons of dry matter (d.m.) per hectare, and in case of single use within two or three years up to 6 Mg/ha/2 years and 9 Mg/ha/3 years. As a result big municipal treatment plants with population over 100 thousand, with the equivalent number of inhabitants (ENI) for complete agricultural sludge management per year, would need over a few hundred hectares of arable land for complete agricultural sewage sludge management to be used once within 3 years. It is clear that providing such enormous acreage is impossible.

Nevertheless, it is absolutely necessary to remove harmful organic matter containing heavy metals. In case of exceeding concentration of heavy metals or sanitary indicators, instead of mass recirculation it is an obligation to recover energy by sludge combustion or co-combustion. Basing on the official programmes accepted by Poland's government (KPGO 2022) thermal methods of sludge processing are to be recognized as the most promising and developmental. The purpose of the carried out research of heat combustion and elementary analyses of sewage sludges in the two largest treatment plants in the Pomeranian region was to examine their energy potential. The composition of sludges before and after fermentation allows to assess the correctness of the conducted stabilization process. HHV and LHV of sludges may be decisive in the choice of thermal treatment method, parameters of the process, but also in earlier management technology, for instance the intensity of biogas production, dehydrating methods. They may also be decisive in profitability of the whole undertaking of thermal utilization.

2 Experimental - investigation sites

2.1 The WWTP in Gdańsk Wschód

Gdańsk Wschód is the largest wastewater treatment plant in the Pomeranian Province, it collects municipal sewage from Gdańsk, Sopot, Straszyn and the surrounding districts: Pruszcz Gdański, Kolbudy, Żukowo. The person equivalents (p.e.) in 2009 was 650 000, the daily average flow was almost 94 thousand m^3/day.

The treatment technology includes mechanical, biological treatment and sludge processing. Sewage after treatment is directed to the waters of Gdansk Bay by pipeline of 2.5 km length. The mechanical treatment system consists of 4 mechanical screens, 3 grit chambers and 4 primary clarifiers. Mechanically treated sewage is then pumped to the separating chamber and later to one of the six parallel biologically treated process lines. Biological treatment, where there are integrated processes of removal of organic carbon, nitrogen and phosphorus compounds carried out, is based on MUCT – Modified University of Cape Town System. Each of the six bioreactors consists of five chambers (dephosphatation, denitrification of 1st and 2nd degree, nitrification and deoxidation), which assure keeping differentiated oxygen and hydraulic conditions.

The treated sewage from biological reactors is carried to two radial secondary clarifiers (there are 12 of them), which allow separation of activated sludge from sewage. Then sewage is carried by the open channel to the measuring flume, and later by closed channel to the lift station to the Gdańsk Bay by pipeline. Gravitationally thickened sludge from the lower part of secondary clarifiers is partly recirculated to the first hypoxemic chamber of the biological reactor and partly to mechanical sludge thickening (filter presses). Then it goes to the mixing chamber and together with preliminary sludge it goes to closed fermentation chambers - the place of sludge collection before fermentation. After anaerobic methane fermentation sludge is mechanically dewatered in sedimentation centrifugal separators – samples are collected from the pipeline carrying fermented sludge to separators and from the screw conveyor behind the separator. The average sludge production per day is over 31 Mg d.m.

2.2 The WWTP in Kościerzyna

The municipal wastewater treatment plant is located in the southern part of the town. Its present condition is the effect of the modernization and expansion terminated in September 2007. The new mechanical and biological treatment plant consists of two completely independent technological treatment lines using activated sludge method in A2/O technology with increased removal of nutrients. Raw sewage is delivered to the wastewater treatment plant from the storage tanks, which makes their parameters average. In the course of the extension trietary treatment was applied, ie. elementary filtration of secondary effluent WWTP, which makes full retention and averaged sewage possible , as well as using them as technological waters in the treatment process. The modernized wastewater treatment plant collects sewage from 33.8 thousand person equivalents (p.e.), the average flow capacity of the modernized waster water treatment plant was 3,379.4 m^3/d in 2009 and the maximal flow for rainy weather was 12,000 m^3/d. The treatment plant delivers treated sewage to the Bibrowa River and then to Wierzysko Lake and the Wierzyca River. The treatment plant has its own waste management, which consists of the mixing facility where the mechanically dewatered sludge in presses is mixed with straw and then directed to the closed chambers of the compost site. The daily average volume of produced sludge in 2008 was about 2 Mg d.m. (742 Mg s.m./year).

3 Material and methods

The samples of volume from 1 to 3 liters, after collection were placed in cooler boxes in 4 ºC. The first introductory determinations were started on the day of collection or they were stored in the refrigerator till the next day in the laboratory of Faculty of Civil and Environmental Engineering, Gdańsk University of Technology. After drying and determining humidity the samples were transferred to the laboratory of Faculty of Chemistry to indicate heat of combustion, calorific value and sulphur content. Then small quantities of a few grams of dried sludge were delivered for elementary analysis to the laboratory in Molecular and Macromolecular Research Centre of Polish Academy of Science in Łódź.

From the municipal waste treatment plant in Gdańsk 123 averaged samples were collected (mixed primary sludge and secondary sludge for fermentation – 41 samples, fermented sludge – 42 samples, dewatered sludge in the centrifuge – 40 samples), WWTP in Kościerzyna – 68 averaged samples (dewatered sludge in presses – 38 samples and composted sludge – 30 samples). Totally, in the period of over 2 years 191 samples were collected from both WWTPs.

3.1 Analytical procedures

The analyses were conducted according to PN-G-04571 ”Solid fuels. Determination of C, H and N by automatic analyzers. The Macro method”. Although the standard concerns only the determination of carbon, hydrogen and nitrogen, the determination of sulphur was carried out in a similar way.

The determination of carbon, hydrogen, nitrogen and sulphur was carried out by the Vario MICRO cube automatic analyser produced by Elementar Analysensysteme GmbH. As a result of an exothermic reaction it is burnt in oxygen in 1150 °C and the burning products N_2, CO_2, H_2O, SO_2 are adsorbed in a special column. Next, according to the program, they are desorbed at the right temperature and are directed to a thermal conductivity detector (N_2, CO_2, H_2O). In this case the SO_2 to an infrared detector. The analyser is connected to the computer, which both controls the combustion process and calculates the content of the elements in the analysed sample. The determination was conducted in two test portions of each substance.

The determination of oxygen was carried out using the automatic analyser EA1108 produced by Carlo Erba. The test portion is weighed in a silver foil container and placed inside the incinerator heated up to 1070 °C, where it undergoes pyrolysis. The quantitative conversion of oxygen to carbon oxide takes place in nickel-coated carbon. Gases are directed to a chromatographic column, and then to a thermal conductivity detector. By means of the Eager 200 program, both the calibration curve and the results of the analysis are obtained. As in the case of the analyses mentioned earlier, the determination was carried out in two test portions of each substance.

The analysis of the energetic potential carried in the sludge from the wastewater treatment plants in the Pomeranian Voivodeship based on measurement of heat of combustion (higher heating value HHV) and calculation of calorific values (lower heating value LHV - including moisture content) was conducted using the automatic calorimeter KL–10. The apparatus measures the heat of combustion of solid fuels, such as: peat, hard coal, brown coal, hard coal briquettes, brown coal briquettes, coke, semi-coke as well as inexplosive flammable organic matter. A sample of fuel is completely burnt in oxygen under pressure in a bomb calorimeter immersed in water, where increase in water temperature is measured. The heat of combustion of the fuel is automatically calculated and shown on a digital display. The calorimeter measures heat exchange, and characteristic temperatures converted to digital form are stored by the system. Heat gain is measured by a thermistor sensor.

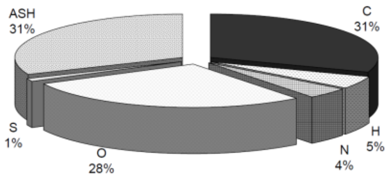
Heat of combustion is the quantity of heat released during complete combustion of solid fuel in the bomb calorimeter with oxygen under the temperature of 25 ºC (PN-81 G-04513, 1981). Calorific value is the heat of combustion reduced by heat of water evaporation emitted during combustion of fuel and created from hydrogen contained in the fuel in MJ/kg (PN-81 G-04513, 1981). Calorific value – it is the useful heat effect of combustion [3].

4 Results and conclusions

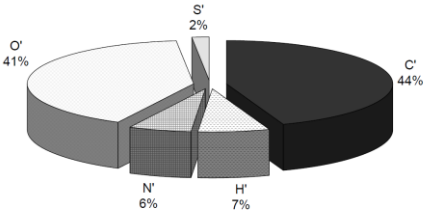
The fuel is composed of the combustible substance consisting of chemical compounds of elementary carbon (C), hydrogen (H) and sulphur (S), as well as mineral substances (ash) and moisture. Fuel can be used for external and internal combustion . Depending on the state of aggregation one can distinguish solid, liquid and gaseous fuel, and depending on the origin there is natural, artificial and waste fuel [17, 18].

Solid fuels are characterized by a series of indicators, such as heat of combustion HHV (MJ/kg), calorific value LHV (MJ/kg), ash content (%), sulphur content (%). Fuel’s calorific value and heat of combustion depends on its chemical composition disclosed in the result of technical analysis (moisture content, ash content or volatile substances) and elementary analysis (C, H, O, S). The average combustible material of mixed sludge

(60 % primary sludge, 40 % secondary sludge) from German urban agglomerations consists of [13]: C – 50 %, O – 38 %, H – 7 %, N – 4 %, S – 1 %, Cl ≤ 0.2 %, F ≤ 0.01 %.

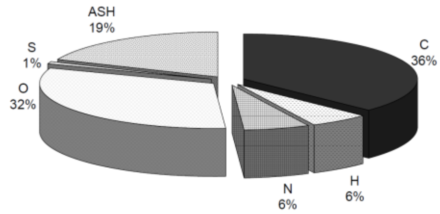


a) in the sludge dry mass (dm*)

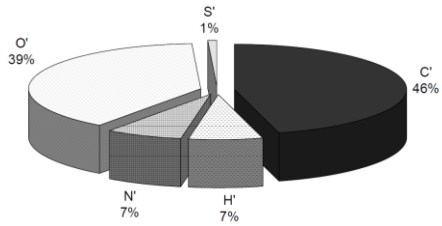


b) in dry organic mass (daf**)

Fig. 1. The average content of C, H, N, O, S in the sludge from the centrifuge in Gdańsk WWTP.



a) in the sludge dry mass (dm*)



b) in dry organic mass (daf**)

Fig. 2. The average content of C, H, N, O, S in the sludge dewatered in presses in Kościerzyna WWTP.
* dm – dry matter, **daf – dry and ash free matter

Table 2. Elementary analysis and calorific values (LHV, HHV) for the sludges and the coal.

Sample material	Raw sample								
	Water	Ash	LHV	C	H	N	S	O	HHV
	%	%	MJ/kg						MJ/kg
Kościerzyna dewatered sludge in presses	81.3	18.8	-0.048	37.3	5.6	5.9	0.8	31.7	17.44
Kościerzyna composted sludge	65.4	18.8	3.47	37.8	5.1	2.9	0.6	34.8	17.90
Gdańsk before digestion	94.9	23.2	-2.53	36.8	5.3	4.9	0.8	29.0	17.69
Gdańsk digested sludge	95.1	34.9	-2.59	28.8	4.4	4.0	0.9	27.0	13.83
Gdańsk from the centrifuge	79.4	31.3	0.12	30.6	4.6	4.3	1.1	28.1	14.92
sludge from very low industrialized town (Spain) [6]	4.3	31.2		38.2	4.3	4.5	0.9	20.9	17.61
sludge from higher degree of industrialization town (Spain) [6]	3.9	53.8		22.7	3.3	3.1	1.6	15.5	9.48
coal (Spain) [6]	1.2	17.7		73.5	3.2	1.6	2.2	1.8	28.87
coal (PL) [12]	9.8	17.9	2.30	67.1	4.7	1.5	0.5	8.3	
dry sewage sludge (PL) [12]	7.4	36.8	1,19	33.6	4.8	4.8	1.3	18.5	
Soft brown coal: [9]	Raw sample				Dry ash free matter				
Rhineland (D)	50–62	5–20	6.3–9.6	68.3	5	0.5	0.5	27.5	26.38
Helmstedt (D)	42–46	12–22	9.2–10.5	72.6	5.8	0.4	4.4	16.7	29.75
Schwandorf (D)	50–58	6–20	6.3–7.5	63.6	5	1.3	4	26.1	25.33
Lausitz (D)	55–60	2–5	8.2–8.5	67.5	5.2	1	0.8	25.5	25.37
Leipzig (D)	50–55	5–7	9.0–11.0	71.6	6.1	0.7	2.1	19.5	28.35
Halle-Bitterfeld (D)	52–56	5–7	9.6–10.0	72	5.5	0.8	3.4	18.3	29.81
Ptolemais (USA)	52–60	6–22	3.6–6.7	65.3	5.3	1.6	0.5	26.5	25.25
Megalopolis (USA)	60–64	13–17	2.8–4.0	60.5	6.2	1.3	1.4	30.6	24.45
Yallourn (AUS)	63–72	1–2	5.0–7.5	67.5	4.8	0.7	0.3	26.7	25.54
Patnow (PL), Lusatia (D)	52–58	6–15	8.0–8.8	73.6	5.1	0.5	1.1	19.7	28.56
Gyöngyös/Visonta (H)	46–54	15–30	5.0–6.7	63.8	4.8	1.1	3.5	26.8	24.83
Elbistan (TR)	48–62	8–24	3.3–6.2	61.4	5.1	0.8	5.1	29.6	23.69

Despite different sewage flows, various technologies of waste treatment, sludge treatment, and processing the composition of dry organic mass of dewatered sludges (daf) from both municipal wastewater treatment plants did not show any significant differences C – 44÷46 %, H – 7 %, N – 6÷7 %, O – 39÷41 %, S – 1÷2 % (Fig. 1b and 2b). Comparing the achieved results from Gdańsk and Kościerzyna with German literature data [13] lower carbon content (6% on average) and higher oxygen content (3% on average) should be underlined, however the differences are small. Greater differences in carbon content are to be noticed when comparing the obtained results with sludge composition coming from Danish WWTPs: C – 52÷58 %, H – 7÷8 %, O – 29÷31 %, N – 4÷9 %, S – 1÷1.5 % [8], Czech WWTPs: C – 67 %, H – 5%, O – 25 %, N – 2.2 %, S – 0.8 % [10] and Chinese WWTPs: C – 52.4 %, H – 9.3 %, O – 27.4 %, N – 7.9 %, S – 3.0 % [19].

The difference in the applied wastewater treatment technologies and sludge processing is noticed when dry sludge is compared (dm – without omitting ash content) (Fig. 1a and 2a). Sludges from Gdańsk are considerably highly mineralized than sludges from Kościerzyna, which results from methane fermentation before dehydration. Sludges from Kościerzyna are excessively unstabilized. The comparison of percentage composition of sludges from both treatment plants with literature data is presented in Table 2.

The heating value of raw sludge is about 17 MJ/kg; for activated sludge, about 15 MJ/kg, and for stabilized sludge (digested: anaerobic, aerobic, or lime stabilization) around 11 MJ/kg [14]. The value of HHV was considerably higher in excess sludge from Kościerzyna, it was on the level of 17.5 MJ/kg. The fermented sludge from Gdańsk was also characterized by higher value of HHV, which was almost 14 MJ/kg.

Heat of combustion of dry sewage sludges is about 15÷17 MJ/kg and is almost twice lower than heat of combustion of good quality coal.

Generally, it is assumed that one ton of hard bituminous coal is energy-efficient to 2 tons of dry sludges.

The combustion process can be autothermic or it can require heat supply. When one third of the sludges is inflammable, the heat from burning dry sludge does not exceed 14 MJ/kg, and after subtracting the heat necessary to evaporate water, the calorific value of the sludges decreases to about 9 MJ/kg. The calorific value of the digested sludge is lower than that of the raw non-digested sludge by about 2 MJ/kg [7]. If the humidity of sludges is high, the heat of combustion is equal to 0. If the heat from burning sludge is insufficient to evaporate the water present in it, it is necessary to supply an additional heat source e.g. coal, heating oil, straw, biogas or woodchips.

According to Austrian researchers, the calorific value of the wastewater sludge which contains 50 % of organic substance and dewatered till dry matter content 50 % is equal to 4 MJ/kg. The calorific value of the one that contains 75 % of organic substance and dewatered – having a moisture content of 50 % – is equal to 6.5 MJ/kg. When the moisture content is equal to 85 % in the hydrated sludge, which contains 50 % of organic substance, the calorific value is equal to 0 [7].

The values of heat of combustion obtained in the course of laboratory tests (Fig. 3) are at the level 13.8÷17.7 MJ/kg and the variation of this parameter referred to the applied treatment processes. Methane fermentation in Gdańsk caused reduction of heat of combustion by about 3÷4 MJ/kg in comparison to not fermented sludges. In comparison to the literature data fermented sludges from Gdansk waste treatment plants were characterized by high value of HHV and low content of ash – just 34÷35 % at this stage of treatment. Czech sources say that digested sludge contented, on average, 49.2 % of organics and 50.8 % of ash in dry matter. The higher heating value was 12.18 MJ/kg of dry matter. The lower heating value was 11.23 MJ/kg of dry matter [4].

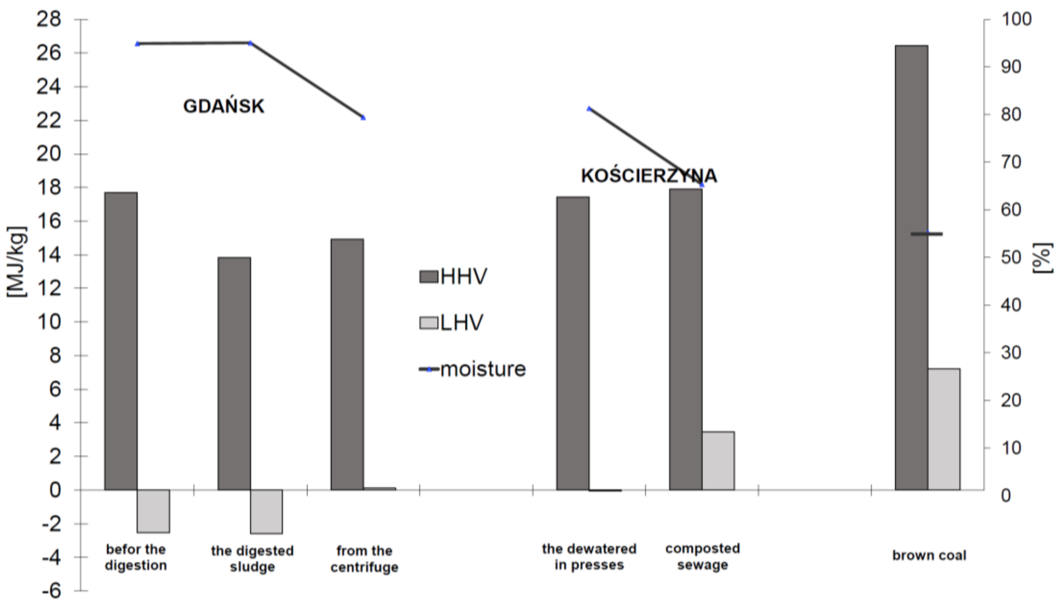


Fig. 3. The average HHV, LHV and moisture of the sludges from WWTPs Gdańsk, Kościerzyna and brown coal.

The achieved values of heat of combustion are consistent with the presented literature data, although fermentation and stabilization processes could be more efficient and reduce the value of heat of combustion even more. In case of Gdańsk it is possible to obtain bigger quantities of biogas. Nevertheless, it should be connected with proper utilization of fuel to make it sensible.

It must be noted that composting, which is the final stage of sludge processing in Kościerzyna WWTP, improves energy parameters of the sludge HHV – 17.9 MJ/kg, LHV – 3.5 MJ/kg with humidity > 65 %. Composting prepares sludge for natural utilization and does not exclude thermal methods of utilization.

5 Conclusions

1. Although it is consistent with the matter cycle in nature, utilization of sludges for natural purposes would be more and more difficult. Requirements for treated sludges are higher and higher, there is no sufficient acreage for fertilization or reclamation – particularly in large WWTPs. However, natural methods should be promoted for small treatment plants collecting mainly municipal sewage. Energy utilization of sludges seems to be attractive provided combustion gas is properly treated.
2. Comparing the results of the elementary components of the sludges with the literature, a lower content of carbon and higher content of oxygen can be observed.
3. Sludges are a good source of energy. The average heat of combustion (HHV) of wastewater sludge was 13.8÷15 MJ/kg for the digested sludge and 17.5÷17.7 MJ/kg for the non-digested sludge from the both NBR (nutrients biological removal) WWTP. Two - three tons of sludges, after drying of about 40% humidity, are the equivalent of one ton of hard bituminous coal. Thus, sewage sludges are a good energy carrier. High water content is the problem, as it lowers the useful effect of heat.
4. Composting prepares sludge for natural utilization but also improves energy parameters of the sludge (HHV – 17.9 MJ/kg, LHV – 3.5 MJ/kg with humidity >65 %) and does not exclude thermal methods of utilization.

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