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Anaerobic Co-Digestion of Sewage Sludge and Waste in High Solid State

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ABSTRACT

In this study, the effect of thermal pre-treatment (TP) on the physical characteristics and co-digestion of a mixture of food waste and sludge was investigated. The food waste (FW) to sewage sludge (SS) ratio used in this research is 1:2 (VS-based) to form a final concentration of 11.20%. The inoculum to substrate ratio was set at 1:1 (volume-based). Undoubtedly, the results show that TP has changed the physical characteristics of the food waste to sewage sludge mixture. The results show that the pretreatment increased the biogas production from 4385 ml for the untreated reactor to 5685 for the reactor R2(140) at 140 °C and the improvement in biogas production reaches 29.65% in the reactor R2(140) and the removal of volatile solids was 58.90%. Therefore, after the biomethane potential test, the temperature of 140 °C was found to be optimal in the production of biogas. The optimal condition is to use a mixture of pre-treated SS at the temperature of 140 °C and untreated FW, so TP is recommended to be used in anaerobic digestion of the mixture of food waste and sewage sludge.

Keywords: anaerobic co-digestion, thermal pretreatment, hydrolysis, waste, food waste, sludge.

INTRODUCTION

During the wastewater treatment process, sewage sludge (SS) production is unavoidable. Rapid industrialization and urbanization have resulted in an increase in wastewater production, causing an increase in sludge formation in recent years (Yang et al., 2014; Zhen et al., 2015). Anaerobic digestion is a mature and well-proven technology for methane-rich biogas production from organic waste decomposition. This technology has been used to treat biodegradable wastes (Kim et al., 2017). The bulk of biogas plants (72%) are fueled by agricultural resources, while the rest primarily use organic waste substrates and sewage sludge (Torrijos, 2016). Due to a lack of nutrients and a low organic loading rate, the mono-digestion of sludge is slow and unstable (Mata-Alvarez et al., 2014), exhibiting low biodegradability (Appels et al., 2008), and high toxicity of contaminants (fragrances, antibiotics, etc.) (Zhang et al., 2018). Such problems can be properly resolved by adjusting the unstable substance composition by co-digestion of two or more substrates, which can improve the buffering capacity, accelerate the hydrolysis rate, and thus enhance the stability of the system, and biogas production (Mehariya et al., 2018), as well as increase organic loading rates and methane yield (Khalid et al., 2011; Mata-Alvarez et al., 2011). Researchers are paying more attention to co-digestion, since it has higher energy recovery efficiency. The production of municipal solid waste was approximately 1300 million tons per year globally in 2013 (Hoornweg & Bhada-Tata, 2012), and it is expected that by 2025, production will have increased to 2200 million tons per year with about 46% organic content (Al Seadi et al., 2013). Organic Fraction of Municipal Solid Waste (OFMSW) has a high C/N ratio because of the existence of paper materials and other carbon-rich compounds (Campuzano & González-Martínez, 2016). Sewage sludge, on the other hand, has a low C/N ratio, ranging from 6:1 to 13:1. Appropriate sewage sludge and OFMSW mixing ratios can give an optimal C/N ratio (20:1–30:1) for anaerobic digestion (Zhang et al., 2008). Moreover, sewage sludge is rich in other macro- and micro-nutrients that enhance the anaerobic digestion process (Silvestre et al., 2015).

Food waste as a co-substrate

Environmental authorities in certain developed countries implement landfill disposal of sewage sludge. According to recent laws in some European nations, sludge should be incinerated first, and the ashes obtained from the combustion should be stored in properly sealed warehouses (Kwarciak-Kozłowska, 2019). Regarding these applications, the cost of sludge management accounts for around 50% of the whole operating costs of a WWTP (Pan et al., 2019). Anaerobic co-digestion is one of the best techniques for the disposal of sewage sludge, since it is easily applicable, economic, and an environmentally agreeable technique. As a result of economic development and population increase, food waste is becoming more prevalent. According to estimates released by the Food and Agriculture Organization of the United Nations, one-third of all food produced, or nearly 1.3 billion tons per year, is lost or wasted worldwide (FAO, 2014). Several studies have proven that food waste is a reasonable co-substrate in Anaerobic co-Digestion (AcoD) with other main substrates. The most recent data on biogas production improvement from AcoD food waste research are summarized in Table 1. The use of food waste as a co-substrate enhanced the biogas production performance in terms of methane yield in all of these studies. Sewage sludge is one of the most widely used main substrates in AcoD when food waste is used as a co-substrate. Low carbon/nitrogen (C/N) ratios are common in these primary substrates, resulting in a high ammonia concentration in the AD system (Gert-Jan & Eberhard, 2007). The C/N ratio of food waste is high, so it enhances the C/N ratio of mixture, and leads to improvement in biogas production by decreasing the ammonia inhibition (Kim et al., 2003; la Cour Jansen et al., 2004). The optimal C/N ratio for the Anaerobic Digestion process has been suggested to be in the range of 20 to 30 by many researchers (Haider et al., 2015). An ideal substrate mixing ratio should be obtained to achieve the highest performance in biogas production from AcoD. The optimization of the C/N ratio is a typical method for determining the substrate mixing ratio (Mata-Alvarez et al., 2014).

Although many studies have established the great performance of the SS and FW co-digestion, the synergies and biodegradation kinetics have still not been elaborated and recognized clearly during the co-digestion (Xie et al., 2017). The co-digestion of FW with SS can be associated with a number of restrictions due to the troubles it can cause to the anaerobic system. By raising the fraction of FW, the risk of increasing the concentration of light metal ions and/or biodegradation intermediates at levels that can be toxic to

Table 1. Comparison of biogas production performance from AcoD of FW with other substrates

Substrate	Mixing ratio (basis)	Study scale	Temperature (°C)	Total solid (TS)	C/N ratio	Methane yield (L CH_4/g VS)	Improvement of biogas production (%)	Reference
OFMSW:SS	50:50 (volume)	Lab-scale	37	2.50 %	11.10	365	47.20	(Cabbai et al., 2013)
FW:SS	1:2 (VS)	Lab-scale	35	1 gVS L^{-1}	n.a.	492.10	19.40	(Prabhu & Mutnuri, 2016)
FW:PS	1:2 (VS)	Lab-scale	35	5.40 %	n.a.	205	n.a.	(Marcelo et al., 2017)
FW: SS	12.50% (mass)	Lab-scale	38	n.a.	n.a.	360	n.a.	(Koch et al., 2016)
ES:FW	4:1 (weight)	Lab-scale	37 ± 0.5	30 ± 0.3 g/l	n.a.	45	n.a.	(Zhang et al., 2019)
SS:FW	1:1 (VS)	Lab-scale	35 ± 1	15 gVS L^{-1}	22.30	415.30	2.80 times	(Wang et al., 2020)

the anaerobic population becomes greater (Chen et al., 2008). The primary biodegradation intermediates of AD are volatile fatty acids (VFAs), long-chain fatty acids (LCFAs), and ammonia (NH_3). Mixing of food waste with sewage sludge results in an initial increase in VFAs concentration because of the rapid acidification of soluble organic compounds found in food waste (Heo et al., 2003; Kim et al., 2003).

Thermal pre-treatment

Hydrolysis, acidogenesis, acetogenesis, and finally methanogenesis are the four basic processes of anaerobic digestion (Wang et al., 2018). Here, the rate-limiting stage is the hydrolysis in which complicated organic molecules are converted into smaller and simpler molecules by the extracellular enzymes of microorganisms (Deepanraj et al., 2017). It is useful to apply various pretreatment technologies like chemical, mechanical, thermal, or biological to the substrates to increase the rate of hydrolysis, to dissolve organic compounds for increasing their biodegradability, to enhance the stability of anaerobic digestion, and to increase the production of biogas (Caroca et al., 2021; Liu et al., 2020). SS and other wastes are subjected to high temperatures in the thermal pretreatment process, which cause hydrolysis and improve the digestibility of SS and other wastes (Meegoda et al., 2018; Taboada-Santos et al., 2019). This pretreatment process breaks down cell membranes resulting in insoluble organic substrates that are easily hydrolyzed during the anaerobic digestion (Ariunbaatar et al., 2014; Suárez-Iglesias et al., 2017) Thermal pretreatments are useful in terms of pathogen sterilization, odor removal, sludge volume reduction, and enhanced sludge dewaterability (Jo et al., 2018; Nazari et al., 2017). The thermal pretreatment of SS has been carried out at various temperatures (50–250 °C) (Ariunbaatar et al., 2014). On the other hand, Dwyer et al. (2008) found that while increasing temperature above 150 °C, the solubilization increased, but no increase in methane production was observed. Treatments at excessively high temperatures (higher than 170–190 °C) lead to reduced sludge biodegradability, despite achieving high solubilization efficiencies. This is usually ascribed to the so-called Maillard reactions (Dwyer et al., 2008), Melanoidins, which are difficult or impossible to break down, and are formed by combining carbohydrates and amino acids. (Bougrier et al., 2008). Melanoidins also increase the color from the anaerobic digester, which can increase color in the final effluent (Dwyer et al., 2008). The soluble carbohydrate content first increased to a peak at 140 °C when hydrothermal pretreatment HTP of food waste

Table 2. Impact of thermal pre-treatments on sewage sludge and food waste anaerobic co-digestion

Substrates	Thermal treatment (°C) / Time (min)	Anaerobic digestion	Results	Reference
FW&WAS mixing ratio is 7:3 volume ratio	120 / 60	Batch reactors, 20 days, mesophilic conditions at 35±1°C	Increase the methane production from 208.9 ± 15.2 to 288.1 ± 16.1 mL / gVSS by approximately 37.90% for co-digestion of FW and WAS	(Naran et al., 2016)
OFMSW and sludge mixing ratio is 1.25:1 volume ratio	65 / 60	Batch, 30 days, mesophilic conditions at 37°C	Increase of biogas production from 0.35 $m^3 \cdot kg^{-1}$ COD to 0.38 $m^3 \cdot kg^{-1}$ COD (+8.60%)	(Amiri et al., 2016)
FW : FVR : DAS mixing ratio is 2:2:1	170–175 / 60	Semi-continuously batch,10 days, mesophilic conditions at 38±1°C	Co-digestion of FW, FVR with thermally treated DAS increase of biogas production from 760 $ml \cdot g^{-1}$ VS added to 810 $ml \cdot g^{-1}$ VS (+6.60%)	(Guo et al., 2014)
FW : FVW : DSS mixing ratio is 1:1:1	175 / 60	BMP TEST, mesophilic conditions at 35±1°C	Cumulative methane production of MB and THMB were 544 $mL \cdot g^{-1}$ VS and 618 $mL \cdot g^{-1}$ VS, with an increase of 13.6%	(W. Wang et al., 2010)
RKW : FVW : WSS mixing ratio is 1:1:1 by weight	170–175 / 60	BMP TEST, 2 days, mesophilic conditions at 35°C	The maximum biochemical methane production values were 407.5 and 420.7 ml CH_4/g VS added for rMBW and thMBW, with an increase of 3.24%	(Zhou et al., 2013)
MSW and SS mixing ratio is 33:67 by TS.	165°C / 20 min	Semi-continuously batch, 2 days, mesophilic conditions at 35°C	Co-digestion of pretreated municipal solid waste and sewage sludge decrease the methane potential from 386 ± 24 to 381 ± 3 Nml CH_4/g VS by approximately 1.00%.	(Westerholm et al., 2019)

(FW) raised from 100 to 200 °C and then decreased, whereas total carbohydrate content was negatively related with increasing temperature due to the enhanced degradation and Maillard reactions (Dwyer et al., 2008). The most significant methane production for protein-rich antibiotic mycelial residue was generated after considering thermal hydrolysis (TH) pretreatment (THPT) on anaerobic digestion (AD) of protein-rich substrates at 140 °C for 30 minutes; however, protein denaturation and Maillard reaction obviously happened (Liu et al., 2021). Table 2 summarizes the most recent studies in thermal pretreatment on AcoD.

MATERIALS AND METHODS

Seed sludge

The seed sludge used in the experiments was the dried sludge obtained from the drying beds of El Berka wastewater treatment plant in Cairo, Egypt. This plant had a capacity of 550,000 m^3/day and served a population equivalent of 3,000,000 capita. This plant treated domestic wastewater and was operated with aeration (activated sludge, AS) tank. Sludge was stored at 4 °C. For the experiments, sludge was diluted with distilled water in order to obtain total solids concentration (TS) of 16%. The organic solids or volatile solids content was equal to 63.125% of TS.

Substrates

To simulate FW generated in Egypt, municipal solid waste (MSW) was used in this study. Food waste had average TS of 13% and consisted of rice, cabbage, potatoes, carrots, cucumber, apple, milk, honey, and bread. Bones were collected and excluded. The FW was crushed down to 2–4 mm using a cooking mixer and the concentration of TS was controlled by adding distilled water.

Inoculum source

Digested sludge was collected from the inlet and outlet of mechanical dewatering system in the existing El Gabal El Asfar wastewater treatment plant. The digested sludge was brought to the laboratory in a closed container, then pre-incubated at 32°C until it reached the endogenous respiration stage and was then used for the BMP test. The two types of digested sludge (dried and fresh digested sludge) are mixed carefully to obtain the required TS to be used in the reactors. The main substrate, co-substrate, and inoculum used had characteristics as mentioned in Table 3.

Mixing ratio

On the basis of the previous studies (Table 1) in this field, the mixing ratio used in this research between the food waste and sludge was chosen according to (Marcelo et al., 2017; Prabhu & Mutnuri, 2016). To determine the optimal ratio of mixing FW with SS for anaerobic co-digestion, a biomethane potential batch was achieved. The batch results showed that the optimal mixing ratio between FW and SS was 1:2 that generated the highest biogas of 823 ml gVS^{-1} after 21 days and the average content of methane was 60%. The 5 L glass were used as reactors in the batch studies at a mesophilic condition. The impact of various substrate loading rates on the production of biogas was studied. The mixing ratio of FW and SS was 1:2 (VS-based) (Prabhu & Mutnuri, 2016).

Pretreatment conditions

Thermal pretreatment was chosen as a pretreatment method. The homogenized food waste (FW) and sludge were pretreated separately by an electric oven to the following temperatures (100, 120, 140, 160, and 180 °C). Thermal pretreatment was performed in 1 L glass beakers (height, 158 mm; and diameter, 108 mm (approx)). During thermal pretreatment, a sample of FW and SS

Table 3. Characteristics of the substrates and inoculums

Description		PH	TS (%)	VS (%)	COD (mg/l)	TOC (mg/l)
Main substrate Dried sludge (El Berka WWTP)		7.50	16	10.10	150,000	60,000
Co-substrate Food waste		4.70	13	10.20	220,000	82,000
Inoculum (El Gabal El Asfar WWTP)	Dried digested sludge from belt press	7.90	21	10.92	170,000	70,000
	Fresh digested sludge from digesters	7.80	3	2.20	150,000	60,000

was filled into the glass beakers separately and the glass beakers were covered to prevent the water from being evaporated and then pretreated in the electric oven which had been preheated to the required temperature. The samples were preheated for 30 minutes and were then chilled in 10 °C water until the samples cooled to room temperature. After thermal pretreatment, the samples were stored at 4 °C to minimize the volatilization of organic compounds.

Biological methane potential tests

The biological methane potential (BMP) tests, which is considered the most suitable method for a relatively easy evaluation of the anaerobic digestibility, was used as a tool for evaluating the biogas production and biodegradability of the mixtures of FW and SS at different pretreatment temperatures under mesophilic conditions. The BMP test was carried out for the mixed substrates with a constant ratio of mixing of FW and sludge to find out the optimum pretreatment temperature for anaerobic co-digestion. The BMP test was performed using 1000 ml glass bottles (Figure 1). The bottles were prepared by adding the substrates, and inoculum to a final active volume of 500 ml. The substances used for the tests were mixed thoroughly at a ratio according to volatile solid (VS) and the final TS was adjusted to about 11.20%. The mixed substrate having FW and sludge was added to the vials in a certain ratio of 1:2 (Marcelo et al., 2017; Prabhu & Mutnuri, 2016) to a final concentration of 11.20%. The inoculum to substrate ratio was set at 1:1 (volume-based) (Nges & Liu, 2009). The vials were sealed and incubated in a room where the temperature was controlled to allow the anaerobic co-digestion in mesophilic conditions (room temperature 36±1 °C). The test was carried out in replicates. Each reactor was manually shaken for 1 min triples a day for the first 12 days and twice for the reset period. During the experiment, gas composition and total gas volume were monitored several times daily (twice a day for the first 2 days and once for the reset period) and were measured using a water displacement method. The pH, TS, VS, COD, and TOC were determined at the end of each batch experiment. The experiments were run for 23 days and terminated when methane production was less than 5 ml day^{-1}.

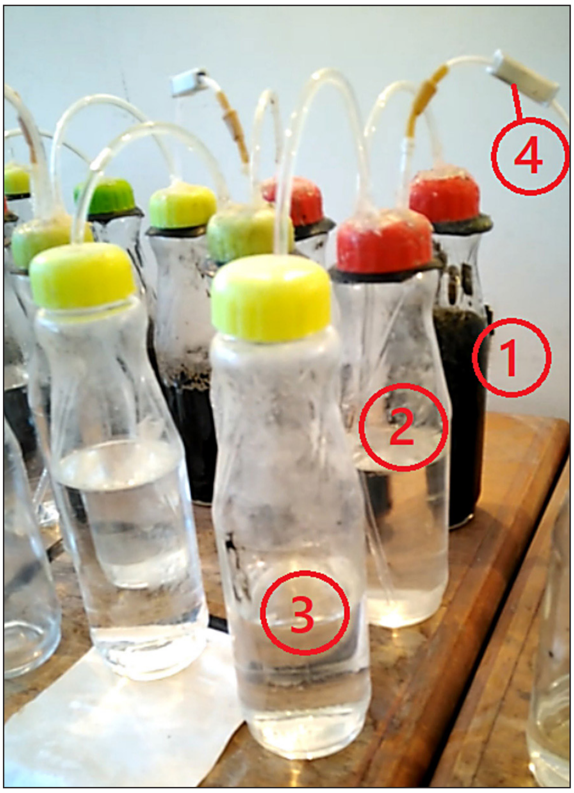

Figure 1. BMP tests reactors. 1 – digestor, 2 – water container, 3 – displaced water container, 4 – biogas control valve

One reactor was used for the untreated mixture (blank) and three reactors were used for each pretreatment temperature, as illustrated in Table 4. Sixteen BMP tests were conducted in total in this study. The BMP tests were carried out in replicates.

Analytical methods

The characteristics of the FW, SS, and Inoculum were determined by using the Standard

Table 4. Reactors are used for each pretreatment temperature

Reactor No.	Untreated		Pretreated	
	Food waste	Sewage sludge	Food waste	Sewage sludge
RB	√	√		
R1(T)		√	√	
R2(T)	√			√
R3(T)			√	√

Methods (APHA & and WEF, 2005). Total solids (TS) and volatile solids (VS) were analyzed for the measurement of solids reduction. Total chemical oxygen demand (TCOD) was analyzed. The pH was measured using the pH meter for each sample in location, such that the pH was measured directly in the location. The biogas produced during the anaerobic batch reaction was measured using a water displacement method. The efficiencies of the TS, VS, COD removal, and biogas improvement were calculated, where the removal rate (%) is given by the ratio between the amount reduced by the digester and the amount added to the digester.

RESULTS AND DISCUSSION

The best conditions and degree of improvement under co-digestion with thermal pretreatment vary noticeably. Accordingly, the temperature and duration of the optimum thermal pretreatment and the mixing ratios depend on the difficulty of the hydrolysis of the substrate and the nature of the biomass. In many cases, thermal pretreatment of biomass can significantly amplify methane production for low-rate systems like a mesophilic anaerobic system. Therefore, some experiments were carried out to study the thermal pretreatment effect as well as the potential of biogas production of food waste and sewage sludge. The parameters monitored along this experiment are pH, TS, VS, COD, TOC, and biogas production. An important parameter to inquire about the stability process of AcoD is its pH. In this experiment, the slightly acidic condition of the pH of the food waste (4.7) was balanced by the high pH value of the sewage sludge (7.5) and inoculum (7.8). The initial value of pH in all used reactors was 7.2 after the mixing, which is appropriate for anaerobic co-digestion, because methanogenic bacteria are incredibly affected by pH variations and require a pH of around 7.0 for optimal growth (Park et al., 2015). The pH of all samples ranged from 7.0 to 7.4, and the final pH ranging from 7.2 to 7.4. There was no decrease in the pH values. This is most likely due to the reactions that occurred between ammonia and carbon dioxide, which produce bicarbonate (Park et al., 2020). The final pH values at the end of the co-digestion process were 7.23 and 7.72. Buffering capacity determines the resilience of the reactor to pH changes.

The volatile solids removal ratio achieved in this study is presented in Figure 2. The minimum achieved removal ratio is 44.77% in R1(120) and the maximum is 64.58% in R3(180). These values

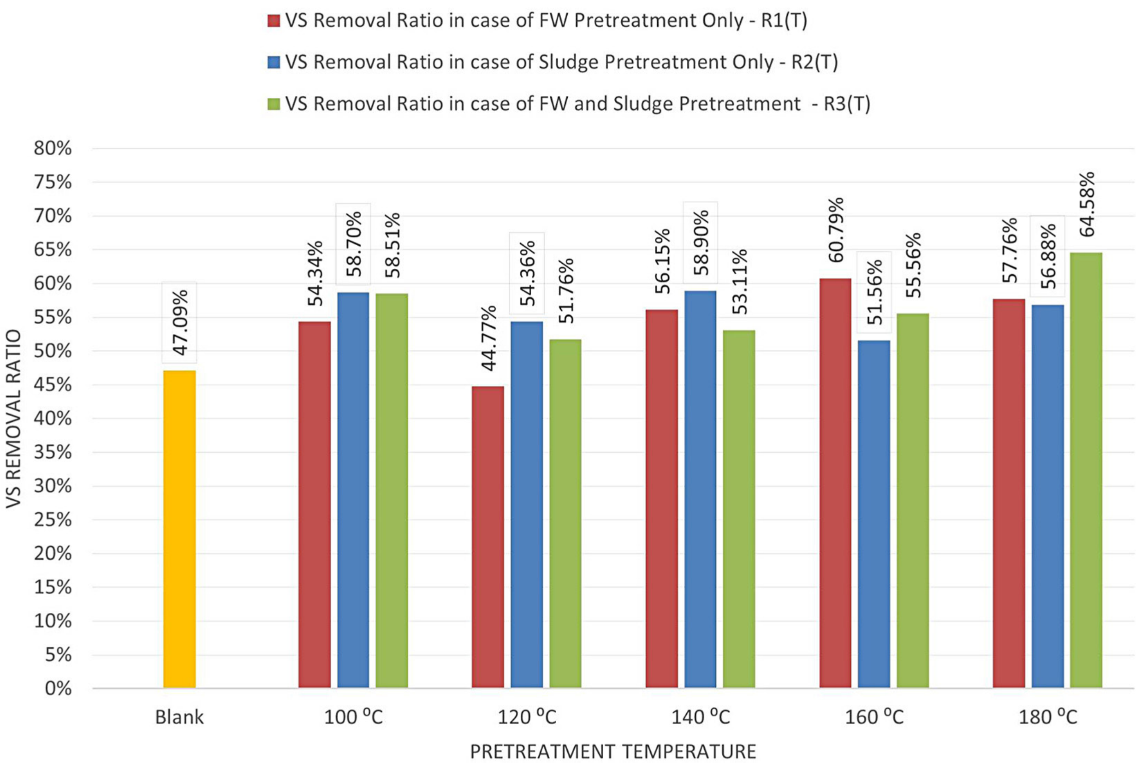

Figure 2. Volatile solid removal ratio

are within the optimal values achieved by most of the studies that reported the optimal temperatures for thermal pretreatment range from 160 to 180°C, and that treatment durations range from 30 to 60 minutes. These optimal conditions can lead to a volatile solid (VS) hydrolysis ratio of 40–60% (Bougrier et al., 2008; Wilson & Novak, 2009). Moreover, the removal ratio in this study is close to the removal ratio obtained for thermal pretreatment of sludge at 135 °C by (Bougrier et al., 2007) which was 41%. TS removal Ratio (Figure 3) ranges between 15.56 to 49.29% and it is higher if compared to the untreated reactor. The removal ratio increases along with the pretreatment temperature. A decrease in the content of TS, VS, and COD after the digestion indicates an increase in the digestion efficiency and stability of the reactor.

COD removal is a key factor in anaerobic digestion. Figure 4 shows the COD removal ratio for the 16 digesters used in the BMP test. The COD removal ratio of the blank digester was 39.54% and it was lower than the removal ratio for all other digesters. The achieved removal ratio ranged between 42.59 and 53.33% in all reactors. It is shown that the removal ratio increases along with pretreatment temperature for R3(T) but it increases up to 160 and 140 °C, and then decreases for R1(T) and R2(T), respectively. The best reactor in COD removal is R1(160). Carrere et al. (2008) stated that the increase of methane production has been linked to sludge COD solubilization by linear correlations (Carrère et al., 2008). Dwyer et al. (2008) found that while increasing pretreatment temperature to over 150°C increased solubilization, but had no effect on increasing methane conversion (Dwyer et al., 2008). Pretreatments at extremely high temperatures (higher than 170–190°C) lead to reduced sludge biodegradability, despite achieving high solubilization efficiencies. The creation of melanoidins, which are difficult or impossible to be degraded, is ascribed to the so-called Maillard reactions, which involve carbohydrates and amino acids (Bougrier et al., 2008) and this may explain why COD removal in reactors R1(180) and R2(180) are lower than R1(160) and R2(160). (Bougrier et al., 2006) reported that thermal pretreatment at high temperatures (>170°C) might create chemical bonds and result in the agglomeration of the particles. Maillard reaction occurs between carbohydrates and amino acids, resulting in the formation of complicated substrates that are difficult to biodegrade. This reaction can occur at extreme thermal treatment with temperatures surpassing 150°C, or longer treatment time at lower temperatures (<100°C) (Carrère et al., 2010; Elliott & Mahmood, 2012).

TP method may improve the biodegradability and solubilization of the food waste and sludge mixture, and it is considered to disrupt the food waste and sludge mixture structure wall by altering the organic solids physical structure; thus, the production of methane may be improved in anaerobic digestion (Mottet et al., 2009). Hendriks, & Zeeman (2009) stated that concerning the

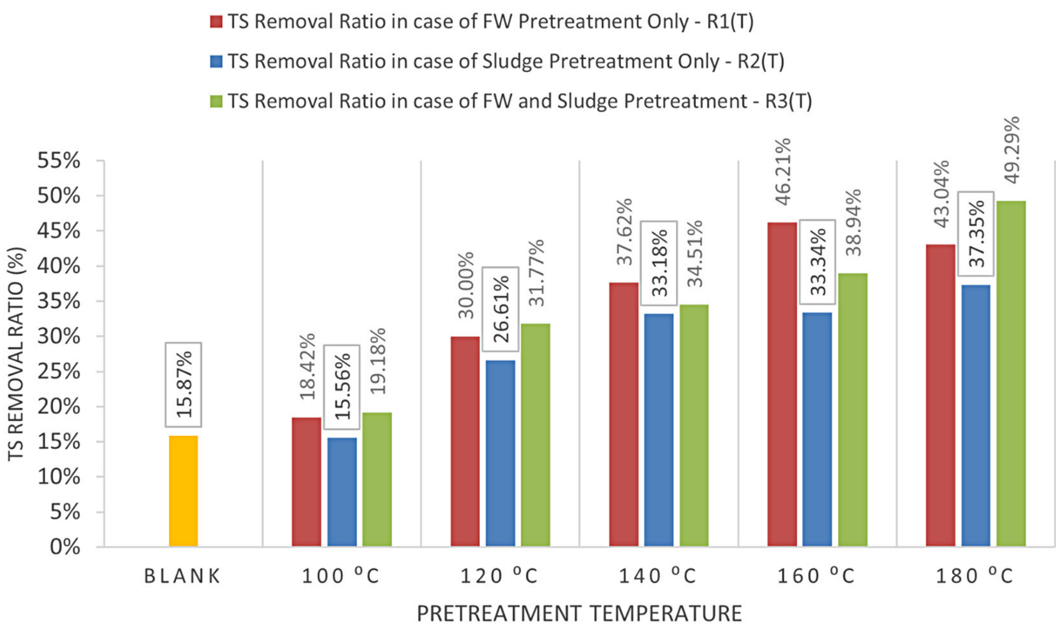

Figure 3. Total solids removal ratio

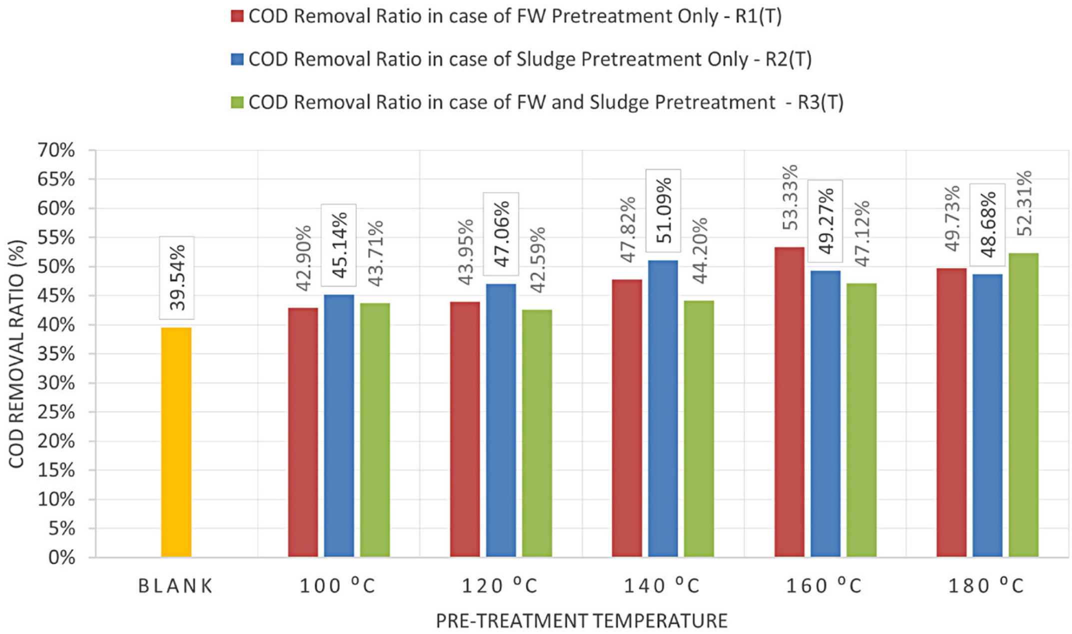

Figure 4. COD removal ratio

lignocellulosic substrates, temperatures exceeding 160 °C cause not only the solubilization of hemicellulose but also the solubilization of lignin. The released compounds are mostly phenolic compounds that are usually inhibitory to anaerobic microbial populations (Hendriks & Zeeman, 2009).

The daily and cumulative amount of biogas produced during the 23-day incubation period of the mixtures pretreated with thermal pretreatment was presented in Figure 5.

The BMP test shows that the co-digestion of the pretreated sludge and untreated food waste generates the highest biogas production then the co-digestion of the pretreated sludge and pretreated food waste and the lowest case in biogas production is the co-digestion of the untreated sludge and pretreated food waste for all pretreatment temperatures. During the BMP test, Figure 5 shows the cumulative biogas production through 23 days. It is noticed that the biogas generation is increased during the first 10 days and then biogas production is decreased. Figure 6 and Figure 7 show the gas production and the improvement in biogas production for all reactors. The biogas production ranges from 4830 for the reactor R1(120) to 5685 for the reactor R2(140) and the

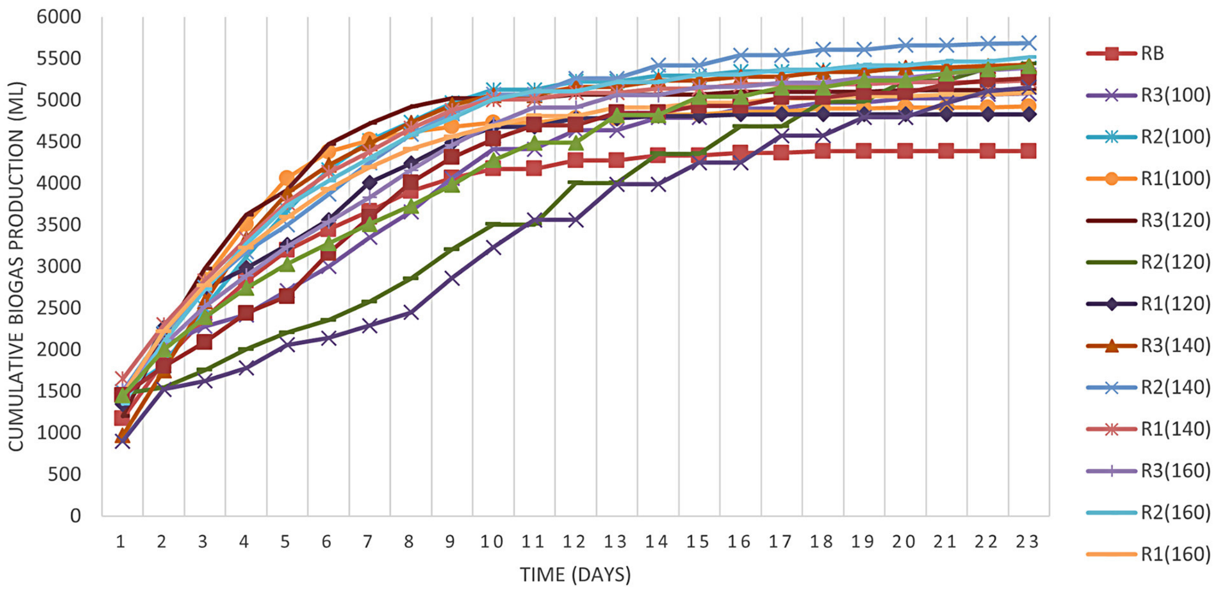

Figure 5. Cumulative biogas production (ml)

improvement in biogas production reaches 29.65 in the reactor R2(140). Clearly, biogas improved with the TP temperature until 140 °C, from 4385 ml for the untreated reactor (RB) to 5685 for the reactor (R2(140) at 140 °C. Therefore, after the biomethane potential test, the temperature of 140°C was found to be optimal in the production of biogas. The anaerobic co-digestion for the pretreated sludge and untreated food waste (R2(140)) is the optimal reactor. The optimal thermal pretreatment (140 °C) in this research complies with the results of Park (2020) who studied the use of HTP for a mixture of FW–SS at 1:1 (weight-based) under various temperatures (80, 100, 120, 140, 160, and 180 °C). The AD batch worked for forty days in mesophilic temperature (38 °C). The assessment results that an HTP of 140°C enhances the production of biogas by 50% (Park et al., 2020) and in this research, all cases were studied under mesophilic conditions (35–37 °C) for 23 days according to Table 4 and found that R2(140) is the optimal reactor and the improvement in biogas production reaches about 29.65%. Moreover, at 160 and 180 °C, although high removal of COD occurred, the biogas production was still higher in the reactor R2(140). It was reported that at temperatures of 160°C and 180°C, the carbohydrate content in the soluble stage reacted with the different components forming the product gradually or to make it scarcely biodegradable (Park & Kim, 2015). These obtained results conform with those acquired by (Mottet et al., 2009). This study also is complying with (Dwyer et al., 2008) who reported that when the pretreatment temperature increased exceeding 150°C, the solubilization improved, but the methane production improvement wasn't observed.

At the end of the batch, the biogas yields for the reactor (R2(140)) and reactor (RB) in terms of COD removal were noticed as 307.80 mL/gCOD$_{removed}$ and 306.78 mL/gCOD$_{removed}$, respectively, and in the case of VS removal it was 559.05 mL/gVS$_{removed}$ and 539.43 mL/gVS$_{removed}$, respectively. As shown in Figure 6, the cumulative biogas production for the reactor (R2(140)) is higher in the untreated reactor with approximately 29.65%, as shown in Figure 7, but the biogas yields in terms of COD$_{removed}$ and VS$_{removed}$ were approximately the same. The biogas yield production resulted in this study is higher than a study of co-digestion of FW and Primary Sludge (PS) which indicated that a mixing ratio of 1:2 produced a maximum biogas yield of 272 ml/ gVS at mesophilic conditions (Marcelo et al., 2017). It is very close to the biogas yield obtained by co-digestion of pretreated OFMSW and sludge with mixing ratio of 1.25:1 (volume ratio) at 65 °C for 60 min by (Amiri et al., 2016) which was 380 ml g^{-1} COD. Table 1 and

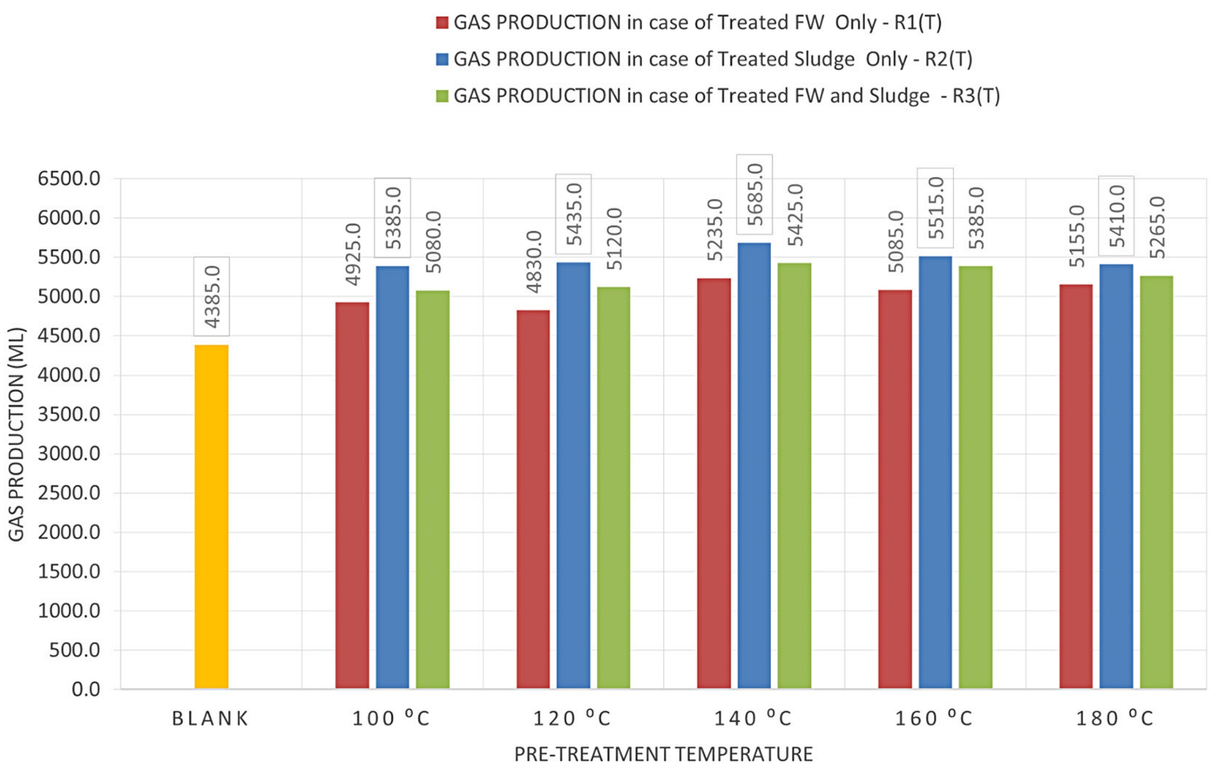

Figure 6. Biogas production in various pre-treatment temperatures and blank

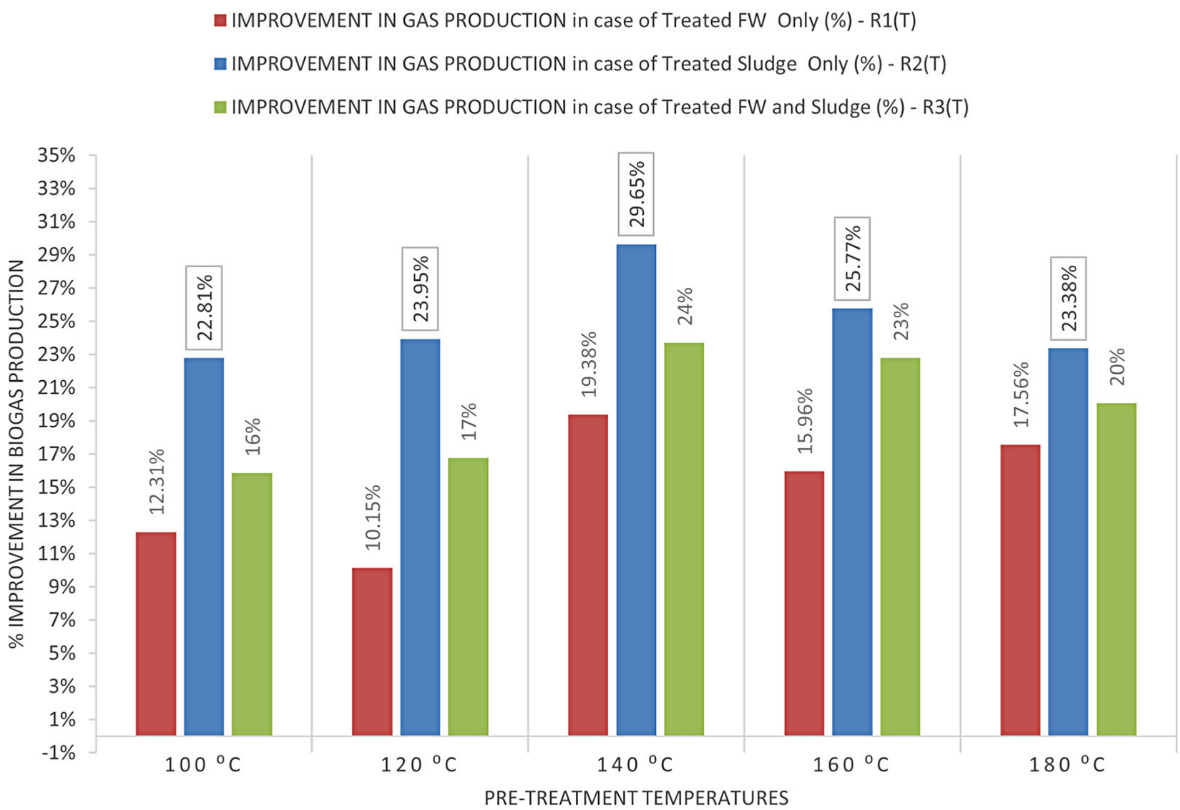

Figure 7. Improvement in biogas production (%)

Table 2 show the biogas and methane production of the previous studies in AD and AcoD.

The optimum thermal pretreatment, biogas production, and improvement in biogas production, the solubility of organic substances may differ from one study to the other. The basic properties and components of food waste and sewage sludge differ from one place to the other. The following studies represent the reason why optimum thermal pretreatment, biogas production, and improvement in biogas production, the solubility of organic substances may differ from one study to the other. The key properties of food waste are the C/N ratio and moisture content. Therefore, the effect of these two parameters on melanoidins formation also needs to be considered. A single variable optimization, on the other hand, is ineffective in evaluating the interacting effects of many factors on the targets (Elksibi et al., 2014). This might be because of a storage issue (sludge temperature fluctuated even at 4 °C) or a high concentration of soluble chemicals in raw sludge (Bougrier et al., 2007). The composition of FW mixed with SS has an impact on the performance of digestion, which, if altered, can lead to anaerobic population instability and, as a result, digestion process instability. This is due to the acclimation of microbes in a certain combination, and changes in the FW to SS mixture might cause variations in process reactions. Furthermore, due to seasonal fluctuations in food waste, CH_4 production may vary (Buffiere et al., 2006). Because the concentration of light metal ions and biodegradation intermediaries may be the considerable potent reasons of toxicity in AD, they are critical to the smooth operation of the process. Toxic or inhibitory means that a compound creates a negative alteration in the microbial population or stops the bacterial growth (Chen et al., 2008). Mixing the food waste with sewage sludge can cause an initial accumulation in VFAs content due to the quick acidification of soluble organic mixtures prevalent in food waste (Sosnowski et al., 2008). The preliminary source of NH3 production and accumulation is the protein-rich mix of FW and SS breakdown. Both the NH3 and ammonium ion (NH_4^+) content exist in AD. NH_4^+ may inhibit the action of methanogens bacteria and therefore, CH_4 generation. Regardless, NH_3 was notified to be more inhibitory than NH_4^+ due to its capability to penetrate via membranes of the cell (Hadj et al., 2009)

CONCLUSIONS

In this study, the effect of thermal pre-treatment (TP) on the physical characteristics and co-digestion of a mixture of food waste and sludge was investigated. The food waste to sewage sludge ratio used in this research is 1:2 (VS-based) to form a final concentration of 11.20%. The inoculum to substrate ratio was set at 1:1 (Volume-based). Undoubtedly, the results show that TP has changed the physical characteristics of the food waste to sewage sludge mixture. The results show that the pretreatment increased the biogas production from 4385 ml for the untreated reactor to 5685 for the reactor (R2(140) at 140 °C and the improvement in biogas production reaches 29.65% in the reactor R2(140) and the removal of volatile solids was 58.90%. The biogas yields for the reactor (R2(140)) and reactor (RB) in terms of COD removal were noticed as 307.80 mL/gCOD$_{removed}$ and 306.78 mL/gCOD$_{removed}$, respectively, and in the case of VS removal they were 559.05 mL/gVS$_{removed}$ and 539.43 mL/gVS$_{removed}$, respectively. Therefore, after the biomethane potential test, the temperature of 140 °C was found to be optimal in the production of biogas. The optimal condition is to use a mixture of pre-treated SS at the temperature of 140 °C and untreated FW so TP is recommended to be used in anaerobic digestion of the mixture of food waste and sewage sludge.

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