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Conversion of Materials and Energy in Anaerobic Digestion of Sewage Sludge with High-Pressure Homogenization Pretreatment

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Abstract: High pressure homogenization (HPH) pretreatment can improve sludge anaerobic digestion; however, the relationship among the material, energy conversion, and gas production efficiency was unclear under different operating conditions in sludge anaerobic digestion by HPH pretreatment. In this study, the performance of HPH pretreatment before sludge anaerobic digestion was investigated, and the relationship among the material, energy conversion, and gas production efficiency was explored. HPH pretreatment induced organic solubilization, and a maximum soluble chemical oxygen demand (SCOD)/total chemical oxygen demand (TCOD) of about 30% was achieved. Results showed that HPH pretreatment significantly improved the biogas production of sludge anaerobic digestion; the maximum increase in CH_4 yield was 57%; and the anaerobic digestion period was shortened by about 10 days. The ratio of CH_4 yield increment to volatile dissolved solids (VDS) increment was 0.21 mL/mg. The CH_4 yield increment of 1 L/g volatile solid (VS) required a specific energy of 0.10 MJ/kg total solid (TS) by increasing the pressure with one cycle and 0.72 MJ/kg TS by increasing the cycle at 60 MPa. The minimum additive energy consumption of HPH pretreatment was 125 J/mL CH_4 yield increment at 20 MPa with one cycle. Considering CH_4 yield improvement and energy conservation, HPH pretreatment should maintain a pressure of no more than 60 MPa in one cycle. This study provides a theoretical reference for the practical application of HPH pretreatment in anaerobic digestion. HPH holds promise as a potential strategy for sewage sludge pretreatment to produce CH_4 in anaerobic digestion.

Keywords: high-pressure homogenization; sludge anaerobic digestion; organic release; biogas production; CH_4 yield; energy consumption

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1. Introduction

Sewage sludge, consisting of massive biological mass, is a very important renewable energy source in wastewater treatment plants (WWTPs). The activated sludge processes produce large amounts of excess sludge, which can cause serious environmental and health issues [1]. Recovery of sustainable energy from sewage sludge complies with the sustainability principle and is becoming more and more interesting [1,2]. To deal with the sludge problem, many technologies have been developed for wastewater and sludge treatment. Sludge anaerobic digestion is an attractive option that can convert organic matter in sewage sludge into biogas. Biogas is a by-product of anaerobic digestion and is further converted into heat and electricity [3,4]. Energy recovery through biogas utilization enables the WWTPs to partially realize energy self-sufficiency [5,6]. For decades, sludge anaerobic digestion has been more and more common in WWTPs.

Anaerobic digestion is a multiple-stage process that mainly consists of hydrolysis, acidogenesis, and methanogenesis [7]. Generally, hydrolysis becomes the speed-limit step in sludge anaerobic digestion for biogas production [8,9]. Sewage sludge mainly consists of extracellular polymeric substances (EPS) and microbiota and can be relatively difficult to degrade in anaerobic digestion [10,11]. Sludge disintegration can disrupt the sludge flocs and microbial wall and release organic components into the liquid phase, which enhances the rate and extent of anaerobic digestion to produce biogas [12]. Therefore, the application of sludge disintegration methods can greatly cut down the anaerobic digestion period and enhance biogas production. Generally, sludge disintegration methods involve physical, chemical, and biological methods or their combinations [13,14]. These pretreatment methods aim to disintegrate the sludge flocs, thereby accelerating the overall anaerobic digestion and improving biogas production. However, these methods are characterized by high energy consumption and complex chemical requirements, thus limiting their application in practical engineering [15,16]. It is of great importance to use efficient pretreatment methods to increase hydrolysis efficiency and enhance methane production.

High-pressure homogenization (HPH) technology has been widely used in the food, chemical, and pharmaceutical industries due to its simple operation, non-pollution, and excellent homogenization effect [17]. HPH pretreatment can destroy microbial walls to release intracellular materials and has obvious advantages for improving sludge anaerobic digestion [18]. Sludge HPH pretreatment was an excellent mechanical disintegration method to improve hydrolysis and biogas production stages in anaerobic digestion [15,19]. The combination of HPH disintegration and anaerobic digestion has been successfully demonstrated in Germany and has gained acceptance in existing WWTPs [20,21]. WWTPs can use biogas, a by-product of the anaerobic digestion process, to achieve partial energy self-sufficiency [6]. The process of HPH technology combined with anaerobic digestion could significantly reduce excess sludge and enhance biogas production [15]. Nabi et al. [19] achieved a biogas production of 240 mL/g total chemical oxygen demand (TCOD)·d in an expanded granular sludge blanket for HPH pretreatment of sludge. However, the relationship among material, energy conversion, and gas production efficiency was unclear under different operating conditions in sludge anaerobic digestion by HPH pretreatment.

This study aimed to explore the relationship among material, energy conversion, and gas production efficiency in anaerobic digestion of sludge by HPH pretreatment. Specifically, the objectives were: (1) to evaluate sludge disintegration by the changes in sludge chemical characteristics related to anaerobic digestion using HPH pretreatment; (2) to express the effect of HPH pretreatment on sludge anaerobic digestion for biogas and CH_4 production; and (3) to calculate the optimal operating parameters in energy cost of HPH pretreatment for improving biogas yield based on biogas yield and energy conservation. HPH holds promise as a potential strategy for sewage sludge pretreatment to produce CH_4 in anaerobic digestion. These findings provide a deeper insight into HPH technology's application in anaerobic digestion.

2. Materials and Methods

2.1. Materials

Sewage sludge was sampled from the membrane bioreactor process at a WWTP in Beijing, China. Before HPH pretreatment, thickened sewage sludge with a total solid (TS) of 15.0 g/L, a volatile solid (VS) of 10.3 g/L, a chemical oxygen demand (SCOD) of 0.12 g/L, and a pH of 7.01 was obtained by gravity settling. Sewage sludge was stored at 4 °C until use. Seed sludge used for anaerobic digestion was gathered from the anaerobic digestion tank of a municipal wastewater treatment plant in Beijing, China, with a TS of 106.4 g/L, a volatile solid (VS) of 60.2 g/L, a SCOD of 0.12 g/L, and a pH of 7.01.

The basal medium contained the nutrients required for optimal anaerobic microbial growth. The ingredients used in the basal medium were as follows: KH_2PO_4 of 2.6 g/L, $Na_2HPO_4 \cdot 7H_2O$ of 4.8 g/L, $NaHCO_3$ of 0.6 g/L, NH_4Cl of 1.8 g/L, $MgSO_4 \cdot 7H_2O$ of 0.8 g/L, $CaCl_2 \cdot 2H_2O$ of 0.7 g/L, $FeSO_4 \cdot 7H_2O$ of 16.8 g/L, H_3BO_3 of 0.3 g/L, $Al_2(SO_4)_3 \cdot 18H_2O$ of

0.7 g/L, $MnCl_2 \cdot 4H_2O$ of 0.3 × 10^3 g/L, $CuSO_4 \cdot 5H_2O$ of 0.6 g/L, $NaEDTA \cdot 2H_2O$ of 2.8 g/L, $ZnCl_2$ of 0.3 g/L, $Na_2(Mo)O_4 \cdot H_2O$ of 0.5 g/L, $CoCl_2 \cdot 6H_2O$ of 0.3 g/L, and $NiCl_2 \cdot 6H_2O$ of 0.6 g/L.

2.2. HPH Pretreatment of Sewage Sludge

HPH pretreatment was set to 20, 30, 40, 60, and 80 MPa HPH pressure and 1, 2, and 3 HPH cycles by a high-pressure homogenizer (APV-2000, Homotech (Beijing) Fluid Technology Co., Ltd., Beijing, China). A high-pressure homogenizer mainly consists of an impact ring, homogenizer valve, valve seat, and positive displacement pump. To study the effect of homogenization cycle number, 1 to 3 homogenization cycles were chosen at a 60 MPa homogenization pressure, according to a previous study [22]. For each HPH experiment, 500 mL of sewage sludge was disintegrated in a homogenizer with a sludge current velocity of 30 L/h.

Energy consumption (E, MJ) of HPH pretreatment was defined on the basis of Equation (1) [22].

$$E = PNV \tag{1}$$

where P is HPH pressure (MPa), N is the number of HPH cycles, and V is sludge sample volume (m^3).

The specific energy (E_S, MJ/kg TS) for the HPH pretreatment was calculated according to Equation (2).

$$E_S = \frac{E}{V \times TS_0} \tag{2}$$

where TS_0 is initial sludge TS (kg/m^3).

2.3. Sludge Anaerobic Digestion

Anaerobic digestion was studied in serum bottles of 250 mL at a temperature of 35 °C. The reactor for anaerobic digestion was equipped with a biogas collection system. Anaerobic reactors were first blown with nitrogen for 5 min to create an anaerobic environment; seed sludge of 100 mL and basal medium were added [23], and sewage sludge of 100 mL was added after 24 h. These fermentation systems were cultured at 35 °C in a constant temperature incubator (HZQ-F160, Shanghai Baidian Instrument Equipment Co., Ltd., Shanghai, China) at a stirring rate of 140 r/min. Biogas production was recorded daily. The experimental period of anaerobic digestion was 30 d.

The additional energy consumption to increase CH_4 production from anaerobic digestion with HPH pretreatment was just the pretreatment energy consumption. Therefore, the additional energy consumption per unit CH_4 yield increment of 1 L/g VS (E_m, MJ/m^3) can be calculated by Equation (3).

$$E_m = \frac{E}{V(CH_4) - V_0(CH_4)} \tag{3}$$

where $V(CH_4)$ and $V_0(CH_4)$ were the CH_4 yields of sewage sludge with and without HPH pretreatment, respectively.

2.4. Analysis Methods

TS, VS, VSS, and SCOD concentration tests were conducted according to APHA standard methods [24]. Sludge pH was determined by a pH meter (pH-meter 537, WTW, Munich, Germany). For volatile fatty acid (VFA) concentration, sludge samples were centrifuged at 10,000× g for 10 min by a high-speed centrifuge (HC-2518R, Anhui Zhongke Equipment Co., Ltd., Tongcheng, China), then filtered by a 0.45 μm filter membrane to obtain the filtrate. VFA concentration was measured using a gas chromatograph (Agilent, GC Model 8860, Santa Clara, CA, USA), as described in detail by Wang et al. [25]. The filtrate was first acidified with 3% H_3PO_4 in a 1.5 mL gas chromatography (GC) vial. An Agilent 8860 GC (Santa Clara, CA, USA) with a capillary free fatty acid phase (polarity) column (DB-FFAP, 30 m × 0.25 mm × 0.25 mm) and a flame ionization detector (FID) was employed to measure VFAs. The temperatures of the injection and detector were 250 °C and 300 °C, respectively. N_2 was the carrier gas, with a flow rate of 2.6 mL/min. The GC oven was programmed to raise the temperature to 180 °C. The initial temperature of the GC oven was 70 °C for 3 min, followed by a ramp of 20 °C/min for 5.5 min, and a final temperature of 180 °C for 3 min. Biogas composition was monitored by a gas chromatograph (GC7890, Tianmei Equipment Co., Ltd., Shanghai, China) with a thermal conductivity detector (TCD) as described in detail by Fang et al. [26]. The column oven temperature was 120 °C, the injector temperature was 140 °C, and the thermal conductivity detector (TCD) temperature was 150 °C.

2.5. Statistical Analysis

All experiments and physicochemical indexes were executed in triplicate, and the results were expressed as the mean ± standard deviation. Data were analyzed using SPSS 22.0 software for one-way analysis of variance and Tukey's HSD test as a post-hoc method. $p < 0.05$ was considered statistically significant.

3. Results and Discussion

3.1. Change of HPH Pretreatment on Sludge Characteristics

The sludge disintegration using HPH pretreatment was estimated by the change in sludge chemical characteristics, which were related to the sludge's anaerobic digestion (Table 1). As HPH pretreatment enhanced organic solubilization in sewage sludge, SCOD, volatile dissolved solids (VDS = VS − VSS), and VFA concentrations in the sludge supernatant presented an obvious increase with pressure and cycle increasing ($p < 0.05$). SCOD and VDS concentrations increased by about 8–37 times, and VFA concentrations increased by about 3–7 times. Sludge pH had a significant decrease from 7.22 to 6.78 ($p < 0.05$) due to the VFA generation during HPH pretreatment. SCOD, VDS, and VFA concentrations of sludge supernatant were significantly enhanced with HPH pressure and cycle number ($p < 0.05$), which is similar to previous studies [26,27]. Some studies showed that the three mechanisms of eddies in turbulence flow—impingement and cavitation—were essential for sludge disintegration [28,29]. Therefore, HPH changed the chemical properties of sludge in relation to the homogenizing pressure and number. HPH pretreatment had a positive effect on sewage sludge disintegration, such as SCOD, VDS, and VFA, which was beneficial to further anaerobic digestion for CH_4 production.

Table 1. Changes in some sludge characteristics before and after HPH pretreatment at different pressures and cycle numbers.

HPH Conditions		SCOD (mg/L)	VDS (mg/L)	VFA (mg CH_3COOH/L)	pH
Pressure (MPa)	Cycle Number				
0	0	120.42 ± 8.19	99.10 ± 6.96	72.23 ± 5.24	7.31 ± 0.072
20	1	1434.3 ± 100.9	676.2 ± 44.4	222.4 ± 16.8	7.22 ± 0.064
30	1	1661.7 ± 112.3	994.8 ± 50.5	276.3 ± 13.2	7.14 ± 0.056
40	1	2005.8 ± 161.4	1223.6 ± 80.3	324.2 ± 20.7	7.04 ± 0.048
60	1	3018.9 ± 184.5	1963.4 ± 121.1	343.6 ± 30.8	6.95 ± 0.031
80	1	3498.2 ± 202.8	2183.8 ± 151.7	358.8 ± 26.6	6.80 ± 0.021
60	1	3018.3 ± 184.5	1963.3 ± 121.1	343.3 ± 30.8	6.95 ± 0.031
60	2	3844.5 ± 242.3	2530.2 ± 161.9	408.4 ± 40.4	6.85 ± 0.025
60	3	4496.2 ± 275.8	2742.6 ± 183.2	499.5 ± 45.9	6.78 ± 0.020

Generally, the organic materials in sludge supernatant are more easily degraded in anaerobic digestion than those in sludge solids [28]. Figure 1 shows that HPH pretreatment enhanced sludge disintegration, further leading to organic component release into the liquid phase to a great extent. Increasing the HPH pressure and cycle number significantly enhanced the sludge disintegration ($p < 0.05$). Both VDS/VS and SCOD/TCOD were about 1% for raw sewage sludge and increased by about 20% with a HPH pressure of 80 MPa. The VDS/VS and SCOD/TCOD increased by about 10% with three HPH cycles instead of a single HPH cycle at 60 MPa. The increases in VDS/VS and SCOD/TCOD were favorable to further anaerobic digestion due to the improvement of biodegradation performances. Therefore, the above results indicate that HPH pretreatment significantly disrupted the structure of sludge and provided suitable conditions for subsequent anaerobic digestion for CH_4 production.

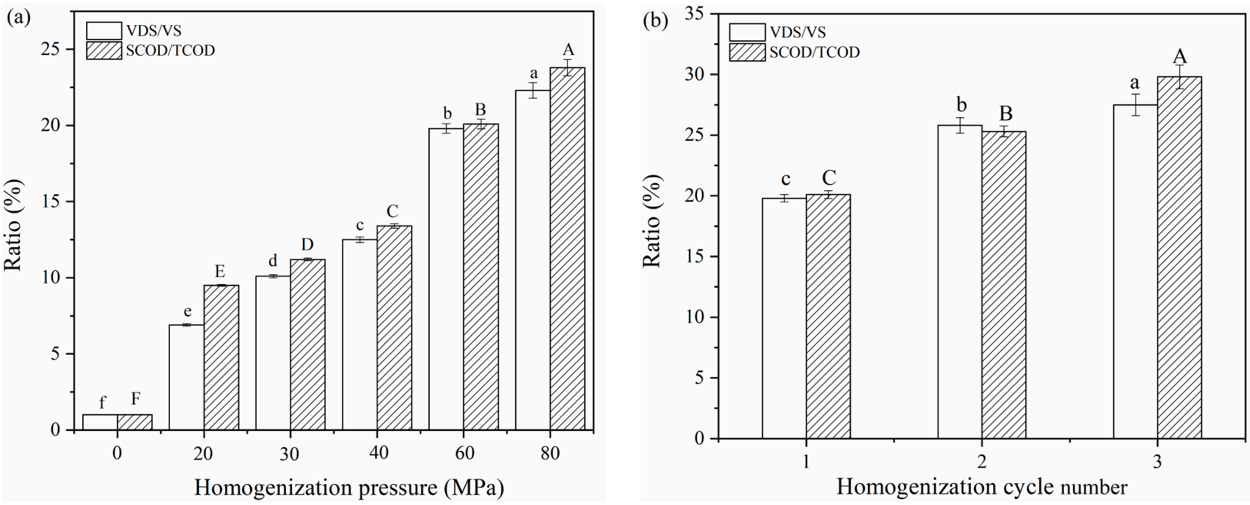

Figure 1. Effect of VDS/VS and SCOD/TCOD on HPH pressure with a single HPH cycle (**a**) and HPH cycle number at a HPH pressure of 60 MPa (**b**) (Different letters represent significant differences between treatments ($p < 0.05$)).

3.2. Effect of HPH Pretreatment on Biogas Yield and Rate of Sludge Anaerobic Digestion

Figure 2 shows the biogas yield and rate of sludge anaerobic digestion with raw sludge and sludge pretreated with HPH. The normalization of biogas production was done according to VS added to reactors [23]. As shown in Figure 2a,c, not only the cumulative biogas yield but also the biogas yield rate increased with increasing HPH pressure. Cumulative biogas yield increased by 22.1%, and the anaerobic digestion period was reduced from about 20 to 10 d for a biogas production of 90% at a HPH pressure of 80 MPa. Sun et al. [30] used hydrocyclone-induced pretreatment to disintegrate sludge, and though the CH_4 yield was 134.3 mL/g TS, which was similar to this study, the retention time of sludge anaerobic digestion was significantly shortened. HPH pretreatment decreased the retention time of sludge anaerobic digestion, which mainly resulted from the biodegradable organics released from sludge solids into the supernatant [31,32]. Shortening the retention time will greatly increase the digester capacity or reduce the digester volume. Moreover, multiple-cycle operation was beneficial to enhancing biogas production (Figure 2b,d). However, the improvement of multiple HPH cycle operations was insignificant compared to the results from HPH pressure.

Table 2 shows the total biogas and CH_4 yield of raw sludge and sludge pretreated with HPH during anaerobic digestion. As the HPH pressure and cycle increased, biogas and CH_4 yield increased. Biogas yield increased by 4–25%, CH_4 content in biogas improved by 12–25% and CH_4 yield increased by 18–57% compared to the anaerobic digestion of raw sludge. HPH pretreatment greatly enhanced biogas and CH_4 production efficiency. The highest CH_4 yield reached 141 mL/g VS at 80 MPa pressure, which was significantly higher than thermal, acidic, and alkaline pretreatments [33]. High HPH pressure and multiple HPH cycles had the benefit of increasing the CH_4 yield, which might be attributed to the release of dissolved organics [26]. Nabi et al. [31] also suggested that the dissolution of organic matter in sludge flocs and microorganisms after sludge HPH pretreatment led to effective biochemical transformation, further increasing biogas generation. These results agreed with the VDS/VS and SCOD/TCOD changes in Figure 1.

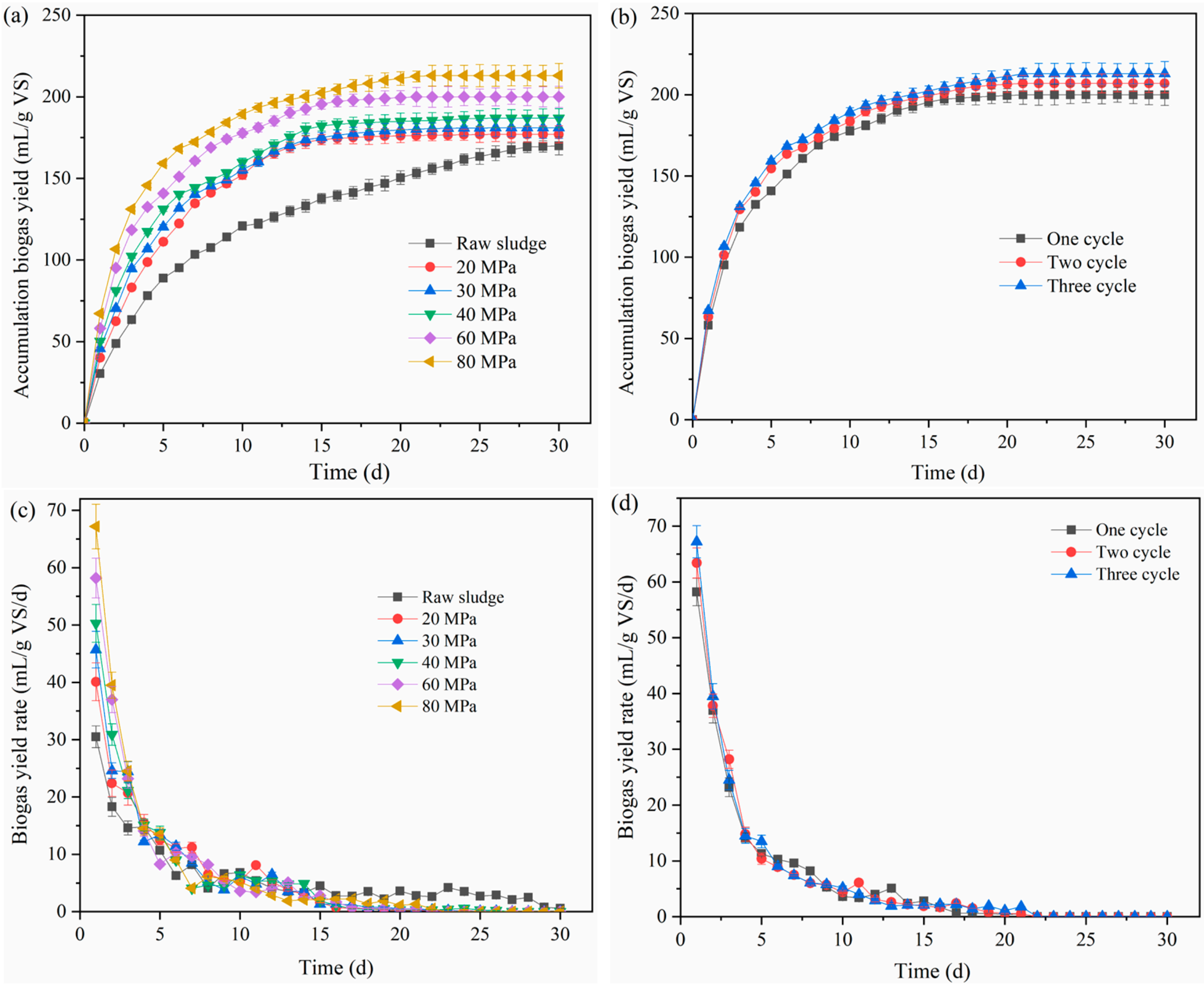

Figure 2. Cumulative biogas production at different homogenization pressures with a single homogenization cycle (**a**), cumulative biogas production with different homogenization cycles at a homogenization pressure of 60 MPa (**b**), biogas production rate at different homogenization pressures with a single homogenization cycle (**c**), and biogas production rate with different homogenization cycles at a homogenization pressure of 60 MPa (**d**) of sludge anaerobic digestion.

Table 2. Biogas yield and CH_4 yield before and after HPH pretreatment at different pressures and cycle numbers.

HPH Conditions		Biogas Yield (mL/g VS)	CH_4 Content (%)	CH_4 Yield (mL/g VS)
Pressure (MPa)	Cycle Number			
0	0	170.1± 6.5	53.2 ± 3.2	90.0 ± 4.2
20	1	177.3 ± 7.1	59.7 ± 3.4	106.4 ± 4.5
30	1	181.6 ± 7.3	61.8 ± 4.2	112.6 ± 5.0
40	1	187.3 ± 8.6	63.3 ± 4.6	118.9 ± 5.4
60	1	200.5 ± 9.4	64.9 ± 5.3	130.4 ± 6.1
80	1	213.2 ± 11.3	65.6 ± 5.6	140.6 ± 6.5
60	1	200.5 ± 8.42	64.9 ± 5.3	130.3 ± 6.1
60	2	207.8 ± 10.2	65.8 ± 4.9	136.6 ± 6.2
60	3	213.9 ± 10.8	66.3 ± 5.3	141.3 ± 6.3

Some EPS and intracellular materials were released into the liquid phase with HPH pretreatment, causing the VDS increase. The VDS increase improved the efficiency of sludge anaerobic digestion as a result of the CH_4 yield increase. VDS increment and CH_4 yield increment had an excellent linear relationship with a coefficient of determination of 0.98 (Figure 3). The slope of 0.21 represented a 0.21 mL CH_4 yield increment per mg VDS increment, indicating that organic materials in sludge supernatant were more efficient for CH_4 yield than those in sludge solid.

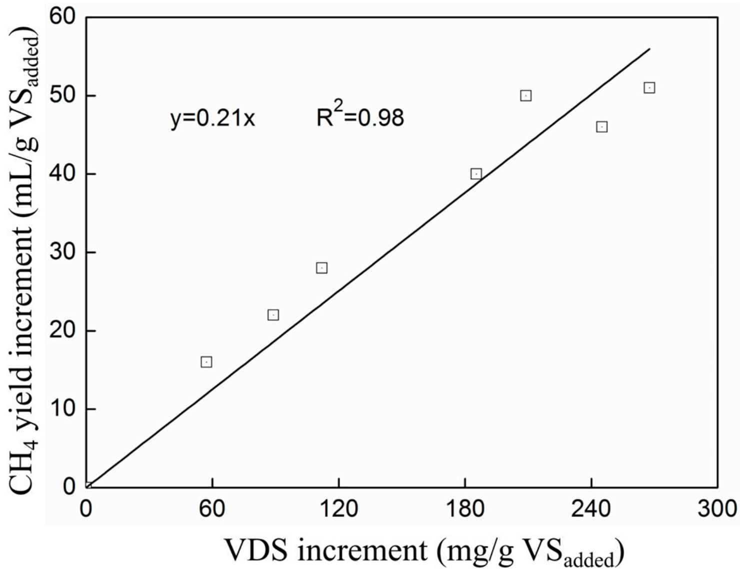

Figure 3. Correlations between VDS increment and CH_4 yield increment under different HPH operating conditions.

3.3. Additive Energy Consumption of HPH Pretreatment for Improvement of Biogas Production

HPH pretreatment increased CH_4 yield in sludge anaerobic digestion, while sludge disintegration using HPH pretreatment as a mechanical method required energy input. The additional energy cost of anaerobic digestion with HPH pretreatment was mainly due to the energy input from sludge HPH disintegration. Figure 4 shows the correlation between the specific energy consumption (E_S) of HPH pretreatment and the CH_4 yield increment. The E_S linearly increased with the CH_4 yield increment, indicating that the greater the increment in CH_4 yield, the more energy input was required. The E_S of 0.10 MJ/kg TS was needed to achieve 1 L/g VS of CH_4 yield increment by HPH pretreatment with a single HPH cycle (Figure 4a), whereas the E_S of 0.72 MJ/kg TS was required to obtain the same CH_4 yield increment by changing the HPH cycle at 60 MPa (Figure 4b). These results showed that adjusting the HPH pressure was more energy-efficient than changing the HPH cycle to achieve the same CH_4 yield increment.

Though higher HPH pressure and cycle greatly enhanced the CH_4 yield (Table 2), the energy cost increased with increasing HPH pressure and cycle. Figure 5 shows the change in additional energy consumption (E_m) of HPH pretreatment per unit CH_4 increment under different operation conditions. The minimum E_m of 125 J/mL CH_4 yield increment within the experimental conditions was obtained at a HPH pressure of 20 MPa. The gradual E_m increase was observed in Figure 5a as the HPH pressure increased at 20–80 MPa, showing that increasing the HPH pressure was disadvantageous for energy conservation ($p < 0.05$). The E_m increase was firstly remarkable with a HPH pressure increase from 20 to 30 MPa, and insufficient sludge disintegration might affect the CH_4 production. Then the E_m increase became slower as the HPH pressure increased from 20 to 60 MPa. While a rapid increase in E_m was observed again when the HPH pressure increased from 60 to 80 MPa, indicating that the optimum HPH pressure might not be higher than 60 MPa considering both CH_4 yield improvement and energy conservation. Furthermore, Figure 5b shows that the E_m

was significantly influenced by increasing the HPH cycle, and the E_m of two and three HPH cycle operations increased by 74% and 135%, respectively, compared to a single HPH cycle, indicating that HPH pretreatment with a single HPH cycle was more energy-efficient than that with HPH cycles.

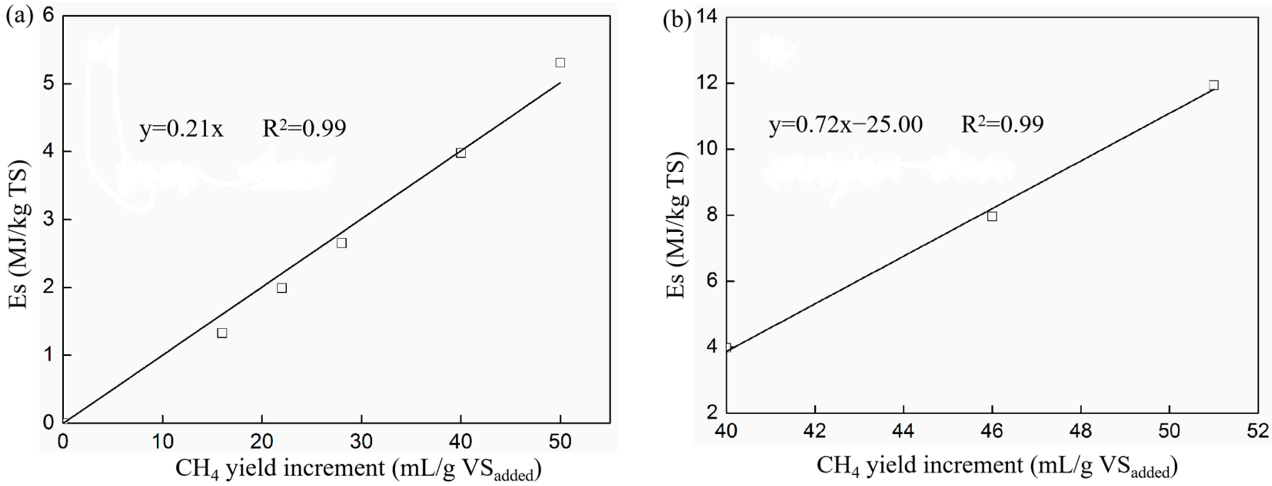

Figure 4. Correlations between specific energy (E_S) of HPH pretreatment and CH_4 yield increment (**a**) at HPH pressures with a single HPH cycle of 20, 30, 40, 60, and 80 MPa and (**b**) 1, 2, and 3 cycle numbers at a 60 MPa HPH pressure.

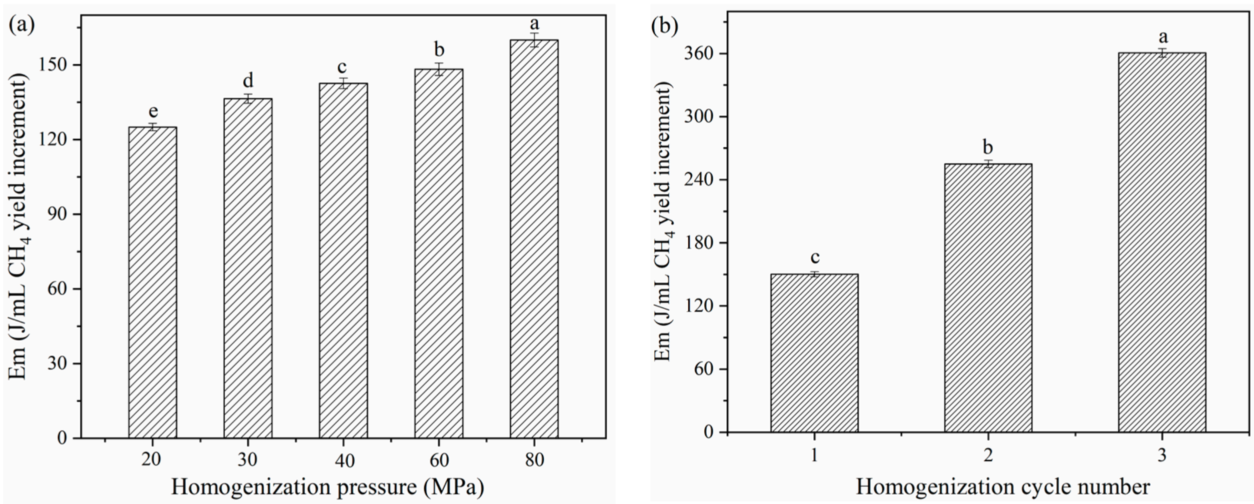

Figure 5. Changes in additional energy consumption (E_m) under different operating conditions. At HPH pressure with a single HPH cycle (**a**) and HPH cycle number at a 60 MPa pressure (**b**) (Different letters represent significant differences between treatments ($p < 0.05$)).

4. Practical Implication on HPH Pretreatment Enhancement in Anaerobic Sludge Digestion

Hydrolysis is normally the speed-limit step in sludge anaerobic digestion for CH_4 production [26], because sewage sludge mainly consists of extracellular polymeric substances (EPS) and microbiota and can be relatively difficult to degrade in anaerobic digestion [33]. HPH pretreatment can destroy sewage flocs and microbial walls to release EPS and intracellular materials, showing obvious advantages for improving sludge anaerobic digestion. Most studies showed that HPH technology combined with anaerobic digestion could significantly reduce sludge amounts and enhance CH_4 production [25,28]. However, it is very important that sludge pretreatment be energy-positive. In this study, energy consumption increased with the increase in HPH pretreatment pressure and cycle number. Considering

CH_4 yield improvement and energy conservation, the HPH pretreatment should maintain a pressure of no more than 60 MPa in one cycle. Therefore, the suitable energy-saving parameters are a pressure no higher than 60 MPa with one cycle. HPH technology has been widely used in the food, chemical, and pharmaceutical industries. However, the following issues regarding sludge HPH pretreatment for anaerobic digestion and high-pressure homogenization still need to be addressed in practical application. (1) High-pressure homogenizers are prone to being clogged in the homogenizing valve when treating highly concentrated sludge, which reduces the cracking performance and decreases the valve life. However, the increase in sludge concentration is conducive to improving the comprehensive efficiency of HPH pretreatment and anaerobic digestion. Therefore, the improvement of homogenizing equipment should be enhanced, especially the selection of suitable valves for different kinds of sewage sludge. (2) HPH pretreatment parameters should be further optimized or used in conjunction with other disintegration technologies to further improve HPH disintegration performances and reduce operation costs. (3) The application of sludge HPH pretreatment prior to anaerobic digestion improves the performance of anaerobic digestion, but energy consumption greatly increases. Mixing the HPH pretreated sludge and unpretreated sludge in a certain proportion for anaerobic digestion may improve the anaerobic digestion performance as well as reduce the energy consumption of HPH.

5. Conclusions

HPH pretreatment prior to anaerobic digestion of sludge led to organic material solubilization and an increase in SCOD, VDS, and VFA concentrations, which enhanced biogas production. HPH significantly shortened the time for anaerobic fermentation of sludge and improved biogas production. Higher pressure and multiple cycles were beneficial to the increase in CH_4 yield. The CH_4 yield increment was linear with the VDS increment. A specific energy of 0.62 MJ/kg TS was saved to realize a per-unit CH_4 yield increment by enhancing pressure instead of increasing the cycle. Changing the HPH pressure was more energy-efficient than changing the HPH cycle number to achieve the same CH_4 yield increment. The additive energy consumption of HPH pretreatment increased with increasing pressure and cycle numbers. Therefore, the best energy-saving parameters are that pressure no higher than 60 MPa with one cycle is suitable for HPH pretreatment ahead of anaerobic digestion based on CH_4 yield improvement and energy conservation. This study provides a theoretical reference for the practical application of HPH pretreatment in anaerobic digestion. Moreover, further research is still needed to optimize process parameters for the practical application of HPH pretreatment in sludge anaerobic fermentation.

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