ERJ
Engineering Research Journal
Faculty of Engineering
Minoufiya University

THE EFFECT OF DIGESTION TEMPERATURE AND THE ORGANIC WASTE TYPE ON THE BIOGAS PRODUCTION

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ABSTRACT

An experimental investigation has been carried out to study the effect of the digestion temperature and the type of organic waste on the biogas production. The experimental work is performed by using three similar lab-scale batch-fed 240 liter biogas reactors. Each of the bioreactors is designed to operate under thermophilic (55 ± 2 ºC), mesophilic (40 ± 2 ºC) and ambient digestion modes during the same retention time of 31 days. Three experimental test runs have been carried out on three different mixtures of organic wastes including pure cattle manure, cattle manure mixed with rice straw and cattle manure mixed with hen manure. Daily measurements are recorded for the generated biogas volumes, pH values, average gas pressure and the ambient temperature during each test run. The results indicate that, total biogas yield in thermophilic mode gives an increase over mesophilic mode by 4%, 6.5% and 80% for the first, the second and the third run, respectively. Also, the total biogas production for ambient mode is lower than thermophilic mode by 72%, 80% and 60% for the first, second and third run, respectively. The maximum daily biogas yield was obtained at pH values in the range of (8.1 – 8.51) and (7.11 – 8.24) for thermophilic and both of mesophilic and ambient modes, respectively. In addition, it was observed that the maximum biogas yield has been achieved at a value of 9.4% of total solid content in the slurry.

تم عمل بحث تجريبي لدراسة تأثير درجة حرارة التخمر ونوع النفايات العضوية المستخدمة علي انتاج الغاز الحيوي. ولانجاز هذا العمل التجريبي, تم استخدام ثلاث مخمرات معملية متماثلة من نوع التغذية بالدفعة بحجم 240 لتر لكل مخمر. وقد تم تصميم كل من المخمرات لتعمل عند درجات حرارة مختلفة لتحقيق وسط ثرموفيليك (55 ± 2 ºC) في الأول ووسط ميزوفيليك (40 ± 2 ºC) في الثاني, أما المخمر الثالث فيعمل عند درجة حرارة الجو عند نفس زمن الاحتفاظ الكلي 31 يوم. ولقد تم اجراء ثلاث مجموعات من التجارب المعملية لثلاث مخاليط مختلفة من المخلفات العضوية والتي تتضمن روث ماشية صافي و روث ماشية مخلوط مع قش أرز و روث ماشية مخلوط مع روث دجاج. وأثناء تلك التجارب تم تسجيل قيم يومية لحجم الغاز الحيوي وقيم الرقم الهيدروجيني (pH) ومتوسط ضغط الغاز ودرجة حرارة الجو المحيط بالمخمرات. أوضحت النتائج أن القيمة الكلية للغاز الحيوي المنتج تزداد في حالة وسط الثيرموفيليك عن نظيرتها في حالة الميزوفيليك بمقدار 4% و 6.5% و 80% في التجارب الأولي و الثانية والثالثة علي الترتيب. كما أظهرت النتائج أن القيمة الكلية للغاز الحيوي المنتج تكون أقل عند درجة حرارة الجو عن نظيرتها في حالة وسط الثيرموفيليك بمقدار 72% و 80% و 60% في التجارب الأولي و الثانية والثالثة علي الترتيب. وقد أظهرت النتائج أيضا أن أعلي المعدلات اليومية للغاز الحيوي كانت عند قيم للرقم الهيدروجيني (pH) تتراوح بين (8.1 – 8.51) و (7.11 – 8.24) لوسط الثيرموفيليك وكلا من وسط الميزوفيليك والوسط المحيط معا علي التوالي. وقد لوحظ أن أعلي قيمة لانتاجية الغاز الحيوي تم الحصول عليها عند قيمة 9.4% للكتلة الصلبة الكلية في المزيج.

***Keywords*:** biogas, anaerobic digestion, thermophilic mode, mesophilic mode, cattle manure, hen

1. INTRODUCTION

Undoubtedly, recycling the wastes becomes the most promising industries in the world and have a greater share of industrial investments of up to 28% in the United States of America, 23% in England and 35% in Germany, while it is found that this kind of investment is almost non-existent in the Arabic countries and limited to a modest individual attempts which in total don't exceed 150 million dollar, mostly in Egypt [1]. The lack of attention of waste recycling lost the opportunity to obtain large quantities of paper, plastics, iron and organic fertilizers that could provide billions of dollars which paid to import these products. The process of biogas generation from crop residues, animal droppings and human wastes has attracted the interest of the Egyptian scientists because of the numerous benefits realized from it. Biogas technology provides a clean and convenient fuel for cooking, lighting and generation of electricity [2].

Many researchers studied the influence of different factors on the biogas production process in order to optimize its yield. Sarapatka [3], Kalia and Kanwar [4] as well as Kalia and Singh [5] concluded that, the ambient temperature has a controlling effect on all performance parameters, such as biogas quantity and methane percentage. They stated that these parameters can be enhanced by the increase of the ambient temperature to about 35 °C. Cecchi et al. [6] conducted an experimental work under mesophilic and thermophilic conditions. Their results showed that the semi-dry thermophilic process (about 20% TS feed), for retention times greater than 11 days assures 100% higher methane production with respect to the mesophilic conditions, and for retention time up to 8 days the methane production became 200% higher in thermophilic conditions. Hammad et al. [7] designed and constructed an experimental setup to produce biogas by using four different animals manure and two different plant wastes under ambient conditions (temperature range [16- 44 °C]). The results showed that both the biogas quantity and methane percentage increased as the ambient temperature was kept at the optimum temperature of about 35 °C. Hejnfelt and Angelidaki [8] accomplished an experimental investigation to study the anaerobic digestion of pig's by-products in batch and semi-continuously fed reactors under thermophilic and mesophilic temperatures. They indicated that mesophilic temperatures are preferable for digestion of animal by-products, while thermophilic digestion resulted in lower yields due to higher ammonia. Al-Masri [9] studied the biogas production for eight experimental groups of fermentation media containing different ratios of animal wastes (sheeps and goats faeces) to olive cake. The results suggested that the gas production decreased significantly with increasing the amount of olive cake in the fermentation media containing either sheeps or goats wastes. Uzodinma et al. [10] conducted an experimental investigation to reveal the effect of adding some organic wastes such as palm oil sludge, soybean cake waste, powdered rice husk and pig dung to carbonated soft drink sludge on the biogas yield. The results of this research indicated that, the low yield of flammable biogas from carbonated soft drink sludge could be enhanced significantly when blended with either soybean cake waste or pig dung. Uzodinma et al. [11] presented an experimental investigation to study the biogas production rate from equal blending of field grass (F-G) with some animal wastes, which include cow dung (G-C), poultry dung (G-P), swine dung (G-S) and rabbit dung (G-R). The results of reference [11] showed fastest onset of gas flammability from the (G-R) followed by the (G-C) blends, while the highest average volume of gas production from (G-R) blend was 3 times higher than that of (F-G) alone. Lastella et al. [12] carried out an experimental investigation to evaluate the effects of using different bacteria inoculums on the anaerobic digestion (AD) process for orthofruit waste where the results showed that recycling of digested sludge improves both the biogas production and its methane content.

The purpose of this paper is to present the effect of the operating temperature and the type of organic waste on the biogas production for lab-scale anaerobic digesters.

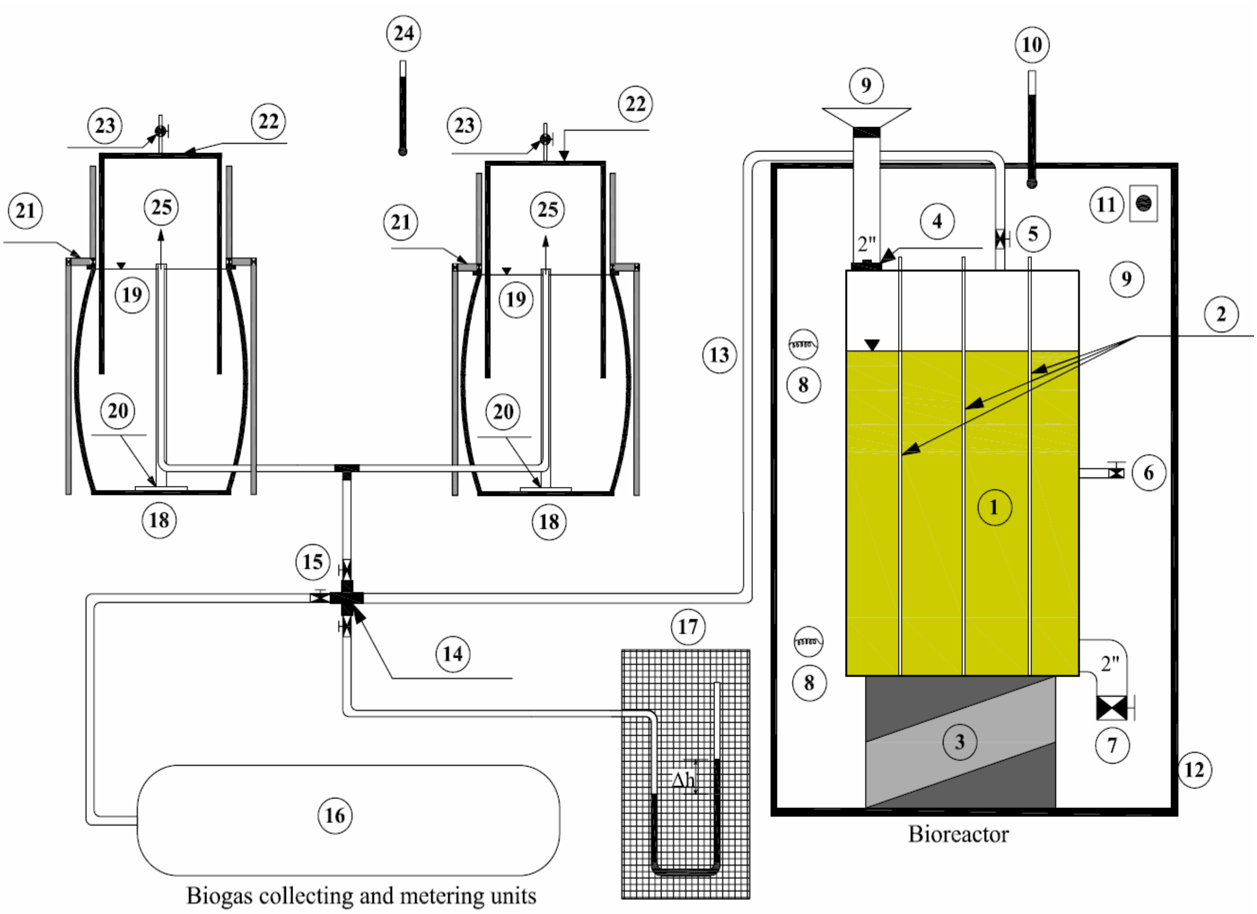
2. EXPERIMENTAL SET-UP AND PROCEDURE

2.1 Experimental Set-Up

The experimental work for this study has been performed using laboratory scale set-up manufactured and assembled at the department of Mechanical Power Engineering, Faculty of Engineering, Menoufiya University at Shebin El-Kom, Egypt. The set-up comprises three similar biogas production units. Each unit consists of a wood chamber containing the anaerobic batch-fed biogas digester, gas collecting and metering units and piping system to transfer the gas from the digester to the collecting units. The details of the experimental biogas production unit are given in Fig (1). As shown in this figure, the barrel formed digester with 240 liter volume is equipped with the necessary openings and valves for feeding, drainage and slurry sampling.

The new feature in the design of the digesters is the use of three internal vertical metal rods extended along the digester and fixed at its top. These rods have two functions. The first one is to collect the methanogenic bacteria responsible for activating the process of biogas production. The second function of these rods is breaking the scum layer when shaking the digester. The gas collecting and metering units consist of an approximately 150 liter rubber tire-tubes connected parallel with floating cap collecting tanks of 120 liter maximum volume. The piping system is plastic hoses with suitable valves and connectors to transfer the produced gas from the digester to the gas collecting and metering unit. As mentioned above each digester is installed in thermally insulated (1×1×1.5) m wood chamber. The chamber is equipped with 1000-Watt electric heaters, analog thermostat to achieve the desired temperature. The chamber temperature is measured with a mercury thermometer; meanwhile the gas pressure is measured with a U-tube manometer.

The digester temperature control system is used to enable conducting experiments under different digestion modes during the same retention time. The first digester is kept under thermophilic condition (55 ± 2 ºC), the second is kept under mesophilic condition (40 ± 2 ºC) while the third operates under the ambient condition.



1. Organic wastes
2. Three metal rods
3. Base
4. Manhole for input slurry
5. Gas valve (1/2")
6. Slurry sampling valve(1/2")
7. Drainage valve
8. Heater
9. Plastic funnel
10. Thermometer (T_{op})
11. Thermostat
12. Wood chamber
13. Plastic hose
14. Four way junction
15. Gas valves (1/2")
16. Rubber tire-tube
17. U-tube manometer
18. Expansion tank (120 L)
19. Water
20. Vertical support
21. Strong frame to guide the floating tank
22. Graduated collecting floating tank of 60 L (tot. vol.)
23. Gas valve (1/4")
24. Thermometer (T_{amb})
25. The biogas exit

Fig.1 The general arrangement of the layout of one of the biogas reactors

Experiments have been done on three types of organic wastes. The used waste types are pure cattle manure, cattle manure mixed with rice straw and cattle manure blended with hen manure. The bacteria required for acid formation and methane fermentation are present in the fresh animal manure but with low numbers. Therefore artificial seeding with the digested sludge rich in methanogenic bacteria is essential for fast activation of the anaerobic digestion process [19]. For this reason, about 10% of the digester charge for each test run was taken from the previous test run which is called digested sludge (inoculums).

After achieving the operating conditions, the digesters are fed with the prepared slurries and then the inlet openings are tightly closed to prevent gas leak.

2.2 Instruments and Measuring Devices

The following tools and measuring devices were used
1- U-tube manometers for each bioreactor for measuring gas pressure in the expansion tanks.
2- 100 kg balance (of deviation ± 100 gram) was used for weighting organic waste samples.
3- 7 kg electronic balance (of deviation ± 0.5gram) was used to weigh the sample of slurry withdrawn from the digesters.

4- Pocket-sized pH meter (HI98103 checker, ± 0.1 pH of deviation) for measuring slurry acidity.
5- Seven plastic barrels (60 liters) for preparing and mixing wastes.
6- Compressor of (245 W) to withdraw biogas from the collecting units and pressurize it into a 100 liter gas cylinder to store biogas.

2.3 Experimental Measurements

The daily measured and recorded parameters are; the volume of the produced gas, the gas pressure, the ambient temperature, pH value and total solid content (TS %).

2.4 Experimental Test Runs

Three test-runs were carried out on the waste combinations given in table (1) for 31 days of retention time for each run. For each run, the three digesters were fed with the same mixture of wastes but each digester operates under different operating temperature.

3. RESULTS AND DISCUSSIONS

3.1 Effect of Digestion Temperature

As stated in most references, operating temperature is considered as one of the most important factors affecting anaerobic digestion. Anaerobic digestion can basically occur under mesophilic mode (32-40 °C), thermophilic mode (45-60 °C) or psychrophilic mode (<20 °C). As mentioned previously, this study has been done to investigate the biogas production process under these three possible digestion modes named thermophilic, mesophilic and ambient condition. Thermophilic anaerobic bacteria have some advantages over mesophilic anaerobes because thermophilic species grow at faster rates and some of them are able to degrade polymers such as cellulose and starch by the secretion of cellulolytic enzymes. As a result, better conversion of waste to biogas is achieved. In addition, thermophilic processes have shorter hydraulic retention times due to the high degradation rate. Additionally, sanitation of the digested sludge is achieved due to the reduction in pathogens caused by high temperature [13].

Figure (2) shows the daily biogas yield for the three digesters during the first test run carried out using pure cattle manure during the period from 10/1/2011 to 9/2/2011. Each of the three digesters operates under one of the pre-mentioned digestion modes. From the figure it can be noticed that the total biogas yield of thermophilic mode (1292 liter) is higher than that given by mesophilic mode (1243 liter). This result agrees with that obtained by Hammad et al. [7]. The ambient mode of the same run gives lower total biogas yield (362 liter). In addition, the peak value of biogas yield for thermophilic mode (85 liter) occurred four days before the peak value for mesophilic mode (66 liter) that can be attributed to the short of retention time because of the high digestion temperature. Another peak of the daily gas yield is shown for mesophilic mode during the 28^{th} and 29^{th} days which could be reasoned due to the increase in the operating temperature to 50 ºC due to temporal technical fault in the thermostat.

Figure (3) shows the daily biogas yield under the different digestion modes for the second test run, which was carried out within the period from 8/3/2011 to 7/4/2011, using cattle manure mixed with rice straw as organic waste. From this figure it can be noticed that thermophilic mode gives the highest total gas yield (2224 liter) followed by mesophilic mode (2089 liter), and the ambient mode comes in the last position (444 liter). Also, these results are consistent with that obtained by Hammad et al. [7] as mentioned above. Moreover, it can be observed that from Fig .3, the daily biogas yield increases gradually for ambient mode at the end of HRT (at day 26). This may be due to the delay in the fermentation process of the used feedstock used mixture, which contains high lignin ratio (8-12%) under lower temperatures [14] leading to low biodegradability under anaerobic conditions as stated by [13].

The obtained daily biogas yields for the three digesters during the third test run (17/4/2011-17/5/2011) are given in figure (4). From the figure it can be observed that thermophilic mode gives higher yield of biogas (5755 liter) than mesophilic mode (3185 liter). These results have the same trend as the last described above two runs; i.e. the biogas yield in thermophilic mode is always higher than that of mesophilic mode. The biogas yield for the ambient mode for this test run is relatively higher than that for the preceding test runs (2325 liter) which can be ascribed due to the higher ambient temperature ranging between 20 ºC to 37 ºC during the 3^{rd} run.

Table 1, The wastes combination ratios for the three test run

Materials		Cattle manure	Rice straw	Hen manure	Digested sludge	Water
Ratio %(v/v)	Run 1	40	0	0	10	50
	Run 2	30	3	0	10	57
	Run 3	22	0	8	11	59

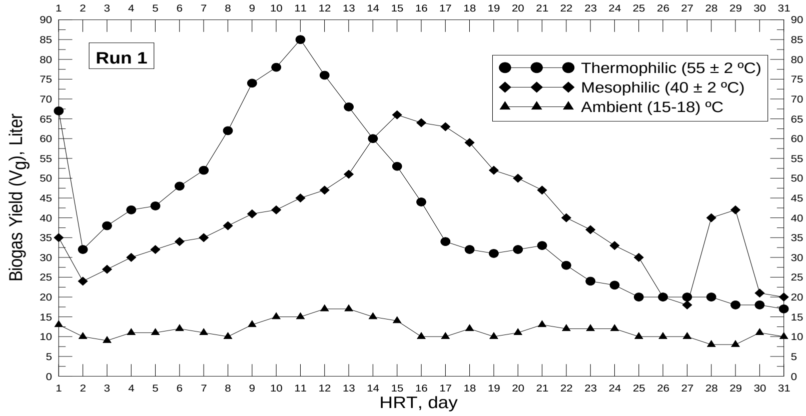


Fig.2 Daily biogas yields in liters at 6mm of average head pressure (Δh) for different digestion modes during 31 day of HRT for Run 1

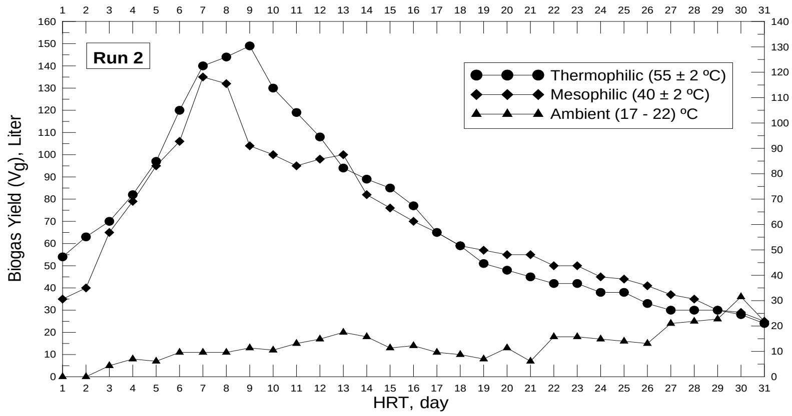


Fig.3 Daily biogas yields in liters at 9mm of average head pressure (Δh) for different digestion modes during 31 day of HRT for Run 2

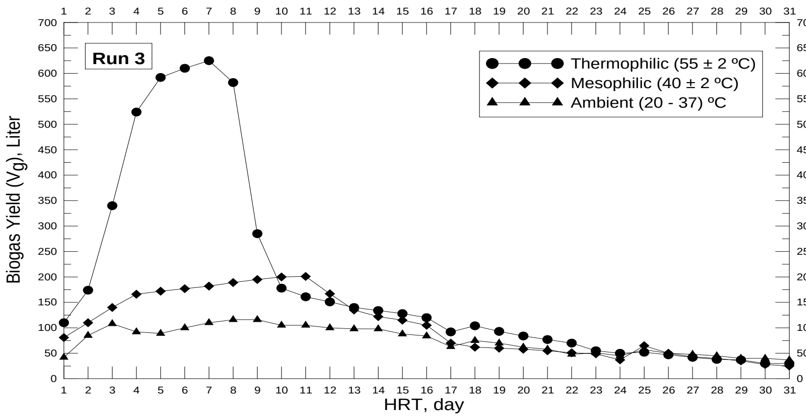


Fig.4 Daily biogas yields in liters at 20mm of average head pressure (Δh) for different digestion modes during 31 day of HRT for Run 3

3.2 PH Value for the Different Digestion Modes

The allowable pH value for biogas production is in the range of 6.6 and 7.6. The pH in the anaerobic digester is a function of the bicarbonate alkalinity of the system, the fraction of CO_2 in the digester gas and the concentration of VFA. The pH may decrease when organic acids are produced during the breakdown of organic materials. When acid forming bacteria and the methanogenic bacteria are present in an equilibrium reaction, the pH of the entire system will equilibrate at a value of approximately 7, since the organic acids will be removed as they are produced [15]. Alkalinity plays an important role in reactors' stability as its buffer capacity maintains the pH at appropriate levels. Long chain fatty acids (more than eight carbons), which are the components of natural fats, are strong inhibitors of methanogenesis from acetate [13]. A slightly alkaline mixture is best for digesters using animal manures or plant wastes.

Table (2) gives the measured pH values for each test run. From this table, it can be observed that all pH values are almost higher than 7, which means that all slurries are alkaline due to existence of cattle manure which contain high ammonia concentration but below the inhibition limit (150 mg/L) [13]. As shown in table (2) the thermophilic mode, which gives the highest biogas yield has pH value more than 8. This may be due to the increased ammonia generation in thermophilic digestion [8]. For mesophilic and ambient modes pH values are lower than thermophilic mode due to lower temperatures for each mode of (40 ± 2 ºC) and (15 – 37) ºC, respectively. Also, it can be observed that, the optimum values of pH are ranging between (8.1 – 8.51) for thermophilic mode while its optimum values are ranging between (7.11 – 8.24) for each of mesophilic and ambient modes.

3.3 Effect of the Type of Organic Waste

It is well known that biogas production rates depend on the composition and biodegradability of the feedstock as well as the digestion temperature as mentioned earlier. Carbon to nitrogen ratio (C/N) is the main parameter widely used to estimate the biodegradability potential of a particular feedstock. Based on biodegradable organic carbon, C/N ratio of 20-30 is considered to be optimum for an anaerobic digester [17]. Animal waste, such as cattle manure, has an average C/N ratio of 24. Meanwhile hen manure and rice straw have C/N ratios of 10, 70 respectively [18]. To maintain the C/N level of the digester material at acceptable levels, materials with high C/N ratio can be mixed with those with a low C/N ratio. The TS content for the used input slurry varies with the type of manure, handling system and mixing ratio. Hen manure has (10 – 30%) TS while, TS for cattle manure ranges between 5 - 12% depending on dilution [16]. Some bedding materials like rice straw (high lignin content) are very resistant to degradation and may require pre-treatment to enhance degradability [15] and therefore; a pretreatment was performed for the used rice straw in the second run by placing it in water for one week before feeding to ease the fermentation process. Table (3) shows the sample compositions and its initial total solid content %TS for each test run. The daily biogas yields for each digestion mode of the three test run are illustrated in the figures (5, 6 and 7). These figures give the effect of feedstock type on the biogas yield for each digestion mode.

Table 2, Measured pH values with respect to peak value of biogas yield for each digestion mode through each test run

Test Runs		Before Peak Value	At Peak Value	After Peak Value
Run 1	Thermophilic	7.4 - 8	8.1	8.12 – 8.33
	Mesophilic	7.5 – 7.62	7.5	7.76 – 8.36
	Ambient (15-18 °C)	7.58 – 7.7	7.11	7.7 – 7.92
Run 2	Thermophilic	7.1 – 8.4	8.51	8.21 – 8.64
	Mesophilic	7.2 – 7.41	7.92	8 – 8.32
	Ambient (17-22 °C)	7.2 – 7.88	7.48	7.42
Run 3	Thermophilic	7.12 – 8.12	8.24	8.26 – 8.51
	Mesophilic	6.91 – 8.13	8.24	8.4 – 8.69
	Ambient (20-37 °C)	7.2 – 7.5	7.63	7.77 – 8.08

Table 3, Samples compositions and its total solid content for each test run

	ITS %	Cattle manure	Rice straw	Hen manure	Digested sludge	Water
Run 1	24.44	40	0	0	10	50
Run 2	7.34	30	3	0	10	57
Run 3	9.4	22	0	8	11	59

From these figures, it can be noticed that the third test run gives higher daily biogas yield for all digestion modes meanwhile; the first run comes at the last stage. It is stated that, the optimum value of the total solid content of the input slurry ranges between 8 to 10% [19]. Based on this statement, it could be concluded that the main reason that the third test run gives the highest biogas yield at its initial %TS value (9.4%) located within the optimum range. There is another reason for the increased biogas yield in the third test run; is to the co-digestion for the input slurries as the use of a co-substrate improves biogas yield due to the supply of essential nutrients by the co-substrates, which reduces process inhibition and enhances biodegradability [20].

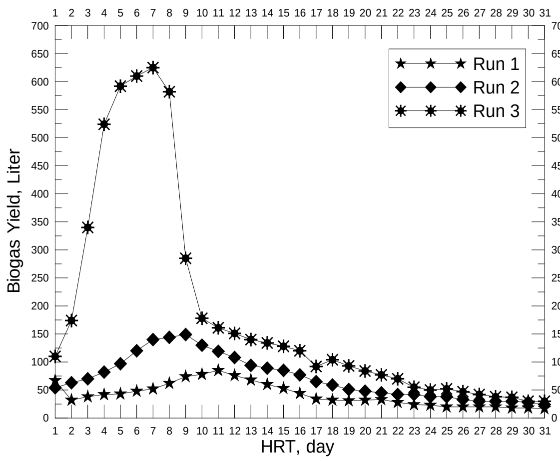


Fig.5 Biogas yields in liters at thermophilic condition (55 ± 2 ˚C) for each test run

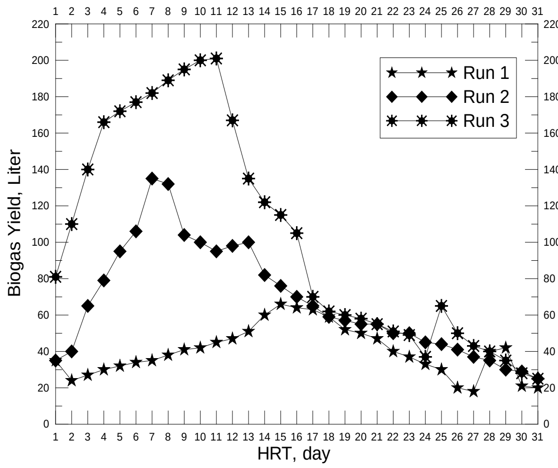


Fig.6 Biogas yields in liters at mesophilic condition (40 ± 2 ˚C) for each test run

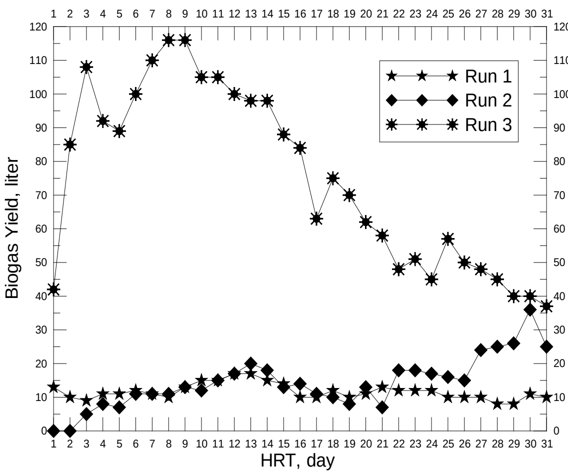


Fig.7 Biogas yields in liters at ambient condition (15 – 37 ˚C) for each test run

4. CONCLUSIONS

Biogas production from organic wastes could be enhanced by controlling the operating conditions such as temperature and the type of organic waste in its optimum values. The following statements could be concluded from the current study:

1. Thermophilic mode gives the best biogas yield for the used organic wastes.
2. Thermophilic mode is more suitable for anaerobic digestion of the high solid organic wastes than mesophilic mode although thermophilic mode leads to increaseing pH values due to higher ammonia content.
3. The optimum value of pH is about 8.24 for thermophilic mode while it is about 7.92 for mesophilic mode.
4. The co-digestion and mixing substrates can lead to higher biogas yield.
5. Total solid content is an important factor for anaerobic digestion.
6. Adding digested sludge can accelerate the anaerobic reaction and enhance the biogas yield.

Nomenclature

COD chemical oxygen demand (mg/l)
HRT hydraulic retention time (day)
ITS initial total solid (%)
OTS organic total solid (kg)
T_{op} operating temperature (°C)
T_{amb} ambient temperature (°C)
TS total solids (%)
v/v the percentage of waste volume in the total slurry (%)
V volume (liter)
VFA volatile fatty acids (mg/l)
VS volatile solid (gm)
Δh pressure head (mm)

Abbreviations

AD Anaerobic Digestion
C/N Carbon to Nitrogen ratio
COD Chemical Oxygen Demand
MSW Municipal Solid Waste
OFMSW Organic fraction of municipal solid waste
pH Acidity degree value

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