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Substrate-related features to maximize bioenergy potential of chemical enhanced primary treatment sludge

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Abstract

Primary treatment is a major component in modern sewage treatment systems; and chemical enhanced primary treatment (CEPT) process can further enhance its performance for energy recovery or process improvement. With significant benefits on small footprint and sludge dewaterability, CEPT process has been selected and applied as the major wastewater treatment technology in Hong Kong. CEPT sludge, similarly in composition to typical primary sludge, is rich in organic contents and therefore can serve as a proper source for bioenergy production after anaerobic digestion (AD). The heating value of CEPT sludge can be higher than that of secondary sludge, which is mainly composed of slowly degradable organics and microorganisms. If neglecting energy consumed to produce the coagulant a CEPT-AD system shall drive the wastewater treatment process from energy-negative practice to energy-neutral or even energy-positive systems. This paper demonstrates some of the most important substrate-related features to increase the bioenergy production in the CEPT-AD system. Attentions have been paid particularly on the analysis of physiochemical characteristics of the CEPT sludge and their impacts to the biological system with heterotrophic species. An innovative sulfide oxidation process was presented with experimental evidence to overcome the potential problems of sulfide induced growth inhibition of methanogens. It was expected that the new process could reduce approximately 0.744 kWh/m^3 of energy consumption in comparing with conventional activated sludge process without nutrient removal.

Keywords: Anaerobic digestion; Sludge; Biogas production; Bioenergy potential; CEPT

1. Introduction

Water and Energy Nexus is a critical element to achieve sustainable development of water management [1]. Energy consumption currently is mandatory to water and wastewater systems from collection, transportation, and

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treatment. Significant amount of energy consumption in the water management service has been noted by the society due to energy crisis and global warming [2]. For wastewater treatment processes (WWTPs), high stability and easy-to-operate nature of the activated sludge process (ASP) has made it the state-of-the art option for wastewater treatment in the developed and developing worlds [3]. Energy used in the aeration process (*i.e.*, conventional ASP and Nitrification-denitrification (NdN) processes (Fig. 1(a)) have resulted in high operation costs and power consumption in municipal services. Wastewater treatment plant operation and facilities shall be updated to resolve those potential problems.

Aeration is a critical stage to degrade certain emerging pollutants and nutrients in wastewater, hence is not suitable to be completely ruled out from wastewater works. The most feasible energy saving strategy for WWTP are majorly related to energy harvest by treating the sludge in anaerobic digester (AD) and convert organic solids into methane for power generation [4]. The new wastewater treatment concept for energy neutral operation was demonstrated in Fig. 1(b) [5]. It is well-known that primary sludge or sludge generated by short solid retention time (SRT) process exhibit higher amount of easily degradable compounds with higher heating value [6]. To maximize the energy potential of the sludge, a pretreatment process is applied to separate as much particulate (with adsorbed soluble contents) organics in the sewer as possible before aerobic treatment. The preliminary process (unit III in Fig. 1(b)) may either be a short SRT biological process, a conventional primary clarifier, or a chemical enhanced primary treatment (CEPT) process. The polishing process following the primary treatment can be a biological system operating under extremely long SRT or specifically design for low carbon/nitrogen water (*e.g.* Anammox) [7]. In our previous study we monitored and calculated the dynamic changes of aeration efficiencies over different observation periods [8], and calculated the total energy consumption of conventional ASP and NdN processes [4]. Further investigation should be carried out to clarify the energy benefits from a CEPT-AD process.

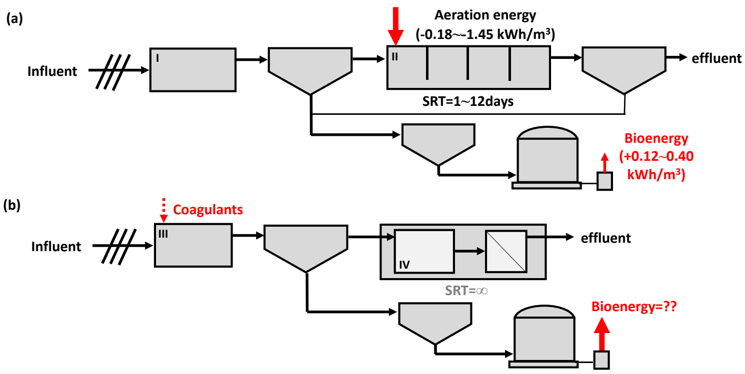

Fig. 1 Flow chart of (a) conventional and NdN wastewater treatment processes; and (b) CEPT process. Unit-I: pretreatment or grit chamber; unit-II: aeration tank (with baffles for NdN); unit-III: enhanced physical/chemical process; and unit-IV nutrient removal process.

CEPT was proposed to tackle the conflict between land use and water quality in highly populated cities like Leiden Noord [9] or Hong Kong [10]. Through the coagulation and flocculation in CEPT by adding ferric chloride and alum, particulate organics was trapped and precipitated at the bottom of primary clarifier and generates sludge. The Stonecutters Island Sewage Treatment Works (SCISTW) in Hong Kong currently treats approximately 1.4 million m^3 of municipal wastewater daily by using the CEPT process, resulting in nearly 600 tons of dewatered CEPT sludge which is a severe issue in treatment [11]. In this study, the CEPT sludge was therefore utilized as a representative case to apply AD process to maximize the energy potential instead of current incineration treatment. The results and experimental observations could be the reference for other solid wastes like contaminated papers, food container, and textile. The physiochemical characteristics of CEPT sludge were analyzed via studying the organic and inorganic components in the feedstock. The impacts of sulfide contents to the joint-activities of the microbial communities were studied through process control and real-time monitoring. Energy balance of CEPT and conventional WWTPs were quantified and the results were applied to build a pilot-plant in SCISTW.

2. Experiment

In order to provide key information and data for a scaled-up pilot anaerobic digester, the semi-continuous reactor was set-up, then the biogas/methane production, methane yield and measured concentration of sulfide in both gas and liquid phase of AD reactor were tested to analyze the feasibility of promoting this method to larger scale.

2.1. Sludge samples and chemicals

The CEPT sludge was collected from SCISTW in Hong Kong and stored in dark in zip bags at -20°C before using. The seed sludge was obtained from a lab-scale anaerobic digestion running over 6 months with SRT of 20 days under mesophilic condition (35°C). All of the chemicals were analytical reagent grade and without further purification prior to use.

2.2. Effect of solid content on batch AD

In order to investigate the best solid content input for higher efficiency of batch anaerobic digestion. A verified assay was investigated. The different Total Solid (TS) loading ranging from 3% to 6% was studied. The 500ml with 400ml working volume contained sludge substrate and inoculum. The reactor was operating under the mixing condition at 150rpm by a shaking incubator and the temperature was kept at 35°C. The ratio of inoculum and substrate is 0.2 (TS basis) followed to earlier other studies [12]. After adding the substrate and inoculum, the mixtures were supplemented with a 1% (v/v) of a medium containing macro- and microelements [13]. The composition of this nutrient and trace element solution followed previous studies [13]. pH was adjusted to neutral and the reactor was purged with nitrogen for 10min to provide a strict anaerobic environment and sealed. The batch tests were ceased when the biogas production stopped.

2.3. Set-up of semi-continuous batch AD system

The AD reactor with 5 liters working volume and SRT = 20 days was operated. The reactor was agitating at 150 rpm by a motor agitator and the temperature was kept at 35°C. The TS% was chosen based on the results of verified batch assay. The ratio of inoculum and substrate was keep the same as section 2.2. The pH was adjusted to 7.0 and the reactor was purged with N_2 to provide a strict anaerobic environment and sealed.

2.4. Analytical methods

The biogas production was measured by using water replacement method and then normalized to ambient pressure and temperature. The biogas produced (mL /g VSfed) at standardized temperature and pressure (STP: 0oC and 1 atm) that sludge can potentially generated under anaerobic digestion was determined. The produced gas was also collected in gas bags and measured using a portable biogas analyzer (GeoTech 5000). The characteristics of CEPT sludge including TS (% w/w), volatile solids (VS, % of TS), Total/Soluble Chemical Oxygen Demand (TCOD & SCOD), sulfate/sulfide, ammonium (NH_4-H^+) were measured according to standard methods [14]. All the tests were conducted in triplicate (unless indicated otherwise) and results averaged.

3. Results and Discussion

3.1. Chemical composition of CEPT sludge

Although CEPT generates a numerous amount of sludge as a by-product in the settling step which gives constraint on disposal and landfill, the sludge from CEPT without the nutrients removal contains higher energy potential comparing the sludge collected from secondary process. The key factors influence the bioenergy potential of CEPT sludge in ADs can be classified into two categories, *i.e.*, biological factors and substrate-related factors. Substantial attentions have been paid to clarify the biological factors in AD, which are related to sectionalized reaction phases, process control, metabolic kinetics, operation strategies and interactions among different microorganism species, while fewer studies are focused on substrate-related factors due to high complexity of the feedstock and limited applications [15]. The substrate-related factors are mainly involved physiochemical properties of the sludge, which describes the mixture of consumed biomass derived from daily activities. In this study there are several substrate-related criteria should be hypothesized to use CEPT sludge as preferable bioenergy producing substrates as shown in Fig. 2.

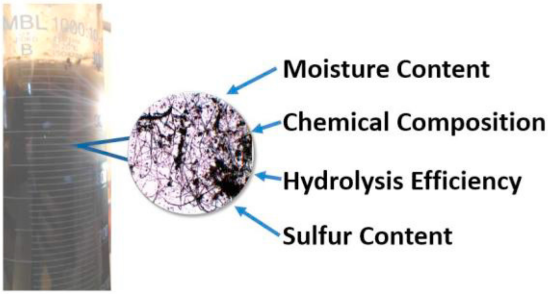

Figure. 2 Factors influence the bioenergy potential of CEPT sludge

Conventional substrate-related factors were classified by the biological reaction rates, *i.e*., rapid and slow degradable organics. Those organics consist of different bio-chemicals such as carbohydrates, proteins, fats, lignocelluloses, and extractives which influence the hydrolysis rate of wastes. Most of the biological processes in WWTPs were competent enough to handle the uncertainties caused by sophisticated chemical composition of sludge, but the energy and chemicals inputs should be reduced for sustainability, under this consideration, CEPT sludge provides a few unique features for waste valorization to increase the energy potential. The chemical compositions of the raw CEPT sludge were analyzed and presented in Table 1. The sludge is with high sulfate (60.67±17.63 mg/L) and organic solids contents (1.48 % VS). The data was similar to previous studies with variation from different samples [16]. The solid content of clarified CEPT sludge was approximately 3-5% which is also suggested solid content in a conventional AD; this number increases to 30-40% to form a "sludge cake" after thickening and dewatering. Low solid content sludge can generate only limited amount of biogas, while hydrolysis rate dropped dramatically if solid content of the substrate increase to more than 15-20% [17].

Table 1. Characteristics of CEPT sludge

Parameter	TS (%w/w)	VS/TS (%)	pH	TCOD (g/L)	SCOD (g/L)	SO_4^{2-} (mg/L)	NH_4-N^+ (mg/L)
Value	3.03±0.68	48.96±0.15	6.99±0.04	16.23±0.13	4.34±0.28	60.67±17.63	283.98±14.0

Besides the factors mentioned above, the high sulfur content in the CEPT sludge have created certain concerns to AD operation in SCISTW, which was originated from the unique sea water toilet flashing system in Hong Kong. Sulfate was reduced to toxic sulfide which inhibit the performance of AD [18]. The inhibiting effects were caused by the effect of Sulfate Reducing Bacteria (SRB) like *Desulfovibrio, Desulfotomaculum* and *Desulfosarcina* to compete the organic and inorganic substrates with various methanogen bacteria [19]. The existence of sulfide provokes the demand of sulfide removal in biogas application when sulfate-contained wastewater is raw material. The biological processes which applies a group of sulfur oxidizing bacteria like *Thiobacilli* [20], under several well controlled parameters, to oxidize sulfide to elemental sulfur and sulfate at low oxygen input. As salinity and sulfide content can affect the kinetics of microbial activities in WWTPs, the experiment results obtained in this study provokes the demand of sulfide removal in biogas before power generation.

3.2. Solid content test of beach reactor

The digestion performance of CEPT sludge at various solid content loading was investigated based on the results from cumulative biogas production and biogas yield as displayed in Fig. 3. Although the cumulative biogas production is higher for higher solid loading. However, when calculation the biogas yield, this number was shown higher in lowest solid loading, showing better biodegradable efficiency of organic matter. The highest biogas yield is 0.17 L/g VS_{added} was observed in the batch containing 3% of TS. This was followed by 0.126, 0.104, 0.102 L/g

VS_{added}, when TS was increased from 3% to 6%, respectively. Therefore 3% solid content should be chosen for following semi-continuous reactor operation.

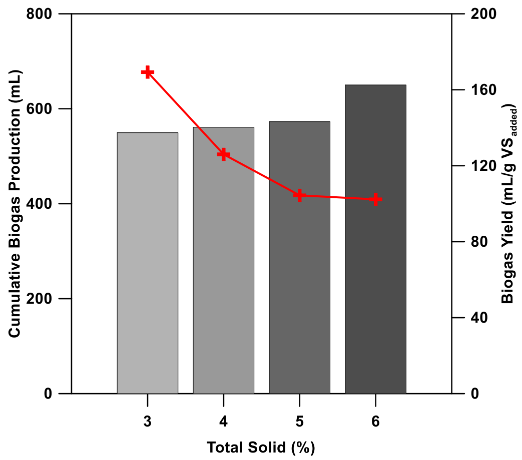

Figure. 3 Cumulative biogas productions of CEPT sludge and yield under different solid content

3.3. Design concept of the pilot-scale system

The concept diagram and appearance of the pilot scale system were demonstrated in Fig. 4(a) and (b). As shown in Fig. 4(a), the system is composed of four-unit processes, *i.e*., a pre-hydrolysis tank (1 m^3), an AD (1 m^3), a sulfide oxidation unit (SOU), and two H_2S scrubbers. The pre-hydrolysis tank serves as an equalization basin to provide steady flow to the AD. The SOU is a 4 meters tall column reactor (150 L) equipped with fine-pore diffuser for micro-aeration. It withdraws and circulates a small quantity of the AD liquid for sulfide removal. It has been shown in some studies that sulfide can be oxidized to elemental sulfur and/or sulfate through controlled aeration to maintain dissolved oxygen and oxidation-reducing potential (ORP) [20]. Finally, the twin scrubbers harvested 99% of the remaining H_2S in the biogas before sending it for power generation in the down-stream process.

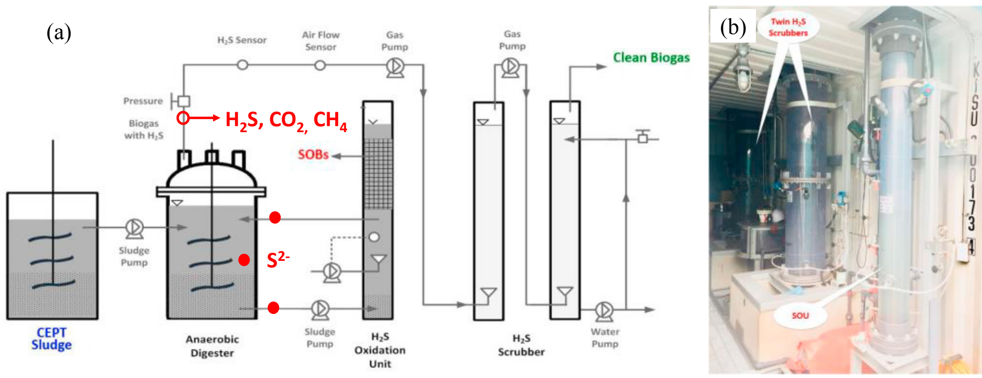

Fig. 4(a) Schematic flow of study and (b) pictorial pilot scale CEPT attached with SOU and sulfide removing scrubbers. Symbols show the parameters measured and sample location

3.4. Biogas analysis from the semi-continuous AD/SOU system

The lab-scale semi-continuous AD system was operated for over 126 days to obtain the stable condition. Its picture is shown in Fig. 5(a) while the results were illustrated in Fig. 5(b). The biogas production increased gradually to a maximum of 2.2 L/day at first 27 days of operation and then decreased to 1.5 L/day after stabilization.

The methane yield was calculated at nearly 400 mL/g-VS_{added} and methane counted over 60% of total biogas which is similar to other previous studies [21]. The heating value of typical fed CEPT sludge was 1.84 MJ/kg DS [22], however 6 MJ/kg DS energy is consumed for drying process only prior to incineration which drives the net energy potential negative [23]. Alternatively, through AD process, based on Fig. 5(b), the heating value of produced methane at stable phase could be up 2.2 MJ/kg DS, which exhibits positive energy potential.

For sulfide, gas phase concentration was observed to increase dramatically at the first 9 days and achieved 22,000 ppm and gradually reduced and faced some fluctuations then stabilized at 5,000 ppm after 18 days of operation. The performance of SOU was described in Fig. 5(b). It was observed that the liquid sulfide concentration in both AD and SOU were decreased in various levels, gaseous phase sulfide in AD dropped from nearly 5,000 ppm to around 3,000 ppm when the SOU started running.

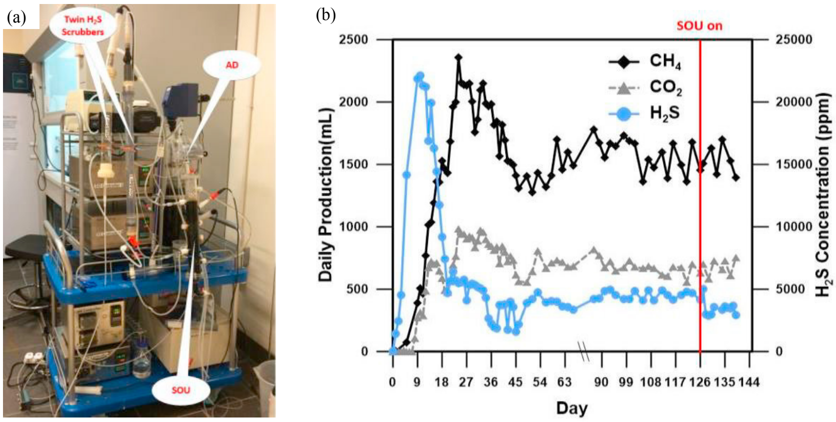

Fig. 5(a) Daily methane, carbon dioxide, gaseous sulfide production in semi-continuous batch reactor before and after the installation of SOU and (b) the image of lab-scale batch reactor with SOU and scrubber

The inverse correction between dissolved sulfide content in the liquid and H_2S concentration in the off-gas were shown in Fig. 6(a), the liquid sulfide concentration changes of inlet SOU followed a contrary trend of hydrogen sulfide concentration in batch reactor, this phenomenon was not fully explained, could due to complicated biological and chemical reaction in the system. Under the effect of micro-aeration, the sulfide concentration dropped 27.9-44.2% at outlet of SOU. The precipitated solids from SOU were exhibiting comparable characteristics as commercial sulfur through elemental analysis. The correlation of liquid and gaseous sulfide in the AD reactor was also found in Fig. 6(b), indicating the stable biological reaction in AD.

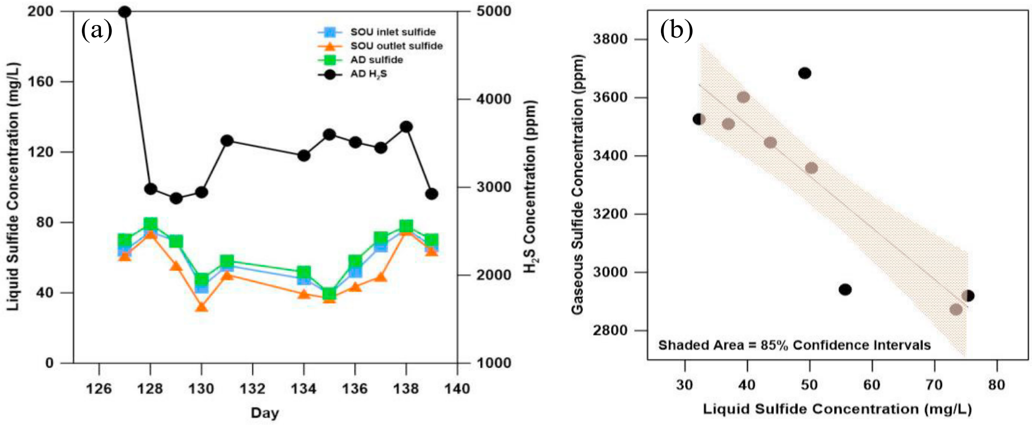

Fig. 6(a) The gaseous and liquid sulfide concentration in both semi-continuous batch reactor and SOU after the attachment of SOU and (b) the correlation of liquid and gaseous sulfide in batch reactor

The energy balance of secondary process, NdN and CEPT were compared in Fig. 7. Previous studies measured the average energy cost of conventional secondary process and NdN are nearly 0.75 kWh/m^3 and 0.94 kWh/m^3, respectively [4]. Their corresponding energy outputs were calculated as 0.1 kWh/m^3 and 0.3 kWh/m^3, when using 0.3 as the activated sludge yield, 0.5 as anaerobic treatment efficiency and 0.5 as methane yield [24]. For the energy balance of CEPT, the Anammox and physiochemical coagulation are main energy cost contributors [25], and their energy consumption were relatively negligible comparing with MBR process. The theoretical energy saved by CEPT was calculated and hypothesized up to 0.744 kWh/m^3 [26].

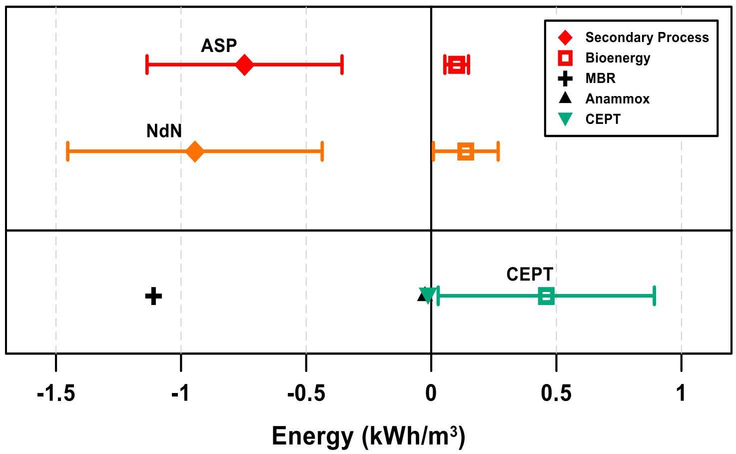

Fig. 7 Comparison of Main energy consumption of conventional secondary process and theoretical energy generation and main energy consumption of CEPT and its theoretical energy generation

4. Conclusion

According to a laboratory scale meso-digestion equipped with SOU system, we established the relationships of reaction kinetics of anaerobic bacteria under high salinity, the correlation of liquid and gaseous phase sulfide in the semi-continuous AD. The collected elemental sulfur revealed similar characteristic as commercial sulfur, nearly 95% purity was obtained. The data collected from this study is not only applicable for the proposed pilot scale digester system, but also provide valuable information to other biological process for H_2S removal. The energy saving could up to 0.93 kWh/m^3 comparing with conventional wastewater treatment.

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