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Review of enhanced processes for anaerobic digestion treatment of sewage sludge

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Abstract. Great amount of sewage sludge had been produced each year, which led to serious environmental pollution. Many new technologies had been developed recently, but they were hard to be applied in large scales. As one of the traditional technologies, anaerobic fermentation process was capable of obtaining bioenergy by biogas production under the functions of microbes. However, the anaerobic process is facing new challenges due to the low fermentation efficiency caused by the characteristics of sewage sludge itself. In order to improve the energy yield, the enhancement technologies including sewage sludge pretreatment process, co-digestion process, high-solid digestion process and two-stage fermentation process were widely studied in the literatures, which were introduced in this article.

1. Sewage sludge and new treatment technologies

1.1. Production and harmfulness of sewage sludge

Sewage sludge is produced from wastewater treatment plant, which contains large amount of organic matters, water content, numerous active microorganism and parasitic ovum [1]. The unsuitable treatment of sewage sludge has induced to secondary pollution on agricultural field, atmosphere, surface water, groundwater and etc. As the development of the scale and capacity of wastewater treatment plant in China, the production of wet sludge increased gradually. It was reported nearly 300 million tons of wet sludge had produced in 2012 for the whole nation, and it will increase to 600 million tons in 2020 [2]. Considering about the harm effects of sewage sludge, the management and treatment technologies are becoming an issue of importance in China.

1.2. New technologies for sewage sludge treatment

The most commonly used process for sewage sludge treatment are as follows: concentration, dehydration and landfill, which is not good for the recycling, reducing and reusing of the sewage sludge [3]. The biomass energy, nitrogen, phosphorus, heavy metals in sewage sludge are valuable to reuse and the recycling treatment technologies are highly recommended in sewage sludge management.

Many new technologies are developed to recycle the energy and resources in sewage sludge, such as gasification, pyrolysis, wet oxidation and microbial fuel cell, and etc. It was reported the hydrothermal gasification of sewage sludge could obtain the hydrogen rich gas, which is feasible in terms of technical and economic evaluation [4]. Pyrolysis is cost-effective and clean technology. During the pyrolysis of sewage sludge, high heat-value fuels could be recycled from solid waste and heavy metals was concentrated, and also the released organic micro-pollutants and pathogens are reduced [5, 6]. The biochar produced by fast pyrolysis of biophysical dried sludge had good thermal stability, safe leaching toxicity, and high adsorption of Cd^{2+} [7]. The microbial fuel cell technology achieved direct and stable electricity production from sewage sludge for 250 h, which was perfect for energy recovery [8]. Although the new technologies had good effects on energy and resources recycling, most of them were still in the research stage and could not be utilized in large scales.

2. Advantages and challenges for anaerobic fermentation of sewage sludge

The anaerobic fermentation, incineration and aerobic composting are applied in industrial scales and it is benefit for stabilization and recycling of sewage sludge. Among them, the anaerobic fermentation process could convert organic matters to combustive biogas with good features of storage and transportation, which increase its commercial value as a bioenergy source [9]. Besides, the biohydrogen, bioethanol and volatile fatty acids (VFAs) are produced in anaerobic fermentation process of sewage sludge at suitable conditions [10]. The heat values for methane and hydrogen were 35.8 kJ/L-CH_4 and 10.8 kJ/L-H_2, respectively, and the high quality biogas with methane or hydrogen content of 50-70% or 40-60% could obtained during anaerobic digestion of sewage sludge and its co-digestion process. Furthermore, most of the value-added products, such as enzymes, bio-plastics, bio-fuels, bio-fertilizer, bio-flocculants and bio-pesticides, are produced by pretreatment followed by fermentation process as the main steps with wastewater and sewage sludge as raw materials [11]. The heavy metals in digested sludge has lower bioavailability and crop-absorption characteristic than raw sewage sludge because of the formation of stable metal-humus complexes in digested sludge [12], so the digested sludge is suitable to be used as soil fertilizer in agricultural field.

However, as the fermentation substrate, the sewage sludge had low carbon-to-nitrogen ratio (C/N), which goes against nutrition balance of microorganism, therefore the co-digestion of sewage sludge with carbon-rich substrate is widely applied for nutrition adjustment [13]. Moreover, Because the flocculating structure are not easy to break and the component of activated sludge is hard to degrade, the release of the organics from sludge has restrained, so the fermentation efficiency is low and long retention time is required. It was reported the sewage sludge pretreatment technologies had good effects on organic matters release and hydrolysis [9]. In this paper, the microbes and its influence factors for anaerobic fermentation were introduced, and the pretreatment processes and co-digestion technologies applied in anaerobic fermentation of sewage sludge were also reviewed.

3. Microbes and their interactions for anaerobic fermentation

During anaerobic digestion process, the sewage sludge is converted into biogas under the function of hydrolysis bacteria, acidification bacteria and methanogens orderly. The micromolecule organics were degraded by hydrolysis and acidification, providing precursors for methanation. Meanwhile, the acidification metabolites are consumed by methanogens, promoting the consistency of acidification reactions and maintaining the pH condition of fermentation system [14].

Extracelllar enzymes are essential for hydrolysis of the particulate bioorganic molecules into monosaccharides, amino acids and fatty acids [15]. However, as one of the main part of sewage sludge, the activated sludge is the most recalcitrant to hydrolysis and thus the hydrolysis is the rate-limiting step during the degradation of sewage sludge [16]. The acidogenesis and acetogenesis are the intermediate process, where lots of products could be collected by cultivate condition controlling. A group of fermentative bacteria involved in acidification of organics, most of them belonged to phylum *Firmicutes* and *Bacteroidetes* [1].

Overwhelming majority of the methanogens are affiliated to domain *Archeae* and phylum *Euryarchaeota*. Limited substrates could be utilized by methanogens. It has been concluded that hydrogenotrophic, methylotrophic and acetoclasic methanogenesis are typical metabolic pathways for methanogens [17]. The operational environment and seed sludge are important for the predominant metabolic pathways and microorganisms during the sewage sludge digestion.

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4. Anaerobic digestion enhanced by sewage sludge pretreatment

4.1. Sewage sludge pretreatment methods
Due to the low hydrolysis efficiency in anaerobic digestion of sewage sludge, many efforts on the broken of sludge structure were performed by the implementation of sludge pretreatment prior to digestion. Various physical, chemical and biological technologies were applied in sewage sludge pretreatment, such as thermo treatment, ultrasonic treatment, acid/alkaline treatment, microwave treatment, freezing/thawing, oxidation agent, phase-separated digestion, and etc [18]. The thermal hydrolysis was developed in early stage and widely applied in full scale unit. The combination of thermo hydrolysis, ultrasonic treatment, the oxidation, pH adjustment were also investigated in the literatures. The mesophilic anaerobic digestion of thermo-treated sludge, ultrasonic-treated sludge and the combined-treated sludge obtained promotion of 30.62%, 32.80% and 36.98% in methane yield compared with raw sludge [19]. It is also reported that the pretreatment of 115ºC for 5 min with pressure of 1 bar and dosage of H_2O_2 had similar methane production with the pretreatment of 170 ºC for 30 min with pressure of 8 bar [20].

4.2. High-solid digestion for methane production
The digestion efficiency is also restricted by the low solid concentration of the concentrated sludge (water content of about 97%). The high-solid anaerobic digestion is commonly characterized by a low moisture content in feedstock, typically less than 85% [12]. With dewatered sludge as substrate, the high volumetric biogas production rate in the small reactor with low heat energy consumption could be achieved. During the high-solid digestion of sewage sludge, as the increase of solid concentration, the main bacteria changed from phylum *Firmicutes* to phylum *Bacteroidetes*, and the *acetoclasic Methanosarcina* reduced but the relative abundance of *hydrogenotrophic Methanobacteria* increased [21]. The methane production yields were 150, 190 and 190 ml-CH_4/g-VS_{added}/d at the feed sludge total solid (TS) of 10%, 15% and 20%, and the corresponding volumetric methane production rates were 1.25, 1.61 and 1.63 l-CH_4/l/d, respectively [22]. However, due to the low hydrolysis efficiency of sewage sludge, the volatile solid (VS) and methane yield were lower than traditional low-solid digestion of sewage sludge. The sludge pretreatment technology is widely applied in high-solid digestion process of sewage sludge. The high-temperature thermo hydrolysis process (120-160 ºC) accelerated the digestion rate and increased the biogas yield compared to low-temperature thermo hydrolysis process (60-90 ºC), and the sludge retention time could reduce from 18-20 d to 12-14 d under the thermo pretreatment of 140-160 ºC for high-solid anaerobic digestion with TS concentration of 16.7 g/l [23].

4.3. Hydrogen production from pretreated sludge
Hydrogen is produced during the acidogenesis and acetogenesis of organic matters in anaerobic fermentation process. Hydrogen is considered as the ideal substitute for fossil fuels because of its high combustion value and cleansing [13]. However, hydrogen production by anaerobic fermentation would inhibited by hydrogen consuming metabolic pathways, such as butyrate acid fermentation, lactic acid fermentation, homoacetogenesis, hydrogenotrophic methangenesis, and so on [24]. Hydrogen production from anaerobic fermentation highly depends on the operational controlling to enrich the hydrogen producing bacteria and inhibit the activity of hydrogen consuming microbes. It is hard to produce hydrogen from raw sewage sludge and various pretreated methods could enhance biohydrogen production from sludge. The pH of sewage sludge was adjusted to 12.0 and maintained for 24 h during alkaline pretreatment, and the hydrogen yield increased from 9.1ml-H_2/g-TS in raw sludge to 16.6 ml-H_2/g-TS at the initial fermentation pH of 11.0 [25]. The sludge under the thermophilic bacteria pretreatment reached hydrogen yield of 48.6% higher than raw sludge during the thermophilic fermentation process, because microbial abundance was distinctly reduced and the *Thermoanaerobacterium* was the dominant [26].

5. Anaerobic digestion enhanced by co-digestion process

Except for sewage sludge pretreatment, the co-digestion process was also reported to be effective in biogas production promotion. Several carbon-rich substrates, such as meat-processing by-products, organic fraction in municipal waste, livestock and poultry manure, food waste and etc, were commonly used to adjust nutrition balance of fermentation substrate. The biogas production from co-digestion of meat-processing by-products and sludge is higher than sole sludge digestion [27]. When the mixing ratio of sludge and organic fraction in municipal waste reached 3:1, the C/N increased to 14:1 and the methane yield raised accordingly [28]. In the studies of the optimal mixing ratio of pig manure and dewatered sludge, the highest methane yield of 315.8mL/g-VS_{added} obtained by co-digestion of mixture of pig manure and dewatered sludge (VS:VS=2:1), which is 82.4% higher than that form sole dewatered sludge [29]. The addition of vegetable and fruit waste resulted to great increase in biogas production in anaerobic sequencing batch reactor [30]. Many efforts had been tried to improve the fermentation efficiency by co-digestion process and the on-sit pilot-scale co-digestion system is reported [31].

High-solid anaerobic co-digestion process were also investigated in recent studies. The mixing ratio and initial pH were optimized to improve the VFAs and methane production from the co-digestion of sludge and manure with the VS concentration of 4%, and the maximum VFAs production of 98.33 g/kg-TS and methane generation of above 120.0 L/kg-TS in long-term operation were obtained at VS ratio of sewage sludge/cattle manure of 3/7 and initial pH of 9.0 [32]. The co-digestion of food waste not only enhanced volumetric biogas production, but improved system stability [33]. The two-stage anaerobic fermentation for separated hydrogen and methane production from co-digestion of food waste and sludge had been successfully operated in semi-continuously mode [34] and the total energy collected had been improved compared to single-stage digestion system [35].

6. Conclusions

Energy recycling from sewage sludge by anaerobic fermentation process has great development potential in the sewage sludge management and treatment. The characteristics of non-suitable nutrition composition and hard-to-degraded component of sewage sludge have reverse effect on anaerobic digestion. The fermentation efficiency of sewage sludge was improve by the enhanced process, such as pretreatment, co-digestion, two-stage fermentation, high-solid fermentation and their combinations. Those enhanced processes could be further investigated in the full scale to evaluate the cost, production, and stability. Furthermore, the selection and optimization of specific process should also be based on availability of raw materials and local requirement for biogas and fertilizer.

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