Energy efficiency of dry sewage sludge before and after low-temperature microwave pyrolysis

J. Raček [1], T. Chorazy [1], V. Novák [1], J. Čáslavský [2], P. Hlavínek [1]

[1] Brno University of Technology, Faculty of Civil Engineering, AdMaS Research Centre, Purkyňova 651/139, 612 00 Brno, Czech Republic
[2] Brno University of Technology, Faculty of Chemistry, Institute of Chemistry and Technology of Environmental Protection, Purkyňova 464/118, 612 00 Brno, Czech Republic

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Presenting author email: racek.j@fce.vutbr.cz

Abstract

This paper deals with current applied research focused on energy efficiency from dry sewage sludge (SS) before and after microwave pyrolysis (MP) of SS at AdMaS Research Centre in the Czech Republic.

The issue of sewage sludge (SS) treatment at wastewater treatment plants is one of the important topics in the European Union (EU) and also in the Czech Republic (CR). Disposal of SS has received significant attention mainly due to new strict regulation of the SS landfilling and direct application in agriculture. The society is looking for a new method of waste recycling, material and energy use closely connected with "Circular Economy". MP as a thermal treatment of SS is a suitable solution in the EU. The products of MP are biochar, pyrolysis oil and pyrolysis gas (Syngas). These MP products should not be classified as a waste but as a resource representing a solution under the terms of the circular economy: carbon footprint reduction, energy use and for many other applications.

Current applied research is carried out at different conditions. First in a laboratory and second in two full-scale appliances using MP units operating at a low temperature less than 300 °C and a low pressure 800 hPa with 3 kW magnetrons with 2.45 GHz. At present, the basic and most common way of dry SS treatment is an incineration using an exothermic reaction the product of which is a thermal energy. The experiments were performed at different samples of dried SS and the biochar as an outcome from MP was tested for contribution tests. All MP products can be used energetically as an alternative to fossil fuels for incineration, cogeneration or combustion engines.

The results were compared with literature for dried SS before MP execution and for biochar after MP execution. The contribution tests carried out by the laboratory MP unit reported higher difference energy efficiency 2.88 $MJ.kg^{-1}$ than before MP process than tests from small full-scale unit. Admittedly, the small full-scale with the difference 1.05 $MJ.kg^{-1}$ after MP process has its value closer to simulating real conditions at WWTP. This difference responds different SS, the heterogeneity of SS, few measurements and is influenced by different device. In a view of the current situation of disposal routes for SS, the compact MP unit with dryer (CMPUD) of SS was design and described by 3 stages for energy efficiency and other use. The Stage 3 considers the use of biochar in agriculture and it represents solution with a positive impact on the environment.

The MP as an eco-friendly treatment of SS with products may represents a solution in terms of circular economy. Pyrolysis gas and pyrolysis of MP will be energy used. Biochar after MP process will be energy used and after the challenges of the present used in agriculture is assumed.

1. Introduction

1.1. Disposal of sewage sludge

At present, the disposal of sewage sludge (SS) is managed by landfilling, agricultural use and incineration. Disposal of the SS is one of the most important issues in circular economy that is a part of the waste management strategy implemented by the European Union (EU). In the Czech Republic (CR) disposal of SS has received significant attention mainly due to new legislation strictly regulating the SS landfilling and direct application in agriculture.

The landfilling of SS as nonecological disposal is not supported by EU and is strictly restricted in several EU countries. SS contains a lot of organic matter which is decomposed at the landfill sites and generates CH_4, which contributes even more than CO_2 to the greenhouse effect. Moreover, the cost of the land needed for landfill is increasing because of its decreasing availability (Fonts et al., 2012).

SS contains organic matter, nitrogen and phosphorus, which are nutrients for soils. These components make the sludge suitable as a fertilizer (Fonts et al., 2012). Currently, the limiting criterion of its use in agriculture is the content of heavy metals (HM), in the near future the content of xenobiotics and microplastics will also be taken into account. HM content in raw SS is biologically available for plants, reflecting the solubility and thereby potential unhealthy impact of HM on the environment.

The incineration of SS reduces volume up to 70 % and decreases pathogens and toxic organic compounds (Fytili et al., 2008; Khiari et al., 2004). SS has an energy value similar to some low-grade coal, therefore its incineration is performed under energy recovery conditions. Fossil fuel savings would be possible and further advantage of the incinerator is that the net CO_2 addition to the atmosphere decreases, thus there is a contributing to overall CO_2 reduction (Fonts et al., 2012). At present, incineration of SS is carried out either directly at WWTP, or as the co-combustion of SS with coal or other wastes, or the combustion SS in cement kilns (Stasta et al., 2016). It is to be mention a relatively small incinerators number of SS located at WWTP recover the energy of waste to the treatment process (Fonts et al., 2012). Ash of incineration of SS contains larger quantities of metals, namely Cr, Cu, Ni, Pb, Zn and Fe, and is more toxic than the ash from coal combustion (Cenni et al., 2001). The reuse of the ash of SS is another topic that has to be addressed and the incineration of SS in cement kilns could solve the problem of ash disposal (Fonts et al., 2012; Cenni et al., 2001; Chang et al., 2010).

Implementation of circular economy strategy postulates a search for new ways of waste recycling, and its material and energy exploitation with incineration and thermal treatment of SS. Thermal treatment such as torrefaction, gasification and pyrolysis of SS is consequently one of the most significant challenges in wastewater (WW) management and represents the most suitable solutions of SS disposal. Based on the data found in the literature review the pyrolysis of SS seems to be a suitable thermal treatment method to transformation raw SS to sources with HM fixation in output product (Zhao et al., 2017; Liu et al., 2016; Jin et al., 2016; Liu et al., 2018; Huang et al., 2016). Currently, HM fixation by pyrolysis is addressed in research not real condition at the WWTPs for agricultural use. The incineration and pyrolysis seems the current suitable solution for WWTPs. The aim of pyrolysis can be the obtaining of these products: biochar, pyrolysis oil and pyrolysis gas (Syngas) (Callegari et al, 2018). The lignocellulosic biomass pyrolysis has balance values for products: the yields achieved are 60 – 75 wt % for the liquid, 15 – 25 wt % for the char and 10 – 20 wt % for the gas (Mohan and Pittman, 2006). The share of yields depends on raw feedstock characteristics. Char and gas can also be considered as fuels and be reused in the process itself (Fonts et al., 2012). Pyrolysis liquid from lignocellulosic biomass has already been successfully tested as a direct fuel in engines, turbines and boilers (Chiaramonti et al., 2007; Czernik and Bridgwater, 2004). However, the potential direct substitution of pyrolysis oil for conventional petroleum-based fuels in transport applications requires upgrading processes which are currently under development (Fonts et al., 2012).

Importantly, the nomenclature "biochar" refers only to charcoal used as a soil amendment (Conte et al., 2015) and it is not commonly used for the product produced from 100 % SS, but we use this nomenclature in following text. The pyrolysis process has considerable potential for SS management since it achieves up to 50 % reduction of the waste volume (Inguanzo, 2002), the stabilization of the organic matter, and the production of fuels and valuable chemical products from the liquid obtained (Fonts et al., 2012). Thus, the incineration of SS and pyrolysis seems to represent a solution in terms of circular economy, carbon footprint reduction, energy recovery.

1.2. Products of microwave pyrolysis of SS

<u>Pyrolysis oil of MP</u>

Pyrolysis oil is a very complex mixture, which was necessary to analyze by advanced analytic methods. The composition of pyrolysis oil is as follow: 20 % of water, 40 % of compounds possibly detected by gas chromatography (GC), 15 % of non-volatile compound, which is possible to detect by liquid chromatography (HPLC) and 15 % of non-detected compounds (Žvaková, 2017). Chemical characteristics of pyrolysis oil is generally oriented at fractionation into purposive categories, which are the base to create a method of following final analysis. The segregation into the categories (co called chemical families) simplify the overview of pyrolysis oil, which changed from the mixture of hundreds of substances into the mixture of several groups (Garcia-Perez, M. at al., 2007, Sipilä, Kai at al., 20161).

Table 1. Fractionation method.

Stationary phase	Fraction	Eluent
Activated silica gel	Aliphatic hydrocarbons	Pentan
	Polyaromates	Pentan / DCM (1:1)
	Polyaromates derivatives	DCM
	Polar compounds	DCM / Met-OH (1:1)

It is not possible to determine individual chemical compounds, which are assigned at pyrolysis oil, by only universal instrumental method, because characteristics of these compounds vary. Therefore, it was selected the fractionation into 4 fractions showed in Table 1. These are following: polyaromates, functional derivatives of polyaromatic compounds and polar compounds (Žvaková Eva, 2017).

The characteristics of pyrolysis oil originated from MP is different in comparison with pyrolysis oil originated from conventional way of heating. The advantage of oil from MP is higher content of carbon, higher caloric value and lower content of oxygen (Huang, Yu-Fong, at al., 2016).

Oxygen content of pyrolysis oil.

Due to the presence of 35 – 40 wt% of oxygen in the pyrolysis oil result in different characteristics of such oil with comparison to fossil fuels. The effect of this high content is lower density of energy, immiscibility with hydrocarbons and instability (Gooty, A., 2013).

Acidity and corrosivity

Pyrolysis oil contents significant amount of carboxyl acids, especially the acetic and formic acids. This content has effect with acid pH, which range from 2 – 3 and it depends on the content of hemicellulose at the income material and reaction conditions. Due to the high acidity, the pyrolysis oils are corrosive for current metals as is steal. The corrosivity of pyrolysis oil increases with the growing process temperature and with the increasing water amount (Gooty, A., 2013).

Water content

High water content is the result of two contributions. These are the water content at the income biomass, which condensate at oil and also the water, which is produced by pyrolytic reactions, specially by dehydrogenation reactions. The high content of water results on only of low caloric value, but also of corrosive characteristics. The viscosity of pyrolysis oil is 400 x higher than water viscosity at 25 °C (Gooty, A., 2013).

Energy efficiency in pyrolysis oil

Pyrolysis oil has a density around 1200 $kg.m^{-3}$ and the caloric property 16 - 20 $MJ.kg^{-1}$. The caloric value of pyrolysis oil is comparable with the caloric value of rare biomass and it correspond with approximately 40 % of fossil fuels. The lower caloric value is caused by the high content of water as well as the high content of oxygen (Gooty, A., 2013).

There is a simple storage and a transport possibilities of it. As mentioned, the oil is possible to use as a quality liquid fuel (Hlavínek P., 2015). Pyrolysis oil has a lot of positive characteristics comparing with some other oil fuels as is a high caloric property, lower total impact on environment and lower need of its processing. Some disadvantage of pyrolysis oil is its high viscosity, low vaporization and high reactivity (due to the high content of unsaturated hydrocarbons). There is quite complicated direct use at engines due to its polymerization reactions. Pyrolysis oils could replace the fuels on oil basis, but it is mostly to be use the refining treatment of characteristic to be able the wider applications. Typical characteristics of pyrolysis oil from biomass and heating is showed in table 2. (Jayasinghe at al., 2012).

The pyrolysis oil obtained by the process of quick pyrolysis can be used after the next purification and treatment either as the chemical production, or as a fuel for mobile diesel engines or directly as a fuel as a heating oil for boilers or as a fuel for electricity production at combustion engines or combustion turbines (Hlavínek, P; 2015).

Table 2. Typical characteristics of pyrolysis oil from biomass and heating oil (Jayasinghe at al., 2012).

Physical characteristics		**Pyrolysis oil**	**Heating oil**
Water content (wt %)		15 - 30	0.1
pH		2.5	-
Specific density ($g.cm^{-3}$)		1.2	0.94
Elementary structure (%)	Carbon	54 - 58	85
	Hydrogen	5.5 - 7	11
	Oxygen	35 - 40	1
	Nitrogen	0 - 0.2	0.3
Ash		0 - 0.2	0.1
Viscosity (cP)		40 - 100	180
Solid share (wt %)		0.2 - 1	1
Caloric value ($MJ.kg^{-1}$)		16 - 19	40

Biochar of MP

Biochar is usually the main byproduct of SS pyrolysis for liquid production. The biochar yield given in the existing literature varies greatly, usually between 35 and 80 wt%, on a dry basis. This is mainly due to the different origins of the sludges and their ash contents. The most distinctive feature of SS biochar, if compared to those of lignocellulosic origin, is their high ash content. During pyrolysis, the organic content of biochars reduces with increasing temperature, while most of the inorganic content remains in the solid matrix. As commented before, the majority of metals originally contained in SS remain in the biochar after pyrolysis, except the volatile elements mercury and cadmium; moreover, heavy metals are more strongly incorporated in the matrix of pyrolysis residue than in the incineration ash or in the SS itself (Fonts et al., 2012).

The energy characterization of biochar is stated below. Some next important characteristics are the content of heavy metals (HM), organic content or surface analysis.

The share of organic matter in all input samples was around 50 %, which, with a small deviation, confirms the data obtained from the WWTP when dried sludge is extracted. Similarly, large variations could be observed for TOC in input pellets. Its value was around 29 %. To assess the porosity of biochar it is advisable to take into account the content of organic matter in which most pores are likely to be present. The TOC results, which ranged between 23.1- 39.4 % for biochar compared to the proportion of organic matter determined by thermogravimetry (22.8 to 44.6 %) offer the possibility of deepening the considerations of the proportion of organic matter related to other results (Raček, J., 2017).

From the point of view of environmental protection, Cd, Hg, Pb, As, Cr are designated as hazardous, along with, e.g. Ni, which is then defined by the relevant EU and Czech national regulations. As regards HM, aqua Regia leachates and aqueous extract were observed and the values were evaluated. Depending on individual metals and samples, fixation of 81 up to almost 100 % of HM in biochar was achieved. The 100 % value is based on the fact that the concentration in the aqueous extract was below the level of possible detection (measurability). These figures are the average values of the 12 sample leachates (suspicious input data excluded) for each HM (Raček, J., 2017).

The remaining organic fraction gives a modest porous nature to the biochar. The highest values of BET surface area of biochar reported from a single pyrolysis step are around 150 $m^2\ g^{-1}$ (Fonts et al., 2012).

The surface of biochar is investigated by BET surface analysis and it depends of appropriate pre-treatment – palletisation, the content of organic matter or added catalyst. Appropriate results are arranged for publication.

Pyrolysis gas of MP

Like liquid yields, gas yields vary greatly depending on the experimental conditions. Temperature appears to be the most influential parameter. It is generally accepted that an increase in temperature in fluidized bed pyrolysis increases the gas yield. Reported values for gas yields range within 8–45% or 5–30% (sludge basis). Similarly, to biomass pyrolysis, the main compounds detected in SS pyrolysis gas are CO, CO2, CH4, H2 and light hydrocarbons. (Fonts et al., 2012).

Also, depending on the parameters mentioned, reported heating values of the gas vary between 5 and 36 MJ kg^{-1}. Some authors propose using pyrolysis gas to provide heat for the pyrolysis process itself or running it autothermally, and even for drying part of the SS. Nevertheless, one of the main drawbacks for this final use of the gas would be the potentially high amounts of H_2S as the main gas pollutant. (Fonts et al., 2012).

1.3. Energy characteristic of raw SS and products of MP

The heating value of the SS is affected by the type of sample. It is greater when the moisture content and the ash content are lower. It is true also when the organic matter has not been digested. The heating value of digested and dry SS may range between 8.5 and 17 MJ kg^{-1} and, when the sample has not been digested, it can reach a considerably higher value (23 MJ kg^{-1}). The origin of the SS may also have an important effect on its heating value. SS obtained in the purification of WW from certain industries such as canned food or petrochemicals has significantly higher heating values than that obtained from urban WWTPs (Fonts et al., 2012).

Based on the literature review data published by authors Fonts et al. the heating value of biochar after pyrolysis is 5-21 MJ kg^{-1} (Fonts et al., 2012). The heating values near to 5 MJ kg^{-1} make it generally unattractive for incineration or any other energetic vaporization. However, the energetic valorization of the sludge char products with high heating value could be very interesting (Fonts et al., 2012).

Pyrolysis oil from lignocellulosic biomass is a liquid output which can be considered as a macroemulsion of organic macromolecules stabilized in an aqueous solution of smaller organic molecules (Fonts et al., 2012). Macroemulsion stabilization is achieved by hydrogen bonding and nanomicelle and micromicelle formation (Piskorz et al., 1988). A typical heating value of biomass pyrolysis liquid is around 17 MJ kg^{-1} (Mohan and Pittman, 2006) which is 40 – 45 % of that exhibited by hydrocarbon based fuels (Czernik and

Bridgwater, 2004). Two of the main chemical differences between biomass pyrolysis oils and hydrocarbons fuels are water and oxygen content (Fonts et al., 2012).

Authors Fonts et al. describes in a literature review the heating values of the pyrolysis gas between 5 and 36 MJ kg^{-1} (Fonts et al., 2012). Some authors propose using pyrolysis gas to provide heat for the pyrolysis process itself (Fonts et al., 2008) or running it auto thermally, and even for drying part of the SS (Stammbach et al., 1989). Nevertheless, one of the main drawbacks for this final use of the gas would be the potentially high amounts of H_2S as the main gas pollutant. (Fonts et al., 2012).

Furthermore, unlike other thermochemical processes such as combustion or gasification, pyrolysis is an endothermic reaction and this means that the pyrolysis products may have a more elevated heating value than the pyrolyzed raw material (Fonts et al., 2012). Kim and Parker (Kim and Parker, 2008) found that the liquid (pyrolysis oil) and the solid products (biochar) of pyrolysis at 300 °C of TWAS (thickened waste activated sludge) had an energy content between 0.16 and 1.9 MJ kg^{-1} more than the raw SS (Fonts et al., 2012).

Current applied research at Brno University of Technology, Faculty of Civil Engineering, AdMaS Research Centre (BUT AdMaS) focuses on a low temperature slow MP of SS. This research is conducted in cooperation with engineering company Bionic E&M. The research is focused on HM fixation after MP for agriculture use and the second way is energy efficiency from dry SS before and after MP.

Currently, due to regulating landfilling and agriculture use, many owners and operators of waste water treatment plants (WWTPs) consider incineration as an immediate solution of SS disposal. The aim of this research is to compare the energy efficiently of dry SS before MP and the products of MP process: biochar and pyrolysis oil. The MP tests were carried out by using full-scale MP unit, which corresponds to real conditions at WWTP. In this work, we focused on investigation of indicators of pyrolytic processes such as dry solids, MP process time, maximal temperature of the MP. The combustion tests were performed on the samples. For this article, MP of SS was also investigated with the aim of obtaining data of energy efficiency in the input drying sludge and the output biochar and pyrolysis oil of the small full-scale MP unit. Based on the data of results, the compact MP unit with dryer of SS was design for energy efficiency and other use.

2. Materials and methods

2.1. Low temperature slow MP unit

The pyrolysis can be carried out either by using conventional heat transfer via conduction or microwave heating of pyrolyzed material. The microwave pyrolysis (MP) has already been tested for lignocellulosic materials, but its application for SS pyrolysis is reported only in a few papers (Callegari et al., 2017; Capodaglio et al., 2016, 2017, Menéndez et al., 2002; Zhao et al., 2017).

MP represents an eco-friendly disposal of SS resulting in production of biochar, pyrolysis oil and pyrolysis gas (Syngas) (Callegari et al, 2018). Importantly, the nomenclature "biochar" refers only to a charcoal used as a soil amendment (Conte et al., 2015) and it is not commonly used for the product produced from 100 % SS, but we use this nomenclature in following text.

At BUT AdMaS there is installed one laboratory and two full-scale units of SS using low temperature slow MP (Raček et al., 2017). Two units for test of different samples are used there. The tests were performed by a laboratory and small unit to simulate real conditions at WWTP.

The laboratory scale MP unit represents the experimental apparatus consists of a procedural one batch reactor, equipped with two high efficient microwave generators of 3 kW output, 1 x 3 kW magnetrons, at a frequency of 2.45 GHz. Batches of up to 3 kg/batch can be processed at low pressure (800 hPa). The temperature was continuously monitored by an infrared thermometer, it increased maximally up to 250 °C. The attached glass condensation allows the separation of the pyrolysis oils and residues produced in the microwave supported catalytic cracking process for later analysis. Possible input materials are solid materials with a diameter of less than 8 mm.

The small full-scale MP unit has capacity around 10 kg/batch of dried SS, the device work discontinuously. It consists of one batch reactor equipped with one high efficient microwave generator of 3 kW output, at the frequency 2.45 GHz. Batches of dried SS were pyrolyzed at low pressure (800 hPa). The temperature was continuously monitored by an infrared thermometer, it increased maximally up to 250 °C. The glass condenser attached to the pyrolyzer was used for separation of the pyrolysis oil and gaseous products. For incoming and reflected waves is installed a tuner. The pyrolyzed materials were samples of SS made directly by belt dryer (noodle shape).

2.2. Sewage sludge and biochar after MP

From the chemical point of view, SS is a heterogeneous mixture of undigested organic matter (paper, plant residues, oils, etc.) microorganisms, inorganic materials and water. The content of inorganic material in the

SS is usually higher than 50 %. The undigested organic matter of SS consists of several hydrocarbons like proteins, peptides, lipids, polysaccharides, phenolic and aliphatic structures containing macromolecules, polycyclic aromatic hydrocarbons, etc. (Fonts et al., 2012). Dry SS contains also molecules containing nitrogen and phosphorus, which are nutrients for soils. The problematic substances for direct application in agriculture are considered xenobiotics, microplastics and HM.

The sludge composition depends on quality and quantity of the inflow and treatment processes at WWTP. The quality and quantity of the inflow strongly influence the chemical composition and physicochemical properties of SS. The SS was contaminated by various HM originating largely from industrial WW. The treatment processes at WWTP are unique and depend on design of WWTP especially the design of the biological treatment and sludge management.

The testing of MP at the BUT AdMaS was carried out with 2 different samples (SS from a different time period, designation SS1 and SS2) of anaerobically digested and thermally dried SS from one municipal WWTP which has a capacity of around 90 000 population equivalent (PE), the sludge was dried using a belt dryer at temperature lower than 85 °C. Tested raw dried SS samples from WWTP had DS around 90 % and output fraction from dryer was a noodle of around 25 mm in length and around 5 mm in diameter. Our previous research was focused on pretreatment of dried SS prior to the MP, and it was focused on pelletization of SS and its mixing with additives (Raček et al., 2017). These energy efficiency tests were performed on SS without additives and without pelletization to simulate current real conditions for incineration at WWTP.

The tests of energy efficiency on SS and biochar, which are shown in Figure 1, before and after MP can be classified into the two groups:

- Group 1: SS1 from WWTP by laboratory MP unit;
- Group 2: SS2 from WWTP by small full-scale MP unit;

In Group 1, the raw sample of SS1 was noodles and input to batch. The test was performed in the reactor of laboratory MP unit. The temperature was managed via magnetron power control. After the MP test of SS was completed, the vacuum pump was stopped.

In Group 2, the raw sample of SS2 was noodles and input to batch. The test was performed in the reactor of small full-scale MP unit. The temperature was managed via magnetron power control. After the MP test of SS was completed, the vacuum pump was stopped.

Figure 1. SS (SS2) before MP with noodle shape (left), biochar (BC2) after MP (right).

Figure 1, on the right, is shown the biochar after MP of SS. The weight was reduced in terms of yields of products of MP process. Generally, during our pyrolysis for SS1 and SS2 the following yields are achieved: biochar yield was 86.5 %, pyrolysis oil yield was 7.8 % and pyrolysis gas yield was 5.7 %.

2.3. Contribution tests

Energy efficiency were determined in both raw SS (SS1, SS2) and biochar (BC1, BC2). In principle, the contribution tests were performed for SS1, SS2 and after MP process for BC1 and BC2. The combustion tests were carried out according to the Czech standard ČSN EN ISO 1716 (7300883). The energy efficiency of samples was measured by semi-automatic device (IKA C 200) at standard laboratory conditions.

At the first part, for each sample (SS1, SS2, BC1, BC2), the representative small doses were determined for contribution tests. The small doses grind to fine dust by friction dishes. The quantity of fine dust 0.4-0.8 g was prepared for measurement of energy efficiency and input to calorimetric bomb of the specimen holder. The dose was interfaced with the spark plug circuit using by a cotton thread. The entire specimen holder assembly was placed in a calometric bomb which was sealed and supplemented with pure oxygen at an internal pressure of 34 bar. The calometric bomb was input to a calometric heat-insulated container with demineralized water. With constant intensive stirring of water in a calorimetric vessel, the water temperature was monitored for 3 minutes until a constant value was established. Subsequently, a bomb sample was ignited by the ignition circuit, and a calorific value was determined from the temperature change in the calorimetric vessel as a result of the contribution tests of the sample. The result was the average of the three calorific values for each sample.

3. Results and discussions

Energy efficiency in raw SS

The energy efficiency was measure by device at the laboratory of AdMaS Research Centre. The contribution tests were performed for raw SS, different SS1, SS2, from the one WWTP. After MP process, the contribution tests were carried out for appropriate samples of biochar BC1 and BC2. SS1 appropriate BC1 as Group 1 and SS1 appropriate BC2 as Group 2. The results of contribution tests of SS were reported in Table 3.

Sample of SS1 before MP process reports average value 13.85 $MJ.kg^{-1}$ of the energy efficiency and different sample SS2 from same WWTP represents lower average value 12.15 $MJ.kg^{-1}$. The difference of number was due to different SS, the heterogeneity of SS and few measurements.

Table 3. Energy efficiency in raw SS (SS1, SS2) before MP process.

Description			**The energy efficiency ($MJ.kg^{-1}$)**	
			Value	**Average value**
Laboratory MP unit	SS1	Dose 1	13.86	13.85
			13.86	
			13.83	
Small full-scale MP unit	SS2	Dose 2	12.14	12.15
			12.12	
			12.20	

Energy efficiency in biochar

The data reported in Table 4 represent the energy efficiency for biochar BC1 and BC2 after MP process. Sample of BC1 by 3 doses were carried out by laboratory MP unit and average value achieves 16.73 $MJ.kg^{-1}$. This value is higher than 2.88 $MJ.kg^{-1}$ before MP process 13.85 $MJ.kg^{-1}$. The average value after MP process by small full-scale MP unit represents higher value 13.20 $MJ.kg^{-1}$ than before MP for SS 12.15 $MJ.kg^{-1}$, the difference is 1.05 $MJ.kg^{-1}$.

Table 4. Energy efficiency in biochar (BC1, BC2) after MP process.

Description			**The energy efficiency ($MJ.kg^{-1}$)**	
			Value	**Average value**
Laboratory MP unit	BC1	Dose 3	14.92	16.73
			15.05	
			15.02	
		Dose 4	16.59	
			16.49	
			16.41	
		Dose 5	18.88	
			18.58	
			18.67	
Small full-scale MP unit	BC2	Dose 6	13.22	13.20
			13.47	
			12.92	

The compact MP unit with dryer of SS

Based on literature review, the compact MP unit with dryer (CMPUD) of SS was design for energy efficiency and other use. This CMPUD of SS as roughly energy-conscious can be designed and implemented at WWTPs. We propose the implementation of this device by 3 stages:

- Stage 1: construction of SS dryer;
- Stage 2: construction of CMPUD;
- Stage 3: construction of biochar silo.

In the Stage 1, a construction of SS dryer will be built up. The dry solid (DS) in the SS will be increased and the dried SS will be more economical to transport. Dried SS it can be energy used directly to the WWTP to the boiler or an incineration. In the first case, the energy thus obtained can be used for drying additional SS.

The MP unit will be added to the SS dryer which represents the CMPUD. The products of CMPUD as pyrolysis oil and pyrolysis gas will be used to improve the energy efficiency at the WWTP. The recovery energy will be used directly by cogeneration to input energy to CMPUD. The product biochar will be energy use at the WWTP to the boiler or an incineration.

Finally, the Stage 3 represents solutions with a positive impact on the environment. Current global research of MP of SS focused on HM fixation, reduction of xenobiotics, carbon footprint reduction, water retention has received significant attention for agriculture use.

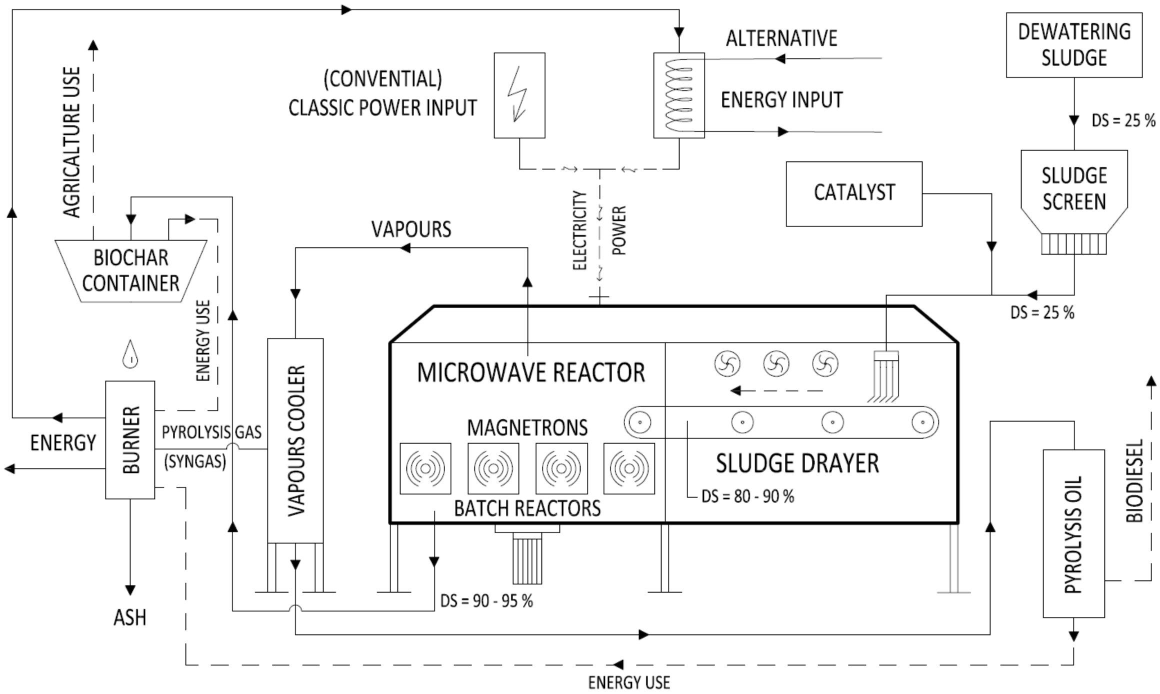

Figure 2. The scheme of the compact MP unit with dryer of SS (CMPUD)

The Figure 2 describes the scheme design of the CMPUD at the WWTP. Dewatering SS with 25 % DS is extruded by sludge screen thus obtained a noodle shape. Due to our research, HM fixation in biochar after adding additives is increased and thus biologically unavailable for plants. Dewatered SS with additives is dried and after MP process distributed to vapors (pyrolysis gas and pyrolysis oil) and solid matter (biochar). The pyrolysis gas is burned at the WWTP for energy use. The pyrolysis oil is energy used at the WWTP or petrochemically processed used for biodiesel production. The biochar at the Stage 2 is energy used at the WWTP or incinerators and at the Stage 3, the biochar has a high potential for agricultural use.

Summarizing discussion

The introduction part of article, the review was carried out by several authors who have compared various alternative disposal routes for SS with energy efficiently.

Based on the reported data in Table 3 and 4, contribution tests carried out by the laboratory MP unit reported higher difference energy efficiency 2.88 MJ.kg^{-1} than before MP process than tests from small full-scale unit. Admittedly, the small full-scale with the difference 1.05 MJ.kg^{-1} after MP process has its value closer to simulating real conditions at WWTP. This difference responds different SS, the heterogeneity of SS, few measurements and is influenced by different device.

In a view of the current situation of disposal routes for SS, the CMPUD of SS was design and described by 3 stages for energy efficiency and other use. The Stage 3 considering the use of biochar in agriculture represents solutions with a positive impact on the environment.

4. Conclusions

At the present first part, the applied research team of AdMaS Research Centre focused on description of the products of low temperature slow MP of SS: biochar, pyrolysis oil and pyrolysis gas. The contribution tests of dried SS and biochar were carried out by the laboratory MP unit and full-scale unit. The contribution tests of the small full-scale has a value of energy efficiency closer to simulating real conditions at WWTP. Currently, due to legislation regulation of landfilling and agriculture use, many owners and operators of WWTP consider incineration as an immediate solution of SS disposal and designed device CMPUD seems to be an acceptable solution.

This research suggests that MP of SS can be considered as suitable available technology for eco-friendly disposal of SS or different waste materials as well as with respect to the use of this technology to produce resources for energy efficiency and agriculture use. Currently applied research of MP treatment of SS is a solution in terms of circular economy, carbon footprint reduction, HM fixation, energy recover and water retention.

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References:

Callegari A. Hlavinek P. and Capodaglio A.G. (2017) Production of energy (biodiesel) and recovery of materials (biochar) from pyrolysis of waste urban sludge. Revista Ambiente e Agua ISSN 1980-993X, Revista Ambiente & Água, Brazil, 2018.

Capodaglio AG, Callegari A, Dondi D. Microwave-Induced Pyrolysis for Production of Sustainable Biodiesel from Waste Sludges. Waste and Biomass Valorization. 2016;7(4):703-709. doi:10.1007/s12649-016-9496-2.

Capodaglio AG, Callegari A. Feedstock and process influence on biodiesel produced from waste sewage sludge. J Environ Manage. April 2017. doi:10.1016/J.JENVMAN.2017.03.089.

Cenni R, Janisch B, Spliethoff H, Hein KRG. Legislative and environmental issues on the use of ash from coal and municipal sewage sludge co-firing as construction material. Waste Manage (Oxford) 2001;21:17–31.

Chiaramonti D, Oasmaa A, Solantausta Y. Power generation using fast pyrolysis liquids from biomass. Renew Sustain Energy Rev 2007;11: 1056–86.

Chang F.C., Lin J.D., Tsai C.C., Wang K.S. Study on cement mortar and concrete made with sewage sludge ash. Water Sci Technol 2010;62:1689–93

Conte, P., H.-P. Schmidt, and G. Cimò, Research and Application of Biochar in Europe, in Agricultural and Environmental Applications of Biochar: Advances and Barriers, M. Guo, Z. He, and M. Uchimiya, Editors. 2015, SSSA: 5585 Guilford Rd., Madison, WI 53711, USA.

Czech standard ČSN EN ISO 1716 (730883) Reaction to fire tests for products – Determination of the cross heat of combustion (calorific value), 2010.

Czernik S, Bridgwater AV. Overview of applications of biomass fast pyrolysis oil. Energy Fuels 2004;18:590–8.

Garcia-Perez, M., A. Chaala, H. Pakdel, D. Kretschmer a C. Roy. Characterization of bio-oils in chemical families. Biomass and Bioenergy [online]. Elsevier Ltd, 99 2007, 31(4), 222-242 [cit. 2016-11-26]. ISSN 09619534.

Fonts I, Juan A, Gea G, Murillo MB, Sánchez JL. Sewage sludge pyrolysis in flu- idized bed. 1. Influence of operational conditions on the product distribution. Ind Eng Chem Res 2008;47:5376–85.

Fonts I., Gea G., Azuara M., Abrego J., Arauzo J., Sewage sludge pyrolysis for liquid production: A review, Renewable and Sustainable Energy Reviews 16 (2012) 2781– 2805.

Fytili D., Zabaniotou A., Utilization of sewage sludge in EU application of old and new methods – a review. Renew Sustain Energy Rev 2008;12:116–40.

Gooty, A.Tumbalam. Fractional condensation of bio-oil vapors, 2013.

Hlavínek, P. Microwave pyrolysis of sewage sludge. Vodovod.info - vodárenský informační portál [online]. 16.11.2015. 112015 [cit. 2016-11-30]. ISSN 1804-7157.

Huang H., Yuan X., The migration and transformation behaviors of heavy metals during the hydrothermal treatment of sewage sludge, Bioresource Technology 200 (2016) 991–998.

Huang, Yu-Fong, Pei-Te Chiueh a Shang-Lien Lo. A review on microwave pyrolysis of lignocellulosic biomass. Sustainable Environment Research [online]. Elsevier B.V, 2016, 26(3), 103-109 [cit. 2016-12-04]. ISSN 24682039.

Inguanzo M, Domínguez A, Menéndez JA, Blanco CG, Pis JJ. On the pyrolysis of sewage sludge: the influence of pyrolysis conditions on solid, liquid and gas fractions. J Anal Appl Pyrolysis 2002;63:209–22.

Jayasinghe, Punyama a Kelly HAWBOLDT. A review of bio-oils from waste biomass: Focus on fish processing waste. Renewable and Sustainable Energy Reviews [online]. Elsevier Ltd, 2012, 12(16), 798-821 [cit. 2016-12-02]. ISSN 13640321.

Jin J., Li Y., Zhang J., Wu S., Cao Y., Liang P., Zhang J., Wong M.H., Wang M., Shan S., Christie P., Influence of pyrolysis temperature on properties and environmental safety of heavy metals in biochars derived from municipal sewage sludge, Journal of Hazardous Materials, Volume 320, 2016, Pages 417-426, ISSN 0304-3894.

Kim Y, Parker W. A technical and economic evaluation of the pyrol- ysis of sewage sludge for the production of bio-oil. Bioresour Technol 2008;99:1409–16.

Kistler R.C., Widmer F., Brunner P.H.: Behavior of Chromium, Nickel, Copper, Zinc, Cadmium, Mercury and Lead during pyrolysis of sewage sludge, Environ. Sci. Technol. 21, 704-708 (1987)

Khiari B, Marias F, Zagrouba F, Vaxelaire J. Analytical study of the pyrolysis process in a wastewater treatment pilot station. Desalination 2004;167:39–47.

Liu T., Liu Z., Zhengc O., Lang Q., Xia Y., Peng N., Gai Ch., Effect of hydrothermal carbonization on migration and environmental risk of heavy metals in sewage sludge during pyrolysis, Bioresource Technology 247 (2018) 282–290.

Liu X., Wang Y., Gui C., Li P., Zhang j., Zhong H, Wei Y., Chemical forms and risk assessment of heavy metals in sludge-biochar produced by microwave-inducted pyrolysis, RSC Adv. 6, 101960-101967, 2016.

Menéndez JA, Inguanzo M, Pis JJ. Microwave-induced pyrolysis of sewage sludge. Water Res. 2002;36(13):3261-3264. doi:10.1016/S0043-1354(02)00017-9.

Mohan D, Pittman CU, Steele PH. Pyrolysis of wood/biomass for bio-oil: a critical review. Energy Fuels 2006;20:848–89.

Piskorz J, Scott DS, Radlein D. Composition of oils obtained by fast pyrolysis of different woods. ACS Symp Ser 1988;376:167–78.

Raček J., Capodaglio A., Ševčík J., Chorazy T., Hlavínek P. Microwave pyrolysis treatment of sewage sludge: Performed at laboratory and full-scale conditions. In 17 th International multidisciplinary scientific geoconference SGEM 2017. International multidisciplinary geoconference SGEM. Bulgaria: SGEM, 2017. s. 107-114. ISBN: 978-619-7408-28-7. ISSN: 1314-2704.

Sipilä, Kai, Eeva Kuoppala, Leena Fagernäs a Anja Oasmaa. Characterization of biomass-based flash pyrolysis oils. Biomass and Bioenergy [online]. Elsevier Ltd, 1998, 14(2), 103-113 [cit. 2016-12-02]. ISSN 09619534. Stammbach MR, Kraaz B, Hagenbucher R, Richarz W. Pyrolysis of sewage sludge in a fluidized bed. Energy Fuels 1989;3:255–9.

Stasta P, Boran J, Bebar L, Stehlik P, Oral J. Thermal processing of sewage sludge. Appl Therm Eng 2006;26:1420–6.

Zhao B., Xu X., Xu S., Chen X., Li H., & Zeng F. (2017). Surface characteristics and potential ecological risk evaluation of heavy metals in the bio-char produced by co-pyrolysis from municipal sewage sludge and hazelnut shell with zinc chloride. Bioresource technology, 243, 375-383.

Žvaková, Eva. Detailed characterization of pyrolysis oil by separation techniques and mass Spectrometry. Master´s Thesis. Brno University of Technology, Faculty of Chemistry. Brno 2017. Available at: https://dspace.vutbr.cz/handle/11012/65062