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Sustainable approach to energy recovery from sewage sludge

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Abstract. Sewage sludge-to-energy approach was evaluated from the perspective of energy efficiency. Two conversion technologies including anaerobic digestion (AD) for biogas production and fast pyrolysis either targeting bio-oil or pyrolytic gas production were investigated. Use of the AD process can commonly give a specific energy production around 11.6 MJ/kg VS input. On average, the pyrolysis scenario for oil production recovered 62 % of the energy in sludge, while the pyrolysis scenario for gas production recovered 67 %. The results also suggest that the oil-targeted pyrolysis scenario favors the feedstock with High VS content, while the gas-targeted scenario possesses distinct potential for energy recovery from low VS content of sludge. Two parallel conversion pathways were comparatively studied. Pathway-1 is based on the AD followed by pyrolysis conversion, while pathway-2 based on pyrolysis process alone. Pathway-1 had higher energy conversion efficiency than pathway-2.

Keywords: sustainable approach, sewage sludge, anaerobic digestion, fast pyrolysis

1. Introduction

Current global trends in energy supply, production and consumption are unsustainable. According to the World Energy Outlook of IEA (2009) [1], if governments around the world maintain the existing policies, global primary energy demand will rise by 1.5 % per year on average between 2007-2030, while fossil fuels will remain persistently as dominant energy source, accounting for more than 75% of the overall increase in energy consumption. How to sustain the supply of reliable and affordable energy for our future generations and ourselves is a projected challenge that needs to be addressed urgently.

In addition, the fossil fuels-dependent energy production and consumption have practiced a wide range of impacts on the environment and on public health [2-6]. The most widely-known environmental consequence is greenhouse effect. Even though some scientists have published data raising doubts the scale of climate changes [7-9], precautionary principle needs us to take some measures. Possibly more unfavourably, while control of greenhouse gas emissions is capable of relieving climate warming, the current control measures generally cause slowdown or even shutdown of economic development. Another alarming problem is the ubiquitous and long-standing heavy metals pollution; it is unarguable that the fossil fuels-based energy production and use have something to do with this problem [10-13]. According to Pawłowski [14], environmental pollution by heavy metals may become the biggest treat in the coming decades.

To seek solution to these issues, fundamentally, one needs to turn to the road of sustainable development. Sustainable development has been defined in many ways, but the most frequently quoted is the definition described in the Breundtland Report: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". It contains two key concepts: the concept of *needs*, in particular the essential needs of the world's poor, to which overriding priority should be given; and the idea of *limitations* imposes by the state of technology and social organization on the environments ability to meet present and future needs. What the Bruntland definition implies is an equitable resource distribution and consumption, not only spatially but also temporally.

There are many publications addressing different aspects of sustainable development: philosophical, mostly ethical [15-24], economical [8, 25-28], technical [16, 22, 29-30], educational [31] and environmental

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[14, 29, 32-33]. Some researchers thereof claim that we are living in era of sustainable development revolution that affects all aspects of our lives filled with multidimensional characters [8, 34]. All walks of sustainable development require to see the world as a system - a system that connects space and a system that connects time. This underlines the need for global solidarity and cooperation [6, 21, 28]. Currently, implementation of sustainable development should target to gradually change our unsustainable production and consumption patterns and move towards a better integrated approach to policy-making at regional, national and global scales.

The road to address and unlock the energy-related issues is to look at and solidly implement sustainable development. One of small step towards this direction is of waste-to-energy approach. It has been widely evidenced that organic wastes (waste biomass, sewage sludge, animal manure, etc.) holds substantial potential for energy generation. While un-appropriate treatment or un-treatment of the waste can incur environmental pollution and health risk, the waste-to-energy strategy appears to be more attractive. The objective of this work was to evaluate efficiency of energy recovery from a representative organic waste, sewage sludge. Two highlighted sludge-to-energy conversion technologies were investigated, including anaerobic digestion and fast pyrolysis.

2. Methods

The energy efficiencies of sludge pyrolysis were evaluated by using laboratory data summarized from previous studies [35-37].For anaerobic digestion, mass and energy balances were carried out, in conjunction with the following expressions,

$$M_{ADS} = \frac{M_{RSS} \times (1 - VS_{RSS})}{1 - VS_{ADS}} \qquad \text{Eq. (1)}$$

$$Y_{biogas} = SP_{biogas} \times (M_{RSS} - M_{ADS}) \qquad \text{Eq. (2)}$$

$$E_{biogas} = Y_{biogas} \times HHV_{biogas} \qquad \text{Eq. (3)}$$

- where M_{RSS} (kg) and M_{ADS} (kg) are the amount (on dry matter basis) of the sludges before and after the AD process (raw sewage sludge/RSS and anaerobically-digested sludge/ADS), VS_{RSS} (wt. %) and VS_{ADS} (wt. %) are the VS contents in the RSS and ADS;
- Y_{biogas} (m^3) is the volume amount of the biogas produced, and SP_{biogas} is the specific biogas production (1.0 m^3 /kg VS degraded) [38];
- E_{biogas} (MJ) is the biogas energy yield, HHV_{biogas} is the high heat value (HHV) of biogas, calculated at STP (standard temperature and pressure). It was assumed the biogas consists of 35 % of CO_2 and 65 % of CH_4 (the HHV of CH_4 is 39.6 MJ/ m^3).

These expressions were established, based on the assumption that dry matter in sludge is a mixture of fixed solids (FS) and volatile solids (VS), and that amount of FS in the sludge remains constant during the AD process.

3. Results and discussion

3.1. Energetic performances of pyrolysis: two fast pyrolysis scenarioes

Two fast pyrolysis alternatives have been developed for energy recovery from sewage sludge. One is a moderate-temperature pyrolysis (400-550 ºC) targeting oil production (pyrolysis scenario-1); the other is a high-temperature pyrolysis (~1000 ºC), where gas is considered as priority energy product (pyrolysis scenario-2).

Table 1 shows the energetic performance of the pyrolysis scenario-1 investigated. For conversion of the sludges with VS contents ranging from 59 to 84 %, the projected apparent energy efficiency (AEE) reached 62 % on average. A higher VS content of sludge contributed to a greater value of the AEE, indicating share of the energy distributed from sludge to bio-oil can be increased if converting sludge feedstock with higher VS content. If biochar product is also considered as energy recoverable, the accumulative energy efficiency can reach 88-92 %. Yield and heating value of pyrolysis gas in the scenario-1 were not experimentally measured. Based on mass and energy balances (the yield of the gas was estimated by difference, and the energy of the gas was assumed to be energy loss), the heating value of the gas was predicted to be approximately 9 MJ/kg. This estimated value is comparable to the results of the previous study where the yield and heating value of the gas produced were less than 12 % and 9 MJ/kg, respectively [39]. Therefore, it could be suggested that the gas product under such pyrolysis scenario has no or limited potential for energy recovery.

Alternatively, energy in sludge can also be recovered by pyrolysis in the form of gas as preferred product (pyrolysis scenario-2). This scenario has been intensively investigated in Spain (Instituto Nacional del Carbon, CSIC, Apartado) [36-37, 40]. In most cases, about 50 wt. % of sludge feedstocks (on dry matter basis) can be converted to pyrolytic gas. In this study, we identified and assessed its performances from the perspective of energy recovery efficiency. The results are listed in Table 1. In contrast to scenario-1, pyrolystic gas produced under scenario-2 dominated the overall energy output. The apparent energy efficiencies (AEE) reached 67 % on average. The produced biochar had a low calorific value around 6 MJ/kg. Considering the favourability for energy utilization, the biochar is inappropriate to act as energy source.

Table 1. Mass and energy analyses for the two pyrolysis scenarios

Sludge feedstock			Pyrolysis products			AEE [b]
Type	VS [a]	HHV [a]	Yield (wt. %) + HHV(MJ/ kg)			
	(wt. %)	(MJ/ kg)	Bio-oil	Biochar	Gas	(%)
Fast pyrolysis scenario-1						
PS [a]	84	23	42 + 37 [c]	33 + 17	Loss	67.6
WAS [a]	69	19	31 + 37 [c]	43 + 13	Loss	60.4
ADS [a]	59	17	26 + 37 [c]	53 + 10	Loss	56.6
Fast pyrolysis scenario-2						
AEDS [a]	62.3	16.7	8.5 + 36.3 [c]	Loss	54.6 + 18.1 [d]	59.3
ANDS [a]	54.7	14.0	3.9 + 36.3 [c]	Loss	51.4 + 20.3 [d]	74.6

The data was derived from the previous studies [35-37] ;
[a] PS = primary sludge, WAS = waste activated sludge, ADS (pyrolysis scenario-1) or ANDS (pyrolysis scenario-2) = anaerobically-digested sludge, AEDS= aerobically digested sludge, VS =volatile solids content, HHV=high heating value;
[b] AEE is the apparent energy efficiency, defined as the ratio of the energy content in the targeted bio-fuels (bio-oil or pyrolysis gas) to the energy content of sludge feedstock;
[c] HHV of the bio-oils was estimated values (approximately on average), based on the observation that HHV of bio-oils produced was independent on the type of sludge feedstock;
[d] HHV of gas produced in the pyrolysis scenario-2 was calculated according to the composition of the gas product and volume content of each of the components (see the previous work [36] for the initial data).

One unanticipated finding is that, the energy-related performance of scenario-2 was negatively dependent on feedstock energy content or VS content (Table 1). Although the ANDS feedstock possessed a lower VS content than the AEDS, and the yield of gas produced from the ANDS pyrolysis was also less than that from the AEDS pyrolysis, the pyrolysis of the ANDS gave an AEE value higher than the pyrolysis of the AEDS. Such observation is distinctly different from the results of scenario-1, in which both the energy efficiency and the bio-oil energy output increased with the VS content of feedstock. This abnormity may be due to the claimed fact that, the gas from the ANDS pyrolysis contained higher concentration of H_2 than that from the pyrolysis of the AEDS [36].

3.2. Energetic performance of anaerobic digestion

Anaerobic digestion (AD), as a microorganisms-based process without present of molecular oxygen, is one of the most cost-effective approaches to energy recovery from sewage sludge (typically a mixture of primary and waste activated sludge). More desirably, energy in the volatile solids (VS) destroyed via the AD process is mostly transferred to a high energy-density fuel (biogas). In this regard, the AD conversion is also one of the most energy-effective processes. However, the AD process can not completely degrade the VS in sludge, unavoidably leaving a substantial amount of residue (digestate or anaerobically-digested sludge, ADS). The ADS waste likewise contains considerable organic matter that is energy recoverable.

Table 2. Performance parameters of the anaerobic digestion of sewage sludge

	VS destruction [a] % VS input	Specific biogas production [a] m^3 biogas /kg VS destroyed	Biogas HHV MJ/ m^3	Energy input MJ/kg VS input
Range of value	40-50	0.8-1.2	25.8	
Typical value	45	1.0	25.8	11.6

[a] The data of volatile solids (VS) destruction and the specific biogas production were derived from a scientific and technical report of European Communities on disposal and recycling routes for sewage sludge [38].

Table 2 summarizes several performance parameters for the AD process of sewage sludge. The energy output is value predictable by using these parameters, once the VS amount of the sludge influent to digester is available. For example, assuming 100 kg sludge (on dry matter basis) containing 70 % of VS is subjected to the AD process, the resultant energy output in the form of biogas could reach about 812 MJ (calculation according to the typical values in Table 2). It should to mentioned that a variety of efforts (e.g. sludge pre-treating and process improvement) have being made to improve VS destruction, and have evidenced an enhanced biogas yield and quality. Expectably, the bioconversion of sludge to energy can receive more desirable energy recovery.

3.3. Comparison of two sewage sludge-to-energy pathways

It have been evidenced that both raw and anaerobically-digested sewage sludges can be successfully converted into desirable energy fuels (oil or gas) via fast pyrolysis process. On the other hand, energy in raw sewage sludge (RSS) can also be extracted by application of anaerobic digestion. This indicates two conversion pathways can be alternatively used for energy recovery from sludge. Pathway-1 is based on anaerobic digestion (AD) followed by pyrolysis process, while pathway-2 relies on the pyrolysis conversion alone. Since sludge before AD process contains higher level of organic matter than the digested sludge (ADS), pathway-2 can give higher yield of pyrolysis products than pathway-1, but pathway-1 gives additional energy product of biogas. In this work, energy recovery efficiency of the two sludge-to-energy conversion pathways was comparatively evaluated.

The typical value of the specific biogas production for the anaerobic digestion described in section 2.1 (see Table 1) and the process performances of the demonstrated pyrolysis scenario-2 (see Table 2) were used to perform mass and energy balance for the two pathways. For convenience in calculation, a common dry mass base of 100 kg RSS was assumed. The results are listed in Table 3.

Table 3 Results of mass and energy analyses for the two pathways

	Pathway-1: RSS→ AD→ADS → Pyrolysis		Pathway-2:
	RSS → AD	ADS→ Pyrolysis	RSS→ Pyrolysis
For conversion of 100 kg PS (VS in the PS = 84 %; VS in the ADS = 59 %)			
Energy input of the PS	2300.0 MJ		
Process yield	61.0 m^3 biogas + 39.0 kg ADS	10.2 kg bio-oil	42.0 kg bio-oil
Energy output (MJ)	1573.2 (biogas)	375.4 (bio-oil)	1554.0(bio-oil)
AEE (%)	84.7		67.6
For conversion of 100 kg WAS (VS in the WAS = 69 %; VS in the ADS = 59 %)			
Energy input of the WAS	1900.0 MJ		
Process yields	24.4 m^3 biogas + 75.6 kg ADS	19.7 kg bio-oil	31.0 kg bio-oil
Energy output (MJ)	629.3 (biogas)	727.4 (bio-oil)	1147.0 (bio-oil)
AEE (%)	71.4		60.4

RSS = raw sewage sludge, PS = primary sludge, WAS = waste activated sludge, ADS = anaerobically-digested sludge, VS =volatile solids content, AEE = apparent energy efficiency, defined as the ratio of the energy content in the targeted bio-fuels (bio-oil and biogas) to the energy content of the RSS (PS or WAS).

The apparent energy efficiencies (AEE, calculation on the basis of biogas and bio-oil) in pathway-1 were greater than those in pathway-2 (Table 3), regardless of which sludge feedstock (the PS or WAS) is converted. On the other hand, the variation in feedstock had remarkable impact on each of the two conversion pathways in terms of energy recovery efficiency. As indicated in Table 3, the AEE value for the PS feedstock was notably different from that for the WAS feedstock, either in pathway-1 or in pathway-2. For pathway-2, this difference is caused by sludge feedstocks itself, in particular by their difference in VS content. For pathway-1, however, both properties of the feedstock and performance of the AD process have an effect on the energy recovery efficiency. In the current investigation, the VS contents in the sludges before the AD process were different (84 % for the PS and 69 % for the WAS), while the VS contents in sludge (the ADS) after the AD process was assumed to be identical (59 %). This indicates that the VS degradation extent during the AD process were different. A calculation based on the mass balance can give 72.6 % of VS reduction for the PS and 35.3 % for the WAS. The results implicate that the VS content in the

RSS and its reduction degree during AD process could interactively influence the energy conversion efficiency of pathway-1.These effects needs to be further addressed.

4. Conclusions

In this work, several approaches to energy recovery from sewage sludge were evaluated from energy-efficiency perspective, at the scales of both technology and pathway. Two current highlighted sewage-to-energy conversion technologies — anaerobic digestion (AD) for biogas generation and fast pyrolysis targeting production of either bio-oil or pyrolytic gas — were investigated. Two pyrolysis-based conversion pathways alternatively integrated with AD process were also studied. The results have shown that:

- The AD process has a substantial potential for energy recovery from sewage sludge. The energy conversion efficiency via the AD primarily depends on VS content in sludge and the VS destruction degree. Typically, a specific energy production of 11.6 MJ/kg VS input can be obtained.
- Similarly, the energy recovery efficiency of sludge-to-energy via fast pyrolysis was also related to the sludge feedstock properties, in particular its VS content. High VS content effectively favours energy recovery in the form of bio-oil, whereas the pyrolysis conversion aiming to the production of gas may hold a distinct prospect for energy recovery from low VS content of sludge.
- The combined AD and pyrolysis conversion pathway (pathway-1) consistently exhibited energy-efficiency advantages over the pathway that is based on a unique pyrolysis process (pathway-2). In the cases investigated, the resulting AEE values of using the pathway-1 to convert two sludge feedstocks individually containing 84 and 69 % of VS, reached 85 and 71 %, separately 17 % and 11 % greater than the AEE values of using the pathway-2.

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