Evaluation of moderate temperature thermal pretreatment effects on the high-solid anaerobic digestion of OFMSW

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Research Article

Keywords: Moderate temperature thermal pretreatment, Organic fraction of municipal solid waste, Biomethane production, Net energy generation, High solid anaerobic digestion

Posted Date: April 26th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-346755/v1>

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Abstract

Anaerobic digestion (AD) of Organic Fraction of Municipal Solid Waste (OFMSW), leads to a reduction of methane emission to the atmosphere besides production of bioenergy. In this work, applying moderate temperature thermal pretreatment at 70, 90 and 110°C for the durations of 30,75,120 and 180 minutes on relatively high solid concentration (16%) OFMSW AD using batch biomethane potential assays (BMP) under mesophilic conditions has been studied. To evaluate the effects of each temperature and time of pretreatment and their interactions on methane production, factorial experiments in completely randomized design were implemented. The criteria used for deciding on the effectiveness of the thermal pretreatments were the methane enhancement and net energy production. Though, all the aforementioned thermal pretreatments increased methane yield, the energy balance evaluation revealed that the recovery of bioenergy is feasible for some of these pretreatments and could contribute to a positive energy balance. The best result of methane production (342.66 ± 6.11 ml CH₄/g VS), which was approximately 34% higher compared with the specific methane production of untreated OFMSW, was obtained by implementing pretreatment at 90°C for 120 minutes as well as the net energy generation of 57.26 KWh/ton, resulting from applying this thermal pretreatment.

Introduction

Municipal solid waste (MSW) management is becoming a crucial problem worldwide (Jain, Jain, Wolf, Lee, & Tong, 2015). About 45-50 thousand tons of MSW are generated per day in Iran, approximately 75% of which are biodegradable (Maghanaki, Ghobadian, Najafi, & Galogah, 2013). This quantity of organic fraction of municipal solid waste (OFMSW) can pose risks to the environmental and public health but at the same time represents a considerable potential of renewable energy resource (Morita & Sasaki, 2012) and soil conditioner (Kiran, Trzcinski, Ng, & Liu, 2014).

The main MSW treatment methods include landfill, thermal conversion methods (incineration, pyrolysis and gasification), biological conversion methods and landfiling with gas recovery (Kalyani & Pandey, 2014). However biological treatment is considered as the most effective alternative for treating OFMSW. Anaerobic digestion (AD) is a biological process, during which complex substrates are converted into biogas and digested by microbial activities in an oxygen-free environment. Owing to its capability of waste volume reduction as well as biogas and pathogen-free bio-solid production, anaerobic digestion (AD) has gained much acceptance (Shanmugam & Horan, 2009). Generally, in the literature, two common AD systems have been introduced based on the total solid (TS) content of the substrate to be digested: Dry AD or solid state AD (SS-AD) which takes place at solid concentrations of higher than 15%, and wet or liquid AD which occurs at TS contents below 15% (Momayez, Karimi, & Taherzadeh, 2019). Compared with wet anaerobic digestion, dry anaerobic digestion has several advantages, such as smaller digester volume, fewer moving parts, energetically effective performance (Pavan, Battistoni, Mata-Alvarez, & Cecchi, 2000) and simpler digestate dewatering (Karthikeyan & Visvanathan, 2013; Qian et al., 2017).

Among four principal microbiological stages of AD, hydrolysis is believed to be the rate-limiting step (Khalid, Arshad, Anjum, Mahmood, & Dawson, 2011; Rasapoor, Ajabshirchi, Adl, Abdi, & Gharibi, 2016; Yuan & Zhu, 2016). To improve the hydrolysis rate and hence increase the overall performance of AD, several pretreatment methods including thermal, biological, chemical and mechanical have been suggested (Bougrier, Delgenès, & Carrère, 2008; Carrère et al., 2010). According to European Union Regulation Ec 1772/2002, various types of wastes ranging from MSW to slaughterhouse wastes are required to be pasteurized or sterilized before or after AD (Ariunbaatar, Panico, Esposito, Pirozzi, & Lens, 2014). Beside this, an important point to keep in mind while selecting an appropriate pretreatment to improve hydrolysis is that, pretreatment should be implemented to improve energy recovery and modify the extra cost for pasteurization or sterilization (Eggeman & Elander, 2005). Thermal pretreatment is one of the most studied and industrially applicable pretreatment procedures (Carlsson, Lagerkvist, & Morgan-Sagastume, 2012; Cesaro & Belgiorio, 2014). Thermal pretreatment at moderate temperatures promote profitability of the system by reducing energy requirement compared to high temperature thermal pretreatment, boosting methane production and energy balance (Ferrer, Ponsá, Vázquez, & Font, 2008). Not only is hydrolysis improvement a function of pretreatment temperature, it also depends on pretreatment time (Boušková, Dohanyos, Schmidt, & Angelidaki, 2005).

Despite the significance of HS-AD for OFMSW particularly in developing countries, as well as the convenience and practicality of exercising thermal pretreatment, little attention has been paid over the years to evaluate the process using thermal pretreatment and to the best of our knowledge, no systematic research on the effect of moderate temperature thermal pretreatment and treatment times to enhance AD of high solid OFMSW has been conducted. Hence, this study was carried out to evaluate the effects of moderate temperature thermal pretreatment on HS-AD of OFMSW using statistics technique to validate the results in terms of methane production and net energy generation (NEG) resulted from implementing different temperatures for various durations.

Materials And Methods

2.1. Inoculum and substrate

Since the composition of organic fraction of municipal solid waste (OFMSW) is extremely variable, to reduce experimental bias and provide reproducible, comparable and reliable results, a synthetic waste was prepared based on the approximate composition of the mechanically sorted OFMSW used for composting process in Karaj city composting plant, located in the south west of the city. To this aim, a sample of 100 kg OFMSW was taken from the belt conveyor, conveying separated OFMSW to the fermentation area of the plant. Although the OFMSW was mechanically sorted, it was resorted manually to remove non-OFMSW compounds such as plastic and metal scraps. A part of the prepared sample was selected to generate a relatively similar synthetic OFMSW.

The synthetic OFMSW was generated using a mixture of potato (600 g), banana peel (400 g), vegetable and lettuce (600 g), tomato, onion, cucumber, carrot, eggplant, cabbage, bell pepper and zucchini (1600

g), bread and bakery (200 g), meat product (120 g), dairy product (120 g), steamed rice (120 g), paper and tissue paper (120 g), and miscellaneous materials including tea, eggshell, walnut, date and oil (120 g). The materials then chopped and mixed several times, shredded and ground to less than 2 mm mesh size and were stored at 4 °C before applying thermal pretreatment. The anaerobic inoculum was collected from the anaerobic digester, treating cow dung and food waste, located in Karaj Material and Energy Institute. After removing large particles from the inoculum using a 2-mm sieve, it was incubated at (37 ± 1) °C for days to eliminate the biodegradable organic materials. The main characteristics of the OFMSW and the inoculum, for at least three times measurement, are summarized in table 1.

Table1. Characteristics of the synthetic OFMSW and the inoculum.

Material	TS (wt.%)	VS (wt.%)	Total volatile fatty acids (mg/l)	pH
OFMSW	18.85±0.17	92.12±0.76	4219±149.73	5.63±0.04
Inoculum	16.89±0.42	62.28±0.57	621.43±57.24	8.67±0.06

2.2. Thermal pretreatment and energy calculations

Thermal treatment was performed on the shredded OFMSW with the total solid content of 16% at three different temperatures (70, 90, 110°C) and four different treatment durations (30, 75, 120 and 180 min). A simple oven was used for the thermal pretreatment. Twelve 1-L autoclave glass bottles GL 45, each containing 200 g of the shredded OFMSW, were placed inside the oven and heated at 70, 90, and 110°C for 30, 75, 120 and 180 minutes. The bottles were covered and sealed with silicon gaskets to prevent water evaporation during the pretreatment. After hydrolyzation at these predetermined temperatures for the aforementioned periods, the heating process was stopped, and the bottles were taken out, cooled down to ambient temperature and then were used for the BMP tests. Untreated and pretreated substrates were prepared for digesting by mixing them with inoculum and putting the mixtures into the laboratory bottle digesters. Similarly, thermal pretreatment for the second phase of experiment was carried out to study the comprehensive effects of the selected pretreatment and make comparison with the untreated OFMSW anaerobic digestion. To this aim, three 1-L glass bottles each containing 200 gr of grounded OFMSW were sealed and placed inside the oven at the optimum temperature and time resulting from the previous BMP tests. After thermal pretreatment, the glasses were chilled and directly added with the inoculum so that the substrate to inoculum (S/I) ratio of 1/2 was achieved.

2.3. Digester set up

Assays were carried out in two experimental phases: Firstly, BMP tests were performed following the guidelines proposed by Angelidaki et al., (Angelidaki et al., 2009) to compare the methane yield and net energy generation from anaerobic digestion of treated and untreated OFMSW. Fig. 1 displays the schematic diagram of the proposed AD system for the methane measurement consisted of an anaerobic digestion reactor, a NaOH container, a biomethane storage bottle and a liquid displacement bottle. Both substrate and inoculum were diluted with pure water to reach the total solid content of 16%. The glass

bottles with a working volume of 100 mL were used as digesters. After implementing thermal pretreatments, the substrate (S) and inoculum (I) were placed into the bottles with an S/I ratio of 1:2 on a volatile solids (VS) basis. To remove the inoculum biodegradable materials, inoculum was incubated and degassed before being blended with the substrate. Each digester was connected to 1 L glass bottle containing 3M NaOH to absorb the carbon dioxide. The NaOH containers were placed between the digesters and the methane collector bottles. The upper space of the digesters was flushed with nitrogen for at least 2 minutes to guarantee anaerobic conditions. To prevent biogas leak from the caps of the digesters and the NaOH containers, stainless steel connectors sealed by silicon gaskets were applied. The assays were performed by triplicates to acquire statistically valid results. Moreover, in each experimental run, three control digesters containing untreated OFMSW and inoculum were operated. Simultaneously, three blank digesters holding only inoculums were incubated to correct for methane production from the inoculum itself. The bottles were maintained at mesophilic temperatures (37 ± 1 °C) in an incubator and the digesters were manually shaken once a day for 30 seconds.

Based on the results obtained from the first testing series, In the second experimental session, digestion was conducted in 1 L glass bottles at 37 ± 1 °C for four weeks to carry out a more detailed study on the effects of the best thermal Pretreatment on the anaerobic digestion process of the synthetic OFMSW. Three Glasses were added with 200gr untreated OFMSW as control digesters and the same number of glasses were filled with the equal amount of thermally treated OFMSW, both adjusted to 16% of solid content. Similar to the BMP assays, before incubation at 37 ± 1 °C, the substrate-to-inoculum ratio was set to 1:2 on a VS basis and each bottle headspace was flushed by N₂ gas for two minutes. The gas collector bags were connected to the digester gas outlet ports and samples from the mixtures of substrates and inoculum were taken to analyze their pH and total VFA for the monitoring the anaerobic digestion process. Samplings were performed twice a week inside a glove box to maintain the anaerobic conditions. All analyses were performed in triplicate.

2.4. Analytical method

Total solids (TS) and volatile solids (VS) of both the synthetic OFMSW and inoculum were analyzed in triplicates according to the APHA standard methods (Beutler et al., 2014). Total volatile fatty acids (TVFA) evaluated for samples using titration by 0.05 M sulfuric acid according to Lahav & Morgan (Lahav & Morgan, 2004). Methane production was measured every day during the first days and then every other day until no methane was generated for three successive days. The daily methane production was measured with the liquid displacement method using a sodium hydroxide (120 g NaOH/L) solution to capture carbon dioxide (Browne & Murphy, 2013; Mirmasoumi, Saray, & Ebrahimi, 2018). The net methane production in BMP tests was obtained detracting the inoculum contribution of the blank and reported on the basis of daily and cumulative methane at standard temperature and pressure and normalized based on volatile organic matter present in each sample with units of CH₄ mL/g VS. The results were expressed as average of three samples. Since the aim of this study was to compare the efficiency of the thermal pretreatments, represented by methane production enhancement, net energy generation (NEG) was calculated only for the thermal pretreatment and the required energy for preparing substrate and

operating mesophilic anaerobic digestion were neglected. The net energy generation was evaluated considering differences between the thermal pretreatment energy requirement for treating of 1 ton OFMSW and the enhanced energy associated with the extra methane generated as a result of thermal pretreatment. The extra energy production caused by the enhanced methane arising from the thermal pretreatment can be estimated as follows (Ennouri et al., 2016): **see formulas 1, 2, 3, and 4 in the supplementary files.**

2.5. Data analysis

statistical analyses were performed to determine the effects of thermal pretreatment in terms of the temperatures and exposure times on the enhancement of anaerobic digestion indicated by methane yield and net energy generation. Methane yield experiments for different thermal pretreatment were conducted as a triplicated, completely randomized factorial design arrangement. Treatment temperature and time were considered at three (70, 90 and 110°C) and four levels (30, 75, 120 and 180 min) respectively. Totally, 39 digester settings were incubated in a random order. To determine whether the observed differences between digesters performances were significantly different, data were subjected to the analysis of variance (ANOVA) tests. The single and interactive effects on biogas yield were specified to explore the significance of difference at $p < 0.01$. Table 2 briefly introduced all the treatments which were analyzed during the study without control samples. The statistical analysis performed using the statistical software MINITAB, and a p-value of <0.01 was considered statistically significant.

Table 2. Thermal treatment parameters used in this research in the 16% of total solid.

Temperature (°C)	Treatment time (min)	Temperature (°C)	Treatment time (min)
70	30	90	30
75	75		
120	120		
180	180		
110	30		
75			
120			
180			

Results And Discussion

A Completely Factorial Randomized Design was used to compare the enhancement of high solid anaerobic digestion of OFMSW through thermal pretreatment considering two variable parameters including temperature and treatment time.

3.1. Effects of thermal pretreatment on methane yield

In this study BMP tests of OFMSW under mesophilic conditions were carried out and compared to determine the optimum thermal pretreatment over an incubation period of 25 days.

To consider the effect of thermal pretreatment on final biomethane yield, cumulative biomethane yields were measured for all treatments including thermally treated and control samples. Fig. 2 shows the cumulative methane yield as a function of digestion time for all treated and untreated (control) samples. As has been clearly shown in figure 2 (a, b and c) biomethane production started immediately after incubation. Although, as can be seen in figure 2 (d), depending on the applied temperatures and treatment durations, various results were obtained, it is evident that thermal pretreatment under all treatment temperatures and durations led to increase the specific biomethane yield from the synthetic OFMSW anaerobic digestion which are in accordance with the results reported by others researchers (Ariunbaatar, Panico, Frunzo, et al., 2014; Eskicioglu, Kennedy, & Droste, 2006; Mata-Alvarez, Macé, & Llabres, 2000; Neves, Goncalo, Oliveira, & Alves, 2008), who had obtained more biogas from anaerobic digestion of thermally treated food waste. Statistical analysis in this study revealed that there were significant differences among various combinations of treatment temperatures and times. Therefore, the effects of treatment time and temperature on methane production were meaningful. This rise in biomethane production might be due to the fact that, thermal pretreatment contributes to the floc size reduction (Prorot, Julien, Christophe, & Patrick, 2011) and the cell disintegration as well as the volatile fatty acids formation (Liao, Li, Zhang, Liu, & Chen, 2016; Mirmasoumi et al., 2018). Deflocculation of macromolecules increases the surface area of the substrates resulting in a better contact between the substrate and the microbial population, thus converting more organic matter into biomethane (Esposito, Frunzo, Panico, & Pirozzi, 2011).

Nevertheless, the increase in ultimate methane production did not follow the pretreatment temperature linearly and at the end of the experiments, the cumulative biomethane production of pretreated substrates at 110 °C for 75 and 120 minutes were less than those of OFMSW pretreated at 90 °C for the same time (Fig. 2 d). This can be ascribed to the fact that, thermal pretreatment may result in Maillard reaction, i.e. a reaction between amino acids and sugars. The product from the Maillard reaction, melanoidins, is not easily degraded under anaerobic conditions (Li, Jin, Li, Li, & Yu, 2016; Vavilin, Fernandez, Palatsi, & Flotats, 2008). Therefore, production of Melanoidin and loss of volatile fatty acids while applying pretreatment at the temperatures higher than 100°C might be the causes of diminishing methane production (Eskicioglu et al., 2006). According to figure 3. biomethane production increased with the exposure time expanding from 30 to 75 minutes (8.7% at 70°C, 22.8% at 90°C and 9.87% at 110°C). Expanding this time from 75 to 120 minutes led to increase in biomethane production at 70°C and 90°C up to 3.25% and 2% respectively and decrease at 110°C by 3.75%. With the longer exposure time of 180 minutes, almost a negligible decline in biomethane production obtained at 70°C (less than 1%) whereas a distinct reduction was occurred at 90°C and 110°C (7.87% and 3.57% respectively) compared to the pretreatment duration of 120 minutes. Thus, thermal pretreatment exposure time up to 120 minutes improved biomethane generation substantially. Ariunbaatar et al., (Ariunbaatar, Panico, Frunzo, et al.,

2014) has reported an incomplete or mild Maillard reaction as a consequence of pretreating food waste at lower temperatures (70 and 80 °C) for longer times (4 and 8 hours). At the end of the BMP test the maximum methane production was achieved at 90°C for 120 and 75 minutes, which successively produced 34% and 31.3% higher biomethane as compared to the control.

Furthermore, the results of biomethane production variance analysis versus temperature, time and their interactive effects are presented in Table 3. The results show the effect of these variables at $p < 0.01$ level is significant on methane production.

Table3. Methane variance analysis versus temperature and treatment time

Source	DF	SS	MS	F-value	p-value
Treatment	11	18643	1694.8	14.87	0.00
Temperature (T (°C))	2	6527	3263.4	28.63	0.00
Time (t (min))	3	8869	2956.5	25.93	0.00
t×T	6	3247	541.1	4.75	0.00
Error	24	2736	114.0		
Total	35	21379			

Figure 4, shows the contribution of the variables including temperatures, times and their interactive effects to methane production. The results demonstrate that within the scope of this experiment variables, pretreatment time has the greatest impact on the production of methane (41.49%) followed by pretreatment temperature (30.53%) and their interactive effects (15.19%).

According to figure 5., the comparison of means tests results indicates that the treatment times of 75 and 120 minutes resulted in a significant increase in methane production from anaerobic digestion of the synthetic OFMSW. Similarly, fig 6. shows the simple effects of various applied temperatures. As it can be noted, all three levels of temperatures were seen to be significantly different ($p < 0.01$) in terms of methane yield and pretreatment at 90°C led to the best results.

3.2. Effects of thermal pretreatment on digestion acceleration

Methane production started immediately on the first day of digestion in all the reactors. The average development of cumulative specific methane production through the digestion of control OFMSW samples and OFMSW subjected to thermal pretreatment at 70, 90 and 110°C with different treatment durations are illustrated in Fig. 2. (a, b, c). Comparing the specific methane generation of thermally treated samples with that of untreated synthetic OFMSW during the first week of anaerobic digestion indicated that all treated samples produced more methane, suggesting acceleration of digestion process of the substrate subjected to thermal pretreatment. It was observed that, whereas the control reactors produced less than 50% (123.66 ± 13.79) of their total methane generation in the first week, samples

pretreated at 90°C for 75 and 120 minutes yielded $71.67 \pm 1.39\%$ (240.66 ± 10.01 ml/gVS) and $69.81 \pm 2.4\%$ (239.33 ± 12.42 ml/gVS) of their total CH₄ production respectively, during this period.

From Fig. 2, it can also be seen that for the digesters with pretreated substrate the cumulative methane increased until day 14 and then leveled off. A similar pattern is seen for the untreated samples with the exception of an incessant modest rise in cumulative methane until day 20 for the control digesters. Therefore, compared to the untreated controls, the whole digestion time was shortened for all the pretreated samples. While untreated samples produced methane until the 20th day, almost no biomethane generation was seen after the day 14 in other reactors. These findings are in line with those reported by Jin & Li (Jin, Li, & Li, 2016) who had conducted a research on the influence of thermal pretreatment on properties of kitchen waste and the efficiency of anaerobic digestion. They reported that thermal treatment had resulted in relatively shorter time for treated samples digestion to complete compared to untreated samples, since the destruction of large molecules and refractory organic matter had led to the increase in the proportion of biodegradable ingredients so that the digestion process could be completed in less time (Jin et al., 2016). It can also be inferred from figure 2.(a, b and c) that, although thermal pretreatment has shortened the digestion time of the synthetic OFMSW, when the effects of pretreatment at different temperatures and durations on digestion time are compared, no distinct difference can be seen among them. Furthermore, these results showed that, thermal pretreatment not only expedited the synthetic OFMSW anaerobic digestion remarkably, it also had a significant effect on biomethane yield during the initial stage of the process.

3.3. Net Energy Generation

Since thermal pretreatment process requires extra heat, therefore, this procedure should contribute a positive energy balance to be feasible. Net energy generation is considered as the difference between the total energy production resulted from thermal pretreatment and energy consumption to apply the pretreatment (Wang et al., 2018). The total energy consumption for treating OFMSW was determined by adding the heat required to raise the substrate temperature to the pretreatment temperature to the required energy for maintaining the substrate at that temperature. The energy production from implementing thermal pretreatment was calculated from the difference between the energy content of methane generated after each pretreatment and that of the control. The survey results showed that although all thermal pretreatments led to promotion of biomethane generation, there were limits to the usefulness of thermal pretreatment and when energy balance is factored in, only some of them are justifiable.

According to Fig. 7, it could be concluded that not all pretreatment conditions considered in this study enhance the anaerobic digestion performance in terms of net energy generation compared to the untreated OFMSW. The results illustrated that implementing thermal pretreatment at 70°C and 90°C for 75, 120 and 180 minutes, and at 110°C for 75 minutes has improved the energetic efficiencies of the synthetic OFMSW anaerobic digestion so that the extra energy produced could cover the required energy for exercising the thermal pretreatment.

In contrast, some conditions resulted in negative energy balance, which meant that the required energy for thermal pretreatment at those temperatures and durations exceeded the generated energy from the extra biomethane produced. For example, pretreatment at 110°C for 30, 120 and 180 minutes gave a negative net energy production (Fig. 7), offering the higher temperatures are not advisable for pretreating OFMSW. Ariunbaatar et al (Ariunbaatar, Panico, Esposito, et al., 2014) reported almost the same results and suggested that the energy requirement for thermal pretreatments higher than 100°C is mostly utilized for evaporating the water, thus high temperatures (>100°C) were not suitable for the pretreatment of food waste due to a higher energy requirement.

Variance analysis of net energy generation versus simple and interactive effects of the pretreatment temperature and duration ($p < 0.01$) was conducted as presented in table 4. All the three above-mentioned sources of variation caused statistically significant differences in net energy production. Figure 8. Shows the contribution of treatment variables including temperature, treatment time and their interactive effects to net energy production from the synthetic OFMSW.

Table 4. NEG variance analysis versus temperature and treatment time.

Source	DF	SS	MS	F-value	p-value
Treat	11	36562	3323.8	13.57	0.00
T (°C)	2	11539	5769.4	23.56	0.00
t (min)	3	17870	5956.5	24.32	0.00
t×T	6	7153	1192.2	4.87	0.00
Error	24	5878	244.9		
Total	35	42440			

According to the results obtained from the comparison of means tests (figure 9.) it was revealed that treatment times of 75 and 120 minutes significantly increased the net energy production from anaerobic digestion of the synthetic OFMSW. Figure 10. displays the simple effects of the applied temperatures at 70, 90 and 110 °C. It is clear that pretreatment temperature of 90 °C has resulted in the highest level of net energy generation.

Additionally, net energy generation appeared to be more effectively affected by the treatment durations than the applied temperatures. It is worth noting that, according to the variance analysis, the contribution of variables including treatment durations, temperatures and their interactive effects to net energy production were 42.11%, 27.19% and 16.86% respectively.

3.4. Total fatty acids (TVFAs) and pH variations

Depending on the concentration, VFAs can be regarded as either the main precursor or the prominent deterrent of biomethanation process (Rasapoor et al., 2016). The concentration of these volatile acids in

the digester is a function of their production and consumption rates (Fernández, Pérez, & Romero, 2008; Forster-Carneiro, Pérez, & Romero, 2008). The methane yield, which is one of the most important variables to be determined in the anaerobic digestion of OFMSW, is directly related to the presence of total volatile fatty acids in the reactor content (Aboudi, Álvarez-Gallego, & Romero-García, 2017; Ahring, Sandberg, & Angelidaki, 1995) and the conversion process of the organic matter into CH₄ is strongly connected to the evolution of the volatile fatty acids concentrations in digesters (Ahring et al., 1995). In the second experimental session, pH and VFAs variations of anaerobic digestion of the untreated control and those of the pretreated samples under optimum thermal treatment conditions (90°C for 120min) were investigated. It is worth mentioning that the methane productivity and net energy generation were regarded as the criteria to opt the most suitable pretreatment conditions.

The profile of volatile fatty acids and pH over the length of the digestion period for optimally treated and untreated samples under mesophilic conditions are shown in Figs. 11 and 12 respectively. During the early stage of digestion, the VFAs accumulation was noticed in parallel with a drop in pH. This drop in pH slowed down the methanogenic activity. The VFAs patterns of both treated and untreated samples followed very similar trend. The main difference in the two trends was a more substantial rise in VFAs accumulation for the treated sample during the first days of inoculation. The more pronounced peak of VFAs can be explained by the improved hydrolysis of the substrate exposed to thermal pretreatment. At the same time, since a higher concentration of VFAs would easily result in a drop in pH values and could disturb the methanogenic activity (Montingelli, Benyounis, Stokes, & Olabi, 2016; Morita & Sasaki, 2012) and hamper the digestion process, it is not always an indicative of more effective AD process (Jin et al., 2016). Due to the accumulation of VFAs, the pH decreased to less than 6.5 for both treated and untreated reactors at the second day. This might be the main reason for the drop in biomethane production for the next couple of days after the dramatic rise in VFAs concentrations was observed. Therefore, methane production declined until the activity of the acid-consuming microorganisms resumed. Thereafter, VFAs were continuously consumed until the end of the AD process.

As might be expected, it is clear from figure 12. that the pH values had been in constant rise after bottoming out to around 6.5 over the same period to the end of the inoculation and it soared to almost 8.72 and 8.65 for treated and control samples respectively.

The concentration of fatty acids at the early stage of the process, as well as the rate of VFAs consumption in the digestion of treated OFMSW over the ensuing days (fig. 11) and methane production (fig. 13) were higher than those of untreated substrates, which indicates that thermal pre-treatment enhanced anaerobic digestion through releasing VFAs and improving the biodegradability of the substrates.

Conclusion

In this study, the effect of thermal pretreatment at moderate temperatures on high solid anaerobic digestion of synthetic organic fraction of municipal solid waste to increase the biomethane productivity

of OFMSW AD was investigated. The possibility to enhance the high solid AD of OFMSW under mesophilic conditions applying thermal pretreatment was studied through a series of batch experiments.

Statistical analysis showed significant differences in the biomethane yields obtained using thermal pretreatment. The results demonstrated that biogas yields after 25 days of digestion were heavily influenced by thermal pretreatment. Compared to untreated substrate, all pretreatment conditions enhanced the methane production rate and final methane yield (up to 34% increase). The temperature and treatment time play an important role for the enhancement of AD though, the pretreatment efficiency was mostly influenced by treatment time. Furthermore, the batch biomethane potential test of different digestion conditions showed that the thermal pretreatment of OFMSW at 90°C is more effective than pretreatment at 70°C and 110°C. This can be attributed to the increased solubilization of organic solids and/or the improved hydrolysis made the OFMSW more available for the microorganisms, thus the biomethane production was enhanced.

Thermal pretreatment also reduced the retention time and made the AD process faster and finally led to a significant increase in the biomethane productivity. Thermal pretreatment enhanced the digestion performance by increment of biomethane production and accelerating the digestion time. However, some temperatures and pretreatment times were more effective than others. It should be noted that, while all the thermal pretreatments promoted biomethane production, some of them eroded the net energy generation. Nevertheless, when a comparison is made between digestion times of treated and untreated synthetic OFMSW, the application of thermal pretreatment may still seem reasonable. Energy calculation results suggested that thermal pretreatment of OFMSW at 90°C for 75 and 120 minutes led to the highest net energy generation.

The second experiment results highlighted the difference between VFAs variation trends of the digestion of control samples and the OFMSW treated under the optimal pretreatment conditions derived from the BMP tests. The results suggested that thermal pretreatment would result in hydrolysis improvement via releasing more volatile fatty acids in the samples. Further study is required utilizing continuous reactors as well as other solid contents of digestate material to make a more pragmatic evaluation and comparison of the net energy production resulting from thermal pretreatment application.

Declarations

Author contribution: Masoud Kamali: Conceptualization, Investigation, Methodology, Project administration, Resources, Software, Writing original draft. Reza Abdi: Supervision, Abbas Rohani: Validation, Formal analysis, Writing, review & editing. Shamsollah Abdollahpor and Sirous Ebrahimi: Supervision. All authors participated in writing the manuscript and read and approved the final manuscript.

Funding: This work was financially supported by the University of Tabriz, Iran.

Data availability: Not applicable

Declarations: Ethics approval and consent to participate Not applicable

Consent for publication: Not applicable

Competing interests: The five authors declare no competing interests.

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Figures

Figure 1

Biomethane measurement setup

Figure 2

Fig. 2. Cumulative methane production (STP, mL/gVS) from untreated (control) and thermally treated synthetic OFMSW at (a) 70°C (b) 90°C (c) 110°C for different durations (30, 75, 120 and 180 min) and (d) Mean comparison results of methane production at various pretreatment temperatures and durations

Figure 3

Cumulative methane production of thermally treated samples at different temperatures based on treatment duration.

Figure 4

Contribution of treatment temperature, duration and their interactive effects on methane production.

Figure 5

Average methane production at different pretreatment times (mL/gVS).

Figure 6

Average methane production at different pretreatment temperatures (mL/gVS).

Figure 7

Mean comparison results of net energy generation from AD of OFMSW pretreated at various pretreatment temperatures and durations.

Figure 8

Contribution of treatment temperature, duration and their interactive effects on net energy generation.

Figure 9

Average net energy generation at different pretreatment times.

Figure 10

Average net energy generation at different pretreatment temperatures.

Figure 11

TVFA profiles of optimally treated and control samples

Figure 12

pH profiles of optimally treated and control samples

Figure 13

Methane production of optimally treated and control samples

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