A review of food waste characterization and treatment in anaerobic digestion

Tengku Nuraiti Tengku Izhar\textsuperscript{1,2}, Irnis Azura Zakarya\textsuperscript{1}, Siti Khadijah Zaaba\textsuperscript{3}, Ahmad Hadwan Mohd Yusof\textsuperscript{1} and Najwa Mohd Shahril\textsuperscript{4}

\textsuperscript{1}Faculty of Civil Engineering Technology, Universiti Malaysia Perlis, Malaysia
\textsuperscript{2}Water Research Group (WAREG), Faculty of Civil Engineering Technology, Universiti Malaysia Perlis, Malaysia
\textsuperscript{3}Faculty of Electronic Engineering Technology, Universiti Malaysia Perlis, Malaysia
\textsuperscript{4}E-Idaman Sdn.Bhd. Wisma Idaman, Alor Setar, Kedah, Malaysia

email: nuraiti@unimap.edu.my

Abstract. Anaerobic digestion is one of the main biological techniques to convert organic waste to energy. The resulting biogas can be harvested as renewable energy and as a nutrient rich compound that can be converted to soil conditioner. Food waste varies seasonally and geographically. It is resulting in a multiple potential for biogas between different studies. This article studies the anaerobic digestion of food waste in two sections, which are food waste characteristics and mono digestion of food waste. The purpose of this review is to connect the features of food waste to the biogas potential and to propose improved method to increase biogas production. It was concluded that, in terms of physical and biochemical properties, the variation in food waste characteristics would affect the efficiency of the process, including nutrient balance, mechanical treatment, thermal treatment and two-stage configuration. Thermal treatment can increase biogas production but unnecessary treatment can decrease the biodegradability of food waste.

1. Introduction
The global economic and population increase has induced food waste production. Generally, more food waste produced through accommodations, restaurants, households, canteens and commercial premises. A growing country such as Malaysia has recorded a generation of municipal solid waste (MSW) in 2018 at 38,000 t/d \cite{1}. Most of the MSW, the primary element is organic waste, consisting of food waste. Food waste can comes from food preparation or as fruit-vegetable waste. Most of the food wastes are characterized as readily degradable, high moisture content, low pH and high in solubility. It gives higher energy content per dry mass. Anaerobic digestion (AD) is one of the biological treatments for organic waste that is gaining growing popularity because of its high waste value. AD of organic waste provides opportunities for energy recovery and nutrient recycling opportunities. It requires less area and energy than landfilling, composting and incineration \cite{2}. Organic waste for instance food waste, MSW and agricultural wastes are process feeds. Characterization of raw material of biomass that includes post-harvest variability, energy density, moisture content and degradation during storage is needed when developing a biogas chain of source for bioenergy.
In order to identify the relevant existing literature in accordance with the purpose of this study, a variety of papers reviewed were based totally at the keywords searches on published papers. The keywords were anaerobic digestion, anaerobic digestion of food waste, biogas from food waste and anaerobic digestion of kitchen waste. This review focused on food waste from canteen, restaurants, household food waste and kitchen waste. The focus of this research was on the articles that enabled to identify anaerobic digestion from food waste variables utilized in different studies. The study addressed the variables by checking how the attribute variables were correlated as extracted from the literatures examined (table 1). The review had been divided into the subsequent sections:

a) The characteristic of raw material in anaerobic monodigestion and anaerobic co-digestion was compared (table 2). The characteristic chose includes country, source, total solids (TS) and volatile solids (VS), carbon to nitrogen (C/N) ratio, and pH.

b) Methods used in the monodigestion of food waste to increase the biogas yields. Table 3 shows the highest biogas yield resulted from different treatments. Various units were used by the previous authors to depict the biogas or CH4 yield, primarily in L/g VS, m3/kg VS, m3/t VS and L/g VS. All data were recalculated in this paper and described in m3/kg VS, a standardized unit to contrast and discussed.

2. Biogas from food waste as raw material

2.1. Food waste characteristic

The resemblances and differences of raw material characteristics, which were used for AD are shown in table 2. Food waste is referred to raw material. Food waste and kitchen waste are used to identify waste originating in certain areas, such as a canteen at the university. There are several benefits to food waste as raw material, including low handling expenses because of minimum collection and transport cost, high biodegradability and high decimat ing of VS [3]. In mono-digestion, food waste is used as the only substrate at a low organic loading rate (OLR) to attain the minimum retention time and stable biogas production. The high organic loading rate (OLR) of food waste is linked with process complication of acid accumulation, excess inhibitory component concentration and nutrients contrast [4]. Throughout this analysis, high total solid digesters with high biogas production were found to be associated with accumulation of both acetoclastic and hydrogenotrophic methanogenesis while hydrogenotrophic methanogenesis is the primary one for those with low biogas production.

2.1.1. Solids content. Food waste has greater solid material compared to animal slurry and sewage sludge mainly because of heavy organic matter present and its thickness. The quality of solids inside the raw material restricts the loading capability to a low organic loading rate (OLR) to intercept overloading and accumulation of inhibitory compounds. The usage of solid rich in organic matter is based on its solubilization and subsequent biodegradation by using the microbs. Pretreatment, thermal pretreatment and thermophilic AD has been used to increase the solubilization of raw material.

2.1.2. C/N and pH. Food waste has low C/N ratio and pH, compared to fruit-vegetable waste. Fruit-vegetable waste, which includes fruits and vegetables peelings, are rich in lignocellulose waste. Lignocellulosic materials are better immune to microbial attacks, which cause acidification to slow down. The released NH3 or NH4 can both enhance the system through their buffering with the metabolic acids produced or emerge as inhibitory to the process [5]. The nitrogen and protein content varied following different diet styles. Sufficient nitrogen content contributes to a rise of 20% in biogas production as compared to the reactor without nitrogen addition. It undergoes nitrogen deficiency [6].

2.1.3. Biodegradability. The rapid degradation of volatile solid in the food waste results in rapid acidification and volatile fatty acids’ accumulation. Low pH and high acidity are inhibitory to methanogens. The optimum pH for acidogens and methanogens had been observed to be 4.5 - 5.5 and 5.5 - 6.5. The anaerobic digestion of food waste by a low organic loading rate was limited by the high
biodegradability of the organic matter portion. Instability and degradation of the mechanism was avoided.

2.1.4. Variation in quality. The most raw materials used (table 2), is restaurant food waste, university canteens and similar sources. For food waste and kitchen waste, the recorded value for total solids (TS) and volatile solids (VS) was close, between 20% and 30%. Wu et al. (2016) used the food waste from an institute dinner hall and Kawai et al. (2014) used the food waste from garbage collection company, each research had a total solid content less than 10%, in comparison to the food waste collected from the university canteen in China which has a total solid content of more than 20% [7] [8]. Among the food waste, the pH tends to differ. However they could be categorized as low pH. The lowest pH recorded was 3.65 from the institute’s dinner hall in Japan [7]. Table 2 showed raw material using municipal biomass waste had yield starting from 0.3 to 0.8 m³/kg VS. For the bromatological analysis, the comparison is complicated due to the limited data. Food waste may be summarized as a raw material with high TS and VS, with high biodegradability. However it low in C/N, N content and pH. The physical properties, which included in TS and VS did not vary substantially compared to the biochemical properties. The difference was caused by the spatial and seasonal changes, which is a feature of municipal solid waste. Biodegradability such as TS, VS and pH has been measured by most researchers. Interestingly, not all starch, protein, lipid and total acid number (TAN) content recorded will have a direct effect on the actions of the cell.

2.2. Anaerobic mono-digestion of food waste
Food waste was used as the primary raw material through mono-digestion. The OLR was held lower than 2.5g VS/d for mono-digestion of food waste for long-term production of biogas [5]. It limits a big scale anaerobic digestion for food waste because high retention time and low OLR will exerts high cost and lower return. Compare to raw material includes animal manure and sewage sludge that may be loaded at higher OLR and shorter retention time. The two-stage system, thermophilic anaerobic digestion, modification of initial pH, thermal pretreatment and use of acclimatized microbes are aiming to improve biogas yield, CH₄ content and high organic loading rate content. Table 3 summarizes researches using anaerobic mono-digestion of food waste as the primary raw material. The biogas is includes a combination of gases, commonly methane (CH₄), carbon dioxide (CO₂), hydrogen (H) and hydrogen sulphide (H₂S). Based on table 1, the highest biogas yield was from the system with thermal pretreatment, which yielded 1.2 m³ CH₄/kg [8]. However, Tampio et al. (2014) who conducted thermal pretreatment at 160°C, reported a 12.4% decrease in biogas production [9]. Ventura et al. (2014) performed two-phase anaerobic digestion (thermophilic-mesophilic configuration) and leads to a comparable biogas yield resulting in the best configuration [10].

2.2.1. Pretreatment. The use of thermal pretreatment increases the solubilization of organic matter via the thermal breakdown of the large organic matter into basic forms. Which can be reached more easily with the assistance of microbes to maximize the biogas yield. The efficiency of the thermal pretreatment depends on the type of waste, the temperature and the treatment time. These conditions are the predominant factors in investigating whether the enhancement in biogas production might outweigh the energy consumption [9]. A moderate temperature and low heating period gave the best mixture. At higher temperatures, organic solubilization increased with higher NH₃ volatilization.

2.2.2. Two-stage anaerobic digestion. Two-stage anaerobic digestion contains two separated reactors for acidogenesis and methanogenesis. The acidogenesis tank to be load higher, with low pH because to rapid organic matter degradation and acid accumulation. This design rarely applied for mono-digestion of municipal biomass waste. The single-stage anaerobic digestion is more preferred [11]. The higher production of CH₄ content (0.44 m³ CH₄/kg VSadded) in mesophilic-acidogenetic mechanism and configuration of thermophilic-methanogenesis, is because of material’s size is smaller than 2 mm. High temperature favours methanogenesis. The two-stage technique was performed in a higher
organic loading at higher stability with better pH self-adjusting potential, higher efficiency resistance to organic loading shocks and a higher rate of conversion in organic matter to methane (CH₄).

To summarize, the mono-digestion overview, the nutrient balance, the addition of sufficient nitrogen and trace element can enhance the stableness process underneath high loadings. Mono-digestion of food waste is constrained to the accumulation of volatile fatty acids. A broad range of inhibitory concentration of volatile fatty acids has been identified and the dominant acid species differed through studies with each stable and stressed reactor. The two-stage set up is to facilitate acid inhibition on the methanogenesis. Acclimatization of microbial through feeding the desired microbial inoculant with the desired raw material can also make a major contribution to improve system efficiency. For instance underneath high loading, higher tolerance for inhibition of volatile fatty acids, shorter lag phase and greater production of biogas. Thermal pretreatment on raw material with high cellulosic content is more applicable which includes agricultural and green waste (GW), greater solubilization might not result in overloading.
### Table 1. Studies of anaerobic digestion process on food waste generations.

| Source/location | Method | Objective | Result | Source |
|-----------------|--------|-----------|--------|--------|
| Household waste from Tikathali of Lalitpur district. | ARTI model compact biogas plant of 1 m³ capacity of water storage tank for digester. | To study the production of biogas as an alternative energy by using biodegradable wastes (BWs). | It showed that the plant might be an effective way for management of biodegradable domestic wastes at the household level. | [9] |
| Restaurant food wastes, Brazil. | Substrate and inoculum. | To determine the optimum operating conditions on food waste. | The food waste inoculum mixing ration 10:90 presented the best performance in the AD process, considering the 4 days mechanical aerobic pretreatment. | [12]. |
| Food waste from Central Marin Sanitation Agency (CMSA), San Rafael, California. | Biopower with internal combustion (IC) engine. | To develop scientific data in regards to quality and amount of biogas from anaerobic co-digestion of food waste. | Food waste makes up about 25% of TS or VS loading to the anaerobic digesters. The digesters are being operated under stable conditions. | [13] |
| Food and garden waste from Natural Resources Institute Finland. | Inoculum pretreatment on the composition of microbial communities. | To modulate the microbial communities via inoculum treatment to improve the production of green chemicals. | There was a strong correlation between volatile fatty acids production and the relative abundances of the microbial orders. | [14] |
| Food waste from National Institute of Technology Calicut, Kerala, India. | Four reactors of volume 2 L each were made of glass vessel. | To study the effects of ultrasonication, microwave and autoclave pretreatments on the anaerobic batch digestion of food waste. | Experimental studies simply indicated that each one pretreatment technique used in this study enhanced biogas production and degradation efficiencies. | [15] |
Table 2. Characteristic of raw material used in different studies.

| Country | Source                                           | TS %  | VS %  | C/N   | pH   | CH₄ yield | CH₄% Source |
|---------|--------------------------------------------------|-------|-------|-------|-------|-----------|-------------|
| Japan   | Food waste: Institute dinner hall                  | 7.21  | 94.62 | -     | 3.65  | -         | - [6]       |
| Japan   | Food waste: waste collection company and adjusted to standard food waste | 4.1   | 93.81 | -     | -     | 0.435 m³/kg VS | 30-60 [7] |
| Korea   | Food Waste: food waste recycling center            | 5.5   | 5.25  | -     | 3.75  | 0.44 m³/kg VS added | 70.7 [10] |
| China   | Kitchen waste: university canteen                  | 22.17 | 17.87 | 13.98 | 5.08  | 0.7 m³/kg VS added | 60 [16] |
|         | Fruit-vegetable waste: university canteen          | 7.94  | 6.74  | 17.21 | 5.28  | 0.64 m³/kg VS | - [16] |
| Singapore | Kitchen waste: university canteen                 | 3.2   | -     | -     | 5.1   | 0.46 m³/kg VS added | 40 [17] |
| China   | Kitchen waste: university canteen                  | 22.73 | 21.01 | -     | 6.86  | -         | - [18]       |
| UK      | Food waste: university farm                        | 12.8  | 11.3  | 13.6  | 4.3   | -         | - [19]       |
| China   | Kitchen waste: university canteen                  | 24.9  | 23.1  | 18.24 | -     | 0.501 m³/kg VS | - [20]       |
| Brazil  | Fruit-vegetable waste: central food distribution    | 13.8  | 12.88 | -     | 4.5   | 0.516 m³/kg VS | - [21]       |
| China   | Food waste: local supermarket                      | 10.86 | 10.22 | 15.18 | 4.16  | 0.460 m³/kg VS | - [22]       |
Table 3. Operational parameters for the mono-digestion of food waste and respective biogas yield as reported in the literature studied.

| Raw material | AD mode | Organic loading rate | Hydraulic retention time (d) | T(0 C) | Biogas yield | CH4 (%) | Remarks |
|--------------|---------|----------------------|-----------------------------|--------|--------------|---------|---------|
| Household kitchen waste segregation | Continuous | 2.5 kg VS/m³.d | 80 | 42 | 0.642 m³ CH4/kg VS | 62 | The energy balance reveal a possibly recoverable energy was 405 kWh/t. | [4] |
| Food waste from institute dinner hall | Continuously stirred tank reactor (CSTR) | - | - | - | 0.60 m³ biogas/kg VS | - | Co-digestion with an elevated CH4 yield for over 30%. | [6] |
| Adjusted food waste from garbage collection | Batch: Standard Food waste | 0.33 g VS substrate/g VS inoculum | - | 37 | 0.435 m³ CH4/kg VS | 40 | As the amount of inoculum increased, the lag phase rose | [7] |
| Food waste from university canteen | - | - | 21 | 35 | 1.2 m³ biogas/kg VS at 120 °C for 50 min | 74.92 | Higher thermal temperature gradually improved biogas production, with an increase of 50% - 147% compared to raw kitchen wastes. | [8] |
| Food waste from recycling center | S2: Mesophilic acidogenesis (MA) | 4.5 g COD/L.d | 5 | 36± 1 | 0.44 m³ CH4/kg VS | 70.7 | In a thermophilic setting, methanogens flourish better than acidogens. | [10] |
| Segregated domestic food waste from a organic waste processing plant | Semi-continuous | 3 kg VS/m³.d | 78 | 37 | 0.483 m³ CH4/kg VS | 58 | 12% reduction in biogas production was demonstrated by thermal treatment. | [11] |
3. Conclusions
The anaerobic digestion of food waste has a high benefit in terms of waste and energy. By accumulating carbon dioxide and methane on site, anaerobic digestion will decrease the greenhouse gas footprint of food waste while generating additional carbon credits through the provision of renewable energy. The yield of biogas for food waste mono digestion is approximately 0.435 until 0.642 m$^3$ CH$_4$/kg VS. Thermal pretreatment has led to a maximum biogas yield of 1.2 m$^3$ CH$_4$/kg VS. Unrestrained thermal treatment results in higher solubility due to the development of inhibitory compounds, but biodegradability has reduced. In the process of high processing efficient method to increase efficiency, consist of the nutrient balance, sufficient nitrogen supplement and inclusion of trace elements that are benefited for future research.

Acknowledgment
This work was carried out with the support of University Malaysia Perlis and E-Idaman Sdn.Bhd.

References
[1] SWCorp 2018 Kompendium Pengurusan Sisa Pepejal Malaysia Kementerian Kesejahteraan Bandar, Perumahan dan Kerajaan Tempatan Malaysia
[2] Zhang C, Su H, Baeyens J and Tan T 2014 Reviewing the anaerobic digestion of food waste for biogas production Renew. Sustain. Energy Rev. 38 383-392
[3] Dhar H, Kumar P, Kumar S, Mukherjee S and Vadiya A N 2016 Effect of organic loading rate during anaerobic digestion of municipal solid waste Bioreour. Technol. 217 56-61
[4] Banks C J, Chesshire M, Heaven S and Arnold R 2011 Anaerobic digestion of source segregated domestic food waste: performance assessment by mass and energy balance Bioreour. Technol. 102 612-620
[5] Garcia-Pe~na E I, Parameswaran P, Kang D W, Canul-Chan M and Krajmalnik- Brown R 2011 Anaerobic digestion and co-digestion processes of vegetable and fruit residues: process and microbiol ecology Bioreour. Technol. 102 9447-9455
[6] Wu L J, Kobayashi T, Kuramochi H, Li Y Y and Xu K Q 2016 Improved biogas production from food waste by co-digestion with de-oiled grease trap waste Bioreour. Technol. 201 237-244
[7] Kawai M, Nagao N, Tajima N, Niwa C, Matsuyama T and Toda T 2014 The effect of the labile organic fraction in food waste and the substrate/inoculum ratio on anaerobic digestion for a reliable methane yield Bioreour. Technol. 157 174-180
[8] Li Y and Jin Y 2015 Effects of thermal pretreatment on acidification phase during two-phase batch anaerobic digestion of kitchen waste Renew. Energy 77 550-557
[9] Lungkimbha H M, Kariki A B and Shrestha J N 2011 Biogas Production from Anaerobic Digestion of Biodegradable Household Wastes Nepal Journal of Science and Technology 11 167–172
[10] Ventura J R S, Lee J and Jahng D 2014 A comparative study on the alternating mesophilic and thermophilic two-stage anaerobic digestion of municipal solid waste J. Environ. Sci. 26 1274-1283
[11] Tampio E, Ervasti S, Paavola T, Heaven S, Banks C and Rintala J 2014 Anaerobic digestion of autoclaved and untreated food waste Waste Manag. 34 370-377
[12] Bruna Patricia d O, Luisa Helena d S O and Gilberto M 2017 Anaerobic Digestion of Food Waste 25th European Biomass Conference and Exhibition 902-906
[13] Kuo J and Dow J 2017 Biogas production from anaerobic digestion of food waste and relevant air quality implications Journal of the Air and Waste Management Association 67(9) 1000–1011
[14] Blasco L, Kahala M, Tampio E, Vainio M, Ervasti S and Rasi S 2020 Effect of inoculum pretreatment on the composition of microbial communities in anaerobic digesters producing volatile fatty acids Microorganisms 8(4) 1–21
[15] Mostafa A, Im S, Song Y C, Kang S and Kim D H 2020 Enhanced Anaerobic Digestion of Long Chain Fatty Acid by Adding Magnetite and Carbon Nanotubes Microorganisms 8(3) 333
[16] Wang L, Shen F, Yuan H, Zou D, Liu Y, Zhu B and Li X 2014 Anaerobic codigestion of kitchen waste and fruit/vegetable waste: lab-scale and pilot-scale studies Waste Manag. 34 2627-2633
[17] Menon A, Wang J Y and Giannis A 2017 Optimization of micronutrient supplement for enhancing biogas production from food waste in two-phase thermophilic anaerobic digestion Waste Management 59 465–475

[18] Li Y, Liu H, Yan F, Su D, Wang Y and Zhou H 2017 High-calorific biogas production from anaerobic digestion of food waste using a two-phase pressurized biofilm (TPPB) system Bioresource Technology 224 56–62

[19] Shamurad B, Sallis P, Petropoulos E, Tabraiz S, Ospina C, Leary P and Gray N 2020 Stable biogas production from single-stage anaerobic digestion of food waste Applied Energy 263

[20] Jiang J, Li L, Cui M, Zhang F, Liu Y, Liu Y, Long J and Guo Y 2018 Anaerobic digestion of kitchen waste: the effects of source, concentration, and temperature Biochem. Eng. J. 135 91–97

[21] Edwiges T, Frare L, Mayer B, Lins L, Mi Triolo J, Flotats X and de Mendonça Costa M S S 2018 Influence of chemical composition on biochemical methane potential of fruit and vegetable waste Waste Manag. 71 618–625

[22] Xiao B, Zhang W, Yi H, Qin Y, Wu J, Liu J and Li Y 2019 Biogas production by twostage thermophilic anaerobic co-digestion of food waste and paper waste: effect of paper waste ratio Renew. Energy 132 1301–1309