Applied Energy Symposium 2020: Low carbon cities and urban energy systems
October 10-17, 2020
Paper ID: CUE2020-D-093

Enhancement of energy recovery from synergetic treatment of sewage sludge and food waste

Chunxing Li[1,2], Jie Li[3,#], Shengyu Xie[1], Xinyu Zhu[2], Xiaonan Wang[3*], Yin Wang[1*], Irini Angelidaki[2]

1 CAS Key Laboratory of Urban Pollutant Conversion, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen 361021, China

2 Department of Environmental Engineering, Technical University of Denmark, Kgs. Lyngby DK-2800, Denmark

3 Department of Chemical and Biomolecular Engineering, National University of Singapore, Singapore 117585, Singapore

*Corresponding author: E-mail: chewxia@nus.edu.sg; yinwang@iue.ac.cn

The first two authors contribute to the work equally

ABSTRACT

Waste-to-energy is one of the feasible approaches to reduce the dependence of fossil fuel. Sewage sludge and food waste, as main municipal wastes from water and food consumption, have potential to be converted into energy (methane and biochar) to alternative non-renewable energy. In the present study, sewage sludge was hydrothermally treated to improve its dewaterability. The separated filtrate and food waste were applied for mesophilic anaerobic digestion for biogas generation with methane yields of 253 and 510 mL/gVS, respectively, at organic loading of 20 gVS/L. The food waste digestate was used for co-pyrolysis with separated filter sludge cake for improving flammable gas, oil, and biochar generation. Additionally, Cu and Zu in biochar were significantly immobilized after co-pyrolysis, and higher pyrolysis temperature and more digestate addition led to better immobilization performance. In brief, the present work paves the path for friendly treatment of sewage sludge and food waste with energy recovery and improved biochar production, and provides valuable guidance for the operation of our pilot-scale and full-scale reactors to realize the energy self-sufficiency and net energy generation.

Keywords: Sewage sludge, Food waste, Energy recovery, Pyrolysis, Anaerobic digestion, Heavy metals.

NONMENCLATURE

Abbreviations	
TS	Total solid
VS	Volatile solid
F1	Acid soluble/exchangeable fraction
F2	Reducible fraction
F3	Oxidizable fraction
F4	Residual fraction
HTS	Filter cake from hydrothermally treated sewage sludge
FWD	Solid from food waste digestate
BX-Y	Biochar sample obtained pyrolysis temperature of X with digestate addition of Y wt.%

1. INTRODUCTION

Renewable energy generation is the key for sustainable development. Waste-to-energy has attracted widespread attention due to its benefit of both energy and environment. Sewage sludge and food waste are two main municipal waste generated from water and food consumption in cities. The generation of sewage sludge significantly increased with urbanization, social-economic development, and population growth in the world [1]. It was reported that the quantity of sewage sludge showed an average increase of 13% every year from 2007 to 2015 with about 30-40 million tons generation in 2015 [2]. Approximately 1.4 billion tons of food waste was generated globally [3], and it was predicted that 2.2 billion tons of food waste would be produced up to 2025 [4]. Therefore, it is urgent to accelerate the development of waste-to-energy technologies for environmental protection and renewable energy recovery.

Different technologies have been applied to deal with sewage sludge, such as anaerobic digestion, thermochemical methods (e.g. pyrolysis, gasification and incineration) and compost [5]. The main limitation for treatment of sewage sludge is its difficulty in dewaterability [6]. So, various pretreatment methods are used for improving the dewaterability of sewage sludge, like thermal (alkaline) pretreatment, microwave treatment and enzyme treatment [7]. After pretreatment, the separated filtrate and filter cake can be used for methane and biochar generation via anaerobic digestion and pyrolysis [5]. Another bottleneck for sewage sludge treatment is its low organic contents and high concentration of heavy metal, especially for Cu and Zn. In our previous work, pyrolysis was proved a promising technology for heavy metal immobilization with converting sewage sludge into biochar [8]. Additionally, food waste is suitable for anaerobic digestion with methane production due to its containing high content of organic matters. However, the produced digestate residue needs further treatment due to its containing harmful substrate [9]. Previous work reported co-pyrolysis of sewage sludge and biomass presented huge advantage in heavy metal stabilization and biochar improvement [10]. Therefore, the co-pyrolysis of filter cake from hydrothermally treated sewage sludge and food waste digestate is a promising approach for synergetic treatment for sewage and food waste for promoting energy recovery and low-toxicity biochar production.

According to the above, a new treatment system is proposed for treatment of sewage sludge and food waste. Hydrothermal pretreatment was first applied for dewatering sewage sludge. The separated filtrate and food waste were used to anaerobic digestion for methane generation. The separated filter cake was pyrolyzed with food waste digestate for flammable gas, oil, and, biochar production. Additionally, the concentration and stabilization performance of Cu and Zn were analyzed during in biochar samples.

2. MATERIAL AND METHODS

2.1 *Materials*

The filtrate and filter cake from squeezing hydrothermally treated sewage sludge (hydrothermal treatment condition: 180 °C, 30 min) were obtained from our pilot-scale sewage sludge treatment plant in Tong'an, Fujian province, China. The food waste was transported from the East solid waste center in Xiang'an, Fujian province, China. The obtained filtrate and raw food waste were stored in refrigerator at 4 °C for following anaerobic digestion. Table 1 shows the detail characterization of the filtrate and food waste. The filter cake and food waste digestate were dried at 105 °C for 24 h to remove moisture and were sieved to particle size less than 0.15 mm for further pyrolysis experiment.

Table 1 Characterization of sludge filtrate and food waste.

Items	TS (wt.%)	VS (wt.%)	VS/TS (%)	pH	NH_4^+-N (mg/L)
Filtrate	5.03	4.22	83.89	6.01	1940
Food waste	11.30	8.62	76.32	4.50	274

TS, total solid; VS, volatile solid.

2.2 *Anaerobic digestion and pyrolysis experiments*

The obtained filtrate was used for methane production via anaerobic digestion. Glass bottle (2500 ml) with working volume of 2000 mL was used as the anaerobic digestor. For each experiment, 1500 mL diluted filtrate was added with organic loading of 5 gVS/L, 10 gVS/L and 20 gVS/L. 500 mL inoculum was added as the seed sludge. After flushing with nitrogen for 10 min to remove the oxygen in the reactor, a bag was connected to the reactor for biogas collection. The prepared reactors were set in the incubator for anaerobic digestion (37 °C). More detail information about the anaerobic digestion can be referred to our previous work [6].

All the pyrolysis experiments were conducted in a fixed bed quartz reactor. For each pyrolysis experiment, 20 g filter cake, solid digestate or their mixture were inserted in the quartz tube. The pyrolysis temperature was 300°C, 500°C and 700°C with time of 30 min. The solid digestate addition was 0 wt. %, 20 wt.% and 50wt.%. An electric furnace was used to heat the reactor to the preset temperature controlled by a PID temperature control unit. The produced biochar was moved out after cooling the quartz tube to room temperature. The detail procedure for the pyrolysis experiment can be seen in our previous work [10].

2.3 *Characterization methods*

A pH meter and rapid ammonia detection device were used to measure the pH value and NH_4^+ -N concentration. The Chinese standard methods (GB/T 28731-2012) was applied to test the parameters like total solid (TS) and volatile solid (VS). The methane content in biogas was characterized by a gas chromatography (FULIGC9790II, China) [11]. An Agilent inductively coupled plasma mass spectrometry (ICP-MS) analyzer (Optima 7000DV, Perkin Elmer, USA) and BCR were employed to measure the contents and analyze the chemical speciation of different heavy metals [12].

3. RESULTS AND DISCUSSION

3.1 Methane generation from sludge filtrate and food waste

The separated sludge filtrate and food waste are used for mesophilic anaerobic digestion for methane generation with three different organic loading, and the results are presented in Fig. 1. The cumulative methane yield of filtrate reached to 253 mL/gVS under organic loading of 20 gVS/L after 31 days digestion. The cumulative methane yield and digestion duration increased and decreased with decline of organic loading, which is consistent with our previous research on such filtrate anaerobic digestion at thermophilic digestion [6]. Because low organic loading supplied a better environment for growth of microorganisms due to the lower inhibitors, such as ammonium concentration and heavy metal concentration. However, the methane yields at mesophilic digestion are slightly lower than that of thermophilic condition due to the higher activity of microbe at thermophilic condition [13]. In terms of anaerobic digestion of food waste, the methane yields are much higher than that of filtrate under same organic loading with 510 mL/gVS at organic loading rate of 20 gVS/L. This is mainly due to that food waste consist of high content of carbohydrate and protein which are easily biodegradable substrates with high methane potential. Similar with the anaerobic digestion, the cumulative methane yield of food waste increased with decrease of organic loading. To be specific, the cumulative methane yields are 489 mL/gVS and 472 mL/gVS at organic loading of 10 gVS/L and 5 gVS/L, respectively. The results proved that sludge filtrate and food waste can be successfully applied for methane recovery via anaerobic digestion.

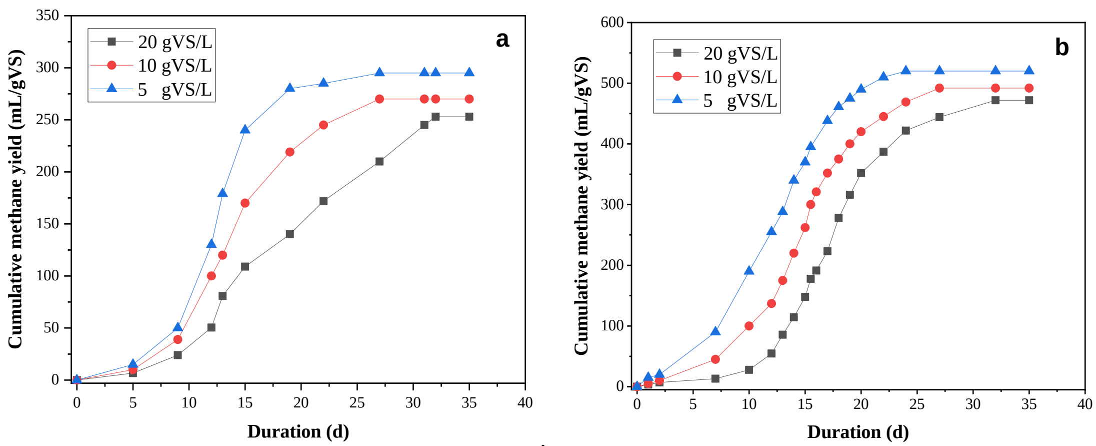

Fig. 1 Cumulative methane yields of (a) sludge filtrate and (b) food waste under different organic loading.

3.2 Heavy metal in biochar

Only Cu and Zn were analyzed due to their higher concentrations in sewage sludge (Fig. 2a). The concentrations of Cu and Zn were 3856.72 mg/Kg and 4137.98 mg/Kg in the filter cake, respectively. Their concentrations significantly increased in produced biochar samples, and higher pyrolysis temperature led to higher concentration in biochar sample. To be specific, the concentration of Cu and Zn increased to 5860.91 mg/Kg and 6056.46 mg/kg in biochar obtained from 700 °C. This was mainly resulted from the higher decomposition of organic matters than heavy metal volatilization [10]. In addition, the concentrations of Cu and Zn declined with digestate addition, and more digestate addition resulted in lower concentration. This can be explained by the dilution effect due to the lower concentrations of Cu and Zn in digestate. Another explanation is that the digestate addition can enhance the immobilization of Cu and Zn. It was also reported that sawdust/rice straw addition could significantly enhance the immobilization performance of heavy metal during sewage sludge pyrolysis process [14].

In fact, the toxicity of heavy metals is mainly related their speciation distribution. There are four forms of heavy metals including F1, F2, F3 and F4. The F1 fraction presents the percent of exchangeable or carbonate-associated metals, the F2 fraction presents the percentage of metals bound to Fe and Mn oxides, the F3 fraction presents the percent of metals associated with organic matter, and the F4 fraction presents percent of metals combined with silicate minerals. So, the bioavailability of heavy metals is F1 > F2 > F3 > F4. The F1 and F2 fractions have direct eco-toxicity, the F3 fraction has potential eco-toxicity, and the F4 fraction is a safe and harmless metal form when used in the environment [12].

The distribution of Cu and Zn in raw material and biochar samples are shown in Fig. 2b. Cu mainly exited in F3 fraction in the filter cake. It was transferred into F4 fraction after pyrolysis, and higher temperature and more digestate addition led to higher increase, which is also consistent with previous research [8]. This proved that Cu was immobilized from organic matter complexes to Cu-mineral compounds with increasing pyrolysis temperature and digestate addition. In term of Zn, the stable F4 fraction increased with decrease of F1+F2 fractions after pyrolysis. This can be explained by the elimination of bound water and dehydration of Fe-Mn oxyhydroxides in the pyrolysis process [15]. In brief, pyrolysis is proved a promising technology for immobilization of Cu and Zn, and higher temperature and more digestate addition lead to better performance.

3.3 *Future work*

From above lab-scale experiments, it is found that the synergetic treatment of sludge and food waste through anaerobic digestion and pyrolysis can enhance the bioenergy generation and obtained low-toxicity biochar. This indicates that it is feasible to develop the integration system for co-treatment of sludge and food waste for bioenergy production. The fuel properties of bigas and biochar, including the heating value, energy recovery efficiency, and energy densification will be further in the coming work to evaluate their potential as fossil fuel alternatives.

According to the data from lab-scale anaerobic digestion, we have successfully built and operated full scale anaerobic digestion of filtrate and food waste in an up-flow anaerobic sludge blanket (volume of 50 m^3) and a continuous stirred-tank reactor (volume of 500 m^3). Additionally, a pilot-scale pyrolysis reactor was built with treatment capacity of 20t biomass per day to deal with hydrothermally treated sewage sludge and food waste digestate with improved biochar generation. The energy balance will be analysis by considering the consumption of energy in the system and the production of bioenergy from anaerobic digestion and pyrolysis.

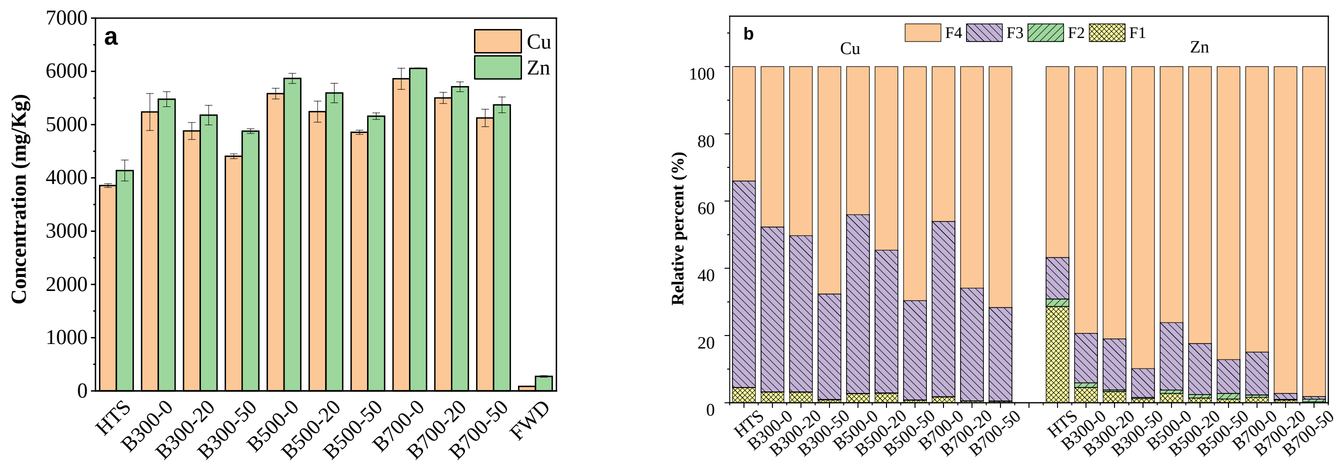

Fig. 2. (a) Total concentrations and (b) speciation distributions of Cu and Zn in raw material and biochar samples (HTS: Filter cake from hydrothermally treated sewage sludge, FWD: Solid from food waste digestate, BX-Y: Biochar samples obtained pyrolysis temperature of X with digestate addition of Y wt.%, F1: Acid soluble/exchangeable fraction, F2: Reducible fraction, F3: Oxidizable fraction, F4: Residual fraction).

4. CONCLUSIONS

Sewage sludge and food waste were synergistically treated with bioenergy (methane and biochar) generation via anaerobic digestion and pyrolysis. The separated filtrate from hydrothermally treated sewage sludge and food waste were applied for mesophilic anaerobic digestion for methane generation with yields of 253 and 510 mL/gVS, respectively, at organic loading of 20 gVS/L. Decreasing organic loading increased methane yield and shortened digestion duration. The separated filter cake was used for co-pyrolysis with food waste digestate for biochar generation to improve its fuel properties. In addition, the heavy metals of Cu and Zn were significantly immobilized after co-pyrolysis, and higher pyrolysis temperature and more digestate addition lead to better immobilization performance. This work provides valuable insights for our pilot-scale and full-scale utilization of these wastes to produce bioenergy in near future for reducing the dependence of fossil fuel.

ACKNOWLEDGEMENT

This work was supported by the Strategic Priority Research Program of the Chinese Academy of Sciences (XDA23030301, XDA23020500); the Natural Science Foundation of Fujian Province (2019J01135); the Science and Technology Program Project Funds of Xiamen (3502Z20193076).

REFERENCE

[1] Gu J, Liu R, Cheng Y, Stanisavljevic N, Li L, Djatkov D, et al. Anaerobic co-digestion of food waste and sewage sludge under mesophilic and thermophilic conditions: Focusing on synergistic effects on methane production. Bioresource technology. 2020;301:122765.

[2] Li X, Chen L, Mei Q, Dong B, Dai X, Ding G, et al. Microplastics in sewage sludge from the wastewater treatment plants in China. Water research. 2018;142:75-85.

[3] Wong JWC, Kaur G, Mehariya S, Karthikeyan OP, Chen G. Food waste treatment by anaerobic co-digestion with saline sludge and its implications for energy recovery in Hong Kong. Bioresource technology. 2018;268:824-8.

[4] Mehariya S, Patel AK, Obulisamy PK, Punniyakotti E, Wong JWC. Co-digestion of food waste and sewage sludge for methane production: Current status and perspective. Bioresource technology. 2018;265:519-31.

[5] Li C, Wang X, Zhang G, Li J, Li Z, Yu G, et al. A process combining hydrothermal pretreatment, anaerobic digestion and pyrolysis for sewage sludge dewatering and co-production of biogas and biochar: Pilot-scale verification. Bioresource technology. 2018;254:187-93.

[6] Li C, Wang X, Zhang G, Yu G, Lin J, Wang Y. Hydrothermal and alkaline hydrothermal pretreatments plus anaerobic digestion of sewage sludge for dewatering and biogas production: Bench-scale research and pilot-scale verification. Water research. 2017;117:49-57.

[7] Zhen G, Lu X, Kato H, Zhao Y, Li Y-Y. Overview of pretreatment strategies for enhancing sewage sludge disintegration and subsequent anaerobic digestion: Current advances, full-scale application and future perspectives. Renewable and Sustainable Energy Reviews. 2017;69:559-77.

[8] Wang X, Li C, Zhang B, Lin J, Chi Q, Wang Y. Migration and risk assessment of heavy metals in sewage sludge during hydrothermal treatment combined with pyrolysis. Bioresource technology. 2016;221:560-7.

[9] Li C, Li J, Pan L, Zhu X, Xie S, Yu G, et al. Treatment of digestate residues for energy recovery and biochar production: From lab to pilot-scale verification. Journal of Cleaner Production. 2020;265:121852.

[10] Xie S, Yu G, Li C, Li J, Wang G, Dai S, et al. Treatment of high-ash industrial sludge for producing improved char with low heavy metal toxicity. Journal of Analytical and Applied Pyrolysis. 2020;150:104866.

[11] Lv N, Zhao L, Wang R, Ning J, Pan X, Li C, et al. Novel strategy for relieving acid accumulation by enriching syntrophic associations of syntrophic fatty acid-oxidation bacteria and H2/formate-scavenging methanogens in anaerobic digestion. Bioresource technology. 2020;313:123702.

[12] Tian R, Li C, Xie S, You F, Cao Z, Xu Z, et al. Preparation of biochar via pyrolysis at laboratory and pilot scales to remove antibiotics and immobilize heavy metals in livestock feces. Journal of Soils and Sediments. 2019;19:2891-902.

[13] Liu C, Wang W, Anwar N, Ma Z, Liu G, Zhang R. Effect of Organic Loading Rate on Anaerobic Digestion of Food Waste under Mesophilic and Thermophilic Conditions. Energy & Fuels. 2017;31:2976-84.

[14] Huang H-j, Yang T, Lai F-y, Wu G-q. Co-pyrolysis of sewage sludge and sawdust/rice straw for the production of biochar. Journal of Analytical and Applied Pyrolysis. 2017;125:61-8.

[15] Weng HX, Ma XW, Fu FX, Zhang JJ, Liu Z, Tian LX, et al. Transformation of heavy metal speciation during sludge drying: mechanistic insights. Journal of hazardous materials. 2014;265:96-103.