Enhanced high-quality biomethane production from anaerobic digestion of primary sludge by corn stover biochar

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Abstract

This study conducted batch and continuous tests to reveal the feasibility of corn stover biochar on improving anaerobic digestion of primary sludge (PS). Dosing biochar (1.82, 2.55 and 3.06 g/g Total Solids (TS)) in digester improved methane content increasing from 67.5% to 81.3-87.3% and enhanced methane production by 8.6-17.8%. Model analysis indicated that biochar accelerated PS hydrolysis and enhanced methane potential of PS. The mechanistic studies showed that biochar enhanced process stability provided by strong buffering capacity and alleviated NH_3 inhibition. In continuous test over 116 days, the volatile solids (VS) destruction in the biochar-dosed digester increased by 14.9%, resulting in a 14% reduction in the volume of digestate for disposal. Biochar changed microbial community in an expected direction for anaerobic digestion. This work suggests that biochar technology would apply to co-digestion of WAS and PS to maximize the energy recovery and sludge reduction from the two sludge streams.

Keywords: Biochar; primary sludge; anaerobic digestion; methane; volatile solids destruction

1. Introduction

Wastewater carries a lot of chemical energy, which is partly consumed by municipal and industrial wastewater treatment plants (WWTPs). In Australia, the energy in wastewater is equivalent to ~150 kWh/Population Equivalent (PE)/year, but only 1/6 the amount of energy is consumed via WWTPs (Lazarova et al., 2012). Excess sludge is substantially generated in WWTPs. This means that a substantial amount of energy is transferred into the sludge. The average sludge production in global reaches to 20-40 kg/PE/year (PE: population equivalent) (Xie et al., 2016). The transfer and disposal of sludge is costly (e.g., $30-150 per wet ton in Australia), representing 40-60% of the total operating expenses of a WWTP (Semblante et al., 2014). In order to ensure WWTPs' continuous and regular task, therefore, the effective technique for energy recover and sludge reduction is extremely vital and urgent.

Anaerobic digestion is a common sludge treatment method adopted by global WWTPs, producing biogas from sludge to recover energy, thereby achieving sludge reduction (Yin et al., 2018). Biogas is a renewable energy source with great potential to generate heat and power. However, the energy recovery via anaerobic digestion is typically only 5-7% of the energy available in the wastewater due to the slow hydrolysis rate and poor biochemical methane potential of sludge (Appels et al., 2008; Wang et al., 2013). To maximize energy recovery and sludge reduction, various sludge treatment technologies like physical (Muller et al., 2003), chemical (Wang et al., 2014) and biological methods (Ge at al., 2010) have been proposed. Biogas generated from sludge anaerobic digestion based on these treatment technologies typically includes CH_4 with 50-70%, CO_2 with 30-50% and other gas (e.g., H_2S) with trace amounts. However, onsite utilization of biogas for heat and power generation requires high quality methane with the content more than 96% (Petersson and Wellinger, 2009). The biogas upgrading and cleanup process for the removal of CO_2 and other gas impurities is costly, results in the limiting use of biogas from anaerobic digestion (Shen et al., 2015a).

Biochar is a solid carbonaceous residue, derived from thermochemical processing of carbon-rich biomass under oxygen limited conditions (Ni et al., 2019). It has been proven to be effective in increasing the methane production rate by 15-86% and enhancing the methane production by 10-13% in anaerobic digestion of solid waste (Fagbohungbe et al., 2016; Luo et al., 2015; Shen et al., 2016; Sunyoto et al., 2016). Additionally, biochar was found to be effective in enhancing the anaerobic digestion of waste activated sludge (WAS) (Wu et al., 2019; Zhang et al., 2019). The existing WWTPs typically produce two sludge streams, primary sludge (PS) and WAS. PS is the sludge from primary settler and are rich in fatty acids, but WAS is the sludge produced by biological process and mainly contains biomass and extracellular polymeric substances (Carrère et al., 2010; Foladori et al., 2010). These two sludge streams are commonly mixed and co-digested in the anaerobic digester. It was found that the different sludge properties had significant impact on the efficiency of treatment techniques. For example, although the pre-treatment technology with free nitrous acid (FNA) (1.0-2.0 mg HNO_2-N/L, 24 h) was effective in enhancing methane production from WAS by 20-50% (Wang et al., 2013; Wei et al., 2018a), it decreased methane production from PS under the same pre-treatment and digestion conditions. This indicated that FNA approach should be solely employed to pretreat WAS for enhancing the methane production instead of the two sludge streams. On the contrary, the feasibility studies showed that zero valent iron (ZVI) addition method had the capacity in enhancing methane production from both WAS and PS (Feng et al., 2014; Wei et al., 2018b), suggesting that ZVI could be dosed in the anaerobic digester with the mixture of WAS and PS to maximize methane production. Recent studies using batch and continuous tests by Shen et al. (2015b and 2017) demonstrated that corn stover biochar increased methane production from WAS and produced high-quality methane from WAS via in-situ CO_2 removal. However, the functions of biochar in the anaerobic digestion of PS still remain unknown. Therefore, what happened to PS anaerobic digestion with biochar addition needs to be explored, which will determine whether biochar could be dosed in the anaerobic digester with the mixture of WAS and PS to enhance the performance of anaerobic digestion in WWTPs.

This study, for the first time, is aimed at assessing the effects of biochar on anaerobic digestion of PS. By using batch biochemical methane potential (BMP) tests, the effectiveness of biochar addition technology was investigated in terms of methane content and production. The mechanisms of biochar were explored based on the model analysis and the change of sludge characteristics before and after anaerobic digestion. Finally, continuous anaerobic digesters were operated to assess the effect of biochar on VS destruction of PS.

2. Materials and methods

2.1. Sludge and biochar preparation

The PS used in this study was collected from the primary sedimentation tank of a local WWTP. The anaerobically digested sludge (ADS) used as the inoculum was harvested from the thermophilic anaerobic digester in the same WWTP. This digester receiving the mixture of PS and WAS was operated with a sludge retention time (SRT) of 15 d at 55 ± 1 °C. The corn stover biochar was prepared according to the method described in Shen et al. 2015b. Briefly, the corn stover was crushed to a particle size of < 2.3 mm in diameter and then pyrolyzed with nitrogen at approximately 600 °C for 2 h in kilns. The biochar produced was cooled, weighed and stored in a desiccator for later use. The Table 1 presented the properties of the produced corn stover biochar, which were similar with the biochar used in Shen et al. 2015b. All biochar used in this study refer to the corn stover biochar.

(Approximate position for Table 1)

2.2. Biochemical methane potential (BMP) experiments design

The effects of biochar addition on the anaerobic digestion of PS were performed by BMP tests, as detailed in our previous studies (Wei et al., 2019). Each serum bottle (160 mL) was fed by PS (30 mL) and ADS (70 mL) with their VS mass ratio of 2.0 ± 0.1. Shen et al. (2015b) have found that 1.82-3.06 g/g TS of biochar-dosed could increase both methane content and production from WAS during thermophilic (55 ± 1 °C) anaerobic digestion, therefore, the corresponding levels of prepared biochar (i.e., 0, 1.82, 2.55 and 3.06 g/g TS) were dosed in the serum bottle, respectively. Each bottle was flushed with N_2, tightly sealed that maintains anaerobic condition, and then placed in a thermophilic incubating shaker (55 ± 1°C) until the cumulative methane volume remains unchanged. A blank test was carried out to eliminate interference of ADS for methane production. The cumulative methane production from PS anaerobic digestion was calculated by subtracting the value in the blank test. Three parallel experiments were conducted for each BMP test. The volume and content of biogas produced from each bottle during the whole BMP period were monitored for determining the methane production (recorded as mL CH_4/g VS). In addition, the pH value, total alkalinity (TA), ammonia nitrogen (NH_3-N) and conductivity of sludge via anaerobic digestion were measured according the methods in section 2.4.

2.3. Continuous anaerobic digesters setup and operation

The two continuous anaerobic digesters were operated in order to scale up anaerobic process from shake flasks digesters and provide a long-term evaluation. More importantly, continuous operation allows direct measurement of VS destruction, based on which the reduced sludge volume using biochar technology were determined.

Two identical 1.8 L stirred anaerobic reactors (working volume 1.5 L) were set up, as shown in Fig. 1. Each digester was added by ADS and PS with VS ratio of 2:1 and placed in an incubator (55 ± 1°C) after oxygen removal. The pH in each digester was recorded by pH meter and the biogas production rate was monitored using gas flow-meter. For the initial operation stage, the two reactors are operated under the same condition. The 100 mL of digestate was manually withdrawn from the reactor every day and 100 mL of PS was replenished, resulting in a SRT of 15 days. Until these two digesters reached the stable and convergence performance in terms of daily methane production and VS destruction, the experimental stage was started. One digester as control group was operated as before, while the other as experimental group was fed by PS with biochar. Specially, the 1.82 g/g TS of biochar was dosed in the experimental reactor at the beginning of experimental stage. Afterwards, the 0.12 g/g TS of biochar was supplemented every day. Other operation conditions were the same as the control group. Two anaerobic reactors were continuously operated for 116 days. The VS concentrations of the PS and digestate as well as the daily methane production from each digester were regularly measured with the method descripted in section 2.4. Three samples were withdrawn from each reactor at the stable state (1 sample/SRT) and the microbial communities were analyzed using Illumina Miseq sequencing, as described in our previous publication (Wei et al., 2019).

(Approximate position for Fig. 1)

2.4. Analytical methods

2.4.1. Chemical determination and statistical analysis

The TS, VS, TCOD and SCOD were determined according to Standard Methods (APHA, 2012). The TA and NH_3-N were analyzed using Hach test kits (Hach, Loveland, CO). The volume of biogas from BMP bottle was measured using a manometer, based on the pressure increase in the headspace volume at 25°C and 1 atm. The content of biogas from BMP bottle and continuous digester was recorded by a gas chromatograph equipped with a thermal conductivity detector (GC-TCD, Lunan 6890). The product of the biogas volume and methane content is equal to the methane production. The organic contents (C, H, O and N) in biochar were determined using elemental analyzer (Carlo-Erba NA-1500). The metal elements in biochar were measured by the ICP-OES (PE Optima 5300 DV, USA). According to the Brunauer-Emmett-Teller (BET) method, the N_2 adsorptiondesorption isotherms were performed to analyze the surface area, the total pore volume and the average diameter of pores. Statistical analysis was performed to assess the differences of results and $P < 0.05$ was considered to be statistically significant.

2.4.2. Modeling analysis

In order to investigate the kinetics and potential of methane production from PS anaerobic digestion with and without biochar addition, three parameters (i.e., the maximum methane production rate (P, mL CH_4/g VS/d), the hydrolysis rate (k, d^{-1}) and biochemical methane potential (B, mL CH_4/g VS)) were evaluated based on the experimental methane production curves.

The modified Gompertz equation as expressed in Eq. (1) was applied to fit the experimental data to estimate the maximum methane production rate (P) (Yin et al., 2018) using the software program OriginPro (version 8.0).

$$Y_t = Y_0 \times exp\left(-exp\left(\frac{P \times e}{Y_0} \times (\lambda - t) + 1\right)\right) \quad (1)$$

where Y_t (mL/g VS) is the cumulative methane production at time t; Y_0 (mL/g VS) is the maximum methane production; P (mL CH_4/g VS/d) is the maximum methane production rate; e is 2.71828 and λ (d) is the lag-phase time.

The hydrolysis rate (k) and biochemical methane potential (B) were evaluated based on the one-substrate model as expressed in Eq. (2) using a modified version of Aquasim 2.1d, as detailed in Batstone et al. 2009. Two parameters were got until the residual sum of squares between the experimental data and fitted data is minimized.

$$B_t = B \times (1 - exp(-kt)) \quad (2)$$

2.4.3. Conductivity measurement

The conductivity of the suspended sludge from BMP bottles with and without biochar addition after anaerobic digestion was measured according the method detailed in Zhao et al. 2016. Briefly, the sludge sample was collected after centrifugation and wash with 0.1 mol/L of NaCl. Two gold electrodes were placed on the glass and separated by 0.5 mm gap, which was covered by the sludge sample. Then an electrochemical workstation generated -0.3~0.3 V voltage. The electric current generated from each voltage was recorded to obtain current-voltage curve. The conductivity (σ, S/m) of the sludge sample was calculated by Eq. (3):

$$\sigma = \frac{L}{R \times S} \tag{3}$$

where R (Ω) is the reciprocal of the slope in the current-voltage curve; L (m) is the gap width; S (m^2) is the gap cross-sectional area.

3. Results and discussion

3.1. Effects of biochar on the methane content and production from anaerobic digestion of primary sludge

The BMP tests with biochar addition (i.e., 0, 1.82, 2.55 and 3.06 g/g TS) was performed to evaluate the impacts of biochar on methane content and production from PS during anaerobic digestion.

The methane content in biogas produced from PS in all tests throughout the BMP tests period were reported in Fig. 2A. The methane content (%) in each test with biochar was higher (P = 6.31E-07, 1.94E-07 and 5.52E-08) than that of no-biochar dosage (Fig. 2B). The methane content (%) with biochar addition started from above 92.1% on Day 1 and dropped gradually, while it with no-biochar dosage gradually increased from 43.9%, and thereafter reached the steady state. At the dosages of 1.82, 2.55 and 3.06 g/g TS, the methane content (%) over the whole BMP test period was 81.3 ± 0.8%, 84.1 ± 1.3%, 87.3 ± 2.0%, respectively, as compared to that of no-biochar dosage (67.5 ± 2.6%). The cumulative methane production from PS in Fig. 2B showed that the cumulative methane production stopped rising in each test on Day 41. The cumulative methane production from PS without biochar addition over the whole period was 337 ± 10 mL/g VS. The biochar addition was effective in enhancing the methane production during anaerobic digestion of PS, but the cumulative methane production decreased with the increase of biochar dosage. The maximal methane productions from PS with adding 1.82, 2.55 and 3.06 g/g TS of biochar was 397 ± 7, 377 ± 3 and 366 ± 6 mL/g VS, representing the relative increases of 17.8 ± 0.1%, 11.9 ± 0.1% and 8.6 ± 0.1%, respectively. It was likely due to the increased leaching and dissolution of potassium, calcium and even heavy metals from biochar, resulting in the toxicity. The carbon dioxide content in biogas from PS exhibited a contrary tendency with the methane content (Fig. 2C). The biochar addition decreased the carbon dioxide content in biogas and the increased biochar dosage resulted in the decreased carbon dioxide content. At the highest dosage of biochar with 3.06 g/g-TS, the carbon dioxide content over the 41 days' BMP test period was 10.6 ± 0.4%, representing a significant (*P* = 0.0004) decrease of 65.1 ± 0.1% compared to that without biochar addition. Correspondingly, biochar addition significantly decreased (*P* = 2.18E-08, 7.39E-09 and 1.46E-11) carbon dioxide amount in biogas. The cumulative carbon dioxide production decreased from 18.2 ± 1.1% of the control to 12.3 ± 0.9% of the control when biochar increased from 1.82 g/g TS to 2.55 g/g TS, and then further significantly decreased to 7.6 ± 0.2% of the control with increasing biochar dosage to 3.06 g/g TS.

The performance in the biochar-dosed digester was closely related to the biochar characteristics depending on the production conditions and feedstock. Based on Langmuir or Type I isotherm, the adsorption capacity of biochar was governed by the BET surface area and pore volume (Shang et al., 2013). The BET surface area (302.6 m^2/g) of the biochar used in this work (Table 1) is remarkably higher than the corn stover biochar produced by slow pyrolysis (15°C/min, 20.9 m^2/g), fast pyrolysis (up to 500°C/s, 0.76-12 m^2/g,) and gasification (higher temperatures with some oxygen, 23.9-29 m^2/g) (Brewer et al., 2009). High pyrolysis temperature also increased pore volume (Ahmad et al., 2013). Furthermore, the biochar used had higher content (~42.4 wt%) of ash (i.e., inorganic elements) compared to wood biochar (<5 wt%) at similar pyrolysis temperature (Keiluweit et al., 2010), which might due to the high ash content in the corn stover feedstock. The performance results above indicated that the biochar addition improved methane production with the higher methane content. This was probably because the strong adsorption capacity of biochar for carbon dioxide. The biochar used in this study was highly porous (0.11 cm^3/g) and had the large surface area (302.6 m^2/g), which would favor the capture of carbon dioxide produced in digester. Moreover, the high concentrations of alkaline earth metals (e.g., Ca, K and Mg) in ash of biochar resulted in the slightly alkaline pH in the biochar-dosed digesters, as seen in Fig. 3A, which would promote the carbon dioxide to be absorbed in the aqueous phase and converted to bicarbonate/carbonate via mineralization (Smith et al., 2014). Yin et al. (2018) also demonstrated that high K concentration (14.2%) in incineration bottom ash enhanced in-situ removal of carbon dioxide in the digester. Potassium carbonate has been widely used in the commercial process for carbon dioxide absorption. Additionally, it is reported that various amino acids produced via sludge hydrolysis in the digester may further facilitate potassium-mediated carbon dioxide absorption (Thee et al., 2014).

(Approximate position for Fig. 2)

3.2. Model based analysis

The maximum methane production rate (*P*), the hydrolysis rate (*k*) and biochemical methane potential (*B*) of PS in all cases were determined based on model fitting to further investigate the function of biochar.

The simulated methane production curves by the modified Gompertz model and one-substrate model showed that both models captured the experimental data well with high fitting degrees (R^2 > 0.94 in all tests). Table 2 summarized the estimated *P*, *k* and *B* of PS in the digesters with different biochar dosages. In general, biochar addition increased *P*, *k* and *B* of PS in the digesters. The *P*, *k* and *B* of PS in the digesters without biochar addition was 69.9 ± 2.2 mL CH_4/g VS/d, 0.31 ± 0.01 d^{-1} and 328 ± 4 mL CH_4/g VS, respectively. The highest increase was achieved at 1.82 g/g TS biochar added, being approximately 53.8 ± 0.1% (P = 0.001), 64.5 ± 0.1% (P = 0.001) and 13.7 ± 0.1% (P = 0.0004), respectively. The decreased *P*, *k* and *B* were observed with biochar dosage continued to increase to 2.55 and 3.06 g/g TS. Overall, biochar at the studied dosages (i.e., 1.82, 2.55 and 3.06 g/g TS) was effective in speeding up methane production and improving the hydrolysis and methane potential of PS in the digester, which suggested that a shorter hydraulic retention time or a smaller anaerobic digester with biochar dosed would achieve the similar methane production as that without biochar added, thereby greatly reducing the cost for sludge treatment (Ge et al., 2010). Nevertheless, the biochar dosage was negatively correlated to their performance, which was in accordance with the results observed in Fig. 1C. This could result from the toxicity of biochar at the higher concentration. It was reported that the thermophilic temperature in digester could conduce to the leaching and dissolution of potassium, calcium and even heavy metals from biochar (Shen et al., 2015b), which may exert the adverse impacts on the anaerobic digestion (Chen et al., 2008).

(Approximate position for Table 2)

3.3. Sludge and digestate characteristics

The initial and final characteristics of sludge in anaerobic digester with the different biochar dosage were compared and the results were shown in Fig. 3. The initial pH of sludge in the digester without biochar dosed was 7.3 ± 0.2, whereas the slightly alkaline pH (i.e., 8.1-8.7) in the biochar-dosed digesters was observed (see Fig. 3A). Alkaline pH condition has been demonstrated to facilitate sludge hydrolysis and increase the short-chain fatty acids (SCFAs) production (Yuan et al., 2006; Zhang et al., 2010). The model analysis results above also indicated that the greater hydrolysis of PS in the biochar-dosed digesters. The final pH values in all biochar-dosed digesters substantially decreased to a desired range for methanation (see Fig. 3A), indicating the strong buffering capacity. After digestion, total alkalinity (TA) of all digesters increased after anaerobic digestion and all biochar-dosed digesters provide higher alkalinity ranging from 3530 to 4680 (mg/L $CaCO_3$) (see Fig. 3B). This was probably because the slightly alkaline pH in the biochar-dosed digester was effective in converting CO_2 produced to carbonate/bicarbonate, which could further react with calcium content in the biochar to generate calcium carbonate (Yin et al., 2018). High alkalinity meant the strong buffering capacity. These results revealed that biochar could provide the strong buffering capacity, which would contribute to prevent pH drop resulting from the organic acids produced, thereby maintaining stability for anaerobic digestion.

It is well known that the organic nitrogen-compounds in sludge are degraded via anaerobic digestion to generate ammonium (NH_4^+-N). As seen in Fig. 3C, the ammonia nitrogen (NH_3-N) concentration in no biochar-dosed digester increased by 60.9 ± 0.1% after anaerobic digestion due to NH_3–NH_4^+ equilibrium. Nakakubo et al. 2008 demonstrated that ammonia had the great inhibitory effect on the activities of microbes involved in sludge anaerobic digestion. The slightly alkaline pH in the biochar-dosed digester would facilitate the NH_3–NH_4^+ equilibrium towards NH_3 formation (Wei et al. 2017), which was unfavourable for anaerobic digestion. However, the NH_3-N concentrations in biochar-dosed digesters after anaerobic digestion were lower (910-920 mg/L) than that in no biochar-dosed digester (1030 mg/L), which was likely attributed to the NH_3 adsorption by biochar. That is, although the slightly alkaline pH with biochar addition increased NH_3-N production, biochar had strong adsorption capacity for NH_3 resulted in the less NH_3 accumulated in the digester. This suggested that biochar could mitigate ammonia inhibition, thereby enhancing the performance of anaerobic digestion. The conductivities of the sludge after anaerobic digestion in each case were determined (see Fig. 3D). Results showed that biochar at the studied dosages drastically improved the sludge conductivity by 0.75-1.25 times, which might due to the metals (e.g., Ca) content in biochar. Previous studies (Barua and Dhar, 2017; Morita et al., 2011; Summers et al., 2010) have shown that direct interspecies electron transfer (DIET) between exoelectrogenic/fermentative bacteria and electrotrophic methanogen could accelerate the methane production from organic compounds during anaerobic digestion. Liu et al. 2012 reported that activated carbon can function as an electron conduit to promote DIET between syntrophic partners. Considering the higher electrical conductivity and the faster methane production rate in the biochar-dosed digesters (Fig. 2C and Fig. 3D), the biochar will probably facilitate DIET to improve methane production (Li et al., 2015). However, this warrants further investigations.

(Approximate position for Fig. 3)

3.4. Overall performance of continuous anaerobic digesters with primary sludge with biochar addition

The continuous anaerobic reactors with and without biochar dosed were operated to investigate the effects of biochar on VS destruction of PS. Fig. 4 presented the VS destruction with daily methane production in the control and experimental digester during initial and the experimental stage. In the initial stage (Day 1-41), two digesters were operated without biochar dosed. On Day 25, both digesters reached stable performances with the similar VS destruction and methane production. The average VS destruction of PS in the two systems from Day 25 to Day 41 (i.e. over 1 HRT after stable) was 61.7 ± 1.3% and 60.9 ± 0.4% (P = 0.37). Corresponding, the similar (P = 0.94) daily methane productions (694 ± 17 and 695 ± 12 mL/d) with the same methane content of 66.9 ± 0.7% in the two digesters were observed. This indicated that the two systems reached convergence performance.

(Approximate position for Fig. 4)

During the experimental stage (Day 41-116), one digester as experimental group was dosed 1.82 g/g TS of biochar. The VS destruction in the experimental group gradually exceeded that in the control group from Day 41 to Day 68 and then remained stable. There is a similar trend in daily methane production profile. For the control group, the average VS destruction of PS from Day 68 to Day 116 was 61.7 ± 1.0%. In contrast, VS destruction in the experimental group was 70.9 ± 0.9%. Biochar addition significantly (P = 0.0003) enhanced VS destruction of PS by 14.9 ± 0.2%. Aligning with VS destruction data, the daily methane production in the experimental group from Day 68 to Day 116 was 13.8 ± 0.1% higher than that in the control. The experimental digester produced high-quality methane with the average methane content of 80.9 ± 0.7%, whereas the average content of methane from Day 68 to Day 116 in the control was 66.5 ± 1.2%. Based on the VS destruction results, PS anaerobic digestion with 1.82 g/g TS of biochar added was estimated to decrease the volume of waste sludge by 14%, which translates to lower costs for sludge disposal.

3.5. Microbial community analysis

The microbial communities in the control and experimental continuous digesters were analyzed in order to further understand the function of biochar on anaerobic microbes. 16S rRNA gene sequences of microbial taxa from two digesters yielded 58,027 sequences on average. Distributions of microbial populations at the phylum level were shown in Fig. 5A. Bacterial populations in two digesters were dominated by *Proteobacteria*, *Bacteroidetes*, *Firmicutes* and *Acidobacteria*, which have been reported to have abilities of degrading organic substrates (e.g., proteins and carbohydrates) with VFA and hydrogen as major products (Wang et al., 2017). The abundance of these four phyla in the control digester was 64.8 ± 0.5%, while it reached up to 70.8 ± 0.2% in the experiment digester with biochar added, representing a relative increase of 9.3 ± 0.1%. In particular, *Proteobacteria* represent organotrophs, including various hydrolytic strains (Wei et al., 2019). Biochar addition increased their abundances by 15.4 ± 0.1%. As the most abundant archaeal phylum, *Euryarchaeota* shared in two reactors, which have been documented to be methanogens (Vanwonterghem et al., 2014). Similarly, *Euryarchaeota* appeared to be more abundant in the experimental reactor. This revealed that biochar enhanced the populations of anaerobic microbes associated with organic compound degradation and methanogenesis, which was in accord with the improved VS destruction and methane production observed in the biochar-dosed digester.

Further exploration on microbial community at the genus level in Fig. 5B found that two digesters contained various anaerobic microbes associated with hydrolysis-acidogenesis and methanogenesis. Biochar addition had significant impacts on their abundances. For example, *Rhodobacter* sp. was known as hydrolytic microbes, which was more abundant in the biochar-dosed reactor. *Paludibacter* sp. and *Proteinclasticum* sp. have been documented to be organic matter-utilizing bacterial genera with VFA and hydrogen generation (Wang et al., 2017), whose relative abundances increased by 39.4 ± 0.1% and 46.2 ± 0.1%, when biochar was dosed. Acetoclastic and hydrogenotrophic methanogens, like *Methanosaeta* sp. and *Methanolinea* sp., were also detected in the two digesters. *Methanosaeta* sp. was dominant, indicating that the main pathway of methanogenesis was acetate utilization. Biochar addition increased the populations of these methanogens. Overall, these variations suggested that biochar changed microbial community in an expected direction for anaerobic digestion, aligning with the higher VS destruction and increased methane production.

3.6. Implications for sludge treatments

This work revealed for the first time that anaerobic digestion of primary sludge (PS) by dosing corn stover biochar can combine the benefits of higher high-quality methane production and greater VS destruction to maximize energy recovery and sludge reduction.

More importantly, WAS is the other major sludge stream in existing WWTPs, which is also generally treated by anaerobic digestion. The previous studies (Shen et al. 2015b and 2017) demonstrated that corn stover bioc har was effective in increasing methane production from WAS. Therefore, as shown in Fig. 6, this study suggested that corn stover biochar could be dosed in an anaerobic digester with the mixture of WAS and PS to enhance anaerobic digestion instead of separate anaerobic treatment in WWTPs, remarkably reducing the treatment cost. The high high-quality methane produced by biochar addition would substantially reduce energy/cost for biogas cleanup and upgrading processes. Furthermore, sludge anaerobic digestion with corn stover biochar dosed is an integrated process based on waste control by waste. Using waste corn stover as raw materials, the cost of biochar production is only associated with the machinery and heating, approximately $4 per gigajoule. No additional treatment is required for the biochar in the digestate, which could function as fertilizer for soil and reduce the mobility and bioavailability of toxic chemicals in contaminated soil. Therefore, this technology attains double effects in technology and economy.

(Approximate position for Fig. 6)

4. Conclusions

The biochar-addition (1.82 -3.06 g/g TS) technology enhanced methane production from PS with high-quality biomethane. Model analysis revealed that biochar increased the maximum methane production rate, the hydrolysis rate and methane potential of PS. Biochar provided the strong buffering capacity, alleviated NH_3 inhibition and increased sludge conductivity. In the continuous test, biochar increased VS destruction by 14.9% with 14% reduced volume of digestate. Microbial community was changed by biochar in an expected direction for anaerobic digestion. Biochar technology should implemented on the mixture of WAS and PS to maximize the energy recovery and sludge reduction from the two sludge streams.

Appendix A. Supplementary data

E-supplementary data for this work can be found in e-version of this paper online.

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List of Figures and Tables

Table 1

Main characteristics of corn stover biochar used in this study.

Analysis	Contents	Corn stover biochar
Chemical	pH	10.1 ± 0.4[d]
	C[a]	55.31 ± 0.50
	H[a]	0.29 ± 0.03
	N[a]	0.52 ± 0.06
	O[a]	0.21 ± 0.03
	H/C[b]	0.063 ± 0.012
	O/C[b]	0.003 ± 0.0001
	N/C[b]	0.008 ± 0.0001
	Total Na[c]	1.2 ± 0.3
	Total K[c]	58.4 ± 1.2
	Total Si[c]	66.8 ± 1.7
	Total Ca[c]	12.2 ± 0.8
	Total Al[c]	9.1± 0.9
	Total Mg[c]	9.8 ± 1.2
	Total Fe[c]	5.1 ± 0.6
	Total Ti[c]	0.9 ± 0.1
Physical	Surface area (m^2/g)	302.6 ± 9.1
	Total pore volume (cm^3/g)	0.11 ± 0.01
	Average diameter of pores (nm)	5.9 ± 0.3

[a] Indicate weight percentage (wt%);

[b] Indicate molar ratio;

[c] Indicate mg/g;

[d] Indicate standard deviations.

Table 2

Estimated the maximum methane production rate (*P*), the hydrolysis rate (*k*) and biochemical methane potential (*B*) of PS in anaerobic digester with different biochar dosage based on model analysis.

Biochar	Parameters		
	P (mL CH_4/g VS/d)	*k* (d^{-1})	*B* (mL CH_4/g VS)
0 g/g TS	69.9 ± 2.2[a]	0.31 ± 0.01	328 ± 4
1.82 g/g TS	107.5 ± 7.5	0.51 ± 0.04	373 ± 6
2.55 g/g TS	81.1 ± 1.3	0.42 ± 0.02	353 ± 5
3.06 g/g TS	78.3 ± 1.5	0.42 ± 0.03	341 ± 5

[a] Indicate standard deviations.

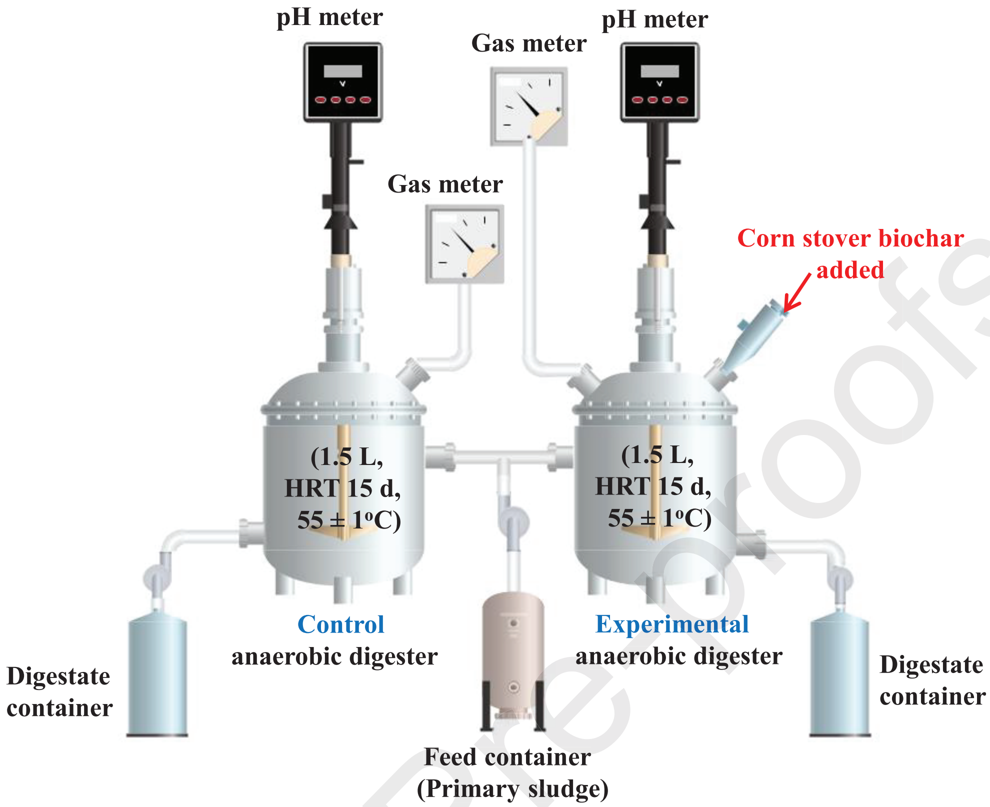


Fig. 1. Schematic diagram of the continuously operated bench-scale anaerobic digesters.

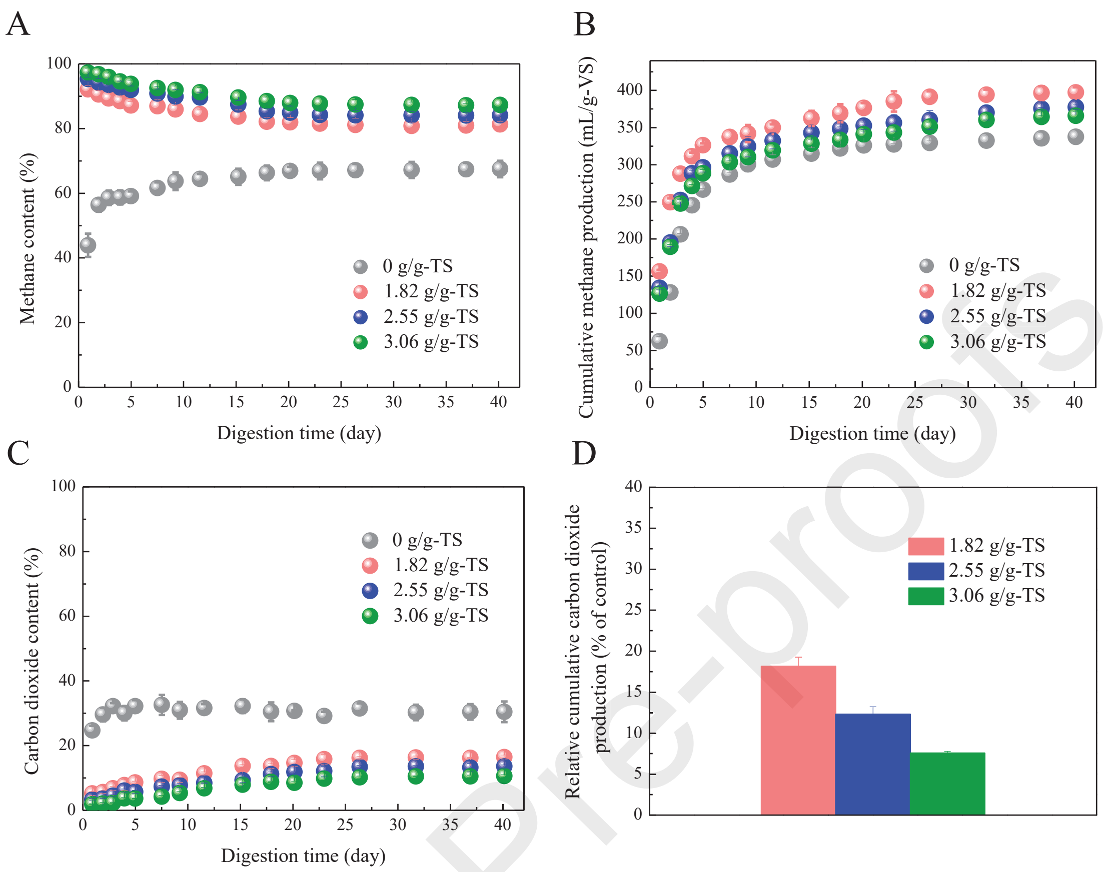


Fig. 2. Effects of the biochar at the different dosages on the methane content (A), cumulative methane production (B), carbon dioxide content (C) during PS anaerobic digestion and relative cumulative carbon dioxide production of the control after the entire period (D). Error bars represent standard deviations.

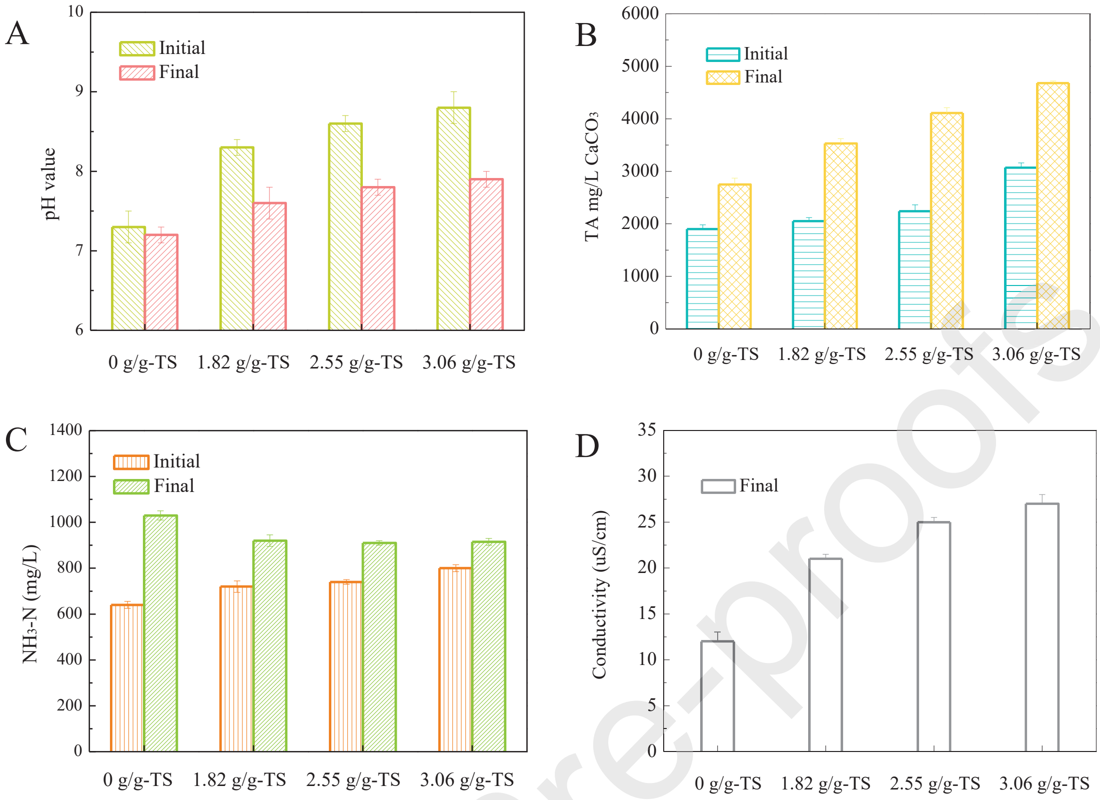


Fig. 3. The main charateristics of sludge before and after anaerobic digestion with different dosages of biochar: pH values (A), alkalinity (TA) (B), ammonia nitrogen (NH_3-N) (C) and conductivity (D). Error bars represent standard deviations.

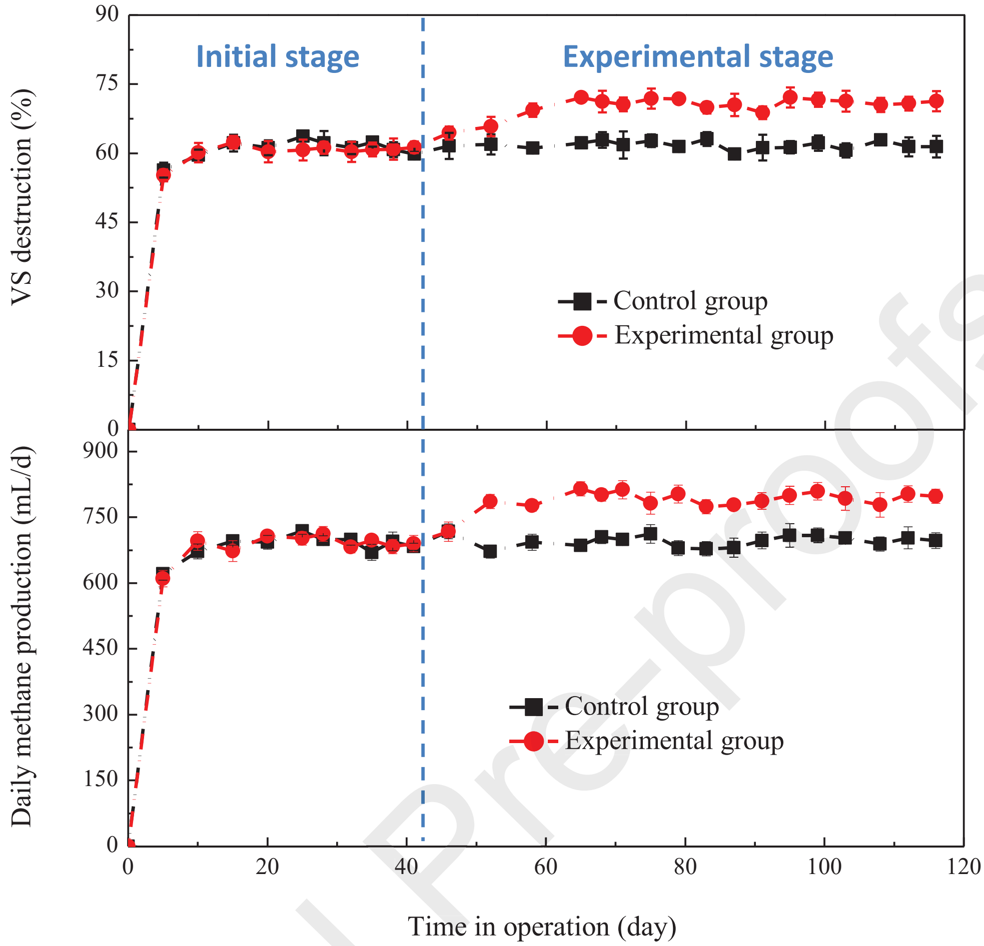


Fig. 4. VS destruction (top) and daily methane production (bottom) in the control digester and experimental digester with biochar added during the initial and experimental stage. Error bars represent standard deviations.

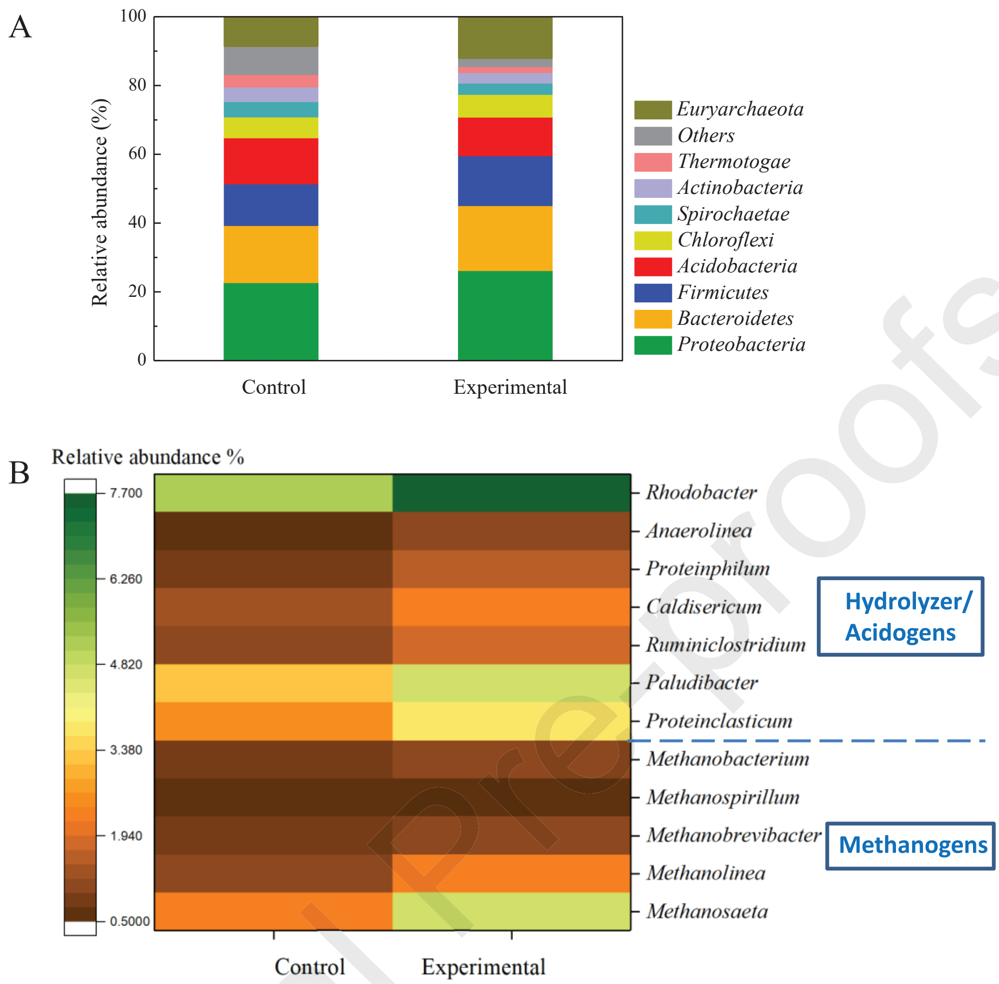


Fig. 5. Microbial community in the control and experimental digester: distributions of microbial phyla (A) and heat map showing the relative abundances of microbial genus related to anaerobic digestion.

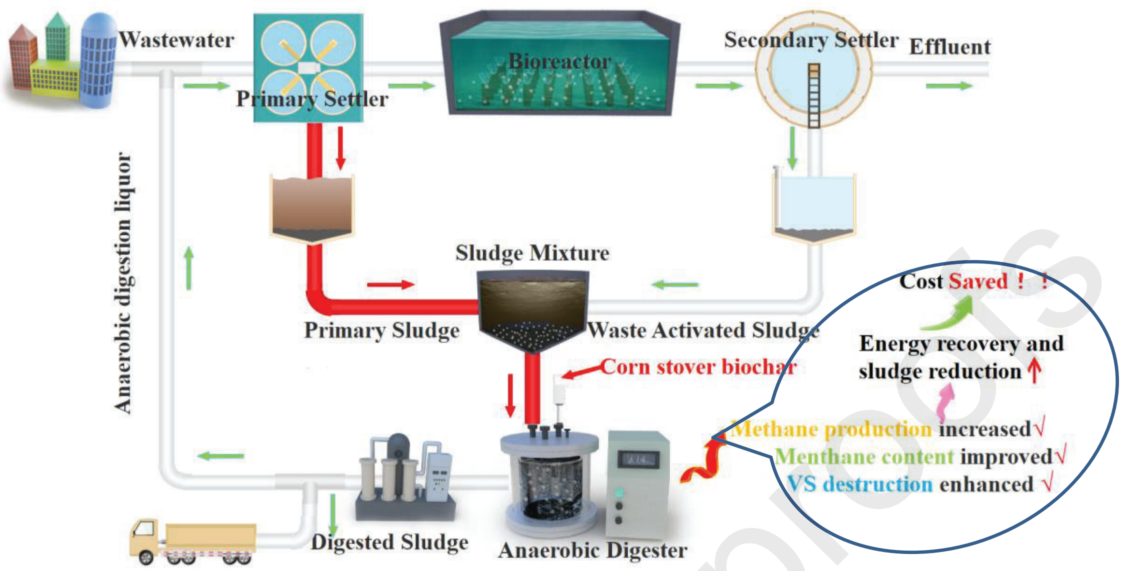
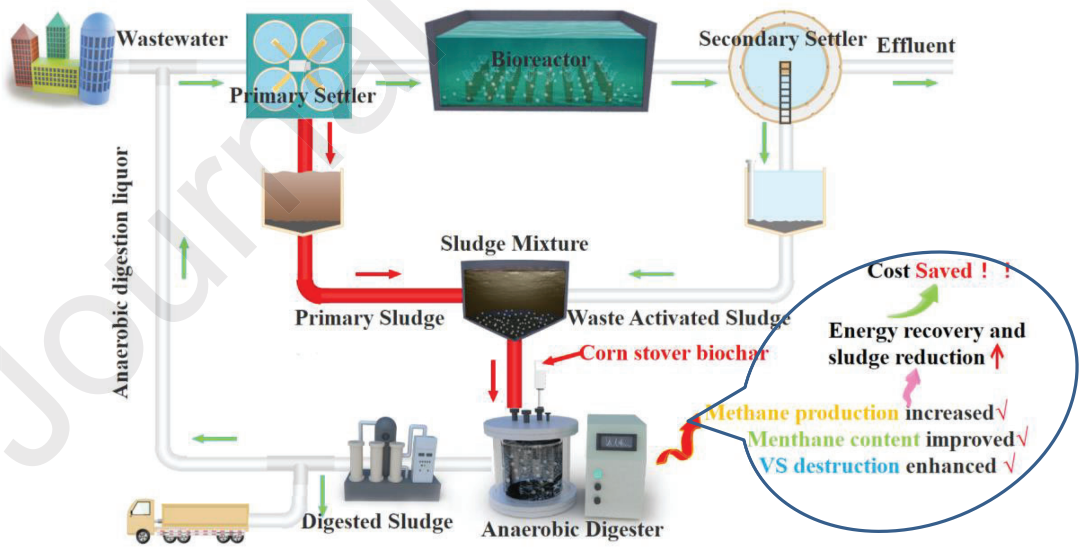


Fig. 6. Conceptual graph of the applied biochar-addition technology for enhancing energy recovery and sludge reduction in a wastewater treatment plant.

Graphical abstract


Wastewater
Primary Settler
Bioreactor
Secondary Settler
Effluent
Anaerobic digestion liquor
Sludge Mixture
Primary Sludge
Waste Activated Sludge
Corn stover biochar
Cost Saved ! !
Energy recovery and
sludge reduction ↑
Methane production increased√
Menthane content improved√
VS destruction enhanced √
Digested Sludge
Anaerobic Digester

Highlights