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Energy Recovery from Sewage Sludge

Yucheng Cao
Zhejing Agriculture and Forestry University, Hagzhou, China
Shengdao Shan
Agriculture and Forestry University, Hangzhou, China

1. Introduction

The current energy production and consumption dominantly depends on fossil fuels, and has posted a wide range of impacts on the environment [1–5]. The most widely-known environmental consequence is greenhouse effect, though there exist some knowledge gaps regarding the scale and scope of climate change [6–8], [44–45]. Another alarming problem is the ubiquitous and long-standing heavy metals pollution [9–12]; according to Pawłowski [13], in the coming decades environmental pollution by heavy metals may become the biggest treat to human being.

To seek for solution to these issues, one needs to follow the idea 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 [14–23], economical [7, 24–27], technical [15, 21, 28-29], educational [30] and environmental [13, 28, 31–32]. Some researchers claim that we are living in era of sustainable development revolution that affects all aspects of our lives filled with multidimensional characters [7, 33], and all walks of sustainable development need to see the world as a system – a system that connects space and a system that connects time, and need consistent solidarity and cooperation at regional, national and global scales [5, 20, 27].

Sewage sludge is the residue produced from wastewater treatment process sector. In China, the amount of sewage sludge produced in 2010 is estimated to reach 8.0 million tons [34]. In the EU as a whole, per capita production of sewage sludge is estimated to be 90 g per person per day [35], meaning that current annual production of sewage sludge exceeds 10 million tons. Sewage sludge is rich in organic matter and holds substantial potential for energy generation. Energy recovery from sewage sludge could offer an opportunity for sustainable management of sewage sludge as well as energy. The objective of this work was to evaluate efficiency of energy recovery from sewage sludge. Two highlighted sludge-to-energy conversion technologies were investigated, i.e. anaerobic digestion and fast pyrolysis. Specifically, a combined pathway based on anaerobic digestion and fast pyrolysis was also examined, and evaluated in comparison with straight application of fast pyrolysis.

2. Materials and methods

2.1. Sewage sludge

Two types of sewage sludge, raw and anaerobically digested sludges, were studied to evaluate energetic performance of the inclusive AD process, as well as that of their pyrolysis. The AD evaluation was conducted using two sets of data associated with carbon content, energy content and VS of the sewage sludge before and after AD process. One set of data was obtained from a scientific and technical report of European Commission [36]. The other was derived from laboratory measurements of previous studies [37–38]. The properties of the sewage sludges investigated are presented in Table 1 and Table 2.

2.2. Mass and energy balance for AD process

The study was carried out not based on the measurement of how much biogas is produced from a given amount of sludge, but based on mass and energy differences between raw sludge and digested sludge.

Two different calculation techniques were used to perform mass and energy analysis for sludge digestion, individually using the values of carbon content and VS content of the sewage sludges (see Table 1). Methods adopted for the mass and energy calculations are described in detail in the following.

Mass and energy analysis based on carbon content. Sludge digestion could be simplified as Eq. (1), assuming that there is no carbon mass loss to or addition from aqueous phase during AD process,

$$RSS \xrightarrow{\text{AD}} ADS + Biogas\,(CH_4 + CO_2) \tag{1}$$

Where:

RSS, ADS and AD represent raw sludge, anaerobically digested sludge, and anaerobic digestion, respectively.

The following equations can be thereof established,

$$M_{RSS} \times C_{RSS} = M_{ADS} \times C_{ADS} + M_{biogas} \times C_{biogas} \tag{2}$$

$$M_{RSS} = M_{ADS} + M_{biogas} \tag{3}$$

A combination of Eq. (2) and (3) can give:

$$SEP = E_{biogas} / M_{RSS} = \frac{C_{RSS} - C_{ADS}}{C_{biogas} - C_{ADS}} \times CV_{biogas} \tag{4}$$

Where:

M_{RSS}, M_{ADS}, and M_{biogas} are the dry mass amount of RSS, ADS and biogas, respectively;

C_{RSS}, C_{ADS} and C_{biogas} are the carbon content of the RSS, ADS and biogas, respectively;

SEP is the specific energy production, expressed as biogas energy produced from per unit mass of sewage sludge;

E_{biogas} is the energy amount of the biogas produced, and CV_{biogas}s is the calorific value of the biogas.

Furthermore, it is widely observed that AD process of sewage sludge can produce biogas consisting of 60–70% of CH_4 and 30–40% CO_2 (by volume), and that volume content of other components (e.g. H_2S and N_2) is less than 1%. Therefore, it is reasonable to assume the biogas produced contains 65% of CH_4 and 35% CO_2 (no other composition). This assumption allows values of C_{biogas} and CV_{biogas} to be quantified, and the values calculated at standard temperature and pressure are 47% for C_{biogas} and 22.4 MJ/kg for CV_{biogas} (the calculation is not shown here).

Using Eqs.(2) though (4), the constant values of C_{biogas} and CV_{biogas} , energy converted from sludge to biogas and the amount of the remaining sludge were quantified for a given amount of raw sludge, where values of the carbon content in raw and digested sludges were used.

Mass and energy analysis based on VS content. In the designing of AD process, it is generally assumed that the dry matter of sewage sludge is a mixture of fixed solids and volatile solids, and that the amount of fixed solids remains unaltered throughout AD process. These assumptions can give rise to the following equations,

$$M_{biogas} = \frac{M_{RSS} \times (VS_{RSS} - VS_{ADS})}{1 - VS_{ADS}} \tag{5}$$

$$SEP = E_{biogas} / M_{RSS} = \frac{VS_{RSS} - VS_{ADS}}{1 - VS_{ADS}} \times CV_{biogas} \tag{6}$$

Where:

VS_{RSS} (wt.%) and VS_{ADS} (wt.%) are the VS contents in the RSS and ADS.

Similarly, specific energy production from sludge to biogas, and amount of the remaining sludge, were also quantified by using a combination of Eqs. (5) and (6), where values of VS_{RSS} and VS_{ADS} were used.

2.3. Mass and energy balance for sludge pyrolysis

Sludge pyrolysis generally produces three products, namely bio-oil, biochar and pyrolytic gas. Their relative energy share distributed from sludge feedstock depends on specific pyrolysis process employed, particularly pyrolysis temperature and heating rate. Fast pyrolysis using a high heating rate (~100°C/min) and a moderate temperature (450~550°C) can dominantly distribute sludge energy into bio-oil that is commonly regarded as a priority energy product; fossil fuel-based oil is being exhausted while biomass including organic waste is the only source of renewable energy that can produce oil.

In this study, fast pyrolysis for bio-oil production was considered. Its energy conversion potential from sewage sludge to bio-oil was evaluated using mass and energy balance analysis. Energy distributed into the other two pyrolysis products (biochar and pyrolytic gas) was neglected. The calculation are based on the following equation,

$$ECE = \frac{CV_{bio-oil} \times Y_{bio-oil}}{CV_{sludge}} \quad (7)$$

Where:

ECE is the energy conversion efficiency from sludge to bio-oil,

$CV_{bio\text{-}oil}$ *and* $Y_{bio\text{-}oil}$ are the calorific value and yield of the bio-oil produced,

CV_{sludge} is the calorific value of sludge feedstock.

3. Results and discussion

3.1. Anaerobic digestion (AD)

The specific energy production (SEP) and energy conversion efficiency (ECE) from sewage sludge to biogas by anaerobic digestion are summarized in Table 1 and Table 2. The calculation was conducted using carbon mass and VS mass balances, respectively (see Section 2.2). The results obtained by the two quantifications are not consistent (Table 1 and 2). Here, we don't argue over that which quantification method is more reliable as both are based on assumptions (see details in Section 2.2), but focus on a preliminary overview on the energy conversion potential of sludge digestion.

As seen from Table 1 and 2, the energetic performances of the sludge digestion are substantially attractive and comparable to thermochemical process such as fast pyrolysis; in general, energy conversion efficiencies from sludge to bio-oil through fast pyrolysis are less than 70% (see details summarized in the following section). Despite its desirable performance in energy conversion, AD process is not universally available and affordable for energy recovery from sludge. One concrete obstacle to apply AD process is that the operation of AD generally requires large amounts of energy for sludge heating and mixing. However, such concern and scruple could be settled down, when taking into consideration the fact that the application of AD process can largely reduce volume and mass amount for sewage sludge, thus allowing energy requirements for subsequent sludge dewatering and drying to be largely reduced. Nevertheless, a comprehensive evaluation on energy sustainability of AD process of sewage sludge remains necessary.

Table 1. Properties of sewage sludges and energetic performances of the inclusive sludge digestion (using summarized data from a scientific and technical report)

Tabela 1. Właściwości i parametry energetyczne osadów ściekowych poddawanych fermentacji (wykorzystano dane publikacji naukowych i technicznych)

Properties of sewage sludges before and after AD			SEP [b] (MJ biogas/ kg-sludge) calculated by		ECE [c] value
	Raw sludge	Digested sludge	Eq. (4)	Eq. (8)	%
Carbon [a] (%)	36.7	24.5	12.1		72.7
VS [a] (%)	72	50		9.9	59.0
CV [a] (MJ/kg)	16.7	10.8			

[a] *on dry mass basis.*
[b] *SEP represents the biogas energy produced from a given amount of sewage sludge; details on calculation described in Section 2.2.*
[c] *ECE is the energy conversion efficiency from sludge to biogas, expressed as the ratio of energy of biogas produced to energy in sludge.*

Table 2. Properties of sewage sludges and energetic performances of the inclusive sludge digestion (using data from laboratory measurement of previous studies)

Tabela 2. Właściwości i parametry energetyczne osadów ściekowych poddawanych fermentacji (wykorzystano dane z wcześniejszych badań)

Properties of sewage sludges before and after AD			SEP [a] (MJ biogas/ kg-sludge) calculated by		ECE [a] value
	Raw sludge	Digested sludge	Eq. (4)	Eq. (8)	%
Calculation using the data from the literature[38]					
Carbon [a] (%)	39.9	27.6	14.2		83.1
VS [a] (%)	53.8	40.5		5.0	29.3
CV [a] (MJ/kg)	17.1	8.8			
Calculation using the data from the literature [37]					
Carbon [a] (%)	NA[b]	NA[b]	NA[b]		
VS [a] (%)	76.5 [c,]	59		16.6	79.0
CV [a] (MJ/kg)	21 [bc]	17			

[a] *The same as description in Table 1.*
[b] *NA refers to "non available"*
[c] *Values are the average value of primary and waste sludges (the original values are presented in the literature [37]).*

It is worth noting that AD process can not sufficiently mineralize organic matter of sewage sludge, while new biomass (anaerobic bacteria) is more or less reproduced and yielded. As a consequence, the discharged residue after AD process, known as digestate or anaerobically-digested sludge (ADS), still contains large amounts of organic matter(about 40–60 wt.%) with substantial potential for energy recovery. However, unlike its original sludge, the organic matter in the digested sludge is biologically resistant, indicating that conventional biological approach to extracting energy from the digested sludge is not appropriate. One feasible and practical option is to use thermo-chemical technologies including pyrolysis, which is discussed in the following section (Section 3.2).

3.2. Fast pyrolysis

The energetic performances of the fast pyrolysis used to convert sewage sludge to bio-oil are summarized in Table 3. The ECE value, which reflects how much energy contained in sludge feedstock is distributed to bio-oil product, varies widely depending on feedstock choice and pyrolysis process. As shown in Table 3, when sludge feedstocks are subjected to pyrolysis process under the uniform conditions (e.g. temperature and heating rate, see details in the ref. [37]), the conversion of the feedstock with a higher VS content generally has a higher ECE value (Table 3). Therefore, it can be concluded that the production of bio-oil from sludge is more energy beneficial if the converted sludge feedstock have a higher VS content.

Besides the priority energy product of bio-oil, sludge pyrolysis also forms a carbon-rich solid byroduct that is commonly termed as biochar. The biochar sequestrates around 20–30% of energy contained in sludge feedstocks, and has substantial potential for energy recovery mostly with heating value no less than 5 MJ/kg. But this byproduct turns out to have an array of environmentally-sound and agronomically-beneficial effects, and is now being exploited intensively for the application of carbon sequestration and soil amendment. An increasing number of evidences have shown that the approach to returning biochar to soil is more sustainable in energy and environment terms than a straightforward combustion for energy recovery. Although the biochar derived from sewage sludge contains unfavourable metals that would pose the risk of environmental contamination when applied to land, such risk is rather lower as compared to the risk incurred by the current two mainstream sludge treatments, land-spreading and land-filling; It has been observed that biochar is environmentally resistant to decay or decomposition [39–40], and that heavy metals retained in biochar are highly stabilized [41–42].

The pyrolytic gas has a low heating value (estimated to be less than 9 MJ/kg, based on mass and energy balance), thus has no or limited potential for heat or electricity production. In practice, however, pyrolytic gas vented from pyrolysis equipment keeps a high temperature, therefore it is possible to use the gas as a heat carrier/exchanger for preheating sludge feedstock.

It should be noted that, for a given feedstock, a pyrolysis process achieving a higher energy output (or higher energy conversion efficiency) does not necessarily indicate the process is more energy effective and beneficial. As pyrolysis is an endothermic thermo-chemical process, energy content of pyrolysis products is partly from reaction heat of pyrolysis, not just transferred from its feedstock. If the accumulative energy content of pyrolysis products overwhelms the energy content of its feedstock, the energy yield of the pyrolysis might be dependent, to a great degree, on the contribution of the reaction heat. In such a case, a high energy output, which is achieved at the expense of a much higher energy input, leads to the net energy yield (net energy efficiency) to be lowered. Therefore, more attention should be given to reaction heat of pyrolysis when considering process optimization and choice.

3.3. Pyrolysis combined with AD versus straight pyrolysis

As indicated previously (Section 3.1 and 3.2), energy in raw sewage sludge can be mostly converted into biogas via AD process, while the rest of energy remained in the digested sludge can be predominantly distributed into bio-oil via fast pyrolysis; on the other hand, energy in raw sewage sludge can also be straight extracted via fast pyrolysis in the form of bio-oil. This raises the concern of which one is more energy beneficial between the two conversion options (a combined AD and pyrolysis option versus an option of straight pyrolysis). For convenience of description, the two options are separately referred to as combined pathway (**CP**, the combination of AD and pyrolysis) and simplified pathway (**SP**, only using pyrolysis).

Table 3. Properties of sewage feedstock and energetic performances of fast pyrolysis
Tabela 3. Właściwości osadów surowych i parametry energetyczne dla szybkiej pirolizy

Sludge feedstock			Yield and energy content of pyrolysis products						ECE [b]	Ref.
			Bio-oil		Biochar		Py-gas			
Type [a]	VS (%)	CV (MJ/kg)	Yield (%)	CV (MJ/kg)	Yield (%)	CV (MJ/kg)	Yield (%)	CV (MJ/kg)	(%)	
Pyrolysis in a batch mode at 500 ºC for maximum bio-oil yield.										
PS	84	23	42	37	33	17	NA	NA	67.6	[6]
WAS	69	19	31	37	43	13	NA	NA	60.1	
ADS	59	17	26	37	53	10	NA	NA	56.6	
Pyrolysis in a continuous mode. Original data were estimated from figure of pyrolysis product distribution.										
ADS	47	12.3	21.4	32.1	25	NA	24.3	NA	55.8	[43]
ADS	38.3	8.9	12.0	30.6	18.5	NA	36.0	NA	41.3	
ADS	46.6	11.9	15.8	31.2	23.5	NA	27.9	NA	41.4	
Pyrolysis at 500 ºC in a semi-continuous mode.										
WAS	53.8	17.1	43.1	NA	35.6	9.9	21.3	NA	NA	[38]
ADS	40.5	8.8	26.7	NA	56.0	5.2	17.3	NA	NA	

[a] *PS = primary sludge, WAS = waste activated sludge, ADS = anaerobically-digested sludge.*
[b] *ECE represents the energy conversion efficiency from sludge to bio-oil.*

Here, the energy-related performances of the two options were compared from the viewpoint of energy conversion efficiency. The previous study [37] that investigated technical performances of fast pyrolysis of sewage sludges before and after AD process (PS, WAS and ADS) was revisited as a case study. The pyrolysis-related result has been summarized in Table 3. The measured energy contents of the raw sludges (PS or WAS) and digested sludge (ADS) were used to examine the energy conversion footprint of the inclusive AD process (details on the calculation method is presented in Section 2.2). The calculated results from AD and the results from ADS pyrolysis were merged, and the overall energy conversion efficiency of the **CP** option was thereof determined.

Fig. 1 shows the energy conversion efficiencies of the CP and SP options. The CP option achieved greater conversion efficiency than the SP option for both raw sewage sludges (PS and WAS). On average between the two raw sludges, the CP option exhibited an energy conversion potential approximating to 78%, as much as 14% greater compared to the SP option. However, this result does not indicate that the CP option have a higher net energy efficiency than the SP option, given that the additional introduction of AD process in the CP option needs additional energy input in process operation. The choice between the two options still requires more information on the overall energy production and consumption involved.

The energy conversion efficiencies of both options were dependent on the sludge feedstock converted. As indicated in Fig. 1, in both conversion options, the ECE value achieved from the conversion of PS feedstock was notably higher than the ECE value from WAS feedstock. For the SP option, this difference is caused by sludge feedstocks itself, in particular by their difference in VS content. For the CP option, however, both properties of the feedstock and performance of the AD process have an effect on the energy recovery efficiency. This could be explained by the facts that the PS feedstock not only has a higher VS content than the WAS feedstock, but also has a higher VS degradation extent in the AD stage; a calculation based on the mass balance of AD process can give 72.6% of VS reduction for the PS and 35.3% for the WAS. However, the result can not provide information on whether there exists interactive effect between the VS content of feedstock and its reduction extent in the AD stage. Such information gap also needs to be filled.

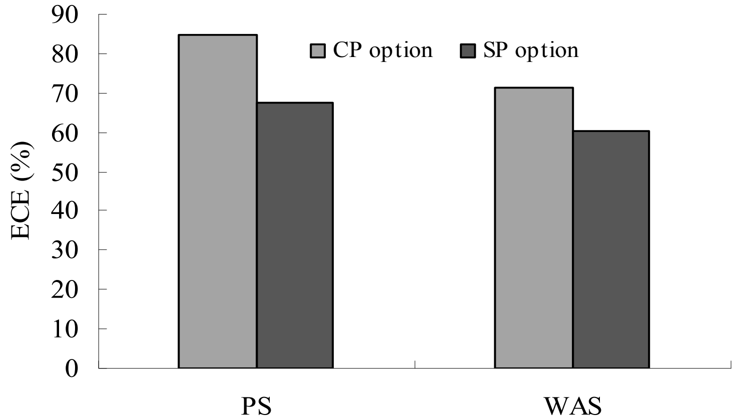

Fig. 1. Energy conversion efficiencies (ECE) of the combined pathway (CP option) and simplified pathway (SP option) for primary sludge (PS) and waste activated sludge (WAS)

Rys. 1. Sprawność przetwarzania energii dla połączonej procedury (opcja CP) i uproszczonej (opcja SP) dla osadów wstępnych (PS) i wtórnych (WAS)

4. Conclusions

A preliminary evaluation on the energy recovery potential from sewage sludge was carried out at both technological and pathway scales. Two conversion technologies including anaerobic digestion (AD) for biogas production and fast pyrolysis for bio-oil production were investigated. A combined pathway based on AD and fast pyrolysis was also examined in comparison with a simplified pathway that only relies on fast pyrolysis for energy conversion. Both AD process and fast pyrolysis have an attractive energy conversion potential while their conversion efficiencies are comparable. The pyrolysis process appears to be a promising approach for sustainable management of sewage sludge, as it not only produces bio-oil as priority product but also forms biochar as by-product that holds potentials for carbon sequestration and land amendment. The combined pathway exhibited advantage in energy conversion efficiency over the simplified pathway, depending on sludge feedstock (particularly its VS content) and VS reduction extent in the AD stage. Uncertainty remains regarding how and to what degree the VS content and its reduction extent by AD influence energetic performances of the combined pathway.

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Odzysk energii z osadów ściekowych

Streszczenie

Różne podejścia do odzysku energii z osadów ściekowych zostały ocenione z punktu widzenia zrównoważonego rozwoju. Badano proces anaerobowej fermentacji (AD) do produkcji biogazu i szybkiej pirolizy do produkcji bio-oleju. Zastosowanie procesu AD umożliwia odzysk energii z osadów ściekowych w znacznym stopniu w postaci biogazu, a przefermentowany osad nadal zawiera duże ilości substancji organicznych ze znaczny potencjał do odzysku energii. Wykorzystanie szybkiej pirolizy pozwala przede wszystkim na przekształcenia energię w osadach na bio-olej, a jego parametry energetyczne silnie zależą od właściwości osadów, w szczególności zawartości VS. Połączona procedura, oparta na AD, a następnie szybkiej pirolizie i uproszczona wykorzystująca tylko szybką pirolizę były również badane. Połączona procedura miała większą sprawność przemiany energii niż uproszczona; badania dla dwóch osadów surowych pokazują, że średnio połączona procedura uzyskała potencjał konwersji energii wynoszący około 78%, o 14% większy w porównaniu do procedury uproszczonej.