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Review

A comprehensive review on food waste anaerobic digestion: Research updates and tendencies

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ABSTRACT

Anaerobic digestion has been practically applied in agricultural and industrial waste treatment and recognized as an economical-effective way for food waste disposal. This paper presented an overview on the researches about anaerobic digestion of food waste. Technologies (e.g., pretreatment, co-digestion, inhibition and mitigation, anaerobic digestion systems, etc.) were introduced and evaluated on the basis of bibliometric analysis. Results indicated that ethanol and aerobic prefermentation were novel approaches to enhance substrates hydrolysis and methane yield. With the promotion of resource recovery, more attention should be paid to biorefinery technologies which can produce more useful products toward zero emissions. Furthermore, a technological route for food waste conversion based on anaerobic digestion was proposed.

1. Introduction

Food waste (FW) is one of the most important components of municipal solid waste, including household food waste, food-processing waste, canteen and restaurant waste. The stacking of FW has gradually become a global problem (Capson-Tojo et al., 2017). It is estimated that the amount of FW sharply increased from 2.78 billion tons to 4.16 billion tons in Asian countries by 2025 (Melikoglu et al., 2013). Especially in China, the growth rate of FW has increased more than 10% with the acceleration of industrial development and urbanization processes (Zhang et al., 2016).

At present, FW regarded as municipal waste is sent to landfills and incineration plants as final disposal points. In some ways, these processes release some stress from garbage siege; at the same time, a series of problems are emerging including the rising cost of waste disposal, the lack of land space, groundwater pollution by leachate, and the emission of toxic and greenhouse gases (Uçkun Kiran and Liu, 2015). The collection rate of landfill gas is generally less than 60% in the developed countries, whereas there are only 20% achieved in China. USEPA estimated that the total anthropogenic emission of methane was 282.6 million tons in 2000, in which 13% (36.7 million tons) was due to landfill emissions. Schott and Andersson (2015) used life cycle assessment from production, transportation, and fosod preparation modeling to assess global warming potential of food waste, and found that incineration and landfill can be replaced by anaerobic digestion or composting. Moreover, FW with high concentrations of organic matter (volatile solids/total solids [VS/TS]: 0.8–0.9), high moisture content, and good biodegradability have been regarded as the most promising anaerobic substrates (Ohkouchi and Inoue, 2007; Zhang et al., 2011).

Anaerobic digestion (AD) is a complex process that involves a diverse assemblage of bacteria and methanogenic archaea (Jang et al., 2015). The decomposition process of organic matter can be divided into four stages. Macromolecule organic matter in solids is firstly broken into easily dissolved monomers including the transformation from carbohydrates, protein and fat to sugar, amino acid and long-chain fatty acid, and this process is called hydrolysis. The hydrolysis step is generally considered as the rate-limiting step for complex organic substrates degradation reported by most researchers, resulting from the formation of toxic by-products (complex heterocyclic compounds) or non-desirable volatile fatty acids (VFAs) during the hydrolysis step (Yuan and Zhu, 2016). In the second stage, called acidogenesis, monomers further decompose into short-chain fatty acid including VFA;

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lactic acid, pyruvic acid, acetic acid, formic acid. And then, in the process of acetogenesis, acids like lactic acid and pyruvic acid start to be digested into acetic acid and hydrogen. In the last stage, called methanogenesis, hydrogen and acetic acids are transformed into methane by methanogenic archaea.

Bibliometric analysis as a common research tool using quantitative analysis and statistics to describe the research trend of a specific field has been applied widely in studies to compare scientific production and research trends in many fields. And the structure of this paper is based on the results of bibliometric analysis.

2. Research tendencies analysis by bibliometric

In this study, keywords such as (food∗ waste∗ or foodwaste∗) and (Anaero∗ or (biogas or methane)) were used as topic search phrases to acquire all the index of articles published from 1992 to 2016 from the Web of Science database. The records of all index were downloaded into spreadsheet software (Microsoft Office Excel 2016) to conduct a digital logical analysis (Fu et al., 2011). Particularly, some keywords which had the same meanings such as “methane” and “methane production” had been combined together in the datum treatment process. After all relevant datum were categorized, the tendencies of publication outputs were analyzed using five-year intervals to minimize year-to-year fluctuations (Xie et al., 2008). After the analysis of keywords, it was easy to find the keyword “Anaerobic Digestion” was referred to the most frequently and ranked first among all keywords. Furthermore, keywords such as “pretreatment”, “inhibition”, “co-digestion”, “microbial community”, showed a sustainable growth tendency and specific data has been shown in Table 1.

Through analysis of the tendencies of keywords, some conclusions were drawn. The problem of poor treatment resulted from inhibition is one of the major factors limiting the large-scale popularization of anaerobic digestion. With regard to mitigation of system inhibition which has been a focus of research for a long time, many related subjects have developed rapidly. Pretreatment can largely alleviate the problem of system collapse caused by poor hydrolysis. Co-digestion can adjust the C/N ratio and water content of food waste, and ensure the smooth production of gas. The study of microbial community can be used as an important indicator to monitor the process of anaerobic digestion. These basic researches provide a solid foundation for the development and upgrading of anaerobic digestion. This paper analyzes the latest treatment methods and related problems about anaerobic digestion and provides some advice for future researches.

3. Inhibition factors during anaerobic digestion process

Food waste has a high potential to produce renewable energy in the anaerobic digestion process because of its high biodegradability and rapid hydrolysis. The rapid hydrolysis of FW often results in some inhibition factors affecting the stability and sustainability of anaerobic digestion. The main inhibition factors are ammonia and VFA.

3.1. Ammonia inhibition and mitigation

Some substrates like food waste which have low C/N ratio and high nitrogen content will produce excessive ammonia in the process of anaerobic digestion. Excessive ammonia leads to an increase of pH, inhibitory effects, and eventually, process deterioration (Drennan and DiStefano, 2014; Akindele and Sartaj, 2017). The total ammonia nitrogen is mainly composed of free ammonia nitrogen (FAN) and NH_4^+. In an anaerobic system, FAN and NH_4^+ can be converted into each other. And under high pH and high temperature conditions, it is beneficial to the transformation to FAN (Zhang et al., 2017a,b,c). FAN is the most toxic species of TAN. Because FAN has the ability to penetrate the bacterial cell membrane, causing proton imbalances, increasing maintenance energy requirements, altering intracellular pH and inhibiting specific enzyme responses (Akindele and Sartaj, 2017). It was reported that the inhibitory concentrations of FAN and TAN were related to substrate, inoculum and environmental conditions, ranging from 53 mg/L to 1450 mg/L and 1500–7000 mg/L, respectively. Shi et al. (2017) observed the inhibitory effects of free ammonia on methanogenesis due to the low C/N ratio of each substrate (15.6 and 17.2, respectively). It was found that high concentrations of ammonia resulted in the accumulation of VFAs with acetic acid as the main type in the batch test, and co-accumulation of ammonia and VFAs, resulted in a stable and neutral pH value, but a low BPR known as an “inhibited steady state” in the semi-continuous experiment.

Furthermore, numbers of studies have reported that the effects of

Table 1
Top 20 most used author keywords.

Author keyword	92–16 TP	R (%)					
		92–16	92–96	97–01	02–06	07–11	12–16
Anaerobic Digestion	671	1 (27.66)	1 (27.58)	1 (29.24)	1 (27.73)	1 (26.38)	1 (28.06)
Methane	586	2 (24.15)	2 (25.86)	2 (18.86)	2 (20.81)	2 (22.86)	2 (25.46)
Food Waste	441	3 (18.17)	#N/A	3 (9.44)	3 (18.32)	3 (14.53)	3 (21.01)
Co-Digestion	239	4 (9.85)	#N/A	30 (1.89)	4 (7.93)	4 (14.18)	4 (9.31)
Hydrogen	284	5 (5.93)	9 (3.45)	4 (6.61)	5 (5.94)	5 (6.84)	5 (5.61)
Sewage Sludge	83	6 (3.42)	9 (3.45)	7 (3.77)	10 (3.47)	22 (1.84)	6 (4.04)
Municipal Solid Waste	77	7 (3.17)	4 (6.9)	5 (6.6)	22 (1.98)	11 (2.84)	7 (3.08)
Volatile Fatty Acids	69	8 (2.84)	3 (12.07)	16 (2.83)	6 (5.45)	22 (1.84)	8 (2.53)
Fermentation	58	9 (2.39)	37 (1.72)	#N/A	10 (3.47)	14 (2.67)	10 (2.33)
Thermophilic	47	10 (1.94)	9 (3.45)	16 (2.83)	10 (3.47)	11 (2.84)	24 (1.23)
Dark Fermentation	47	11 (1.94)	#N/A	#N/A	#N/A	15 (2.5)	11 (2.19)
Renewable Energy	44	12 (1.81)	#N/A	69 (0.94)	122 (0.5)	10 (3.34)	15 (1.51)
Wastewater	42	13 (1.73)	9 (3.45)	5 (6.6)	10 (3.47)	18 (2.17)	38 (0.89)
Biomass	42	14 (1.73)	9 (3.45)	30 (1.89)	30 (1.49)	11 (2.84)	24 (1.23)
Microbial Community	41	15 (1.69)	#N/A	#N/A	#N/A	44 (1)	9 (2.4)
Life Cycle Assessment	39	16 (1.61)	#N/A	#N/A	122 (0.5)	104 (0.5)	7 (3.7)
pH	37	17 (1.53)	#N/A	7 (3.77)	30 (1.49)	22 (1.84)	21 (1.3)
Organic Loading Rate	36	18 (1.48)	#N/A	#N/A	49 (0.99)	29 (1.34)	12 (1.78)
Pretreatment	35	19 (1.44)	#N/A	69 (0.94)	30 (1.49)	29 (1.34)	13 (1.57)
Mesophilic	33	20 (1.36)	9 (3.45)	#N/A	8 (4.46)	28 (1.5)	38 (0.89)

TP: Total numbers of publications.
R (%): Rank (the percentage of articles in total publications is given within brackets).
#N/A: None appeared.

high concentrations of ammonia on anaerobic microorganisms in the anaerobic digestion system (De Vrieze et al., 2015; Zamanzadeh et al., 2016). Williams et al. (2013) reported that ammonia > 156 mg/L caused a shift from aceticlastic to hydrogenotrophic methanogens. The anaerobic system microbes were acclimated by the high ammonia-ammonium-pH system, and the microbial community shift from acetotrophic to hydrogenotrophic methanogens, which were more tolerant of ammonia stress (Dai et al., 2017).

The two main methods to reduce ammonia inhibition in the anaerobic digestion process are physical (air stripping) and chemical (chemical precipitation) methods, which were effective at controlling high ammonia concentrations, and have been applied to wastewater treatment and sludge digestion (Yuan and Zhu, 2016). TAN concentration in the reaction could be reduced to a lower level by side-stream stripping with a biogas stripping medium (Serna-Maza et al., 2014). In the process of anaerobic digestion, the TAN concentration in the system also can be reduced by gas stripping, and recycled ammonia can be used as value-added products (nitrogenous fertilizer). By adding Se and Co to the anaerobic system to enhance the microbial activity by synthesis of enzymes, the TAN concentration in the system was stable at 5000 mg/L, whereas the TAN concentration in the control group increased to 6100 mg/L (Banks et al., 2012). Sheng et al. (2013) used nitrification to convert ammonia into nitrate to reduce ammonia inhibition, but methane production was inhibited when the concentration of nitric acid was more than 1 g/L.

3.2. VFA inhibition and mitigation

The low C/N ratio and high biodegradability of food waste lead to the rapid acidification in the process of anaerobic digestion. During this period, the proliferation of acid-producing bacteria inhibited the activity of Methanogens, resulting in the accumulation of VFAs (Yuan and Zhu, 2016). When the VFA consumption rate was less than the rate of production, the inhibition caused by the decrease in pH occured. Yu et al. (2017) conducted a batch experiment mixed food waste and sludge with a ratio of 2.2:1 in terms of volatile solid (VS). And the results showed that the untreated group showed acidification with methane yield of 35 mL/g-VS. Kong et al. (2016) used different inoculum-to-substrate ratios (ISR) of 0.5, the volatile solids (VS) ratio, to produce excess organic acids and found that little methane and had high volatile fatty acids achieved when the ratio reached to 0.5.

The buffering capacity of anaerobic digestion systems has not been thoroughly reported in the past. The NH_4^+ converted from N-resource combines with the VFAs produced by the hydrolytic acidification bacteria, and established a weak buffering system. In a stable anaerobic digestion system, the concentration of VFA was about 50–250 mg/L, and excessive VFA would form inhibition to the system. NH_4^+ could be converted into NH_3 under certain conditions, which was also harmful to anaerobic digestion system (Wang et al., 2013). Improving the buffering capacity without VFA and NH_4^+ accumulation has become a hot subject and alkalinity, as a stable buffering substance, appears gradually in many researches. Gao et al. (2015) analyzed the anaerobic digestion performance with $NaHCO_3$ buffering and indicated the maximum methane yield and the buffering capacity could be increased by 48% and 33%, respectively. Kong et al. (2016) alleviated the acid inhibition at high OLRs by adding zero-valent iron to the system and found that zero-valent iron could significantly increase butyric acid conversion and methanogen activity. Furthermore, using a two-phase anaerobic digestion reactor to alleviate inhibition also has been reported, and will be discussed in the next section (Cysneiros et al., 2012).

Previous studies have focused on reducing the concentration of VFA to alleviate inhibition. Electrodialysis and ion exchange were reported to separate and recycle VFA in some way (Scoma et al., 2016; Tao et al., 2016; Rebecchi et al., 2016). Furthermore, exploring the inhibition mechanism and the effective inhibition concentrations, and establishing warning indicators (based on propionic/acetic acid ratio, bicarbonate alkalinity/total alkalinity ratio, and volatile fatty acid/bicarbonate alkalinity ratio) which can foresee the system potential risks also can be new subjects. A number of novel research directions are also worthy of attention, including the effect of inhibitors on microbial ecology, and the metabolic pathway of different substrates.

4. Pretreatment

Pretreatments are adopted to accelerate the hydrolysis rate and increase methane yields (Ma et al., 2011; Vavouraki et al., 2013). Because the cellulose content in food waste is more less than other material like plants, physical and biological pretreatments are mainly introduced here.

4.1. Physical pretreatments

Physical pretreatment mainly includes mechanical and heat treatments. Compared with other methods, it was found that microwave heating could dissolve more biopolymers, and no significant difference was evident between steam and electric heating (Mottet et al., 2009).

Mechanical pretreatment decomposes or grinds the solid particles of the substrate to release the cell compound and increase the specific surface area. Increased surface area provides better contact between substrate and anaerobic bacteria, thereby enhancing the anaerobic process (Carrère et al., 2010). Izumi et al. (2010) studied the relationship between particle size and VFA accumulation in anaerobic digestion. They found the methane yield increased by 28% when the particle size decreased from 0.843 mm to 0.391 mm. The undersize particle, however, will lead to an excessive accumulation of VFA and decrease the methane yield.

The main role of thermal pretreatment was to disintegrate the cytomembrane of substrate to promote the hydrolysis process of organic compounds (Marin et al., 2010; Prorot et al., 2011). Ariunbaatar et al. (2015) studied the possibility of enhancing the anaerobic digestion of food waste through a series of batch experiments with thermophilic pretreatment (heating the whole reactor content before mesophilic digestion) and conventional thermal pretreatment (only heating the substrate). Methane production was increased by 40% when it conducted pretreatment for 6–12 h at 50 °C and 1.5 h at 80 °C. Li et al. (2017a,b) investigated the effect of thermal pretreatment on the degradation of organic compounds in FW. Heat pretreatment had no significant effect on the final content of protein, but it decreased the fat, oil, and grease (FOG) potential by 7–36%, and increased the stagnation period of protein (35–65%) and FOG (11–82%) degradation. The cumulative biogas production increased linearly, and the removal efficiency of VS and other organic matter (CP and FOG) also increased exponentially.

4.2. Biological pretreatments

In recent years, biological pretreatments, as a new part of the anaerobic digestion pretreatment, have become a popular research topic including inoculating microorganisms, and enzymes, which can promote the hydrolysis of substrate and increase anaerobic digestion rate.

Zhao et al. (2016) studied the effect of ethanol pre-fermentation on methane yield. They indicated that compared with the control group (without ethanol pre-fermentation), the concentration VFA, propionic acid and acetic acid in pre-fermentation group was lower, and the system was not acidified. At the same time, methane yields were higher than that in the control group by 49.6%. Moreover, the research also showed that inoculation of yeasts inhibited the presence of three pathogens, including Escherichia coli, in the substrate. However, on the basis of microbiology knowledge, pretreatment using high temperature, strong base, and high pH will cause damage to the pathogens. Wu et al. (2015a,b) analyzed the influence on anaerobic digestion of FW and

Table 2
Comparison of different anaerobic technologies.

Substrate	System	Pretreatment	HRT/d	OLR/(g-VS/L d)	CH_4 production/(mL CH_4/g VS)	Explanation	References
FW + piggery wastewater	CSTR	Crushed	20		396	Add trace elements	Zhang et al. (2011)
FW	ADSL	Milled		9	540	Solid waste in FW	Zhang et al. (2013)
Fruits + vegetables waste	Two phases Continuous AD	Crushed		7.9	440		Gunaseelan, (2004)
Yard waste + FW	Solid-state anaerobic digestion	Dried, crushed				80% yard waste + 20% FW	Brown and Li, (2013)
Municipal solid waste	Two-stage AD		20	4	254	41% FW, 11% garden waste and 48% paper waste	Trzcinski and Stuckey, (2011)
FW + sludge	SCR		30	4.16	450.6	Grain (30–50%), vegetables (20–40%) and small amounts of meat and fish	Haider et al. (2015)
FW + sludge	Single-stage wet AD		8	9.2	455	4.0% rice, 2.5% noodles, 1.7% bread, 8.0% tea leaves, 53.6% vegetables, 24.8% fruit, 2.2% meat, 2.7% fish, 0.5% egg shells	Nagao et al. (2012)

distillers' grains by ethanol pre-fermentation (EP) with different inoculum-to-substrate ratios (ISRs). Through EP, the highest methane yield was 581.2 mL/g-VS at ISR 2.5, and ISR 1 and ISR 0.4 methane yields were 41.8% and 71.7% lower than that. The methane yield of EP was 143.2 mL/g-VS, 57.7% lower than that of EP at the same ISR. Compared with the control group, EP effectively alleviated the inhibition of acidification, greatly reduced the lag period, and significantly stimulated the growth of methanogens. Meng et al. (2017) skimmed FOG from FW, and then investigated the effect of lipase pretreatment on the methane field during anaerobic digestion. They found that the lipase-1 and lipase-2 could obtain the best hydrolysis effect at 24 h, 1000–1500 μL and 40–50 °C. The methane yields of animal fat, vegetable oil, and floatable grease were increased by 80.8–157.7%, 26.9–53.8% and 37.0–40.7%, respectively, at the same time digestion time was shortened by 10–40 d.

In order to improve the degradation rate of food waste and increase methane production, it is still an important research direction to develop new pretreatment methods. For instance, aerobic perfermentation of food waste could stimulate the hydrolysis rates. Peces et al. (2016) evaluated the impact of semi-aerobic fermentation on subsequent methane yield from primary sludge and found a statistically significant improvement in methane potential at 20 °C. Sahu et al. (2017) studied the effect of aerobic hydrolysis of food waste, and found that the amount of SCOD and TVFA obtained could be increased with minimized ammonia accumulation by controlling the pH, temperature and aeration rates of hydrolysis. In addition, the heat generation during the aerobic perfermentation might be utilized to increase the subsequent anaerobic digestion, favoring the methane production of the system. On the other hand, the ethanol prefermentation could increase the buffering capacity of the methane digestion system since the majority of the carbon source was converted into ethanol, instead of VFAs, which was beneficial for prevention of the acidification of the fermentation system and consequently might enhance the hydrolysis extent of the substrates and improve the stabilization of the fermentation system. In addition, hydrothermal pretreatment (120–250 °C, high pressure) can greatly improve the organic matter content in the liquid phase without needing to add any other chemical agents. This is beneficial to the subsequent anaerobic digestion process.

5. Co-digestion of fermentation materials

Some characteristics of food waste like low C/N ratio and high biodegradability are the most serious features in the process of anaerobic digestion which will lead to inhibitions to the whole system (Jabeen et al., 2015). Therefore, co-digestion with different substrates is a good way to balance the C/N ratio in an anaerobic system. And mixing with cellulosic waste is a common way to deal with such troubles. Notably, algal biomass, represented by microalgae and macroalgae, has been an important emerging field of research.

Blending FW and cardboard waste with low N content can improve C/N ratio so that sufficient buffering capacity can ensure a stable environment for TS biodegradation in an anaerobic system when pH sharply declines as a result of the rapid hydrolysis of FW. Capson-Tojo et al. (2017) tested the impact of the initial substrate load on the property of a batch dry anaerobic co-digestion system. They found that only when the substrate-to- inoculum ratio was 0.25 g-VS/g-VS could the system produce methane. Jabeen et al. (2015) conducted high solids mesophilic anaerobic co-digestion by mixing FW and rice husk and pointed out that the system achieved stability with a VS removal of 82% when the OLR between 5 and 6 kg-VS/m^3·d.

Microalgae, as a substrate that can meet the requirements of anaerobic digestion and sustainability, mixed with FW to conduct anaerobic digestion has become a new research field (Kim and Kang, 2015; Sialve et al., 2009; Ward et al., 2014). Kim and Kang (2015) found that algae could be used as a digestive substrate mixed with FW for anaerobic digestion and then conducted an anaerobic experiment for the first time with FW, algal biomass, and raw sludge at different mixing ratios. Cogan and Antizar-Ladislao (2016) found that co-digesting FW with seaweed waste (SW) resulted in faster and more stable reactions and indicated that anaerobic co-digestion had the highest methane yield (252 cm^3/g-VS) at a FW:SW ratio of 90:10.

Similarly, the co-digestion of food waste and other appropriate substrates could improve the overall methane yield owing to synergistic effects between the balance of nutrients, the dilution of toxic chemicals and regulating moisture content (Capson-Tojo et al., 2017; Cogan and Antizar-Ladislao, 2016; Kim and Kang, 2015; Zhen et al., 2016). To realize the directional transformation of organic matter, it would be useful to investigate the synergistic effects and co-metabolic mechanisms of different substrates.

6. Anaerobic reactors and technologies

Anaerobic digestion takes place in the fermentation reactor, and many researchers have struggled to improve its structure and function to obtain a higher methane yield. Some researches about anaerobic digestion is summarized in Table 2.

6.1. Single- and two-phase anaerobic digestion systems

Traditional reactors used for the anaerobic digestion of FW mainly contain a single-phase anaerobic digestion system or a two-phase anaerobic digestion system. In the two-phase anaerobic digestion system, hydrolysis and acidogenesis react in the first reactor, while the utilization of those acids by methanogenesis take place in the second reactor (Kondusamy and Kalamdhad, 2014). A lot of researches have concluded that the performance of a two-phase anaerobic digestion system is more efficient than a single-phase one. But in a single-phase anaerobic digestion system, all reactions (hydrolysis, acidification and methanogenesis) occur simultaneously in a single reactor, which allows for simple design (Nagao et al., 2012). It has been reported that in Europe, 95% of anaerobic reactors for organic wastes are single-phase anaerobic digestion system (Forster-Carneiro et al., 2008).

Grimberg et al. (2015) conducted a two-year statistical analysis about two anaerobic digestion systems, consisting of three 5 m^3 single-phase and two-phase anaerobic digestion systems, and found that the reactor could maintain stability even under very low loading rates (0.79 ± 0.16 kg-COD/m^3·d). The first phase of the two-phase anaerobic digestion system is easier to acidify so that it leads to a decrease in hydrolysis efficiency, while higher lipid degradation and long-chain fatty acids transformation were found in the single-phase anaerobic digestion system. Nagao et al. (2012) conducted an experiment about methane yield in single-phase wet anaerobic digestion at OLR from 3.7 to 12.9 g-VS/L·d, and it achieved the highest yield and VS degradation when the OLR reached 9.2 g-VS/L·d. Furthermore, the highest theoretical production of food wastes in single-phase anaerobic digestion was at OLR 10.5 g-VS/L·d.

6.2. The latest anaerobic digestion systems and technologies

Zhang et al. (2017a,b,c) developed a compact three-stage anaerobic digester for FW anaerobic digestion. They combined three independent chambers for hydrolysis, acidification, and methanogenic into an independent chamber, and achieved high methane yield by 24%–54% compared with single single-phase or two-phase anaerobic digestion system. Li et al. (2017a,b) established a two-phase pressurized biological membrane system, including a conventional continuously stirred tank reactor and a pressurized biological anaerobic reactor. They concluded that pressure has significant effects on methane yield and quality, with the highest methane yield achieved under a pressure of 0.3 MPa. Wu et al. (2016) proposed a novel method of two-phase anaerobic digestion system, in which the first reactor was operated at pH 4.0 (without any pH regulation) with lactate as the dominant product and then effluent from the first reactor was degraded in UASB to produce methane. Yan et al. (2016) investigated the influence on the recycling of CH_4 by using acidogenic off-gas in the methanogenic UASB reactor. In addition, Wu et al. (2015a,b) developed a three-stage process that consisted of saccharification, ethanol fermentation of the saccharified liquid, and anaerobic treatment of the saccharified residue to convert FW to ethanol and CH_4, and found compared with the single-stage system, the three-stage process achieved a 27.5% increase in the FW decomposition rate, a 51.8% reduction in the energy requirement for system operation, and a 17.6% improvement in the total energy yield. Therefore, the three-stage process is more suitable for practical application in terms of a lower post-treatment cost for the digester residue, a higher organic carbon utilization rate, and a higher bioenergy recovery efficiency.

A mechanical biological treatment (MBT) system is a type of waste processing facility that combines a sorting facility with a form of biological treatment such as composting or anaerobic digestion. In Europe, MBT plants are commonly designed to treat industrial, commercial and mixed household waste. However, MBT requires a pretreatment prior to anaerobic digestion and a treatment stage for digestate and a series of other complex processes. It can not only increase the processing costs and complexity, but also limit the amount of waste that a MBT plants can deal with. Using solid anaerobic digestion batch to upgrade existing MBT or composting plants can solve this problem from an energy and economic point of view. Di Maria et al. (2012) analyzed the economics of adding solid state anaerobic digestion to upgrade existing MBT plants. They found that the plants best-suited to upgrading exhibited a handling capacity of approximately 33,000 tons per year, where annual total costs decreased from €60,000,000–12,000,000 to €800,000–2,000,000.

A number of novel researches about reactor structure are also worthy of attention, like reactors for biogas recirculation. Recirculating biogas through the digester facilitates mixing in the system and the purification of impurities in the gas. This could also promote the transformation of carbon dioxide to into methane, which would augment the overall production of methane. Adding devices to conduct digestate recirculation can make advantage of the microorganisms and nutrients in digestate and reduce emission of digestate. Moreover, digestate recirculation also plays an important role in reinoculation, flow mixing, dilution of organic loading, and increase of pH buffering capacity, which is regard as the most economical and effective resource recovery method. Furthermore, the upgrading of produced biogas can transform methane into a syngas mixture of H_2 and CO through dry-reforming, partial-oxidative-reforming and steam-reforming (Lau et al., 2011). The production of H_2 can improve the calorific value of gas and the utilization ratio in electricity-generating fuel cells. Anaerobic reactors can be upgraded according to all of these aspects.

7. Studies on microbial community changes

Anaerobic digestion is a complex and multistep microbial process that involves cooperation between microorganisms to realize the main processes of hydrolysis, acidogenesis, and methanogenesis. Microorganisms that participate in anaerobic digestion can be divided into two groups: bacteria and archaea. Bacteria decompose complex substrates into VFA, CO_2 and H_2, while archaea are responsible for methane production. In recent years, with the development of molecular biology techniques, such as the popular high-throughput sequencing technology, it has become easier for researchers to detect changes in complex microbial communities and investigate how to optimize their performance. In this manner, changes in the way that reactors are operated, the local environment or the substrate used can impact microbial communities and be the focus of optimization studies. A summary of findings from studies that have identified and analyzed microbial communities involved in the anaerobic digestion of food waste is given in Table 3.

Fisgativa et al. (2017) analyzed food waste and found naturally present bacteria species, such as Proteobacteria and Firmicutes, and fungal species, such as Ascomycota phylum, actively participated in the aerobic and anaerobic degradation of the food waste. Li et al. (2015) reported that the treatment of food waste by mesophilic anaerobic digestion was hampered by changing the OLR. They suggested that the relative abundance of acid-producing bacteria increased during the deteriorative phase, while the majority of methanogenic bacteria still dominated by acetic acid. This suggested that acidification of anaerobic digestion systems can easily occur with a mismatch between bacteria's and archaea's metabolisms. Jang et al. (2016) compared mesophilic and thermophilic anaerobic digestion treatment of food waste and waste activated sludge mixture. Under the same conditions, the diversity of mesophilic microbial community was more abundant than thermophilic counterpart. Increasing the OLR decreased the diversity of the thermophilic microbial community, but realized a higher concentration of bacteria and archaea. Gulhane et al. (2017) studied the diversity of microbial communities at different locations in an anaerobic baffled reactor, and how the communities were affected by the recirculation of digestate. They found that the concentration of several metabolic functional species varied depending on location within the system and that the microorganisms showed plasticity in adapting to diverse conditions.

In addition, the pretreatment of food waste has also been shown to affect the microbial community involved in the anaerobic digestion process. For example, a number of works have compared the effects of pretreatment using microwaves, a biological method and an autoclave (Blasco et al., 2014; Zhang et al., 2016). Current research into microbial

Table 3
Summary of archaeal and bacterial organisms in anaerobic digestion.

Substrate	Temperature (°C)	OLR	Operating condition	Organisms present	Molecular technique applied	References
Food wastewater	35 °C	3.5–7 kg COD/m^3 d	Changes of OLR	*Methanobacteriales Methanomicrobiales*	Quantitative real-time polymerase chain reaction	Jang et al. (2014)
Food waste	36 ± 1 °C	3–6 g VS/L d	Increased OLR	*Actinobacteria Tenericutes Methanospirillum*	Pyrosequencing	Li et al. (2015)
Food wastewater and waste activated sludge	35–55 °C	2.83–6.88 kg COD/m^3 d	Increased OLR; thermophilic and mesophilic anaerobic digestion	*Petrotoga (assigned to phylum Thermotogae) Petrimonas (assigned to phylum Bacteroidetes)*	Quantitative real-time polymerase chain reaction	Jang et al. (2016)
Food waste	35–55 °C	1–2.5 g VS/L d	Thermophilic and mesophilic anaerobic digestion	*Methanosaeta Methanothermobacter Methanoculleus*	Pyrosequencing	Gao et al. (2015)
Vegetables waste	30 °C	0.5 g VS/L d	Effluent recirculation	*Bacteroidetes and Firmicutes*	Illumina sequencing	Gulhane et al. (2017)
Food waste and sewage sludge	37 °C	–	Microwave pretreatment	*Methanosaeta* *Methanosarcina*	Illumina sequencing	Zhang et al. (2016)
Food waste and waste activated sludge	35 ± 1 °C	2.3–14.1 g VS/L d	Biological co-pretreatment	*Methanosaeta* *Syntrophomonas* *Proteiniphilum acetatigenes*	Illumina sequencing	Zhang et al. (2017a,b,c)

communities tends to use a retrospective technique that explains observed changes in the reactor by reviewing changes in microbial communities. However, little work can be considered to be proactive, that is, managing the microbial community to generate a specific result (Carballa et al., 2015).

8. Perspectives

The use of biohythane as a new type of bioenergy has received an increasing concern since it could improve the value of the product and energy recovery efficiency (Liu et al., 2013). This process combines two stages of hydrogen and methane in which the microorganisms in the two phases are required for monitor and control (Si et al., 2016). The design and automatic control of the fermentation reactors were critical before the application (Yeshanew et al., 2016). Combined fermentation process of food waste for ethanol and methane production could overcome the issue of insufficient utilization of substrate during ethanol fermentation and improve the energy recovery rate of the subsequent methane fermentation system. Therefore, the ethanol-methane combined fermentation system was recognized to be better and has bright application prospect than traditional single methane fermentation (Koike et al., 2009).

Uçkun Kıran et al. (2015) and Venkata Mohan et al. (2016) proposed waste biorefinery models and established a refinery to deal with food waste by referring to the current refinery processing model. The biorefinery is similar to an oil refinery that integrates waste conversion processes and technologies into fuels, electricity, and chemicals production. At present, food waste refineries are still in the early stage of the conceptual research. It might improve the commercial value of the food waste in the near future. Combined with the current researches about anaerobic digestion of food waste, a technological route for methane fermentation combined with biorefinery technologies was proposed to promote substrates conversion into more valuable products. There will be 4 stages in this model, including: (1) pretreatment; (2) resourceful product: during this process, food waste can be used by components to produce hydrogen, lactic acid, acetic acid, ethanol, butanol, etc.; (3) biomethane fermentor: digestate from previous process can conduct anaerobic digestion to product methane; and (4) microalgae CO_2 capture: the carbon dioxide produced in the anaerobic system and the organic components in the digestate are used as dual carbon sources to increase the growth rate of microalgae and oil or starch production. In this model, food waste was used to produce many useful products toward zero emissions. Fig. 1 presents a detailed description of biorefinery process.

9. Conclusion

Food waste is considered as a sustainable energy source in the future owing to its nutrients-rich feature. During the last 20 years, pretreatment, co-digestion, inhibition and mitigation are still research hotspots. Compared with the single-stage system, two-stage anaerobic system combined hydrogen or ethanol with methane fermentation could improve the energy recovery efficiency of the substrate and was considered a promising technology. In addition, the biorefinery would improve the commercial value of the anaerobic digestion of food waste due to the separated treatment on the basis of the component of the substrate.

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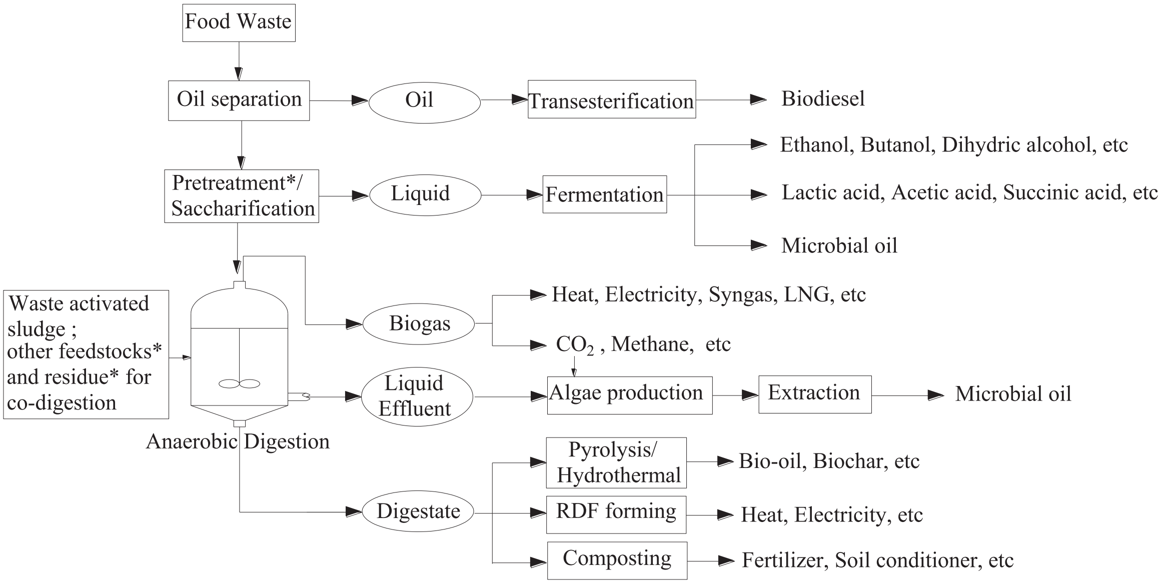

pretreatment*: physical pretreatment (hydrothermal process, etc), biological pretreatment (ethanol or aerobic prefermentation, etc);
feedstocks*: lignocellulosic biomass, etc
residue*: biofuel processing residue, fermentation residue, algal production residue, etc

Fig. 1. A technological route for food waste conversion based on biorefinery.

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