WASTEWATER SLUDGE AS AN ALTERNATIVE ENERGY RESOURCE: A REVIEW

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Abstract: In recent years, concerns regarding to wastewater sludge disposal have increased globally. Production of sludge has increased recently due to the growth of population. Wastewater sludge classified as a hazardous substance, it is not easy to dispose because of certain treatment is required. Typically, sludge is treated at secured landfill which its limited in availability and expensive. On the other hand, wastewater sludge originated from biological treatment contains organic substance that can be converted into alternative energy resources. A technology is needed that is able to reduce the volume of sludge and convert sludge into energy source. We present an overview of various technologies that can be used for conversion of sludge into energy resources. Those technologies are anaerobic digestion, pelletization, combustion, pyrolysis and gasification. Progress and challenges of each technology is presented in detail. A summary of sludge characteristic originated from different source will be discussed as well. Emissions and residues that determines the environmental impact is also considered. Referring to some previous research, it known that wastewater sludge, as unwanted product, has the potential to become future energy resource. This potential can only be used properly if the method of conversion are effective and efficient.

Keywords: *sludge characteristic, energy recovery, thermochemical process, residues, emission*

Abstrak: *Dalam beberapa tahun terakhir, perhatian terhadap pembuangan lumpur yang berasal dari pengolahan limbah cair meningkat tajam di seluruh dunia. Peningkatan produksi lumpur disebabkan oleh peningkatan jumlah populasi penduduk. Lumpur yang berasal dari pengolahan limbah cair diklasifikasikan sebagai limbah B3, sehingga memerlukan proses pengolahan tertentu sebelum dibuang ke TPA khusus yang terbatas dalam ketersediaan lahan dan membutuhkan biaya yang tidaklah murah. Di sisi lain, lumpur yang berasal dari pengolahan biologis mengandung senyawa organik yang dapat dikonversi menjadi sumber energi alternatif. Beragam teknologi yang telah digunakan diantaranya adalah penguraian anaerobik, pembuatan pellet, pembakaran, pirolisis dan gasifikasi. Perkembangan dan tantangan masing-masing teknologi, karakteristik lumpur yang berasal dari berbagai sumber, serta dampak kesehatan dan lingkungan yang disebabkan oleh emisi gas buang dan residu merupakan beberapa hal yang dibahas, dipertimbangkan dan disajikan secara rinci dalam tulisan ini. Mengacu pada beberapa penelitian sebelumnya, diketahui bahwa lumpur yang dihasilkan pengolahan air limbah, sebagai produk yang tidak diinginkan, memiliki potensi untuk menjadi sumber energi masa depan. Potensi ini hanya dapat dimanfaatkan secara optimal dengan metode konversi yang efektif dan efisien.*

Kata Kunci: *karakteristik lumpur, pemulihan energy, proses termokimia, residu, emisi*

INTRODUCTION

Bio-solid, could be defined as wastewater sludge resulted from WWTP that utilize biological process as the main treatment. This kind of sludge is classified as hazardous waste according to Indonesia's Government Regulation No. 101/2014. **Figure 1** shows wastewater coming out from Jababeka Industrial Park (Indonesia) and the sludge resulted from separation process of solid particles from the wastewater. It was dried before being delivered to disposal facility. Daily production in Jababeka WWTP may reach more than 3 ton dry sludge / day. Gao et al. (2014) described that the amount of sludge production is growing due to the rapid urbanization and industrialization.

Disposal of wastewater sludge is crucial process because of its hazardous characteristics. It is not allowed to be disposed at just any landfill; rather it must be disposed at typical secured landfill which is limited and expensive. Johnson et al. (2008) reported that the cost of disposing sludge can be very high so that it become major part of WWTP operational budget. Alternatively, industries can turn dry sludge that contains high organic content as an alternative raw materials for cement production process. On the other hand, organic contents of wastewater sludge has the potential to be used as alternative energy sources (Karayildirim et al., 2006); (Hakiki et al., 2018). It can contribute towards energy supplies in heat, power or in combined Heat and Power (CHP) if properly exploited.

In the light of sludge disposal problem and its energy potential, this topic has drawn interest from various researcher all around the world. Various solutions were reported that aims to reduce the amount of sludge volume and its negative environmental impact by converting sludge into energy resource. This paper aims to investigate those various solutions and present the progress of this topic in systematic manner. A review of various sludge characteristic is presented as well in this paper in order to give overview of sludge content.

WASTEWATER SLUDGE CHARACTERISTICS

Various source of sludge can be grouped into two: Municipal and Industrial. Characterization of municipal wastewater sludge has been done previously by Atienza-Martinez et al. (2015); Folgueras et al. (2013); Fonts et al. (2009); Fonts et al. (2012); Gao et al. (2014); Li et al. (2015) and Kupka et al. (2008).

There were various industrial sludge based on its origin. Chen et al. (2011) conducted characterization of sludge from Thin Film Transitor-Liquid Crystal Display (TFL-LCD) industries. Chiou et al. (2014) used sludge originated from pulp and textile industries. Magdziarz and Werle (2014) performed characterization on thermal power plant originated sludge. The list of various type of sludge and its characteristic is shown in **Table 1.**

Almost all reported characterization activities are based on the use of "end-treatment sludge" that is the sludge resulted from the final process of wastewater treatment in WWTP. However, wastewater treatment consisted of many stages and each stage produces different sludge composition (Syed-Hassan et al., 2017). Manara and Zabaniotou (2012) conducted a review and summarized the characteristics of various type of sludge on each treatment stage. Those types are: are 1) Primary sludge produced from the primary treatment, 2) biological sludge produced from secondary treatment, 3) mixed sludge that is a mixture of primary and biological sludge, and 4) tertiary sludge produced from the tertiary or advanced wastewater treatment.

Figure 1. (a) The Industrial Wastewater ; (b) Mechanical separation of solid particles from wastewater; (c) Dried sludge

The summary of sludge characteristics from various prior researches are shown in **Table 1**. We can see that there are just several parameters shown, such as the % mol of carbon (C), hydrogen (H), oxygen (O), nitrogen (N), sulfur (S), volatile matter (VM), fixed carbon (FC) and ash. Other parameters were not included in this summary such as moisture, dry matter and another trace mineral because of the common facts that the thermal or biological conversion of organic contents could results the energy. Eventhough it may affect the efficiency for thermal or biological conversion process. Variation in composition observed from various prior research (shown in **Table 1**), C content is about 18% - 55% of the total weight; H content is about 1% - 7% of the total weight. O content is about 20% - 78% of the total weight. N content is about 0.8% - 9% of the total weight, S content is about 0.5% - 2.1% of the total weight. The variation of composition depends on the initial chacteristics of treated wastewater.

Table 1. Sludge characteristics from various research

No.	Author	Feedstok (Sewage Sludge Origin)	C	H	O	N	S	Volatile Matter	Fix Carbon	ASH	Calorific Value
			%	%	%	%	%	%	%	%	MJ/kg
1	Atienza-Martinez et al., 2015	Digested (municipal)	29.50	4.67	20.20	5.27	1.31	-	-	39.04	12.79 (HHV)
2	Chen et al., 2011	TFT-LCD industries	50.00	-	-	9.00	2.10	-	-	-	*5016 (cal/g)
3	Chiou et al., 2014	Pulp industries	18.48	1.78	78.82	0.83	-				8.73
		Textile Industries	32.15	5.73	59.04	1.36	1.64				5.1
4	Folgueras et al., 2013	Municipal	38.82	6.19	-	5.78	1.17	64.90	7.90	27.20	17.75
5	Fonts et al., 2009	Municipal	28.50	4.30	22.40	4.10	0.80	47.00	6.40	39.90	12.3 (HHV)
6	Fonts et al., 2012	Municipal	39.90	5.90	23.50	7.90	1.00	66.80	19.70	52.00	-
7	Gao et al., 2013	Municipal	36.45	5.93	25.74	7.03	0.77	59.06	9.36	24.08	-
8	Li et al., 2014	Municipal	36.11	5.25	-	6.50	1.03	57.22	6.09	31.27	15.59 (HHV)
9	Kupka, et al. 2008	Municipal	55.46	7.71	27.35	7.34	2.00	53.48	-	29.93	13.8 (LCV)
11	Magdziarz and Werle, 2014	Thermal power plant	32.30	4.90	24.90	5.30	0.57	64.70	-	-	13.12 (HHV)
12	Manara and Zabaniotou, 2012	Primary treatment	51.50	7.00	35.50	4.50	1.50	65.00	-	-	*4200 (kWh/t)
		Biological treatment (Low)	52.50	6.00	33.00	7.50	1.00	67.00	-	-	*4100 (kWh/t)
		Biological treatment (Low & Mid)	53.00	6.70	33.00	6.30	1.00	77.00	-	-	*4800 (kWh/t)
		Primary & Biological (Mix)	51.00	7.40	33.00	7.10	1.50	72.00			*4600 (kWh/t)
		Digested	49.00	7.70	35.00	6.20	2.10	50.00			*3000 (kWh/t)

Note : *) Value has different units

ENERGY RECOVERY TECHNOLOGIES

There are several options to recover sludge energy content (see **Figure 2)**. Sludge may be digested anaerobically, pelletized or used directly in thermochemical process. Anaerobic digestion process involve microorganisms activities in certain condition to achieve the optimum substrate degradation. Pelletization of sludge produces sludge-Refuse Derived Fuel (RDF) that can be use as fuel in either thermochemical options (combustion, pyrolisis and gasification). Each method will be discussed in detail below. Review on various researches result based on type of conversion technology is shown in **Table 2**.

Table 2. Sludge–energy recovery process by various researcher

Conversion Method	Author	Summary Process Used	Feedstock	Main Focus
Anaerobic Digestion	Ting et al., 2007	Anaerobic digestion	Wastewater sludge	Production of H_2 and CH_4
Pelletization	Chen et al., 2011	Mixing organic sludge with sawdust and asphalt.	Organic sludge from five TFT-LCD factories.	Characteristic of sludge refuse-derived fuel (RDF) and its combustion behaviour. Combustion properties of their RDF.
	Chiou et al., 2014	10 mm diameter pellet with length of 10 – 50 mm.	Pulp sludge & Textile sludge	Manufacturability of extruded sludge RDF by varying pulp sludge/textile sludge concentration and moisture content. Combustion properties of their RDF.
	Jiang et al., 2016	Pellet size 7 mm diameter and 70 mm height.	Urban sewage plant	Manufactured RDF from pure biomass and sludge-biomass mixture. Authors studied the energy consumption for pelletization process: compression energy and extrusion energy. Combustion properties of their RDF.
Pyrolisis	Hossain et al., 2009	Pyrolysis. Fix-bed reactor.	Domestic origin sludge, Commercial origin sludge, Industry origin sludge	Characteristics of synthesis gas component: CO, CO_2, CH_4, C_2H_4, C_2H_6 and H_2. Thermal energy requirement for successful pyrolysis for each different sludge samples.
	Karayildirim et al., 2016	Pyrolysis. Fix-bed reactor.	Industrial sewage sludge and Oil sludge	The characteristic of sludge before and after pyrolysis.
	McNamara et al., 2016	Pyrolysis. Fix-bed reactor	Wastewater biosolids	Energy content of pyrolysis resulted gas (py-gas) and pyrolysis resulted oil (py-oil) and its comparison with energy requirement for biosolids drying.
	Xiong et al., 2013	Pyrolysis. Fix-bed reactor.	Sewage sludge.	Influence of sludge moisture content to pyrolysis product. Pyrolysis was done in fix temperature of 1000^oC. Higher moisture content gives better results: increase H_2 production and reduces tar & light aromatics (toxic) production.
	Salleh et al., 2011	Fast pyrolysis. Fluidized-bed.	Combination of rice waste and sewage sludge	Focus on the production bio-oil by fast pyrolysis process.
	Pokorna et al., 2009	Fast pyrolysis. Fixe-bed reactor.	Activated waste sludge, dewatered sludge	Fast pyrolysis to maximize the yield of oil product. Maximum oil yield is about 40%Wt.
Gasification	Werle, 2015	Air gasification. Fixed bed updraft gasifier.	Sewage sludge	Influence of composition and air temperature to the calorific value of syngas. The higher oxygen content and temperature of air, the higher the calorific value of syngas.
	Acelas et al., 2014	Supercritical water gasification. Batch process inside an autoclave.	Dewatered sewage sludge	Influence of Supercritical water temperature and its residence time to the syngas production. Higher temperature and longer residence time cause better production of H_2 and CH_4.
	Roche et al., 2014	Air and Air-steam gasification. Dolomite was added in the process. Fluidized bed gasifier.	Dried sewage sludge.	Influence of throughput, steam and dolomite to the sludge gasification products. Higher throughput causes increases in tar production and decreases H_2 content. The use of air mixed with steam and dolomite promote H_2 production.
	Xie et al., 2010	Air gasification. Fixed – bed downdraft gasifier.	Sewage sludge.	Influence of sludge moisture content on gasification product. Gasification was performed at 800^oC. Higher moisture content yield increases production of CO_2, CH_4, H_2 and higher calorific value of syngas.
	Nipattumakul et al., 2010	Steam Gasification	Wet wastewater sludge	Syngas production with high concentration of hydrogen.

de Andres et al., 2011	Air gasification. Fixed – bed updraft gasifier.	Dried, aggregated, sewage sludge.	Influence of three primary catalyst: dolomite, olivine and alumina in gasification process. Dolomite performed the best tar reduction. The presence of water vapor and catalysts increases H_2 production by 60%.
Reed et al., 2005	Continuous process fluidized bed gasifier. Air gasification. Air-N_2 gasification Air-steam-N_2 gasification.	Dried sewage sludge pellets.	Influence of gasification bed temperature and type of sewage sludge to the concentration of various trace elements in final solid residues: bariums, copper, mercury, lead and zinc.
Petersen and Wether, 2004	Circulating Fluidized bed gasifier Air Gasification CO_2/N_2 gasification. N_2 Gasification.	Dried sewage sludge pellets.	Influence of air-fuel ratio, gasification temperature, feeding height and fluidization velocity to the gasification product. Authors found air-fuel ratio was the most important parameters affecting the quality of syngas.
Midili et al., 2002	Air gasification. Fixed bed downdraft gasifier.	Undigested and dried sewage sludge pellets.	Authors have successfully uses downdraft gasifier for gasification of sewage sludge pellets.

Anaerobic Digestion

Anaerobic digestion (AD) is one type of bio-chemical process that decomposes organic solid substance into gas phase by the activity of anaerobic microorganisms. Wastewater sludge act as a substrate undergoes processes such as hydrolysis, acidogenesis and methanogenesis step in the absence of free oxygen. Anaerobic miroorganisms will convert carbon compound to produce gases such as CH_4, H_2 and CO_2. The resulted gas mixture is usually called as biogas. Ting and Lee (2007) reported a production of hydrogen and methane from wastewater sludge by using clostridium strain. The sludge sample was obtained from food-processing wastewater. Yang and Wang (2017) provide the critical review on sludge AD process.

Pelletization

Pelletization is a process in which solid waste is pressurized and extruded to form pellet, known as Refuse Derived Fuel (RDF). Typical solid waste formed RDF is 5 – 10 mm in diameter. The reason for making RDF from sludge was it offer easiness for storage and transportation, compared to sludge in its original form. Sludge RDF can be used as additional industrial fuel or combusted in incinerator. Alternatively, pyrolysis or gasification can be performed on sludge RDF in order to produce other kind of fuel, as shown in **Figure 2**.

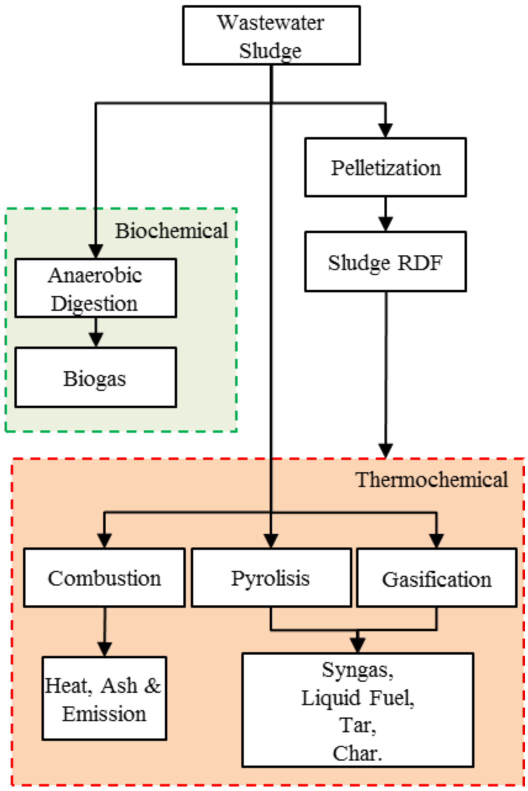

Figure 2. Routes for sludge energy recovery.

Chiou et al. (2014) performed pelletization of pulp & textile sludge mixture to produce RDF which size was 10 mm in diameter and 10 – 50 mm in length. They created and compared four types of RDF by combining variation of pulp sludge moisture content and proportion of textile sludge. They also studied the combustion behavior for each type of RDF. Chen et al. (2011) have created sludge RDF by using five different sludge resulted from TFT-LCD production. They mixed their sludge with sawdust made from waste wooden pallets in order to increase the carbon content of RDF and reduce ash after combustion. The mixing ratio of sludge to sawdust was 10:1.

Asphalt also was added to the sludge mixture as binding agent of RDF. Jiang et al. (2016) investigated various pellet using pure biomass and biomass-sludge mixture. The biomasses were Chinese fir, camphor and rice straw. The sludge was obtained from urban sewage plant. Pellet size was 7 mm and 70 mm in diameter and height, respectively. There are two types of energy consumption for pelletization process: compression and extrusion. Interestingly, it was reported that the energy consumption for making pellet of sludge-biomass mixture was lower compared to the one in pure biomass. While the compression energy reduced to about half, the extrusion energy reduced was much lower, about one fifth of the energy required for making pure biomass pellet. It means that making pellet from sludge-biomass mixture can be conducted at low pressure and temperature.

Combustion

Combustion of solid substance is a process in which solid matter is burned with excessive amount of oxygen (oxidation agent). Its main function is to convert chemical energy of solid fuel into heat. **Figure 3** shows the combustion process of sludge. In the beginning sludge temperature increases and the water content evaporates. As temperature gets higher volatile matter was released and some of it reacts with oxygen, producing heat. After devolatilization, sludge has become char. Then, char react with various gases, forming other kind of gases. The char-gas reaction is also known as gasification. Heat produced from volatile combustion and subsequent processes are enough for continuous gasification process without the need of external heat souce. This is known as auto-gasification. Oxydation process continues during ash melting and chars combustion. When there is no combustible substance left, ash agglomerated. Combustion yields emissions and ash. Combustion of sludge usually occurs by using incineration. Chen et al. (2011); Chiou et al. (2014) and Jiang et al. (2016 have studied the combustion behavior of various sludge RDF.

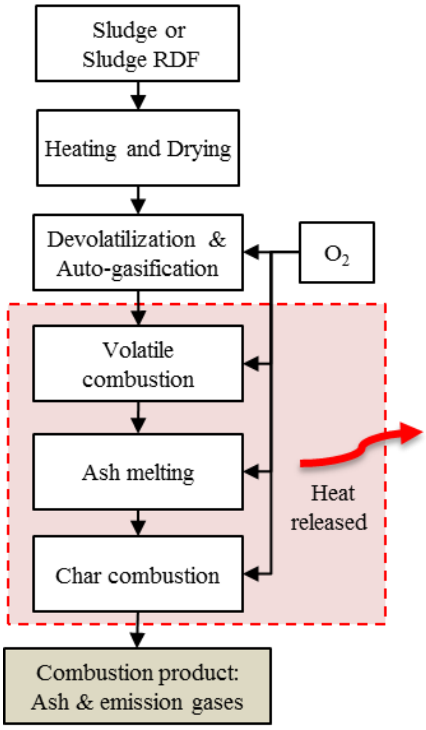

Figure 3. Combustion Process of Sludge.

There are four configuration of combustion chamber based on the flow of working fluid (oxidation medium such as air & oxygen) and the behavior of solid waste (bed): Fixed-bed with updraft flow, Fixed-bed with downdraft flow, Fluidized-bed, and entraned flow. Fixed bed is a reactor that solid fuel is located in fixed position usually above a screen or perforated plate. Updraft and downdraft flow defines the direction of working fluid. Fluidized-bed is condition where solid fuel particle is suspended by the working fluid. As the result of fluidizing, the solid fuel behaves like a fluid. Entrained flow is condition where solid fuel was crushed into very small particle (smaller than the case of fluidized-bed) so that it can be injected to the combustion chamber by using nozzle. These different configurations of combustion chamber were applied as well to gasification and pyrolysis reactors.

Gasification

Gasification is a process, which solid substances are combusted in limited amount of oxidation agent to produce gas fuel that is known as synthesis gas (syngas). Gasification is a better option compared to direct combustion (e.g. incineration) and bio-chemical process because it offers faster route for volume reduction, flexibility usage of produced fuel gas and better control of environmental impact (Arena et al., 2012; Murphy et al., 2004; Young et al., 2010). Gasification is similar to combustion process in a way that both processes use heat (thermal energy) to decompose solid fuel into gas phase.

Typical oxidation medium in combustion is air whereas in gasification can be air, pure-oxygen, steam or other substance. In gasification, the energy released from decomposed solid fuel is packed into chemical energy in the form of gas fuel. On the contrary, combustion decomposes solid fuel and releases as much as possible the energy content in the form of heat. Basu et al. (2013) shows that gasification process can be divided into these stages (see **Figure 4**): 1) Heating and Drying. In this first stage, cold sludge receives heat and its temperature rises. The water starts to evaporate when the temperature reaches water saturated condition. 2) Devolatilization (or pyrolysis stage). In this second stage, sludge undergoes thermal cracking process which releases various light permanent gases. This process occurs from 160 °C until up to 700 °C. For biomass case, it releases gases such as H_2, CO, CO_2, CH_4, H_2O, and NH_3. This stage is also known as thermal decomposition or pyrolysis. 3) Some chemical reactions (or gasification stage). At this stage, there are various chemical reactions occurred. Gas – gas phase reaction is reactions between different volatile gases or between volatile gases and oxidation medium. Char-Gas reactions are a reaction between char and gasifying medium to form gases product. The char – gas reactions is the reactions where solids of sludge are converted into gas (that is gasification process). Because of the char-gas reactions, this stage is usually called as gasification stage.

Midilli et al. (2002); Petersen and Werther (2005) and Reed et al. (2005) reported gasification process using sewage sludge pellet (sludge RDF). While the first author uses fixed-bed type gasifier, the last two authors uses fluidized bed gasifier. All authors have shown promising results of sludge RDF gasification. Although their experiments were not comparable because of different sludge characteristics, it is still worth to point out some of similarities and differences of their experimental results. Fixed-bed type gasifier (Midilli et al., 2002) yield syngas with overall calorific value of 4 MJ/m^3 with hydrogen concentration about 10-11% (V/V). (Petersen and Werther, 2005) reported about the same value of calorific value (average calorific value obtained from various experiments of (Reed et al., 2005) Petersen and Werther (2004) was 4.7 MJ/m^3). However, with higher reactor temperature and air-fuel ratio 0.3, syngas calorific value and hydrogen content was much higher, 5.5 MJ/m^3 and 18%, respectively. (Reed et al., 2005) didn't discuss their gasification experiment from energetic point of view, rather than they focuses on the analysis of various heavy metals in the final solid residues. Xie et al. (2010), de Andrés et al. (2011) and Werle (2015) reported air gasification of sewage sludge (not in pellet form). de Andrés et al. (2011) focuses on the influence of adding catalyst: dolomite, olivine and alumina on gasification process. Xie et al. (2010) has shown interesting finding: gasification of higher sludge moisture yields higher syngas quality that is higher hydrogen concentration and calorific value. Werle (2015) investigated the effect of air composition and temperature to the resulted syngas. It was shown that the higher oxygen content and temperature of air, the higher calorific value of the resulted syngas.

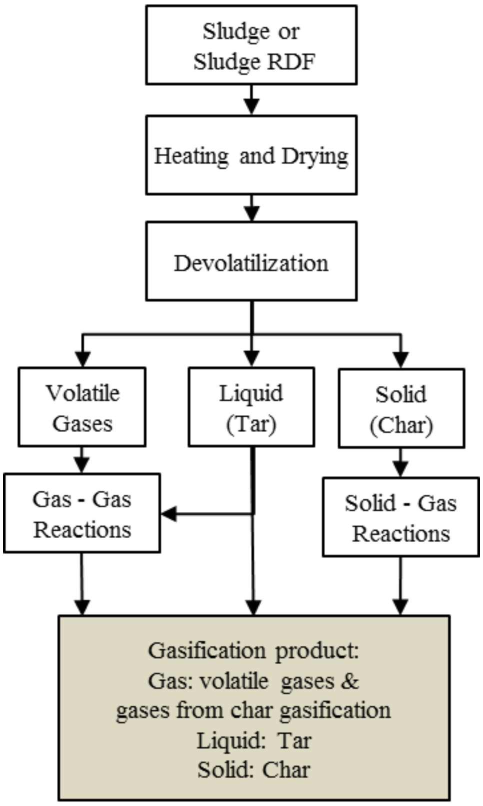

Figure 4. Gasification Process.

Gasification experiment of wet sludge by using steam as the gasifying medium was reported by Nipattummakul et al. (2010). The syngas produced from this process has high concentration of hydrogen, which is considered as high-quality syngas. It is known that steam gasification yields gas fuel with hydrogen to carbon ratio the highest compared to air-gasification or oxygen-gasification. Roche et al. (2014) performed experiment of air-steam gasification and air gasification. It was reported that air-steam gasification promotes hydrogen production compared to air gasification. Acelas et al. (2014) reported typical gasification process using supercritical water. Their experiment results shown that higher temperature and longer residence time enhances the production of hydrogen and methane.

Pyrolysis

Pyrolysis is partial combustion that occurred without any oxygen or oxidating medium. Gasifying medium and heat are the requirements for gasification process, whereas only heat is required for pyrolysis process. One might get confused because pyrolysis which equal to devolatilization is one of the processes in gasification. The process of releasing gases from solid fuel is pyrolysis. In other words, gasification is a special type of pyrolysis which was designed to optimize solid to gas fuel conversion. Hossain et al. (2009) made comprehensive report of wastewater sludge pyrolysis originated from domestic, commercial and industrial wastewater.

Characterization of sludges and its pyrolysis product was reported. Energy balance analysis for successful pyrolysis process was also performed. Karayildirim et al. (2016) studied the characteristic and pyrolysis of industrial sewage sludge and oil sludge. The characterization of pyrolysis results: synthesis gas, liquid tar and char were also reported. McNamara et al. (2016) uses fix-bed type reactor for pyrolysis of wastewater biosolids. He also compared the energy generated from py-gas (pyrolysis resulted gas) and py-oil (pyrolysis resulted oil) to energy required for drying the biosolids.

Since above reports are mostly about pyrolysis experiment, it didn’t address on how to optimize production of syngas out from sludge. The data presented in those report still very useful for theoretical prediction. Xiong et al. (2013) performed pyrolysis of sewage sludge at 1000°C. It was found that higher moisture of sludge cause increase hydrogen fuel production and reduces tar & light aromatic production. Salleh et al. (2011) and Pokorna et al. (2009) reported their experiment about fast pyrolysis of sludge.

Fast pyrolysis is a rapid heating of solid-fuel which followed by cooling process that cause the gas condensed into liquid-fuel. Different from gasification, the main focus of fast pyrolysis is to produce liquid fuel.

FUEL TYPES, EMISSION AND RESIDUES COMPARISON

Fuel Component from Different Recovery Technology

The main component fuel varies according to different characteristic of wastewater sludge, and feedstock. Some of fuel comparison can be seen in **Table 3.** Salleh et al., 2011 describes the majority chemical compounds of bio-oil from fast pyrolysis were phenol, aromatic, nitrogenated compound, alkenes and alkanes. The biomass and bio-oil, includes alkanes, alkenes, ketones, aldehydes, esters, nitrogenous compounds, alcohols, phenols, aromatic/heterocyclic and other compounds (Arazo et al., 2017). Utilization of bio-oil produced from pyrolysis of sewage sludge as feed material seems possible. High distribution of fatty acid can lead to extraction of these acids and their utilization in chemical industry. High presence of nitrogenous compounds can improve added value of bio-oils by isolation of these compounds from the bio-oil. Esterification is also another option. (Pokorna et al., 2009).

Table 3. Fuel Types, Emission and Residues Comparison Review

No.	Author	Technology	Feedstock	Fuel Types	Energy Content/Calorific Value	Emissions/ Residues
1	Karayildirim et al., 2006	Pyrolysis	Mixed Sludge	Gas, Liquid	High GCV 29.9 MJ Nm-3	NO, CO2, CO
			Oil Sludge		35.8 MJ Nm-3	Combustible gases
2	Salleh et al., 2011	Fast Pyrolysis	rice waste and sewage sludge	Gas, Bio-oil	N/A	Char/solid
3	Pokorna et al., 2009	Fast Pyrolysis	sewage sludge	Liquid	HHV/NET Bio-oil: 23.9 - 27.9 MJ/kg	Ash (57.9 - 75.1 wt&)
4	Hossain et al., 2009	Pyrolysis	Domestic, Commercial, Industry sludge	Gas, Liquid	(GCV at 550 ^oC) commercial: 825 kJ/kg; domestic: 660 kJ/kg; industrial: 370 kJ/Kg	syngas (CO, CO_2, CH_4, C_2H_4, C_2H_6 and H_2.)
5	Nipattummakul et al., 2010	Pyrolysis	Wet wastewater sludge	Syngas	HHV ± 24000 J/kg	C_2H_4, C_2H_6, C_3H_6, and C_3H_8
		Gasification		Gas	HHV 17,500 – 19,500 J/kg	
6	McNamara, 2016	Pyrolysis	Wastewater Biosolids	Py-oil	2.1 MJ/kg - 3.0 MJ/kg-feed biosolids	CH_4, CO_2
7	Arazo et al, 2017	Fast Pyrolysis	Domestic WWTP	Liquid	N/A	Ash, HCs, N_2, CO_2
8	Xiong et al., 2013	Co-gasification	Woody biomass and sewage sludge	Py-gas, Py-oil	4.5 MJ/Nm^3.(LHV average)	non condensable gas, char
9	Li et al., 2015	Co-pelletization	Municipal	Py-gas, Py-oil	8.43 kJ/L	non condensable gas, char
10	Atienza-Martínez et al., 2015.	Pyrolysis - Torrefaction	Digested (municipal)	Py-gas, Py-oil	HHV Char 25 - 30 MJ/kg JJV Liquid 41 - 43 MJ/kg	CO_2, non condensable gas, char
11	Fonts et al., 2009	Pyrolysis	Municipal	Py-gas, Py-oil	1934 ± 580 to 2721 ± 321 kcal/m^3 (NTP)	Non-condensable gas

Energy Content/Calorific Value

Energy content from the fuel may vary (see **Table 3**) due to process key parameters, such as the technology process used, temperature, steam to carbon (S/C) ratio, water content, organic matter, characteristic of raw materials, etc. Prior researches are also focus on optimization for pyrolysis/gasification products to gain higher amount of energy. Calorific values of the sludges and the pyrolysis products from three different sample of sewage sludges was conducted comprehensively, with the best results, concerning to pyrolysis products, are obtained with thickened excess activated sludge: 57.5% of organic matter is converted to bio-oil with calorific value of 24.7 MJ/kg and also the water content was the lowest: 10.3% (Gao et al., 2014).

The energy content of py-gas and py-oil was always greater than the energy required for pyrolysis. The enthalpy of pyrolysis for biosolids was calculated as the difference between the energy outputs (heating values of char, py-oil, py-gas plus sensible and latent heat losses) and the energy input (heating value of the biosolids feed). The enthalpy of pyrolysis ranged from 2.1 MJ/kg-feed biosolids to 3.0 MJ/kg-feed biosolids; this variability is due to experimental variation (McNamara et al., 2016) Comparison between steam gasification and pyrolysis had conducted, where the steam gasification yielded more syngas, hydrogen, energy and higher apparent thermal efficiency (ratio of syngas energy to energy in solid sewage material) as compared to that obtained from pyrolysis at the same temperature of 1173 K. Peak value of syngas yield, energy yield, and hydrogen yield was obtained at S/C ratio of 5.62. The results show that HHV obtained from pyrolysis was higher than that from gasification. This is attributed to higher contents of methane and hydrocarbons, and lower content of carbon dioxide. In case of gasification, the increase in S/C ratio slightly increased the HHV value of the syngas (Nipattummakul et al., 2010). Based on this review, by using pyrolysis or gasification technology, there are high potentials of fuel (energy) from wastewater sludge that can be recovered. Gasification and pyrolysis can reduced the amount of wastewater sludge, and gain fuel as energy resources.

Emissions/Residues

Different type of technology will give different emissions and residues. The solid residue of wastewater sludge pyrolysis is a charcoal-like product rich in carbon and mineral matter. The potential use of the char depends on its fundamental characteristics (Karayildirim et al., 2006) Bio-char has recently attracted attention as a soil amendment for improving the quality of agricultural soils for the increase of crop yield and soil properties (Hossain et al., 2009). The potential use of solids depends on their chemical characteristics. Some properties of pyrolytic solids are therefore determined, such as ash content (TGA), (Pokorna et al., 2009). Emissions gases (some of them are greenhouse gases) and residues (some of them has heavy metal substances) from pyrolysis/gasification can be treated in a controlled system by using purification technology to eliminate the negative impacts to health and the environment. Instead, thermochemical process can be combined with technologies to eliminate toxic/harmful substances should be implemented, such as air pollution control, and also carbon capture storage (CCS)/bio-sorption, to eliminate the negative impacts.

CONCLUSION

Characterization of various sludge from different origin presented here have proved the significant level of organic content in wastewater sludge. It means that sludge, as unwanted product, has the potential to become future energy resource. This potential can only be used properly if the method of conversion are efficient. There is no single superior conversion method above the other method. However gasification and pyrolisis have shown promising path of conversion because of their process flexibility. Depending on the sludge conditions, one can choose different configuration of gasification / pyrolisis process in order to produces fuel in the most efficient way. It was shown that high calorific fuel can be produced from gasification and pyrolisis process. For domestic waste, char resulted by gasification and pyrolisis can be used in agriculture. Further research is needed to provide the best options for converting sludge that was derived from different stages of wastewater treament, not only sludge that resulted from the end of treatment process.

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