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Potential Biogas Production Generated by Mono- and Co-digestion of Food Waste and Fruit Waste (Durian Shell, Dragon Fruit and Pineapple Peel) in Different Mixture Ratio under Anaerobic Condition

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This work investigated the potential of generating biogas from mono-digestion of various substrates such as food and fruit waste (e.g., durian shell, dragon fruit peel and pineapple peel) and co-digestion in different combinations of a co-substrate as food waste as well as different types of fruit waste (durian shell, dragon fruit peel and pineapple peel). The mixture of food waste and fruit waste ratio varied as follows: 75:25, 50:50 and 25:75, which was based on weight. The batch experiments were carried out using 125 ml anaerobic digesters and were incubated for 50 days. For a mono-substrate, food waste produced the highest amount of methane gas (60.63 ± 1.02 ml/gvs) followed by durian shell (34.93 ± 1.30 ml/gvs), pineapple peel (31.70 ± 1.60 ml/gvs), and dragon fruit peel (30.12 ± 1.20 ml/gvs), respectively. The highest amount of methane gas came from food waste mixed with durian shell (FW75:D25), and it was on a higher level than food waste mixed with dragon fruit peel (FW75:DF25) and pineapple peel (FW75:P25). The highest methane gas production of co-digestion which was observed at the proportion of food waste and durian shell was 75:25 and produced higher content of methane gas than the highest methane gas production of mono-digestion (food waste) according to the high organic compound and optimum pH value in the system. The results showed that the co-digestion of durian shell and food waste improved methane production and reduced the startup time compared with their mono-digestion. On the other hand, pineapple peel was not suitable for co-digestion with food waste due to a decreasing pH value in the system.

Keywords: co-digestion, anaerobic digestion, food waste, fruit waste.

Introduction

Continuously growing population in developing countries along with urbanization, economic development and rapidly changing lifestyles have contributed to a higher rate of municipal solid waste generation. At this point, developing countries, especially Thailand, face an increasing challenge in the management and disposal of solid waste. Municipal solid waste (MSW) is generated in Thailand at a rate of approximately 0.3–1.44 kg/capita.day (Troshinetz and Mihelcic, 2009). Food waste contributes as the biggest component at all disposal sites, ranging between 60% and 80%, followed by plastic, paper, glass, textile and wood, and the composition of MSW varies across provinces (Wangyao et al., 2010; Suma et al., 2019). Besides, Thailand is a country with one of the most abundant sources of tropical fruits in the world according to the appropriate climate. The consumption of different varieties of fruit produced in Thailand is always on the rise. Even though Thailand has a high fruit consumption along with industrial processing of edible parts, waste such as durian peel, dragon fruit peel, pineapple leftovers along with other fruit residues (primarily peel and seeds) are generated in large quantities throughout big cities. The amount of fruit waste generated highly depends on the seasons. While some of Thai fruits are available year-round, others are seasonal only (in spans of 3–6 months). For example, April to August is durian season, May to October is dragon fruit season, and April to June along with December to January is pineapple season. Besides food waste, the trend of fruit waste production is also increasing due to the growing consumption.

Currently, there are several MSW disposal methods in use, such as composting, incineration and landfills. The landfill is the most common disposal method in developing countries. Landfill gases and leachate are produced when municipal solid waste is buried in a landfill under anaerobic conditions. Methane is one of the many gases that is produced from landfills and is then being released into the atmosphere, which contributes to global warming.

Anaerobic digestion (AD) is one of the preferred MSW disposal technologies for the production of biogas and methane, which can be used as a source of alternative energy. Moreover, the residue produced during the AD process is a stabilized organic material that can be utilized as a bio-fertilizer. Even though AD is considered an efficient technology, this process presents some limitations. The stability of the AD process can be influenced by the accumulation of volatile fatty acids (VFA) when MSW contains plenty amounts of food waste (FW), and long-chain fatty acids which interrupt methanogenic activity (Pavi et al., 2017). In this case, the co-digestion of different feedstock is applied to deal with this limitation and enhance methane yield (Pavi et al., 2017). The main advantages of co-digestion are a better balance of nutrients in terms of the C/N ration, the mineral requirement for equilibrium and an increase in buffering capacity of the system to improve methane productions (Pavi et al., 2017; Korai et al., 2018). Several previous studies used food waste as the mono-substrate to produce biogas or for co-digestion along with sewage sludge (Mehariya et al., 2018), animal manure (Li et al., 2010), fruit, vegetable waste (Shen et al., 2013), and agricultural waste (Yong et al., 2015). Brown and Li (2013), who studied the co-digestion of food waste and yard waste, found that it is possible to increase methane yields and volumetric productivity by tweaking the percentage of food waste, which leads to an increase of yield from 10% to 20%. However, most studies have focused on the use of animal manure and sludge as the co-substrate with food waste, except for a few studies, which involved fruit residual (Li et al., 2010; Shen et al., 2013; Mehariya et al., 2018; Anika et al, 2019). Anika et al. (2019), who determined the amount of potential biogas produced from a combination of mango, pawpaw and watermelon as well as their various combinations, found that a total volume of biogas produced from co-digestion of watermelon and mango (5,103 cm^3) was higher than just mango (1,533 cm^3) and watermelon (2,917 cm^3). There have been many studies investigating biogas production from the co-digestion of food waste but less attention is being paid to the investigation of biogas production from the co-digestion of food waste and different types of fruit waste. Therefore, this study aimed to investigate potentials of biogas generated from mono-digestion of different substrates as food waste and fruit residual (durian shell, dragon fruit peel and pineapple peel) as well as co-digestion of different combinations of co-substrates, for example, food waste and different types of fruit waste (durian shell, dragon fruit peel and pineapple peel).

Methods

Substrate and inoculum preparation

Food waste was collected from a canteen of King Mongkut's University of Technology North Bangkok (Rayong campus) along with the fruit residuals such as durian peel, dragon fruit peel and pineapple peel that were obtained from a local market. The food waste and fruit residuals (durian, dragon fruit and pineapple peel) were crushed in a blender while cow manure was used as inoculum. Before their characterization and use, feedstock (food waste along with fruit residuals) and manure were stored at a temperature of 4°C.

Experimental design

The batch test was divided into three experiments labelled I, II and III. The experimental design for each portion is shown in Table 1. The biogas potential of food waste (FW) mixed with a different type of fruit waste, in particular durian peel (D), dragon fruit peel (DF) and pineapple peel (P),

Table 1. *Experimental conditions of the batch tests*

Experiment	Condition	Feed composition (% weight basis)
I	(FW100)	Food waste 100%
	(FW75:D25)	Food waste 75% + durian peel 25%
	(FW50:D50)	Food waste 50% + durian peel 50%
	(FW25:D75)	Food waste 25% + durian peel 75%
	(D100)	Durian peel 100%
II	(FW75:DF25)	Food waste 75% + dragon fruit peel 25%
	(FW50:DF0)	Food waste 50% + dragon fruit peel 50%
	(FW25:DF5)	Food waste 25% + dragon fruit peel 75%
	(DF100)	Dragon fruit peel 100%
III	(FW75:P25)	Food waste 75% + pineapple peel 25%
	(FW50:P50)	Food waste 50% + pineapple peel 50%
	(FW25:P75)	Food waste 25% + pineapple peel 75%
	(P100)	Pineapple peel 100%

was studied in Experiment I, II and III, respectively. The batch experiment was conducted in a 125 ml serum bottle with a working volume of 100 ml. The proportion of waste mixing was varied on a weight basis.

For experiment I, the food waste-to-durian peel ratios (FW/D) were 0:100, 25:75, 50:50, 75:25 and 100:0 on a weight basis. Then, co-digestion digesters were operated in 3 ratios as 25:75, 50:50 and 75:25, and the mono-digestion of food waste and durian peel (FW/D = 0:100 and 100:0) was operated. The substrate-to-inoculum ratio (S/I) was maintained at 2 based on volatile solids (VS), according to the literature used (Achinas et al., 2019). After adding the required amounts of inoculum and feedstock, each digester was filled with distilled water to maintain a designated volume (100 ml). The initial pH was then adjusted to 7.0 ± 0.5. All serum bottles were sealed with a rubber stopper and aluminium caps as anaerobic conditions required. All bottles were incubated under constant mesophilic temperature (35 ± 1°C) for 50 days and shaken manually twice per day during the experimental period of the assay.

For dragon fruit peel (experiment II) and pineapple peel (experiment III), the procedure of feedstock preparation (proportion of waste mixing) was the same as in experiment I (Table 1).

Analytical method

Chemical oxygen demand (COD) and volatile solids (VS) were analyzed following standard methods. The volume of biogas produced was measured using the water displacement method. The gas composition was analyzed offline by using a gas chromatograph instrument (SCION 456-GC, Bruker) equipped with a flame ionization detector (FID). The injector, detector and oven temperatures were 200°C, 250°C and 150°C, respectively. Helium (99.995%) gas was used as the carrier gas at a flow rate of 1.0 ml/min. The elemental composition of samples was investigated: carbon and nitrogen were determined using a CHNS-O elemental analyzer (TruSpec Micro, LECO). The chemical properties of substrates were determined, and their characteristics are shown in Table 2.

Table 2. *Characteristics of various substrates*

Parameters	Durian shell (D)	Dragon fruit peel (DF)	Pineapple peel (P)	Food waste (FW)
Total Solid (%)^a	21.36 ± 0.38	10.33 ± 0.04	14.91 ± 0.07	41.33 ± 0.28
Volatile solid (%)^a	19.70 ± 1.86	8.21 ± 1.23	13.87 ± 1.52	35.41 ± 1.38
VS/TS (%)	92.23	79.48	93.03	85.68
Moisture content (%)^a	78.64 ± 0.38	89.67 ± 0.04	85.09 ± 0.07	58.67 ± 0.28
pH	7.63	7.51	6.20	4.62
C (%)^b	43.72	36.63	45.71	46.20
N (%)^b	0.58	0.90	0.6	1.89
C/N Ratio	75.38	40.70	76.18	24.44

a As the total weight of samples; b As the TS of the samples

Results and Discussion

Characteristics of substrates

The detailed characteristics of the substrates are shown in Table 2. The TS values of FW, D, DF and PA were low and the moisture content of fruit residuals (78.64–89.67%) was higher than food waste (58.67%). An increase in the moisture content indicated an increase in hydrolysis as well as a gradual complete breakdown of the biomolecules that expectedly assisted in the higher biogas production. The VS/TS ratio of FW and fruit residual were high (79.48–93.03%), which demonstrates high organic and low ash content of TS, and these types of waste were desirable for the anaerobic digestion. The

VS/TS ratio higher than 50% is considered as the one with relatively higher organic content, which is more suitable for anaerobic digestion to produce biogas, and production of methane increases with an increase in VS/TS ratio (Wang et al., 2016). The C/N ratio of fruit residuals (40.70–76.18) was higher than that of food waste (24.44). The optimal C/N ratio of the AD process varied from 15 to 30; after that point, only food waste was located in this range (Zhao et al., 2017). The initial characteristics of the combined substrate after mixing are shown in Table 3. All batch reactors had high organic content. The initial VS of all batch reactors was 9,130–11,980 mg/l, while the initial COD of all batch reactors was 5,300–8,800 mg/l. These results show that all combined substrate ratios had a high potential for biodegradation under anaerobic conditions.

Table 3. *Initial characteristics of mixture the substrate at different ratios*

Experiment	condition	Initial	
		VS (mg/l)	COD (mg/l)
I	(FW100)	9,595.00 ± 35.36	7,600.00 ± 565.68
	(FW75:D25)	9,620.00 ± 70.71	6,200.00 ± 282.84
	(FW50:D50)	10,025.00 ± 63.64	6,000.00 ± 150.00
	(FW25:D75)	11,980.00 ± 27.28	6,100.00 ± 141.42
	(D100)	11,990.00 ± 70.71	5,900.00 ± 141.42
II	(FW75:DF25)	8,990.00 ± 42.43	6,400.00 ± 565.68
	(FW50:DF0)	9,130.00 ± 70.71	5,400.00 ± 848.53
	(FW25:DF5)	9,190.00 ± 42.43	5,300.00 ± 424.26
	(DF100)	9,400.00 ± 28.28	6,100.00 ± 141.42
III	(FW75:P25)	10,100.00 ± 398.37	8,800.00 ± 110.00
	(FW50:P50)	10,967.00 ± 611.25	7,733.00 ± 461.88
	(FW25:P75)	11,700.00 ± 115.45	8,267.00 ± 461.88
	(P100)	10,800.00 ± 210.25	6,933.00 ± 611.01

Effect of the substrate type and proportion on pH

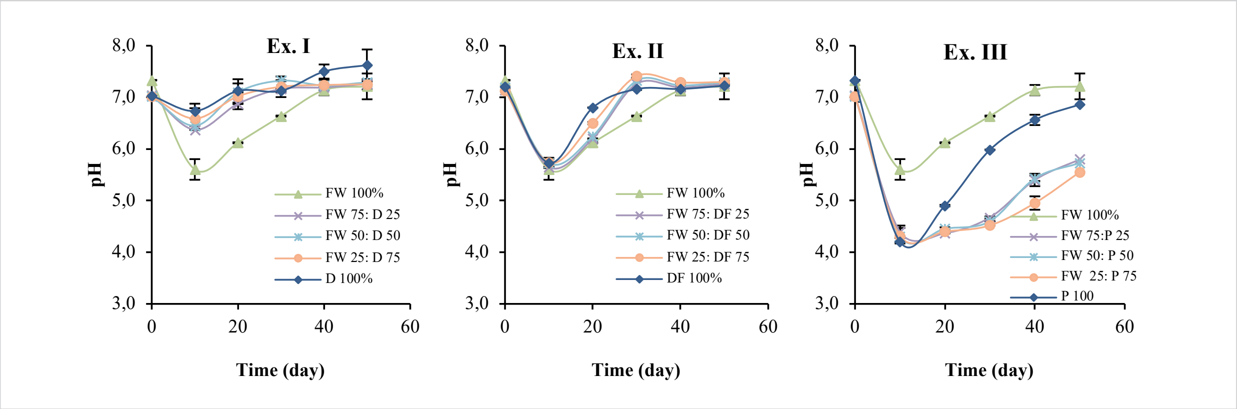
The pH was adjusted to 7 in all batch reactors at the start of the experiment. The pH of all batch reactors was decreasing within the first 10 days and, after that, pH tended to increase reaching a neutral level at 20 days except for the batch reactors of FW (FW100), P (P100) and the mixture of FW and P (FW75:P25, FW50:P50 and FW25:P75) where pH was below 5 (Fig. 1). The drop in pH was observed as a result of the production of volatile fatty acids by acid-forming bacteria. The pH value fell sharply, which confirms that hydrolysis and acidification occurred. With the increase of pH value, the increase of gas formation could be seen at this step (Fig. 2). For mono-substrate digestion, the pH value of P (P100) digestion was the lowest, followed by FW (FW100), DF (DF100) and D (D100) within 10 days since pineapple peel contains weak acids like citric acid and malic acid (Hajar et al., 2012). Beside weak acids, pineapple peel also contains a high concentration of fructose, glucose, sucrose and other nutrients that are useful for acidogen growth (Hamalatha and Anbuselv, 2013). Food waste is an abundant source of an inexpensive organic substrate for fermentative VFAs production because it contains a high level of organic materials such as starches, proteins and lipids. Excess volatile fatty acid (VFA) accumulation commonly occurs in anaerobic digestion of high solid content in food waste (Dhar et al., 2015). The result of mono-substrate digestion was similar to co-substrate digestion. The mixture of food waste with pineapple peel produced the lowest pH (4.20–4.39) when compared with other types of fruit residual, while the duration of the acidogenesis process increased with the addition of pineapple peel in the system.

In contrast, the addition of durian shell (D) in the system reduced the acidogenesis process from 20 to 10 days. Zhao et al. (2017) found that the range alkalinity value of durian digestion after 30 days was 3,500 to 11,250 mg $CaCO_3$/l, and higher alkalinity indicated higher buffer capacity and stability of an anaerobic digestion system. While the trends of pH value changed in DF (DF100) and P (P100) digestions were the same, the duration of the acidogenic process of DF was shorter than in the P. The pH of P (P100) and a mixture of FW also with P was below 5 until 30 days; after that, the pH started to increase slightly, but did not reach neutral by the end of the experiment.

Then the mixture of FW and P (FW75:P25, FW50:P50 and FW25:P75) did not reach methanogenesis (Fig. 2).

The variation in the pH level of the different substrates was observed, and the pH changed progressively from acidic to slightly alkane between 4.2 and 7.6 throughout the study (Fig. 1). The results show that digestion began at an acid condition and later varied due to the digestion of the different substrate types and proportions. This could be attributed to the nature of material feed used, which is a contributing factor that affects both the digestion and microbial environments (Ahmadu et al., 2009).

Fig. 1. *pH value change with time*



Cumulative methane yield

The cumulative methane yields from a mixture of a mono-substrate and a co-substrate are shown in Fig. 2. The methane volume of all batch reactors was low in the first 7 days of digestion as a result of acidic conditions, thereafter rapidly increasing to over 80% within 12 days, 20 days and 23 days in a mixture of food waste with durian shell, pineapple and dragon fruit, respectively. The results showed a lag phase occurring in the batch reactors of food waste, dragon fruit and pineapple peel, which was long; when it comes to food waste and dragon fruit peel, the lag phase was 23 days and for pineapple peel, it was 20 days. This can be explained by the pH value presented in Fig. 1. Microorganisms are sensitive to pH (Pramanik et al., 2019). The methane gas generation started when the pH changed from acidic to neutral. The acidic condition may slow down anaerobic microorganism growth and convert organic wastes into end-products. The pH level required for acid-forming bacteria and methane-forming bacteria to grow should be higher than 5.2 and 6.2, respectively, for an acceptable level of enzymatic activity (Pramanik et al., 2019). Then, low pH in the anaerobic digestion may have been caused by a prolonged lag phase of microbial growth (Darwin et al., 2019). This result is in line with the study by Azouma et al. (2019), who studied biogas production from pineapple waste. It was found that the formation of methane started after 48 days of pineapple waste, and the methane concentration of 41.7% was observed. Moreover, the shortest lag phase was found where durian peel was added to the system. This result indicates that the introduction of durian peel in the system could enhance biogas production.

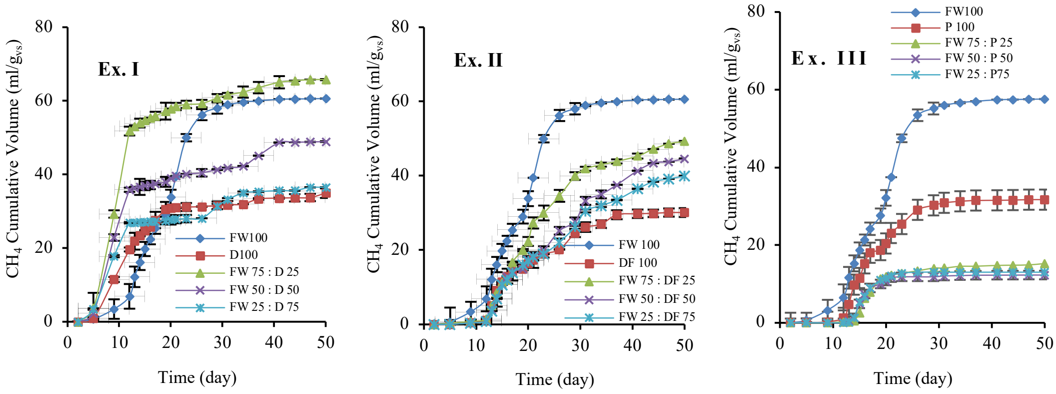
For the mono-substrate, food waste gave the highest methane production (60.63 ± 1.02 ml/g_{vs}) followed by durian shell (34.93 ± 1.30 ml/g_{vs}), pineapple peel (31.70 ± 1.60 ml/g_{vs}), and dragon fruit (30.12 ± 1.20 ml/g_{vs}), respectively. Normally, food waste consists of carbohydrates

(5.70%–53.00%), proteins (2.30%–28.40%), and lipids (1.30%–30.30%) (Pramanik et al., 2019). Carbohydrates and proteins have a higher hydrolysis rate because of their rapid degradability compared with lipids (Meng et al., 2015; Xu et al., 2018). Then, it is important to note that rapidly degradable carbohydrates and lipid-rich food waste can produce a high volume of methane. The fruit and vegetable waste has high cellulosic and lignin content, whereas food waste has higher lipid content because of the presence of animal fat and oil (Bong et al., 2018). As for the residual fruit digestion, higher and faster biogas production in a digester of durian could be attributed to the higher availability of biodegradable material in the durian shell. In contrast, the lowest methane production (31.70 ± 1.60 ml/g_{vs}) was found from the dragon fruit peel digestion because the VS/TS ratio of dragon fruit peel (40.70) was lower than those of the durian shell (75.38) and pineapple peel (76.18) as in Table 2. Moreover, the action of anaerobic bacteria on durian shell was faster relative to that of the dragon fruit peel and pineapple peel which contained more lignin that may not have been completely degraded during the experimental period; the lignin content of durian shell, dragon fruit peel and pineapple peel was 10.90%, 37.18% and 14.33%, respectively (Ferreira et al., 2009; Jamilah et al., 2011). The methane production volume from pineapple (31.70 ± 1.60 ml/g_{vs}) and dragon fruit peel (30.12 ± 1.20 ml/g_{vs}) was not obviously different, although lignin content of pineapple peel was lower than that of dragon fruit peel and the VS/TS ratio of pineapple peel (93.03) was higher than that of dragon fruit peel (79.48). These results can be explained by pH value; lower pH of the pineapple peel digestion interrupted anaerobic digestion, while a lower pH related to the accumulation of VFA that was toxic for methanogenic bacteria in the digesters. However, a previous study has reported that methane could be generated under acidic condition. Darwin et al. (2019) who studied treating tofu-processing wastewater by anaerobic treatment found that anaerobic digestion could reduce organic wastes and convert into biogas although the influent was too acidic (pH 5).

For co-digestion of FW:D, the methane production at ratios of 75:25, 50:50 and 25:75 were 65.77 ± 0.16, 48.93 ± 0.11, 36.50 ± 0.01 ml/g_{vs}, respectively. The range of methane content that was found in all FW:D ratios was 33.18 to 50.18% (Fig. 3). The highest methane content (50.18%) was found in 75:25 ratio, which is slightly higher than the digestion of the durian shell alone (42.10%). Similarly, Shen et al. (2019) who studied biogas production from anaerobic co-digestion of durian shell with chicken manure found that methane content from co-digestion of durian shell with chicken manure at 1:3 ratio (48.40%) was higher than the digestion of durian shell alone (46.70%).

For FW:DF, the methane production at 75:25, 50:50 and 25:75 ratios was 49.26 ± 0.15, 44.57 ± 0.12, 39.92 ± 0.11 ml/g_{vs}, respectively. The methane content of all FW:DF ratios was not obviously different (46.77–47.74%) as shown in Fig. 3. For FW:P, the methane production in all ratios was low (12.29–15.26 ml/g_{vs}). The methane gas produced from food waste mixed with durian shell (FW75:D25) was higher than in food waste mixed with dragon fruit

Fig. 2. *Cumulative methane production*

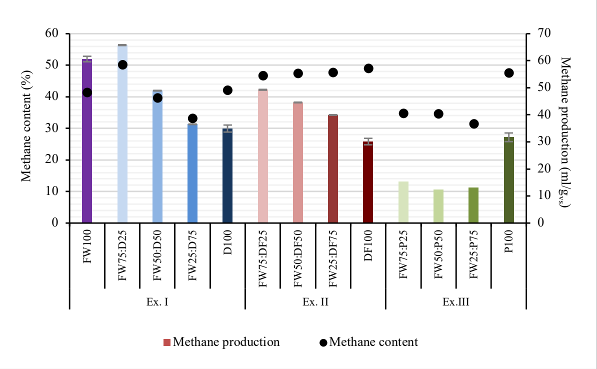


peel (FW75:DF25) and pineapple peel (FW75:P25). For co-digestion of food waste and fruit waste residuals, increasing the proportion of fruit residual in feed mixture can contribute to a decrease in methane gas production due to fruit residual containing lignin, which presents a degradation challenge for microorganisms. Previous work studies on the anaerobic degradation of lignin and lignin-derived aromatics have demonstrated that the lignin degradation rate under anaerobic conditions was low. Triolo et al. (2012) found that lignin-rich substrates yielded less methane than substrates containing simple lipids, carbohydrate and a lower concentration of lignin. However, modified lignin such as lignin with a high degree of methoxylation could be degraded and give rise to methane and carbon dioxide production under anaerobic conditions (Ahring et al., 2015).

In the case of co-digestion of food waste and pineapple peel, the methane production volumes of all proportions did not seem different due to a low pH value in the system. The addition of pineapple peel into the proportion for the co-digester system caused a decrease in methane production, which can be attributed to a decrease in the pH value, even though pineapple peel contains a high concentration of fructose, glucose, sucrose and other nutrients that are useful for microbial growth (Hamalatha and Anbuselv, 2013).

By comparison, when it came to methane production in mono-digestion and co-digestion, the highest volume of methane gas production in co-digestion was observed when the proportion of food waste and durian shell was at 75:25. This is higher than the highest methane gas production of mono-digestion (food waste) according to the high organic compound and optimum pH value in the system. The pH values of durian shell and food waste mixed with the durian shell located in the preferred area of the pH range for methanogenic activity (Rao et al., 2010). Mono-digestion of food waste causes low buffer capacity, although it has high biodegradability of the substrate. For fruit residuals, mono-digestion of plant residues often results in slowdown processes due to its deficiency in nutrients. In addition, complex composition and structure features of plant residues such as lignin content, pectin content, and cellulose crystallinity make them resistant to biological processes (Pramanik et al., 2019). Co-digestion of two or more substrates can be used to dilute inhibitory compounds and enhance biogas production. The results of this study indicate that the limitation of mono-digestion of food waste can be overcome by co-digestion with durian shell, which provides necessary nutrients and buffering capacity to enhance the maximum methane production.

Fig. 3. *Methane gas volume and composition*



Removal of organic matter

The degradation of organic material in all the batch reactors was measured in terms of COD and VS removal (Table 4). In the mono-substrate, COD removal efficiency of food waste digestion was the highest followed by durian shell, dragon fruit and pineapple peel, respectively. The COD removal efficiency trend of the co-substrate was similar to that of the mono-substrate. The COD removal efficiency of FW:D (86.88%–88.71%) and FW:DF (86.79%–87.04%) was higher than FW:P (60.73%–65.23%). The VS removal efficiency in all substrate conditions (32.86%–46.27%) was not different except for the VS removal efficiency of P and FW:P that were lower (10.25%–12.54%). These results related to the methane gas production in Fig. 2 indicate that the methane production in FW:D and FW:DF was higher than in FW:P. COD and VS are removed by converting organic compounds to methane; then, methane production potential of waste is related to the amount of organic matter in waste and the removal efficiency in the system. Also, changes in VS can be attributed to the breakdown of intermolecular bonds of the biomolecules like lignin, cellulose, hemicellulose and polymeric substances. COD and VS removal efficiency was higher when the optimum substrate type and co-substrate proportion were provided. Low methane gas production and low COD removal efficiency were observed where pineapple peel was added in the system, although pineapple peel had a high potential of organic transformation during the AD processes according to high VS content. This can be explained by the decrease of pH value in the system. The acidic condition could potentially stimulate the growth of acid-forming bacteria to convert organic material into organic acids such as volatile fatty acid, while low pH could potentially suppress the growth of methanogens. The optimal efficiency of the methanogens is reached within the pH range of 6.5–8.0, while in the case of acetogens, the respective range is 5.0–8.5 (Rao et al., 2010). An inhibition of methanogen activity could affect the degradation of the organic compound and thereby could limit the process of organic removal during the anaerobic digestion as decreasing in COD and VS removal. Previous studies have reported that the percentage of substrate degradation decreased when pH culture was lower than 5.8, where the inhibition might have been aggravated by acidity in the culture where pH was lower than 5.5 (Hu et al., 2004; Darwin et al., 2009). Despite the type of the substrate, the performance of anaerobic digestion depended on the type of inoculum. Wang et al. (2014) have reported that food waste hydrolysis obviously increased when anaerobic activated sludge was used as the inoculum relative to aerobic activated sludge at any pH investigation.

Table 4. *The value of VS, COD initial and removal in different conditions*

Experiment	Condition	VS Removal (%)	COD Removal (%)
I	(FW100)	46.27	88.47
	(FW75:D25)	41.58	88.71
	(FW50:D50)	37.3	88.33
	(FW25:D75)	33.60	86.88
	(D100)	32.86	86.44
II	(FW75:DF25)	45.22	87.50
	(FW50:DF0)	42.39	87.04
	(FW25:DF5)	41.02	86.79
	(DF100)	36.76	85.25
III	(FW75:P25)	10.45	65.23
	(FW50:P50)	10.25	62.31
	(FW25:P75)	11.29	60.73
	(P100)	12.54	74.15

Conclusions

Food waste and fruit residuals such as durian shell, dragon fruit and pineapple peel can be used as substrates to produce biogas under anaerobic condition. For mono-digestion, food waste as a substrate had the potential to provide high biogas yield and COD removal efficiency in comparison with durian shell, dragon fruit and pineapple peel.The co-digestion of food waste and durian shell improved methane production compared with their mono-digestion, while dragon fruit peel and pineapple peel were not suitable for co-digestion with food waste. The optimum mixing ratio of food waste to durian shell was 75:25, with the highest cumulative methane yield of 65.77 ± 0.16 ml/gvs and methane content of 50.18%. The trend of COD removal efficiency was similar to methane gas production. However, increasing the fruit residual proportion could reduce methane production due to an increase in lignin content which may not have been completely degraded by the end of the experimental period. For co-digestion, the addition of durian shell in the system could reduce the lag phase and promote faster biogas formation, while pineapple peel could increase the lag phase and inhibit biogas formation. Biogas production heavily depends on the type and proportion of the substrate, which affects both the digestion and microbial environment.

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