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REVIEW

Effects of anaerobic digestion of food waste on biogas production and environmental impacts: a review

Kah Rong Chew[1] · Hui Yi Leong[2] · Kuan Shiong Khoo[1] · Dai-Viet N. Vo[3] · Hirra Anjum[4] · Chih-Kai Chang[5] · Pau Loke Show[1]

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Abstract

Anaerobic digestion of food waste appears promising to generate biogas in the context of the growing energy demand and the circular economy. In particular, anaerobic digestion causes less air and solid waste pollution compared to incineration, gasification and pyrolysis. Actual research on biogas production using food waste focuses on the performance of substrates such as manure and bacteria, yet few investigations evaluate the impact of anaerobic digestion on the environment. Here, we review the steps of anaerobic digestion, factors that influence the process, and food waste as main and co-substrate to increase biogas yield. High metabolic activity of anaerobes is optimized by controlling temperature, pH, retention time, carbon-to-nitrogen ratio, volatile fatty acid and organic loading rate. We discuss the effect of pre-treatments such as biological, thermal, chemical and mechanical treatments, on anaerobic digestion performance. The impacts of food waste treatments on the environment are compared by life cycle analysis.

Keywords Anaerobic digestion · Food waste · Biogas · Pre-treatment · Environmental impact

Abbreviations

COD	Chemical oxygen demand
ERS	Economic Research Service
FW	Food waste
GWP	Global warming potential
HRT	Hydraulic retention time
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle analysis
OLR	Organic loading rate
SCOD	Soluble chemical oxygen demand
SRT	Solid retention time
TS	Total solids
TSS	Total suspended solids
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency
VFA	Volatile fatty acid
VS	Volatile solids
VSS	Volatile suspended solids

✉ Chih-Kai Chang
kevinvecent@gmail.com

✉ Pau Loke Show
PauLoke.Show@nottingham.edu.my;
showpauloke@gmail.com

1 Department of Chemical and Environmental Engineering, Faculty of Science and Engineering, University of Nottingham Malaysia, Broga Road, 43500 Semenyih, Selangor Darul Ehsan, Malaysia

2 Key Laboratory of Biomass Chemical Engineering of Ministry of Education, College of Chemical and Biological Engineering, Zhejiang University, Hangzhou 310027, China

3 Center of Excellence for Green Energy and Environmental Nanomaterials (CE@GrEEN), Nguyen Tat Thanh University, Ho Chi Minh City, Vietnam

4 Department of Chemical Engineering, University of Engineering and Technology Lahore, Faisalabad Campus, Faisalabad, Pakistan

5 Department of Chemical Engineering and Materials Science, Yuan Ze University, No. 135, Yuan-Tung Road, Chungli, Taoyuan 320, Taiwan

Introduction

Each year, approximately 1.3 billion tonnes of food produced are wasted around the world (Environment 2020). The definition of food waste is the plate waste by consumers and the food discarded by retailers due to its appearance or color (Agency 2014). Food waste can be generated from grocery stores, homes, bars, company cafeterias, restaurants and factory lunchrooms (Agency 2014).

There is a growing recognition that the improper management or disposal of food waste can cause detrimental impacts on climate change, resource conservation and food security. In the USA, there is an increase in the release of methane gas from food loss and waste (USDA 2015). Food waste in landfills is broken down to form methane, which has a global warming potential that is 28 times greater in comparison with carbon dioxide over a timeframe of 100 years (IPCC 2013). Besides, food waste undergoes decomposition at a faster rate compared to other landfilled organic materials, does not cause sequestration of biogenic carbon compounds in landfills and has a high methane yield.

Apart from landfills, there are several other methods that are commonly used to treat food waste, including incineration, composting and anaerobic digestion. Over the past decades, there is increasing concerns on energy crisis; hence, anaerobic digestion emerges as the most preferred method to treat food waste as the method can generate biogas, which can be used as a source of renewable energy. Additionally, anaerobic digestion can decrease the consumption of fossil fuels to generate energy as a result of the decrease in the release of greenhouse gases (Chiu and Lo 2016). Compared to other treatment methods like incineration, gasification and pyrolysis, anaerobic digestion causes the least pollution of solid waste and the air (Nah et al. 2000). Nevertheless, the anaerobic digestion process is a time-consuming process requiring a duration of 30–60 days for completion. Besides, a huge investment cost is needed to purchase large manure containers and tanks (Gopinath et al. 2020).

Current research on the production of biogas by using food waste focuses on the performance of manure (Ma et al. 2020; Yao et al. 2020). However, limited studies were conducted to evaluate the impact of anaerobic digestion on the environment. The objectives of this review is to discuss the factors influencing the production of biogas in the anaerobic digestion, co-digestion of food waste, as well as the possible environmental impacts in the treatment of food waste, and to provide alternatives to reduce these impacts.

Anaerobic digestion and anaerobic co-digestion of food waste

Anaerobic digestion of food waste

Typically, anaerobic digestion involves the microbial degradation of organic residues, for example, food waste. This process can yield methane-rich biogas when conducted under anaerobic environment. The digestate, which is the outcome of anaerobic digestion, can be treated as a by-product to be utilized as fertilizer or as compost for the enhancement of soil quality or as a residue (Chiu and Lo 2016; Morales-Polo et al. 2018). Anaerobic digestion is commonly used to treat food waste in developed Asian countries, for example, China, Southeast Asia and several countries in Europe like Germany (Abbasi et al. 2011; Slorach et al. 2019; Negri et al. 2020). When comparing other common food waste disposal and treatment methods like landfill, composting and incineration, anaerobic digestion requires less land and recovers less energy, hence making it more suitable to be used (Chiu and Lo 2016).

The biogas production can be affected by the nutrient content of food waste, particularly the contents of carbohydrate, protein and lipid. According to research, lipids have been shown to yield the most biogas (Esposito et al. 2012). However, due to their slow biodegradability, a longer retention time is needed to complete the process (Esposito et al. 2012). On the other hand, carbohydrates and proteins has faster rate of conversion however the yield of biogas is low. Moreover, Zhang et al. (2013) demonstrated the reduced anaerobic digestion performance when food waste was presented with trace elements like calcium and magnesium (Zhang et al. 2013).

Process of anaerobic digestion

Figure 1 shows the four steps of anaerobic digestion process, namely hydrolysis, acidogenesis, acetogenesis and methanogenesis. The composition of the final biogas product includes methane (55–65%), CO_2 (30–45%), trace amounts of hydrogen sulfide and water vapor (Caruso et al. 2019). To purify and obtain a better quality of biogas, CO_2 and hydrogen sulfide need to be eliminated by mixing with lime water and by passing through a stripper.

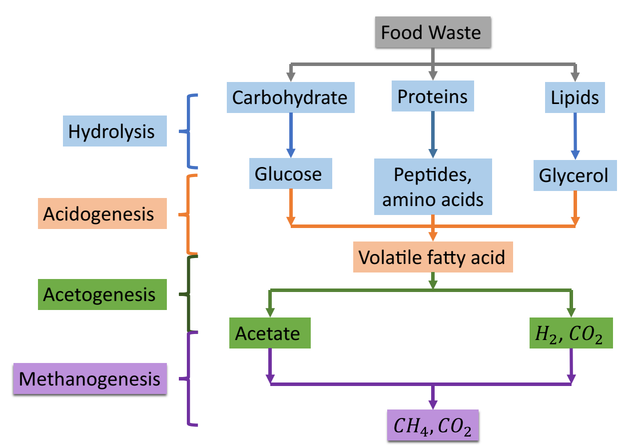

Fig. 1 Summary of anaerobic digestion process, including hydrolysis, acidogenesis, acetogenesis and methanogenesis. Food waste is treated in this process to produce methane and carbon dioxide

Hydrolysis

Anaerobic digestion begins with the hydrolysis of food waste substrates with high molecular weight like carbohydrate, protein as well as lipid to form smaller and water-soluble compounds with the reaction catalyzed by acidogenic bacteria (Kondusamy and Kalamdhad 2014). For example, polysaccharides are broken down into monosaccharides and oligosaccharides. Equation (1) shows the process of starch hydrolysis to form glucose molecules (Kondusamy and Kalamdhad 2014). Besides, peptides and amino acids are formed after protein is being hydrolyzed, whereas the products from the hydrolysis of lipids are fatty acids and glycerol (Morales-Polo et al. 2018).

$$nC_6H_{10}O_5 + nH_2O \rightarrow nC_6H_{12}O_6 \quad (1)$$

Hydrolysis is the rate-limiting stage in anaerobic digestion. This process is directly associated with temperature, pH, substrate nature and its particle size, as well as organic load. In general, hydrolysis takes place under optimum conditions with pH between 5 and 7 and temperature between 30 and 50 °C (Meegoda et al. 2018). According to Menzel et al. (2020), hydrolysis can occur under mesophilic conditions with a pH between 5 to 6 and a short hydraulic retention time of 2–3 days in a continuous stirred tank reactor (Menzel et al. 2020). Other parameters that could influence the rate of hydrolysis include bacterial concentration, enzyme production and adsorption on the surface of the substrate (Morales-Polo et al. 2018). To enable a correct hydrolysis development, it is required to have a good interaction between the substrate and the inoculum (Morales-Polo et al. 2018). This enables the enzymes to be adsorbed on the surface of substrate to carry out an extracellular reaction (Elbeshbishy et al. 2012). Additionally, the availability of a large surface area for bacteria can result in an enhanced biogas production and ensure that the subsequent reactions can have a better development (Marin et al. 2010; Lisboa and Lansing 2013; Murto et al. 2013). The anaerobes that are involved in the hydrolysis process include *Streptococcus* and *Enterobacter* (Kondusamy and Kalamdhad 2014).

Acidogenesis

The second step involves the further decomposition of substrates into volatile fatty acid (VFA) during the reaction catalyzed by acidogenic bacteria (Paritosh et al. 2017). The by-products from the acidogenesis process are CO_2, H_2S and NH_3. The examples of VFA include acetate, butyrate, isobutyrate, propionate and valerate (Paritosh et al. 2017). During the acidification process, facultative anaerobic bacteria use carbon and oxygen to form an anaerobic condition. Acetate, CO_2 and hydrogen are utilized to produce methane. Moreover, butyrate, isobutyrate, valerate and propionate undergo further degradation to produce hydrogen and acetate in the reaction catalyzed by syntrophic acetogenic bacteria (Kondusamy and Kalamdhad 2014). The examples of fermentative microorganisms that are involved to produce VFA in the acidogenesis step are *Bacillus, Salmonella, Streptococcus, Escherichia coli* and *Lactobacillus* (Caruso et al. 2019). The pH drop is because of VFA formation and is favorable to the acidogenic and acetogenic bacteria, which can work optimally at a pH of 4.5 to 5.5.

Acetogenesis

Figure 2 shows the acetogenesis step, where VFA is converted into acetate, H_2 and CO_2 by acetogenic bacteria. Equation (2) demonstrates the formation of acetate from VFA, H_2 and CO_2. The production of acetate molecules takes place through the reduction of CO_2 via hydrogen as the electron source. The acetate molecules generated in this step will be utilized in the methanogenesis process. However, the release of hydrogen in this step will inhibit the activity of microorganisms. Hence, there is a syntrophic relationship that is present between the acetogenic bacteria and hydrogenotrophic methanogens. In addition, acetogenesis can produce 70% of methane during the reduction of acetate, together with the formation of 11% hydrogen (Kondusamy and Kalamdhad 2014). The examples of acetogenic bacteria that are involved in this process belong to genera *Syntrophomonas* and *Syntrophobacter* (Kondusamy and Kalamdhad 2014).

$$nC_6H_{12}O_6 \rightarrow 3nCH_3COOH \quad (2)$$

Methanogenesis

In this step, acetate, H_2 and CO_2 are utilized by methanogenic bacteria in the production of methane gas. This can take place through two pathways, which are acetoclastic or hydrogenotrophic methanogenesis (Paritosh et al. 2017).

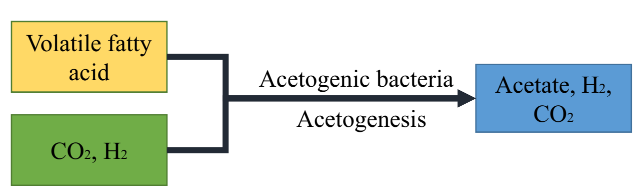

Fig. 2 The acetogenesis stage in anaerobic digestion. Acetate is formed by acetogenesis from volatile fatty acids, CO_2 and H_2 with the help of acetogenic bacteria

Acetate is the main substrate to produce methane in the former method (Eq. 3), whereas hydrogen is used to reduce CO_2 in the latter method (Eq. 4). Moreover, carbon monoxide and carbinol can be converted into methane. Karakashev et al. (2005) demonstrated the amount of methane formed via the reduction of CO_2 by methanogens only consists of 30% (Karakashev et al. 2005). Methane production can be accelerated by the addition of conductive materials (Xiao et al. 2020a, b)

$$CH_3COOH \rightarrow CH_4 + CO_2 \tag{3}$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 3H_2O \tag{4}$$

Hydrogenotrophic methanogens play an essential role to ensure that the hydrogen to be maintained at a partial pressure of less than 10 Pa to enable the acetoclastic methanogens and acetogens to preserve their metabolic activity (Pandey et al. 2020). Studies have demonstrated that faster doubling time can be observed in hydrogenotrophic methanogens as compared to acetoclastic methanogens. In fact, the doubling time of *Methanoculles receptaculi* and *Methanospirillum hungatei* (e.g., hydrogenotrophic methanogens) is 6 h, whereas that of *Methanosarcina thermophila* (e.g., acetoclastic methanogens) is 2.6 days (Ali Shah et al. 2014).

Besides, controlling pH is important for methane production. It was suggested to conduct the methanogenesis step at a pH of above 6.6 and ideally between 7 and 7.5 to ensure maximal activity from the acidifying and methanogenic bacteria (Garcia-Peña et al. 2011). Caruso et al. (2019) pointed out some factors that can negatively influence the bacterial growth and activity, which include the lack of nutrients as well as the presence of inhibitory compounds such as sulfide, causing a reduction in pH and VFA accumulation (Caruso et al. 2019).

Factors affecting anaerobic digestion

For ensuring anaerobic microorganisms to work with high metabolic activity, environmental conditions are necessary to be controlled. To enhance the methanation process, it is required to provide an optimal condition for methanogens, which are highly sensitive towards conditions that are unfavorable for survival (Paritosh et al. 2017). In fact, each of the four steps of anaerobic digestion has different rates of reaction which depends on substrate concentration and operating conditions. Typically, the rate-limiting step affects the rate of stabilization in overall. Besides, Xia et al. (2016) also concluded that the rate-limiting step is usually affected by temperature and in environments that have a low temperature (Xia et al. 2016). Figure 3 shows the factors affecting the rate of anaerobic digestion include temperature, pH, retention time, carbon-to-nitrogen ratio, VFAs and organic loading rate (Paritosh et al. 2017; Rawoof et al. 2020).

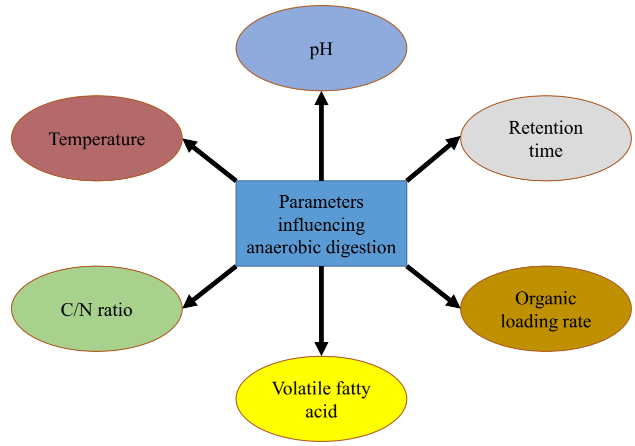

Fig. 3 Parameters influencing anaerobic digestion. These parameters are important to provide an optimal condition for anaerobic microorganisms to work with high metabolic activity. C/N ratio: carbon-to-nitrogen ratio

Temperature

The temperature factor is crucial as it could affect the enzyme and coenzyme activity, which is responsible for methane yield, hydrolysis development and quality of digestate (Sanchez et al. 2001; Coelho et al. 2011). Anaerobic digestion can take place in several temperature conditions, which include psychrophilic condition (below 20 °C), mesophilic condition (25–40 °C) as well as thermophilic condition (45–60 °C) (Chiu and Lo 2016). Research has shown that mesophilic activity works optimally between 35 and 45 °C, whereas thermophilic activity works optimally between 55 and 65 °C (Moset et al. 2015). The rate of anaerobic digestion increases as the temperature increases, along with the rate of biogas production, bacterial growth rate and metabolic rate (El-Mashad et al. 2004; Kim et al. 2006). When anaerobic digestion was conducted in thermophilic conditions, the yield of biogas doubled when compared with that in psychrophilic conditions. Besides, it was also reported that less ammonia inhibition was observed in thermophilic conditions (Morales-Polo et al. 2018).

Increasing temperature is linked to reduced time for reaction and hydraulic retention time due to the increased reaction and kinetics of the biological and chemical processes. Besides, Abdelgadir et al. (2014) showed that increased temperature improves the rate of diffusion and ensures the favorability of the substrate properties in terms of physical and chemical aspects (Abdelgadir et al. 2014). Furthermore, Smith et al. (2005) demonstrated that increased temperature can speed up the rate of pathogen destruction in anaerobic digestion (Smith et al. 2005). Nevertheless, negative effects will occur because of high temperature in thermophilic conditions. For example, it will induce the increased amount of free ammonia that could inhibit microbial activity, causing disturbance to the thermophilic process. In the current anaerobic digestion facilities, Lohani and Havukainen (2018) suggested that the use of mesophilic condition is more appropriate although it requires a longer retention time (Lohani and Havukainen 2018).

pH

Another important parameter is pH because of its ability to control the performance and stability of the digester. The bacteria involved in biogas production consist of methane-producing archaea, fermentative bacteria and hydrolytic bacteria. These anaerobes are pH-sensitive and require different pH range for growth. Studies have evaluated the optimal range of pH for these bacteria to work best. For example, Boe (2006) showed that the pH range that is suitable for methanogenic archaea to function is between pH 5.5–8.5 and the optimal range is between pH 6.5–8.0 (Boe 2006). Other than that, Hwang et al. (2004) reported that fermentative bacteria can function in an environment of pH ranges between pH 4.0–8.5 and can work optimally between pH 5.0–6.0 (Hwang et al. 2004). In fact, the reasons for the variation in pH include the alkalinity of the system, VFA and bicarbonate concentration (Paritosh et al. 2017).

Retention time

Another major parameter that needs to be monitored repeatedly is the retention time. Retention time is the duration to complete the degradation of substrate or the average time spent by the substrate in the digester (Deepanraj et al. 2014; Mao et al. 2015). Microorganisms require sufficient retention time to convert organic substrates into biogas (Khoo et al. 2021). Hydraulic retention time (HRT) and solid retention time (SRT) are the two types of retention times. Deepanraj et al. (2014) defined HRT as the duration for the liquid sludge to remain in the digester, whereas SRT is defined as the duration for the solid (bacteria) to retain in the digester (Deepanraj et al. 2014). Besides, it was shown that the rate of bacterial development related to retention time depends on OLR, substrate configuration and operating temperature (Mao et al. 2015).

Studies have concluded different retention time for organic waste under different temperature conditions (Kothari et al. 2014; Sánchez et al. 2015). For instance, mesophilic conditions require a 10–40 days of retention time, whereas thermophilic conditions require a shorter retention time. In mesophilic anaerobic digesters, the usual average retention time is between 15 to 30 days (Mao et al. 2015). To avoid biomass washout, it is recommended to have a minimum 10–15 days of retention time. However, one of the drawbacks for a longer HRT is that it requires a large reactor volume and high capital cost. Conversely, optimal substrate degradation could not take place in a shorter HRT (Sreekrishnan et al. 2004). A longer retention time will result in higher required digester volume, higher volatile solids reduction and increased acclimatization to different ranges of pH and types of toxic compounds. In contrast, Chandra et al. (2012) demonstrated lower digester volume needed and cost for investment but retaining the quantity and quality of biogas when the retention time is shorter (Chandra et al. 2012).

SRT that plays the role to maintain bacterial population in the reactor causes waste stabilization. Appels et al. (2008) suggested that the process stability can be maintained when bacteria is removed after the withdrawal of sludge (Appels et al. 2008). When a long SRT is applied, the rise of bacterial concentration and digester volume can occur due to the biological acclimatization to toxic compounds (Gerardi 2003). Research has shown the reduction in methane yield when a longer SRT was used (Chen et al. 2018). The highest methane yield was observed when the SRT is 6 days. Furthermore, Fernández-Rodríguez et al. (2014) showed highest methane yield when the SRT of 5–8 days was implemented (Fernández-Rodríguez et al. 2014).

Carbon-to-nitrogen ratio

Nitrogen appears to be one of the major nutrients required by the anaerobic microorganisms for growth. The uptake of nitrogen from the substrate is dependent on the nature of microbes (Kondusamy and Kalamdhad 2014). Kondusamy and Kalamdhad (2014) have concluded the utilization of carbon by the bacteria is 25–35 times higher than the utilization of nitrogen. Hence, optimal C/N ratio of 25–30:1 was recommended to ensure maximum bacterial activity (Kondusamy and Kalamdhad 2014).

Under conditions with low nitrogen content, a longer duration is needed for the digestion of carbon due to the less microbial population. Conversely, excess nitrogen can cause process inhibition as a result of the formation of ammonia. To reduce the effect of ammonia inhibition, the dilution of solid waste with water can reduce the toxicity (Kondusamy and Kalamdhad 2014). Hence, it can be concluded that both nitrogen and carbon are essential in enhancing the microbial population as well as to support their growth.

Studies have demonstrated the effect of using co-substrate in anaerobic digestion of food waste on methane yield at different C/N ratios. Wang et al. (2012) showed that C/N ratio of 27.2 obtained the greatest methane yield under a pH-controlled environment and the co-substrates used in the study were chicken manure, wheat straw and dairy manure

(Wang et al. 2012). In another study, Karthikeyan and Visvanathan (2012) showed the most yield of methane occurs when the C/N ratio was 27 (Karthikeyan and Visvanathan 2012). In fact, introducing an optimal carbon content can give a positive effect on preventing excessive ammonia inhibition (Pramanik et al. 2019).

Volatile fatty acid

VFA accumulation could inhibit the anaerobic digestion process, resulting in decreased biogas yield (Labatut and Gooch 2014; Luo et al. 2019). Besides, it was shown that VFA concentrations can influence each stage of anaerobic digestion, especially the hydrolysis and acidogenesis stage (Kondusamy and Kalamdhad 2014). Bouallagui et al. (2005) concluded that the inhibition of VFA of the methanogen activity is due to a drop in pH, which causes the loss of activity of acid-sensitive enzymes (Bouallagui et al. 2005). Besides, large amounts of undissociated acids may penetrate cell membranes and causes the destruction of macromolecules. Besides, it was demonstrated that 2000–3000 mg/L is the optimum VFA range for metabolic activity (Paritosh et al. 2017).

When the concentration of VFA is at 2 g/L, the cellulolytic activity will be inhibited. VFA with the concentration of above 4 g/L can significantly decrease biogas production because the glucose fermentation and the rate of cellulose hydrolysis were affected. Siegert and Banks (2005) showed that biogas yield decreased at VFA concentration of 1 g/L when cellulose is co-digested with paper (Siegert and Banks 2005). When VFA is accumulated at a specific place, it will disrupt the microbial consortia, resulting in process inhibition and failure (Kondusamy and Kalamdhad 2014).

Organic loading rate

OLR refers to substrate quantity or chemical oxygen demand per unit reactor volume (Dhar et al. 2016). This parameter is important to be controlled as it could affect the cost and process performance as well as stability. According to the study done by Morken et al. (2018), it was shown that the methane yield has increased by 479% as OLR increased from 1.8 to 5.0 kg VS/m^{3}d (Morken et al. 2018). It was shown that biogas production and the microbial community can be influenced by OLR. When the OLR is at the optimal level, biogas production can be enhanced. Conversely, if the OLR is beyond the optimal level, there will be an imbalance between the stages of anaerobic digestion, causing the accumulation of VFA which leads to process inhibition. In fact, an extremely high OLR will cause irreversible acidification and process failure. When OLR of 1.0 kg VS/m^{3}d was increased to 2.5 kg VS/m^{3}d, the methane yield can be preserved under mesophilic conditions (Guo et al. 2014). It was observed that there was higher diversity and abundance of microorganisms retained in the anaerobic digester when conducted under mesophilic conditions. The mechanism suggested was the increased functional equivalence of the acetolactic methanogens.

Anaerobic co-digestion of food waste

Food waste as co-substrate

Anaerobic co-digestion uses food waste alongside main substrates like manure and sewage sludge to enhance biogas production. Nevertheless, main substrates with low C/N ratio can cause the accumulation of ammonia, which leads to process inhibition. Hence, the addition of food waste containing high C/N ratio will enhance biogas yield by reducing ammonia inhibition. Moreover, Chiu and Lo (2016) demonstrated that the anaerobic co-digestion process will work optimally at a C/N ratio of 20–30 (Chiu and Lo 2016).

During the co-digestion of food waste alongside other main substrates, the undesirable products in the mixture can be diluted, leading to increased biogas yield. This is because the sewage sludge consists of high levels of pathogens and metals, which can cause process inhibition. Hence, by diluting the undesirable products, it will increase the efficiency of degradation (Chiu and Lo 2016).

Food waste as main substrate

VFA accumulation can occur during anaerobic digestion of food waste because food waste is highly biodegradable, which can affect the methanogenic activity. Besides, the anaerobic digestion process is not optimized due to the lack of phosphorus, nitrogen and other trace metals (Chiu and Lo 2016). Hence, various types of co-substrates are added to the anaerobic co-digestion of food waste to reduce the inhibitory effect. Several studies were done to assess the production of biogas during the anaerobic co-digestion process by using food waste as main substrate (Cuetos et al. 2010; Mata-Alvarez et al. 2014; Haider et al. 2015; Yong et al. 2015). Table 1 summarizes the recent studies on anaerobic co-digestion of food waste. Yong et al. (2015) showed an increase of 39.5% methane yield when straw is added to the anaerobic co-digestion of food waste. The addition of straw reduces the rate of hydrolysis because the lignocellulose in straw cells has a low biodegradability (Yong et al. 2015). This prevents the rapid decomposition of food waste, causing accumulation of VFA.

However, if lignocellulosic waste was added excessively, it can decrease the biogas yield. A study demonstrated a 38% lower biogas yield after the co-digestion of food waste with lignocellulosic waste when the anaerobic digestion was conducted with a C/N ratio of 35 compared to a C/N ratio of

Table 1 Comparison of anaerobic co-digestion of food waste with different types of co-substrates

Feed	Co-substrate	Operating condition[a]	Effect of co-digestion[a]	References
Municipal food waste	Cow slurry	pH: 7.64 Temperature: 37 ± 2 °C, Organic loading rate: 5.04 g VS/L/day Hydraulic retention time: 17.5 days	The methane yield was 444.7 mL/g VS when 32.2% of food waste was added	Morken et al. (2018)
Cucumber residues	Pig manure and corn stover	Temperature: 35 °C C/N ratio: 14.5 Volatile fatty acid: 0.76 g/L	Maximum methane yield of 305.4 mL/g VS when the ratio is 3:5:2 for cucumber residues, pig manure and corn stover	Wang et al. (2018)
Food waste	Wheat straw	pH: 7.1–7.5 Temperature: 35 ± 1 °C (mesophilic), 55 ± 1 °C (thermophilic) Organic loading rate: 3 kg VS/L/day,	The reaction was unstable when food waste was mono-digested Maximum methane yield was 344 mL/g VS and 369 mL/g VS at mesophilic condition and thermophilic condition, respectively Rate of biogas production was 4.8–18% higher in thermophilic conditions	Shi et al. (2018)
Food waste	Pig manure	pH: 7.6–8.7 Temperature: 37 ± 1 °C (mesophilic), 55 ± 1 °C (thermophilic)	Maximum methane yield was 252 mL/g VS	Jiang et al. (2018)
Food waste	Waste activated sludge	*Mesophilic reactor*: pH: 7.64 Temperature: 35 °C Organic loading rate: 7.75 g VS/L/day Hydraulic retention time: 10 days *Thermophilic reactor*: pH: 7.86 Temperature: 55 °C Organic loading rate: 5.19 g VS/L/day Hydraulic retention time: 15 days	Maximum methane yield was 350 mL/g VS at mesophilic condition and 407 mL/g VS at thermophilic condition	Li et al. (2018)
Kitchen waste	Cow manure	pH: 7.5 Temperature: 35 °C Organic loading rate: 8% total solids Hydraulic retention time: 45 days	Methane yield was 179.8 mL/g volatile solid	Zhai et al. (2015)
Food waste	Sludge	pH:5.8–7.5 Temperature: 35 ± 2 °C, C/N ratio: 6.29	Maximum methane yield was 435.5 mL/g VS when the ratio is 1:3 for food waste and sludge	Wang et al. (2018)

[a]VS, volatile solid; C/N ratio, carbon-to-nitrogen ratio

20 (Haider et al. 2015). It was suggested that the decrease in performance is related to the lack of nitrogen in the anaerobic digestion system (Haider et al. 2015).

Cuetos et al. (2010) demonstrated a decreased methane yield by 53–61.9% after the co-digestion of food waste with treated slaughterhouse waste (Cuetos et al. 2010). The possible explanation was the high VFA levels that accumulate in the reactors, which led to process inhibition due to the acidic environment. Furthermore, Mata-Alvarez et al. (2014) showed that substrates with high OLR can result in lower biogas yield during the anaerobic co-digestion of food waste (Mata-Alvarez et al. 2014). Besides, OLR is important to be controlled because of its high biodegradability.

Type of pre-treatment methods

Pre-treatment of anaerobic digestion and anaerobic co-digestion of food waste is to speed up the rate of biodegradation as well as to increase solubility of substrate and methane content (Mirmohamadsadeghi et al. 2019). This method used to increase the accessibility of the anaerobes to substrates in the hydrolysis stage, causing increased biogas yield. Pre-treatment is used on the substrate before undergoing hydrolysis to weaken its cell wall structure. This can be achieved through the uptake of organic compounds from the cells by the methanogens and enzymes (Mirmohamadsadeghi et al. 2019). Moreover, this process can increase biogas yield by improving the biodegradability of food waste. Additionally, the retention time can be reduced through pre-treatment. However, Satari et al. (2019) suggested that the outcomes are mainly influenced by the substrate characteristics and pre-treatment mechanism (Satari et al. 2019).

There are several categories for the pre-treatments of food waste, which consist of mechanical, chemical, thermal, and biological pre-treatments. Table 2 summarizes the recent studies evaluating the outcomes of various pre-treatments on biogas production. Among the pre-treatment methods, the soluble organic fraction of substrate can be increased with the use of mechanical and chemical pre-treatments. However, it is important to be cautious when applying the pre-treatments on food waste as the organic materials that are present in food waste are easily degradable (Mirmohamadsadeghi et al. 2019). All the pre-treatment methods can lead to solubilization of food waste and improve the hydrolysis process via different mechanisms. Table 3 shows the advantages and limitations of each pre-treatment method.

Mechanical pre-treatment

Disintegration of solid particles can be achieved by the mechanical pre-treatment, leading to increased surface area (Ren et al. 2018). This enhances the hydrolytic step by increasing the contact between bacteria and substrate. It was concluded that a reduction of solid particle size to 2.5–8 mm can result in a higher production of methane (Agyeman and Tao 2014).

One of the mechanical pre-treatments is ultrasonic, which is produced from a large amount of hydromechanical shear force via ultrasonic waves of high intensities and sludge disruption (Deepanraj et al. 2014). Khoo et al. (2020) concluded that pre-treatment using ultrasonic waves for prolonged time can result in various chemical and physical impacts on the substrate such as disintegration of cell walls or cell lysis, solubilization of solid organic substrates, free radical production, micro-bubble production, moderate spreading and partial pressure reduction (Khoo et al. 2020). Rasapoor et al. (2019) demonstrated food waste treatment and evaluation of anaerobic digester performance by using ultrasonic waves (Rasapoor et al. 2019). In comparison with untreated food waste, it was demonstrated that biogas production has improved by 59% when the OLR is 500 g Vs/m^3 while the result showed improvement by 80% when the OLR is 1500 g Vs/m^3. Another study demonstrated that the highest biogas production was achieved at 20 kHz and 80 min of sonification, with prolonged duration of sonification being more conducive to VS reduction (Li et al. 2018).

Besides, liquid shearing, in the form of collision plates, can be used in the mechanical pre-treatment of food waste. This method uses high pressure to enable the sludge to smash against the plate, leading to cell lysis (Nah et al. 2000). Milling is also a mechanical pre-treatment that involves the reduction of substrate size. However, Motte et al. (2014) found that there will be a possibility of acidification due to the excessively fine particles that causes increased solubility of food waste (Motte et al. 2014).

Chemical pre-treatment

During this process, cell walls and membranes will be hydrolyzed by using strong acids and alkalis (Appels et al. 2008). Torres and Lloréns (2008) has demonstrated that the use of alkaline such as lime can cause increased biogas yield by 172% compared to the control group. The authors suggested that the outcome was due to the enhanced surface area and enzymatic activity that stimulates the swelling of particles (Torres and Lloréns 2008). In contrast, acid pre-treatment using hydrochloric acid has shown decreased biogas yield by 66% (Taherzadeh and Karimi 2008). The low pH was suggested to induce the production of phenolic compounds, furans and carboxylic acid, which act as the inhibitors of the reaction.

Some common examples of alkalis used in the pre-treatment of food waste include ammonia hydroxide, sodium hydroxide, aqueous ammonia, potassium hydroxide and calcium hydroxide to enhance biogas yield (Pramanik et al. 2019). However, it is inevitable that the presence of accompanying cations in some reagents like calcium, sodium, potassium and magnesium can promote inhibitory effects especially on the activity of some methanogens (Ariunbaatar et al. 2014). In fact, magnesium and calcium work best at the optimum concentrations of 0.72 g/L and 0.2 g/L, respectively. As for sodium and potassium, the maximum tolerable limits are <5 g/L and 8 g/L, respectively.

To treat lignocellulosic substrates, acid pre-treatment is a useful method as it breaks down cellulose to make them more accessible. Study has found that acid pre-treatment was more suitable to solubilize hemicellulose, whereas for the lignin removal, alkali pre-treatment can give better performance (Rodriguez et al. 2017). Although acid pre-treatment requires less time for degradation, it was less financially effective compared to alkaline pre-treatments (Kumar and Murthy 2011). According to Kim et al. (2016), alkaline pre-treatment can be carried out at room temperature (Kim et al. 2016). Hence, alkaline pre-treatment is more suitable because the reagents can be added for pH balance (Li et al. 2012).

Table 2 The various pre-treatments used to enhance biogas yield from anaerobic digestion

Pre-treatment	Type of food waste	Treatment description	Effect of pre-treatment	References
Mechanical				
High voltage pulse discharge	Food waste in the canteen	Pulse voltage and frequency: 40 kV and 400 Hz Electrode distance: 5 mm Duration: 30 min	High concentrations of soluble protein, sugar, and soluble chemical oxygen demand compared to control, which is 171%, 24.8% and 107.3%, respectively Methane yield increased by 35%	Zou et al. (2016)
Ultrasonic	Fruit and vegetable waste	Treated in ultrasonic sonicator with sonotrode diameter of 38 mm Frequency and amplitude of 20 kHz and 80 µm Feed was treated in 1000 mL glass reactors Temperature: 35 °C Duration: 25 days	Reduction of volatile solids and total solids compared to untreated food waste. More energy is consumed during longer sonication time compared to shorter sonication time Methane yield increased by > 80%	Zeynali et al. (2017)
Ultrasonic	Food waste and waste anaerobic sludge	Treated in an ultrasonic homogenizer Energy intensity: 360 kJ L^{-1} Duration: 30 min	Increased reduction of volatile suspended solids, chemical oxygen demand and total suspended solid by 6.5%, 11.1% and 3.7%, respectively Methane yield increased by 51%	Naran et al. (2016)
Thermal				
Thermal	Kitchen food waste	Treated in pressure vessel containing heating shell A fluid circulating process Temperature: 120 °C Duration: 50 min	The rate of solubility on total solid basis is 26.63% and on volatile solid basis is 49.21%. The methane concentration in biogas is 74.92% (v/v) Methane yield increased by 31.7%	Li and Jin (2015)
Thermal	Food waste	Duration: 60 min Temperature: 130 °C Heated in autoclave	Increased removal of chemical oxygen demand by 9.9%; Reduced volatile suspended solids by 7.2%; reduced total suspended solids by 5.2% Methane yield increased by 32.3%	Naran et al. (2016)
Hydrothermal	Air-dried rice, chopped	Heating rate: 10 °C min^{-1} Temperature: 180 °C Duration: 15 min Feed was immersed in distilled water for 12 h	Increased methane production by 9.5%	Wang et al. (2018)
Chemical				
Alkali	Food waste and waste anaerobic sludge	Addition of sodium hydroxide at concentration of 0.4 mol L^{-1} pH: 12.7 (after treatment)	Increased removal of chemical oxygen demand by 3.4%; reduced volatile suspended solids by 0.8%; reduced total suspended solids by 3%	Naran et al. (2016)
Alkali	Food waste	Addition of calcium hydroxide concentration of 40–190 mEq/L Duration: 1–6 h	The solubilization of chemical oxygen demand was optimized at calcium hydroxide concentration of 166.98 mEq/L Methane yield increased by 20% compared to control	Junoh et al. (2016)

Table 2 (continued)

Pre-treatment	Type of food waste	Treatment description	Effect of pre-treatment	References
Acetic acid	Fruit waste	Addition of 5 N hydrochloric acid solution with pH of 7.0 ± 0.2 Temperature: 37 °C Duration: 86 days Optimization of acetic acid pre-treatment with 0.2 M acetic acid Temperature: 62.5 °C Duration: 30 min	Improvement on the surface roughness and porosity of food waste after acetic acid pre-treatment. Increase crystallinity index by 56% maximum sugar recovery of 95% Methane yield increased by 10%	Saha et al. (2018)
Biological				
Biological co-pre-treatment	500 g food waste + 500 g waste anaerobic sludge	Temperature: 35 ± 1 °C, Duration: 24 h Treated in biological co-pre-treatment reactor Feed was purged for 30 min with pure nitrogen gas	Increased rate of hydrolysis of food waste and waste anaerobic sludge. Increased solubilization rate of particulate organic matter Methane yield increased by 28%	Zhang et al. (2017)
Lipid extraction	Food waste	Use of methanol and chloroform	Lipid content reduced by 30% 4.5% increase in methane yield when conducted under mesophilic conditions, whereas 24.6% increase in methane yield when conducted under thermophilic conditions	Algapani et al. (2017)
Thermophilic digestion	Food waste, co-digested with waste anaerobic sludge and wastewater in a ratio of 75:25	Treated in a semi-continuous digester Thermophilic conditions: operated at 55 °C Mesophilic conditions: operated at 35 °C HRT: 20 days Duration: 300 days	High methane content of 65.21% under mesophilic conditions, and 68.24% under thermophilic conditions Methane yield increased by 15%	Jang et al. (2016)

Table 3 Advantages and limitations associated with different pre-treatments

Methods	Advantages	Limitations
Chemical	Low capital cost Increases surface area Partial solubilization and hydrolysis of lignin and hemicellulose Decreases the ability of crystalize and polymerize High solubilization of hemicellulose, condensation and precipitation lignin	Production of irrecoverable salts Requires high operating cost for large scale Corrosive Inhibitory by-product will be formed Requires long interaction time
Mechanical	Does not require organic solvent Does not have odor problem Increases the accessibility of surface area Can be implemented on a larger scale Better dewaterability of final residue	Requires electricity High start-up cost Removal of pathogen is not significant
Biological	Low consumption of heat and electricity Environmentally friendly Does not require harsh chemicals Does not require restriction of specific digester	High enzyme cost Continuous addition demand Long process time
Thermal	Able to ensure process stability Increases specific surface area Degradation of structure and lysis of cell wall	Requires high energy demand Maillard reaction produces inhibitory intermediates

Thermal pre-treatment

For this method, substrates can be solubilized by disintegrating the cell membrane and cell wall (Prorot et al. 2011). Research has been done to evaluate the use of various ranges of temperature and its effect on food waste via thermal pre-treatment (Cuetos et al. 2010; Ariunbaatar et al. 2014; Li and Jin 2015). Li and Jin (2015) demonstrated that biogas yield and VS degradability had an increment of 30 and 36%, respectively, when thermal pre-treatment took place between 90 to 120 °C (Li and Jin 2015). A decrease in anaerobic digestion performance was observed at temperatures lower or higher than the range. Ariunbaatar et al. (2014) concluded an increase of methane yield by 52% when the food waste was pre-treated at 80 °C (Ariunbaatar et al. 2014). Moreover, Cuetos et al. (2010) demonstrated a decrease of 53–61.9% in methane production due to VFA accumulation and foaming in the reactor (Cuetos et al. 2010). Montgomery and Bochmann (2014) suggested that the pre-treatment of highly biodegradable waste may cause system overload (Montgomery and Bochmann 2014).

The removal of pathogens in food waste can be achieved by using thermal pre-treatment. According to the regulation from European Union (EC1772/2002), food waste needs to undergo pasteurization at 70 °C for at least one hour each time before or after the anaerobic digestion process (Chiu and Lo 2016). The other advantage of using this pre-treatment method is that the process increases loading rates of digesters (Barber 2016). Besides, Ariunbaatar et al. (2014) also suggested that this can enhance dewatering performance and reduce digestate viscosity (Ariunbaatar et al. 2014).

The choice of temperature used in thermal pre-treatments can cause notable influence on the outcome of the pre-treatment process. VS destruction can be caused by extremely high temperature, which depletes the substrate that is available for anaerobic digestion (Barber 2016). According to Dwyer et al. (2008), carbohydrates and proteins that have increased solubility at high temperatures may result in accumulation of toxic melanoidins via the Maillard reaction (Dwyer et al. 2008). Furthermore, Ferrer et al. (2008) showed that low-temperature thermal pre-treatment takes place via enzymatic hydrolysis (Ferrer et al. 2008). Nevertheless, food waste that was pre-treated at 70 °C was still able to significantly reduce the pathogen (Skiadas et al. 2005).

Biological pre-treatment

There are two categories in this method, which are aerobic and anaerobic treatment. In terms of aerobic pre-treatment, it was shown that microaeration or composting can enhance the hydrolytic enzyme population, leading to increased performance of the hydrolysis process (Lim and Wang 2013). The authors also suggested that the biogas yield has increased by 23% when the food waste was pre-treated with microaeration. However, it was shown that excessive aeration can lead to decreased biogas yield due to the lower anaerobic fermentation.

Anaerobic pre-treatment can be called pre-acidification or two-stage anaerobic digestion process. The performance of anaerobic digestion can be enhanced through the separation of the first and second step in anaerobic digestion from the other stages (Mao et al. 2015). In a two-stage digester, Liu et al. (2006) demonstrated an increase in methane yield by 21% for the pre-treatment of food waste (Liu et al. 2006). Deublein and Steinhauser (2011) suggested that the optimal pH in the first stage reactor is 4–6, whereas for second stage is 6.5–8 (Deublein and Steinhauser 2011). Compared to the first reactor, less VFA was produced in the second reactor. The conversion of VFA to methane can prevent the build-up of VFA to impede the bacterial activity. Furthermore, the use of a two-stage reactor contains bacteria that is less sensitive to most inhibitors in the first stage of the reactor (Chiu and Lo 2016). The single stage digestion is preferred due to the lower operational and capital costs, and it is simple to operate (Shah et al. 2015). Nevertheless, one limitation of the biological pre-treatment is that it requires longer retention time, leading to a relatively slow process compared to the other methods (Montgomery and Bochmann 2014).

Temperature-phased anaerobic digestion is another example of biological pre-treatment. According to Carrère et al. (2010), this process aims to enhance the hydrolysis process by digesting food waste under thermophilic or hyperthermophilic conditions (Carrère et al. 2010). Specifically, Ge et al. (2010) showed that thermophilic-mesophilic temperature-phased anaerobic digestion resulted in more VS to be removed and increased production of methane (Ge et al. 2010).

Environmental implications

Life cycle analysis of environmental impacts from food waste management system

It is known that there will be detrimental environmental impacts and health problems among the community if food waste was left untreated. Life cycle analysis (LCA) is commonly implemented to assess a waste management system on its impact to the environment by using the concept "from cradle to grave." The assessment will normally begin from the manufacturing of raw materials to the discarding of waste (Chiu and Lo 2016). Figure 4 shows a summary of the cradle to grave of food waste management obtained from Mondello et al. (2017). LCA can be used to support decision-making regarding waste management. Through LCA, the possible environmental benefits and impacts can be compared. Therefore, this method can also be used to propose solutions that are environmentally friendly or improve management options along the food waste production chain (Notarnicola et al. 2017). Food waste is commonly treated or disposed through various pathways, namely composting, incineration, landfill, and anaerobic digestion. Table 4 summarizes the recent LCA studies that were done on different food waste management systems (Sánchez et al. 2015).

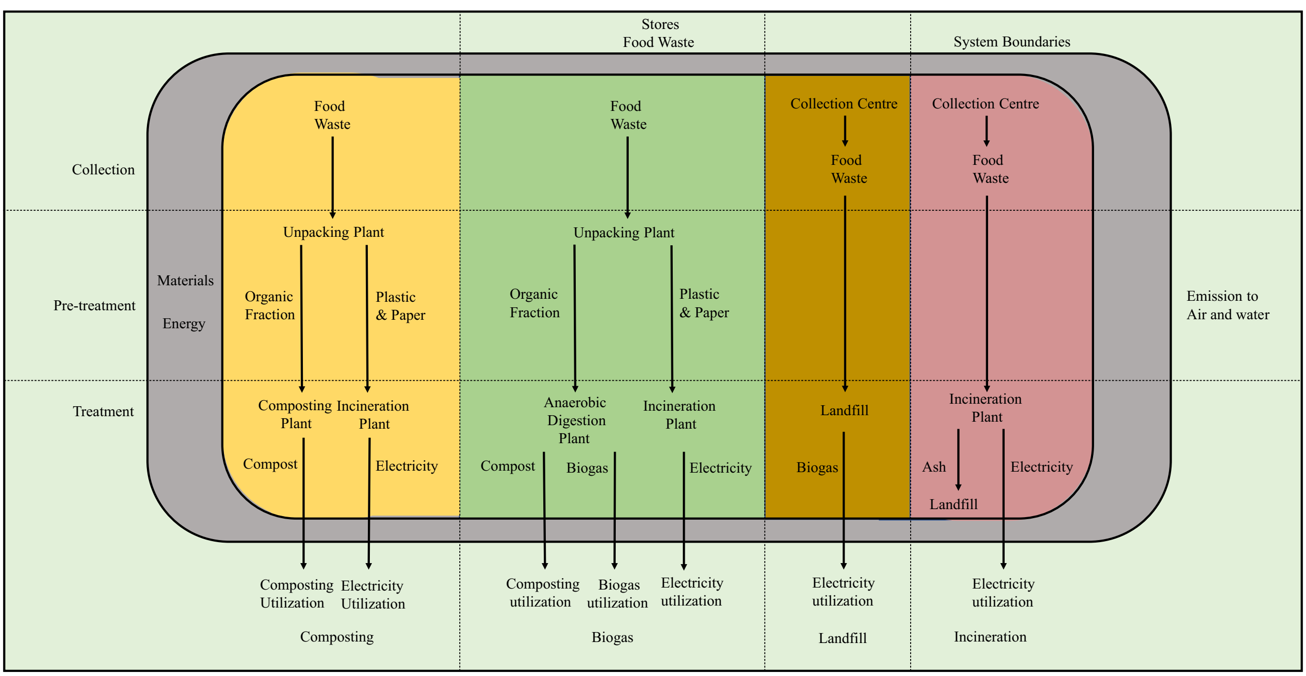

Fig. 4 The food waste management systems of composting, anaerobic digestion, landfill and incineration from cradle to grave. All four food waste treatment methods involve the collection and treatment processes, whereas composting and anaerobic digestion also involve the pre-treatment process. The end product of food waste can be utilized for different uses, which include electricity, composting and biogas utilization (Mondello et al. 2017; Nanda and Berruti 2020)

Table 4 Recent life cycle analysis studies done on different food waste management systems

Methods	Type of impacts	Biogas utilization	Reference
Composting	Acidification potential Photochemical oxidation potential Global warming potential Eutrophication	Fuel for vehicle Production of heat Production of electricity	Börjesson and Berglund (2007)
	Acidification potential Photochemical oxidation potential Ecotoxicity Resource use Global warming potential Energy use		
Anaerobic digestion	Particulate matter formation Global warming potential Acidification potential	Fuel for vehicle Production of heat Production of electricity	Woon et al. (2016)
	Acidification potential Photochemical oxidation potential Energy use Eutrophication Global warming potential		Khoo et al. (2010)
Landfill	Global warming potential	Fuel for vehicle Production of heat Production of electricity	Eriksson et al. (2016)
	Acidification potential Photochemical oxidation potential Eutrophication Global warming potential		Righi et al. (2013)
Incineration	Global warming potential	Fuel for vehicle Production of heat Production of electricity	Eriksson et al. (2016)
	Acidification potential Photochemical oxidation potential Global warming potential Particulate matter formation		Chiu and Lo (2016)
Anaerobic co-digestion	Global warming potential	Production of heat Production of electricity	Zitomer et al. (2008)
	Acidification potential Photochemical oxidation potential Global warming potential Particulate matter formation		Chiu and Lo (2016)

Caputo et al. (2014) utilizes LCA to assess the implication of food waste management in an institution to the environment and focuses on their food chain aspects, which include the management of food waste, food production, processing and consumption (Caputo et al. 2014). The results concluded that the strategies are sustainable and directly linked to the use of locally sourced, seasonal and less energy-intensive products. The authors also proposed that food waste can be managed by the conversion into renewable energy such as biomethane and biodiesel. Naroznova et al. (2016) compared the GWP impacts of organic household waste based on the incineration and anaerobic digestion (Naroznova et al. 2016). It has shown that anaerobic digestion resulted in a decrease in GWP when food waste was treated. Besides, Bernstad and la Cour (2012) investigated the environmental effects of incineration, composting and anaerobic digestion and showed that the production of biogas can lead to environmental benefits as it can be substituted for electricity coal power sources (Bernstad and la Cour 2012).

Environmental implications from the biogas production

The release of fugitive methane gas is one of the main environmental implications of anaerobic digestion or anaerobic co-digestion of food waste. According to the IPCC (2013) guidelines, fugitive emissions are defined as 5% of the biogas (IPCC 2013). Moreover, United States Environmental Protection Agency (USEPA) recommends the fugitive emissions at 10% leakage rate. To reduce the fugitive biogas emissions, any excess gas should be burned off by the flaring systems. By using this method, it is able to decrease any possible safety risk (Chiu and Lo 2016).

Besides, the release of nitrous oxide can also cause climate change and pose detrimental effects to the environment (Møller et al. 2008). Owing to the less implication to the environment, anaerobic digestion is more suitable to be used for the treatment of food waste, as shown in Table 4. There are three different food waste treatment methods, which are incineration, anaerobic co-digestion and a combination of anaerobic digestion and incineration on their environmental impact (Chiu and Lo 2016). It was shown that anaerobic co-digestion had the least impact on climate change as the process reduces the release of greenhouse gas from burning fossil fuels and a greater production of renewable energy for the substitution of conventional energy.

Apart from the release of methane and nitrous oxide, other environmental implications are eutrophication, acidification and the formation of photochemical oxidants. These impacts can occur due to the leakage of biogas which consists of ammonia and hydrogen sulfide. Moreover, Caine (2000) suggested that carbon monoxide, non-methane volatile organic compounds, and nitrogen oxide can be released when the biogas is being combusted (Caine 2000). Although the combustion of biogas was not included in the anaerobic digestion process, many researchers do consider it when investigating the environmental impact of the anaerobic digestion process. Nitrogen oxide and sulfur oxide are the examples of acidifying pollutants that are produced during biogas combustion. When compared to the other methods, anaerobic digestion has a smaller acidification potential (Chiu and Lo 2016).

Environmental benefits of biogas utilization

Lin et al. (2013) and Srivastava et al. (2020) demonstrated that the utilization of biogas can take place in different forms, such as biogas fuels for vehicle use from biogas upgrading as well as in the generation of electricity and heat from biogas combustion (Lin et al. 2013; Srivastava et al. 2020). Typically, a combination of heat and power in a unit will be used to generate electricity and heat from biogas. The generated electricity is utilized in anaerobic digestion facilities, whereas the excess is transported to the public grid. Furthermore, the generation of heat can be utilized by nearby industries and to maintain the reactor temperature. The generation of electricity is utilized at anaerobic digestion facilities while the grids in the public will receive the excess electricity. Exhaust gas treatment system is suggested to decrease the impact of biogas combustion to the environment.

To enable the utilization of biogas as fuel, the gas should undergo proper upgrading and cleaning processes. These processes include physical or chemical absorption, cryogenic separation, water scrubbing and membrane technology. To meet the required fuel standard, the reduction of impurities and increase of calorific value is necessary (Petersson and Wellinger 2009). Additionally, quality of biogas can be improved and utilized for household purpose when injected into the gas grid. However, the methane level will be affected by the gas standard of different countries (Sun et al. 2015). In another study done by Borjesson and Berglund (2007), it was shown that methane loss during upgrading ranged between 0.2 to 2% and can achieve up to a loss of 13% (Börjesson and Berglund 2007). Moreover, Woon et al. (2016) demonstrated that petrol fuel resulted in the greatest avoided emissions when compared to city gas as well as heat and electricity (Woon et al. 2016). The type of fuel used for substitution affects the avoided environmental emissions. According to Chiu and Lo (2016), less environmental impact is observed when a cleaner fuel is being used for substitution (Chiu and Lo 2016). To date, limited studies were done to assess the avoided environmental effects from biogas utilization. This review has shown that the life cycle analysis is useful to assess the environmental implications from biogas utilization. Based on the LCA studies, it was shown that biogas can cause environmental impacts including fugitive methane emissions, eutrophication, acidification and formation of photochemical oxidants. It was suggested to substitute the biogas with petrol fuel to have the greatest avoided emissions.

Challenges and perspectives

There are numerous challenges regard to the anaerobic digestion of food waste on biogas production. Low biogas yield occured due to lack of short process control and optimization. One of the challenges includes the formation of toxic intermediate composites during anaerobic digestion. Besides, Xu et al. (2018) suggested other challenges such as operation and transportation that requires high financial cost, VFA accumulation, process instability and low buffer capacity (Xu et al. 2018). These outcomes arise because of decrease in pH at the start of degradation as well as the inhibition of substances such as long-chain fatty acids, hydrogen sulfide and ammonia (Pramanik et al. 2019).

Besides, another challenge is the lack of appropriate design for reactors as the rule of thumb is still commonly used for reactor design (Appels et al. 2008). In general, the key challenges for biogas production include the biodegradability of food waste, accessibility, nutritional balance, characteristics of food waste, improvement in methane yield and development of bacterial activities (Hagos et al. 2017). Impurities like glass and plastic that are presence in food waste may cause serious consequences to the operation of equipment. The consequences such as the deterioration of start-up as well as long-term shutdown of operating units may occur.

To solve these problems, it is suggested to treat unwanted materials by implementing the source separation and central separation methods. In fact, countries such as UK, South Korea and Sweden have been using the source separation method (Mirmohamadsadeghi et al. 2019). However, there is still a lack of implementation of source separation in many countries as proper schemes are not owned. Therefore, it is recommended to invest in the separation of food waste by central separation or source separation to decrease the environmental implications and increase biogas yield (Mirmohamadsadeghi et al. 2019).

To resolve the instability of the process, adding a co-substrate into the anaerobic co-digestion of food waste acts as an alternative to relieve the burden of elevated capital cost for the construction of new plants. For the anaerobic co-digestion of food waste, recent studies have focused on the addition of sewage sludge to improve biogas production and the investigation on optimization and improvement of anaerobic co-digestion should be continued (Chow et al. 2020; Nguyen et al. 2020). Recently, adding nanoparticles that act as micronutrients was suggested to enhance the growth of bacteria in anaerobic digestion (Menon et al. 2017). Menon et al. (2017) showed an increase of 50% biogas yield and significant decrease in time of degradation when micronutrients such as calcium, nickel, cobalt and magnesium were added (Menon et al. 2017). However, more research is require to evaluate the direct impacts of adding micronutrients in anaerobic digestion.

Due to biogas being a source of renewable energy, its production has the potential to replace fossil fuels due to environmental and economic benefits. Recently, many researches have been done on the application of anaerobic co-digestion of food waste to enhance biogas production (Yong et al. 2015; Chiu and Lo 2016). In fact, food waste, when used as co-substrate and main substrate, has shown promising results when conducted in laboratory scale. Hence, it is important to conduct larger-scale studies with the use of food waste as main substrate to identify the optimal operating conditions before conducting the anaerobic co-digestion system on a full-scale.

Conclusion

Anaerobic digestion is regarded as one of the most preferred methods in food waste management through biogas production. Co-digestion with other substrates like lignocellulosic waste and slaughterhouse waste can be used to improve the process, resulting in higher biogas yield. Furthermore, pre-treatment methods can increase methane production in anaerobic digestion of food waste. According to the LCA studies, it was found that the main environmental concern of anaerobic digestion is climate change, which is due to the fugitive emissions of methane gas. Hence, flaring systems are used to burn out the excess gas to ensure safety and reduce the impact to the environment. The challenges involved in anaerobic digestion include the lack of short process control and optimization as well as the appropriate design for reactors, which often lead to low biogas yield and process instability. Due to the lack of implementation of source and central separation in most countries, it is recommended to invest in these technologies for the separation of impurities in food waste. Besides, the efficacy and safety of adding micronutrient supplements in anaerobic digestion of food waste to enhance its performance requires further investigation.

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Availability of data and material The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Code availability Not applicable.

Declarations

Conflicts of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethics approval and consent to participate Not applicable.

Consent for publication The authors declare that the work described has not been published nor under consideration for publication elsewhere and that if accepted, it will not be published elsewhere in the same form.

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