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Anaerobic Co-Digestion of Mixed Sewage Sludge with Organic Fraction of Municipal Solid Waste

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ملخص البحث

تعتبر معالجة حمأة الصرف أحد المشاكل البيئية الحالية نظرا لتكلفتها العالية. حيث إنه غالبا ما يتم التخلص من هذه الحمأة قبل معالجتها بصورة صحيحة. وأحد حلول هذه المشكلة هو زيادة العائد من عملية معالجة الحمأة . وحيث إن عملية الهضم اللاهوائى وهى أحد مراحل معالجة الحمأة ينتج عنها غاز الميثان والذى يمكن إستخدامه كمصدر للطاقة. فبتحسين كفاءة عملية هضم الحمأة تزداد كمية الغاز المنتجة. وتتحسن كفاءة عملية الهضم اللاهوائى لحمأة الصرف بإضافة مواد أخرى عضوية مع الحمأة . وفى هذا البحث تم دراسة تأثير إضافة الجزء العضوى من المخلفات الصلبة المنزلية إلى نوعين مختلفين من حمأة الصرف أحدهما حمأة منتجة من محطة معالجة تستخدم نظام الحمأة المنشطة والأخرى منتجة من محطة معالجة تستخدم نظام المرشحات الزلطية. وتم عمل نسب خلط مختلفة لهذه الأنواع من الحمأة مع المخلفات الصلبة العضوية مرة بإستخدام حمأة مهضومة مع الخليط فى البداية ومرة أخرى بدون إستخدام حمأة مهضومة. وتراوحت نسبة المخلفات الصلبة فى الخليط من 0:80 % بناء على كمية المواد المتطايرة. فتم عمل 24 خليط قسموا على مرحلتين كل مرحلة تحتوى على عدد 6 إختبارات من مصدر الحمأة الأول وعدد 6 إختبارات أخرى للمصدر الثانى. وتم إجراء إختبار إنتاج الميثان بنظام الدفع على كل هذه النسب والأنواع المختلفة. حيث تبين أن نسبة الخلط 60% حمأة : 40% مخلفات صلبة هى النسبة المثلى فى إنتاج الغاز فى كلا نوعى الحمأة المستخدمين. إلى جانب أنها حسنت من نسبة الكربون /النيتروجين للخليط الناتج بعد عملية الهضم وبالتالى زيادة كفاءته كسماد عضوى. كما تبين أن عملية الخلط هذه تكون اكثر كفاءة فى حالة الحمأة المنشطة.

Abstract

Co-digestion of two different sewage sludge (SS) -trickling filter humus and activated sludge- with the organic fraction of the municipal solid waste (OFMSW) were evaluated by using bio methane potential (BMP) test in two stages. The inoculum / substrate ratio at the first stage was 1:1, while the second stage was carried out without inoculum. For the two used sludge types mixing ratio of SS: OFMSW ranged from 100:0 to 20:80 % as volatile solid (VS) ratio. The amount of gas produced was measured continuously and accumulatively graphed to get the optimum ratio of mixing. The Co-digestion of SS and OFMSW showed more effective results with the activated sludge than the trickling filter humus. When mixing activated sludge with solid waste, the optimum ratio of mixing was 60:40 % at which the gas production increased in stage 1 by 17 % more than that using activated sludge only and by 27 % in stages 2, and with a rate of 0.79 dm^3/gm VS destroyed that was twice the rate of sludge model only. Also this mixing ratio enhancing the carbon/nitrogen (C/N) ratio of the digested sludge by 27 %. As for the trickling filter humus, this ratio achieved an increase of 8% in the gas production and improved the C/N ratio by 21% in stage 2.

Key words: Anaerobic digestion, Biomass, BMP, Methane production, and Solid waste.

1. Introduction

Sewage sludge is a mixture collected or produced during the different stages of wastewater treatment processes. This mixture consists of several components, some of which are organic substances with a fertilizer value and some are pollutants and pathogens. Although the amount of this mixture represents only 1:2% of the amount of wastewater, the treatment of this mixture is a major environmental problem in many countries due to its high cost [1]. The management costs of sludge treatment are usually ranging from 25% to 65% of the total operating costs of the waste water treatment plant (WWTP) [2]. As the quantities of generated sludge increase, the environmental risks resulting from not being treated or incorrectly disposed increase. In 2012, the estimated amount of sewage sludge generated in Egypt, according to annual report for solid waste management in Egypt, 2013 (ARSWME 2013) is 3 million tons of sewage sludge with an average of more than 8200 tons per day [3].

On the other hand, solid waste management remains a major concern in Egypt from environmental and health perspective and has become a major concern for the sustainability of the country's development. The disposal of this wastes is a growing problem with population growth and industrialization, making it a stark problem. According to ARSWME 2013, Egypt generated 21 million tons of municipal solid waste in 2012 [3]. These 21 million containing 56% organic matter, so exploitation of this waste by reusing, recycling or energy recovery is better than direct landfilling.

Anaerobic digestion of sludge is considered to be one of the most important processes in sludge treatment technologies which could produce CH_4 gas that can be used as a source of energy. In light of the global energy crisis, anaerobic digestion of solid waste is a very effective way of reducing the severity of this crisis. It is distinguished from the other methods of disposal of waste by producing energy, in addition to preserving the environment and human health from the negative effects of other methods [4]. Typically the gas produced which contains about 65 – 70% CH_4 from anaerobic digestion of sludge is about 0.75 – 1.12 m^3/kg of volatile solids destroyed [5]. Unfortunately, the volatile solids destruction in the conventional mesophilic anaerobic process is about 40% at retention times ranged between 30 and 40 days (The major percent of solids still unexploited). So increasing the percent of readily biodegradable solids in sludge by mixing it with the organic fraction of municipal solid waste could enhance the degradation ratio of volatile solids and hence increase the amount of the produced gas. As the amount of the produced gas increased, the energy generated from it is optimized and the total cost of operation reduced. In addition, digestion of different organic wastes in the same reactor improves the anaerobic digestion process according to [6-7]. On the other hand, consume a fraction of the municipal solid waste in the co-digestion of sewage sludge could contribute to the preservation of the environment and public health and exploitation of this waste. Many studies have been done in studying co-digestion of sludge with different types of solid waste [7-10], and different conditions to increase the amount of gas produced [11-14].

The present study aims to investigate the rate of gas production obtained from the anaerobic digestion process by mixing the sewage sludge with organic fraction of municipal solid wastes, and study the effectiveness of this mixing process with more than one type of sewage sludge. In addition, the reduction and disposal of the solid waste in a healthy useful way.

2. Experimental model

During this study 24 bio-methane potential (BMP) tests were used at two stages. Each stage consisted of 12 digesters divided into two equal lines depending on sludge type. Two types of sludge were used as a substrate with solid waste. The first type was from a trickling filter humus source (T.F sludge) defined by symbol “A”, and the second was from an activated sludge source (A.T sludge) defined by symbol “B”. All types of sludge (T.F, A.T and the inoculum) were subjected to thickening process for 12 hrs prior to use in laboratory experiments to increase the concentration of total solids and reduce sludge volume used in each experiment. Table (1) shows the properties of the used sludge and solid waste respectively. The first stage was run using a digested sludge as inoculum with inoculum/substrate ratio equal to 1.0 g VS: 1.0 g VS. It was selected as a mean ratio between 0.5 and 2.3 g VS/ g VS to avoid acidification phenomena according to Neves [15]. The second stage was run without inoculum (only a mix of sludge & solid waste). Tables (2-a) & (2-b) show the mixing ratios of SS: OFMSW and quantities for each stage based on VS value. Every line`s ratios (6 digesters) were 100:0 – 80:20-60:40 -50:50 -40:60- 20:80 as a VS. All 12 digesters were placed in the same water bath (Reactor), shaken manually & mechanically and immersed up to half of their height in the hot water path which was kept at a constant temperature of 35 ±2°C. Figure (1) shows schematic diagram for the used model. Each BMP test was performed under controlled conditions in a 1000 mL glass bottle. Each bottle was partially filled (0.5:0.67 of total volume) with inoculum and substrate, according to a ratio depend on their VS content. Tap water was added to the digesters to have the same volume. Where the size of the mixture in each model in the first stage was 550 ml and in the second stage was 660 ml. Each bottle was sealed tightly using silicone cap and connected by a tube to a 2500 mL glass bottle. The produced gas replaced the water in the 2500 ml bottle moving it to 1000 ml graduated cylinder at where the gas produced volume was measured (as equivalent of the replaced water).

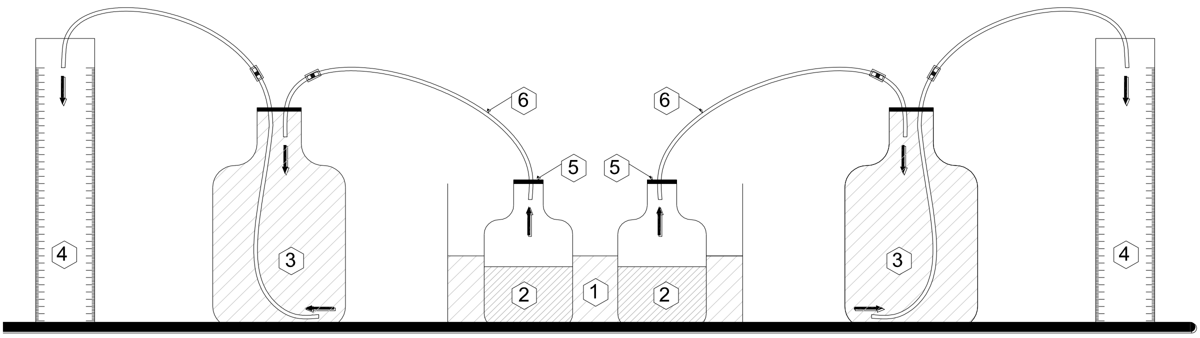


Figure (1) Schematic diagram for the used model

Where:

[1] Water bath (half filled with water at 35 ± 2 ºC)
[2] 1.0 L Digester (partially filled with substrate mixture & inoculum)
[3] 2.5 L Bottle (completely filled with water for gas replacement)
[4] 1.0 L Graduated cylinder (for measuring replaced water)
[5] Silicone cap
[6] Connection tube with control valve

Table (1) Properties of the used sludge and solid waste

Parameter	Unit	Stage 1				Stage 2		
		Trickling filter humus	Activated sludge	Inoculum	Solid waste	Trickling filter humus	Activated sludge	Solid waste
pH-value	---	6.5	7.28	7.6	---	6.75	7.1	---
Chemical oxygen demand COD	mg/l	50000	40000	32000	---	38000	32000	---
Volatile fatty acids VFA	mg/l	1659.03	545.9	343.28	---	1112.72	530.83	---
Water content W/C	%	94.47	96.12	96.19	5.6	94.84	98	2.92
Total solids TS	mg/l	52450	19950	34900	944.04*	49470	33950	971*
Volatile solids VS	mg/l	38450	15630	20900	374.65*	37980	23500	349.5*
VS/TS	---	0.73	0.78	0.6	0.4	0.77	0.69	0.36

* This value was in (mg/g)

Table (2-a) Mixing ratios and mixing quantities of SS & OFMSW for stage 1.

Stage 1		Substrate : inoculum ratio = 1.0 g VS : 1.0 g VS, volume =550 ml					
Model	SS : OFMSW ratio	Total substrate = 6.00 g VS				Total inoculum = 6.00 g VS	
		Undigested sludge		Solid waste		Digested sludge	
		VS g	Vol. ml	VS g	Wt. gm	VS g	Vol. ml
A1	100 : 0	6.00	156.05	0	0	6.00	287.08
A2	80 : 20	4.80	124.84	1.20	3.20		
A3	60 : 40	3.60	93.63	2.40	6.41		
A4	50 : 50	3.00	78.02	3.00	8.01		
A5	40 : 60	2.40	62.42	3.60	9.61		
A6	20 : 80	1.20	31.21	4.80	12.81		
B1	100 : 0	6.00	255.32	0	0	6.00	287.08
B2	80 : 20	4.80	204.26	1.20	3.20		
B3	60 : 40	3.60	153.19	2.40	6.41		
B4	50 : 50	3.00	127.66	3.00	8.01		
B5	40 : 60	2.40	102.13	3.60	9.61		
B6	20 : 80	1.20	51.06	4.80	12.81		

Table (2-b) Mixing ratios and mixing quantities of SS & OFMSW for stage 2.

Stage 2		No "inoculum", total volume = 660 ml			
Model	SS : OFMSW ratio	Total substrate = 10.00 g VS			
		Undigested sludge		Solid waste	
		VS g	Vol. ml	VS g	Wt. gm
A1	100 : 0	10.00	263.30	0	0
A2	80 : 20	8.00	210.64	2.00	5.72
A3	60 : 40	6.00	157.98	4.00	11.44
A4	50 : 50	5.00	131.65	5.00	14.31
A5	40 : 60	4.00	105.32	6.00	17.17
A6	20 : 80	2.00	52.66	8.00	22.89
B1	100 : 0	10.00	639.80	0	0
B2	80 : 20	8.00	511.84	2.00	5.72
B3	60 : 40	6.00	383.88	4.00	11.44
B4	50 : 50	5.00	319.90	5.00	14.31
B5	40 : 60	4.00	255.92	6.00	17.17
B6	20 : 80	2.00	127.96	8.00	22.89

All the measurements were measured according to APHA standard methods.

3. Results and discussion

3.1. Stage 1:

3.1.1 Gas production for stage 1:

Cumulative gas production measurements showed that a significant increase in the amount of gas produced in the first five days of the experiments. After the first five days, the rate gradually began to decrease until gas production stopped after about 65 days. Figures (2-a) & (2-b) show the accumulative gas production of each type of sludge source. The average gas production rate in the first five days ranged from 0.2 to 0.45 dm3/d and from 0.26 to 0.3 dm3/d for T.F and A.T sludge respectively. Then the average rate dropped to less than 0.03 dm3/d for both sludge types in the next 60 days. After that, the average rate was close to zero. This description of the three intervals applies to the reverse L shaped described by Esposito [16]. Figures (2-c) & (2-d) show the gas production rate in three intervals {(0-5), (5-65) and (65-75)} depending on variance of gas produced over time for the same tests. By recalculating the gas production rates in the first five days, but for 1 dm3of the mixture, the maximum rate has become 0.82 dm3 gas/dm3sludge/d. This complies with Sosnowski [7] who conducted -in experiment I- primary and thickened excess activated sludge with initial inoculum in batch process, where the rate of gas produced at the beginning of the experiment increased significantly from the rest of the days, with value of 0.8 dm3/dm3/d in the first 4 days. It should be noted here that the composition of gas in these days was 80% carbon dioxide and 20% methane [7].

By observing the generated gas values for each mixing ratio it has been found that in the case of the T.F sludge type, the final accumulative gas value of all mixtures are less than

the gas value of the individual sludge test (reference model A1) except for model A3 which is almost equal to A1 value. It is also noted that model A5 gave a value much smaller than the value of model A1 and even stopped after about two weeks from the beginning of the experiment. This happens if one of the anaerobic digestion inhibitors (which are collected in [17-18]) is present in this model.
As for the second type of sludge (A.T sludge), all the experiments of different mixing ratios gave higher gas production value than the individual sludge experiment, except for model B6 which gave a relatively lower value (3% decrease) from reference model (B1 which contains 100% sludge). Model B3 gave the highest value for gas production with an increase of 17% over B1 model.

3.1.2 Digested sludge properties for stage 1:

PH values ranges from 7.5 to 7.8 at stage 1. TS reduction % ranges from 17 to 50 % for T.F sludge and from 13 to 23 % for A.T sludge, while VS reduction % ranges from 16 to 54 % for T.F sludge and from 16 to 34 % for A.T sludge. Volatile fatty acids (VFA) values ranged from 6 to 74 mg/l in the case of T.F sludge type and ranged from 3 to 41 mg/l in A.T sludge type with a decrease of up to 99 % in both types. While COD values in T.F sludge type ranged from 18,000 to 28,000 ppm with a reduction of 40 % at maximum, and ranged from 14000 to 31000 ppm in the A.T sludge type with a reduction of 50 % at maximum. Table (3-a) shows the measured parameters at the end of the experiment for all stage 1 models. Rate of gas produced per amount of VS destroyed was calculated for each model in the two stages. The highest rate in the case of T.F sludge was 1.94 dm3gas/ gVS and that was for model A1 while the highest rate of the A.T sludge reached 1.45 dm3gas/ gVS for model B3. Figures (2-e) & (2-f) illustrate these rates and other rates of stage 1.

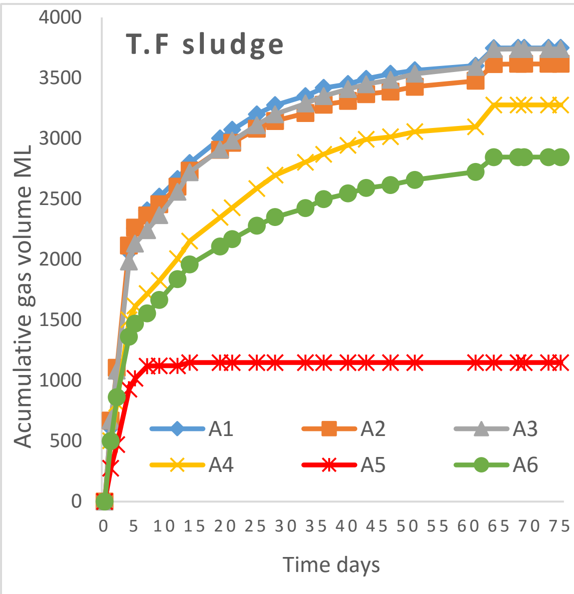


Figure (2-a) Accumulative gas production of T.F sludge source tests at stage 1.

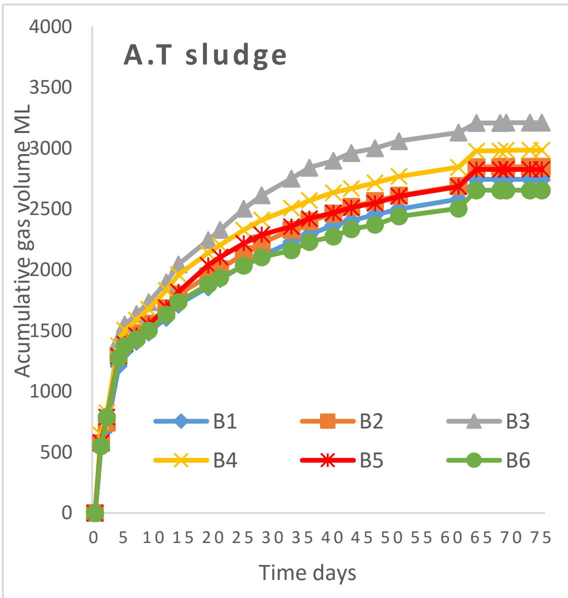


Figure (2-b) Accumulative gas production of A.T sludge source tests at stage 1.

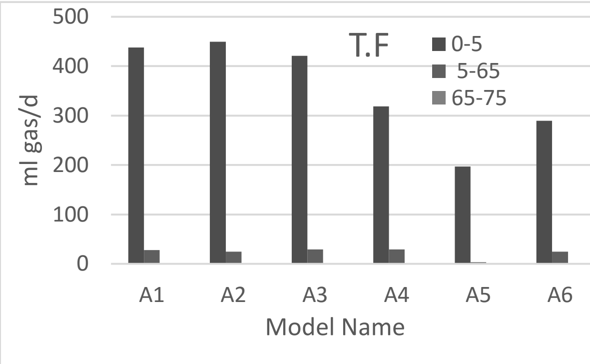


Figure (2-c) Gas production rate of T.F sludge source tests at stage 1.

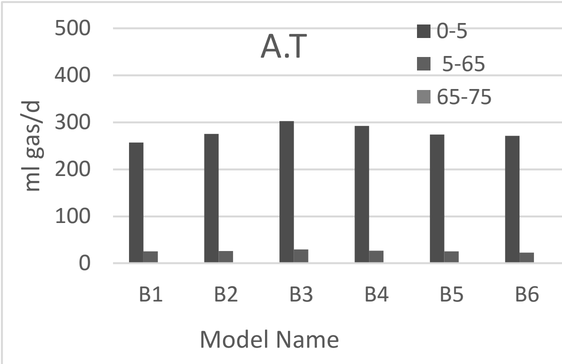
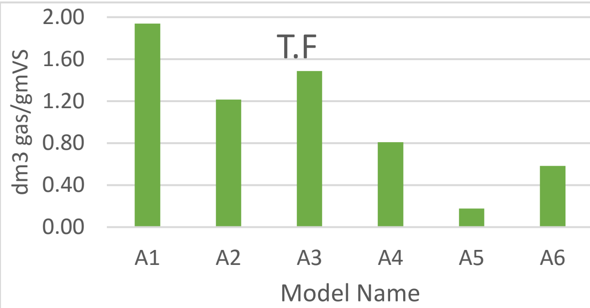
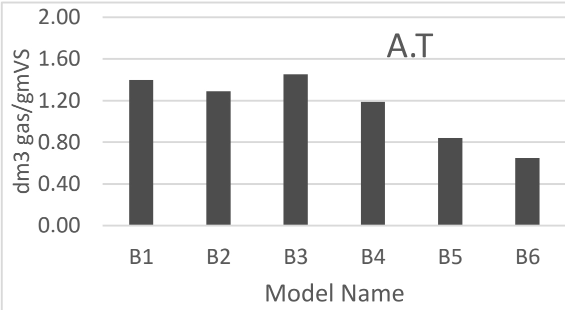


Figure (2-d) Gas production rate of A.T sludge source tests at stage 1.



Figures (2-e) Gas produced / VS destroyed for T.F sludge models in stage 1



Figures (2-f) Gas produced / VS destroyed for A.T sludge models in stage 1

3.2. Stage 2:

3.2.1 Gas production for stage 2:

As for the second stage, which did not contain an inoculum ratio at the beginning. The results of the gas produced in general, unlike the first phase, the gas production rates in the beginning were small. It even began to appear after 3 days in the case of the A.T sludge type. The gas produced rates were small in the first two weeks of the experiment, and then the rates increased significantly in the next two weeks and then dropped again until approaching zero after 70 day. Figures (3-a) & (3-b) show the accumulative gas production of each type of sludge source tests at stage 2. These changes in the rate of gas production over time from small to large and then to very small are finally give a curve on the shape of the letter S and this is what we see in all the experiments of the second stage. This form is also one of two forms (reverse L shaped – S shaped) that can be formed when drawing the amount of gas accumulated over time in anaerobic digestion process as mentioned in [16]. These results are also complies with Sosnowski`s experiment II results, which was conducted a batch co-digestion of sewage sludge (75% vol.) and OFMSW (25% vol.), at which the rate of gas production in the first 6 days was small (0.1dm3/dm3/d) and increased after 3 weeks, to reach 1dm3/dm3/d [7]. Figures (3-c) & (3-d) show the gas production rate in three intervals {(0-15), (15-30) and (30-75)} depending on variance of gas produced over time for the same tests of stage 2. The rates values for the T.F sludge tests in the first interval, they ranged from 0.05 to 0.055 dm3 gas/d except for model A5, which was once again exposed to anaerobic digestion inhibitors. In the second interval, the rates increased from 0.07 to 0.13 dm3/d except, of course, model A5, which stopped producing gas at the end of the first interval. In the third interval, the rates dropped to less than 0.0012 dm3/d. For the final value of gas quantities, model A2 and model A3 gave amount of

gas higher than the A1 model (reference model 100 % sludge) with an increase of 11% and 8%, respectively. For model A3, it was expected to have the highest percentage increase in the amount of produced gas but for a partial obstruction in its connection tubes, its value was slightly reduced but still higher than model A1.
On the other hand, experiments of the A.T sludge type began to produce gas after 3 days at a rate less than the T.F sludge type, and the rate gradually increased. The average values ranged from 0.006 to 0.034 dm3/d in the first interval, and increases in the second interval, ranging from 0.02 to 0.89 dm3/d, and then decreased in the third period, ranging from .005 to .038 dm3/d. Model B1 Unlike other models in stage 2, different behavior was observed on it. Where the gas production rate of it in the third interval was higher than the second interval. In the sense that most of the amount of gas produced for this model came too late for the rest of the models. The gas production rate for other models (except model B5) was almost four times higher than it in the first 30 days of the experiment. As for the model B5, the behavior did not differ significantly from that of the other sludge type (A5). Both of them gave less gas "due to the presence of inhibitors". But the difference between them is that model A5 stopped once the production of gas since the beginning of the second period almost, and the model B5 stopped more than once. For the final value of gas produced quantity, model B3 gave the highest amount of gas with 27% increase higher than B1 model.

3.2.2 Digested sludge properties for stage 2:
PH values ranges from 7.4 to 7.8 at stage 2. TS reduction % ranges from 31 to 65 % for T.F sludge and from 42 to 68 % for A.T sludge. While VS reduction % ranges from 33 to 48 % for T.F sludge and from 28 to 57 % for A.T sludge. VFA values ranged from 24 to 118 mg/l in the case of T.F sludge type and ranged from 28 to 253 mg/l in A.T sludge type with a decrease of up to 95% in both types. While COD values in T.F sludge type ranged from 10000 to 13000 ppm with a reduction of 32 % at maximum, and ranged from 13000 to 18500 ppm in the A.T sludge type with a reduction of 66 % at maximum. Table (3-b) shows the measured parameters at the end of the experiment for all stage 2 models. As for the values of gas produced per amount of VS destroyed, the highest rate in the case of T.F sludge was 0.98 dm3gas/ gVS and that was for model A2 while the highest rate of the A.T sludge reached 0.79 dm3gas/ gVS for model B3. Figures (3-e) & (3-f) illustrate these rates and other rates of stage 2. Percentages of Carbon (C) and Nitrogen (N) are measured in this stage to calculate C/N ratio which is illustrated in table (4). Of these values, we observe that model A3 has improved the C/N ratio by 27.5 % from model A1, while the model B3 has improved the ratio by 21.6 % from model B1.
In the second stage, the model in figure (1) was modified by adding other parts to allow the measurement of the volume of the total gas and also to measure the volume of the resulting methane by passing the total gas after measuring it to another bottle containing a solution of 5% sodium hydroxide, so that the solution absorbs carbon dioxide gas from the total gas mixture leaves methane, which then displaces a volume of the solution, to be measured in another graduated cylinder. The measured methane ratio at this stage for all experiments was greater than 75%.

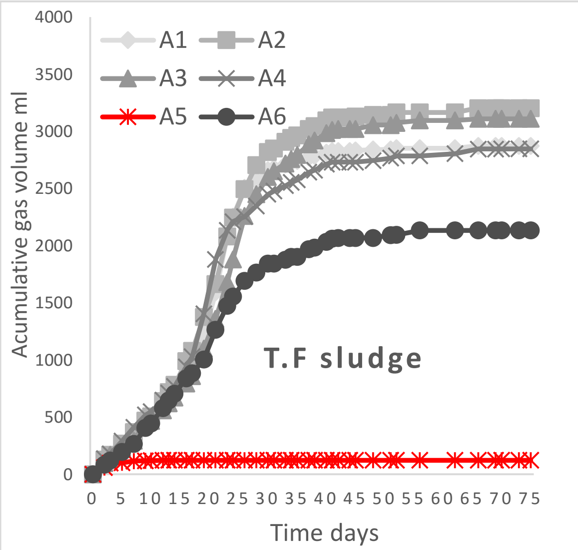


Figure (3-a) Accumulative gas production of T.F sludge source tests at stage 2.

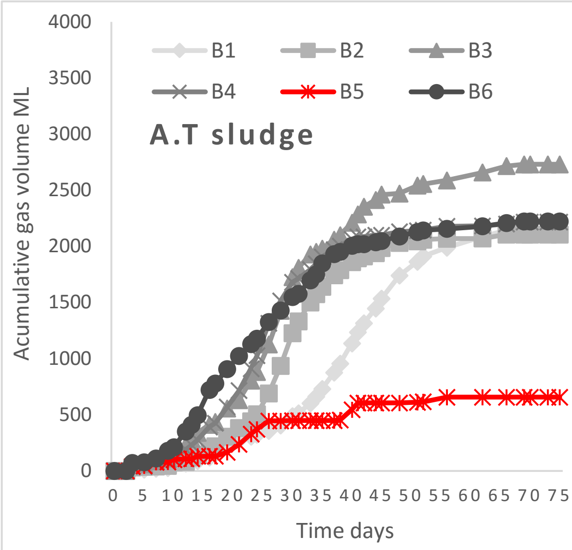


Figure (3-b) Accumulative gas production of A.T sludge source tests at stage 2.

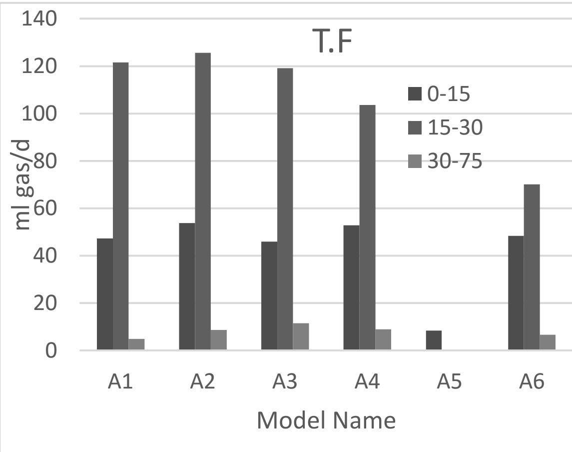


Figure (3-c) Gas production rate of T.F sludge source tests at stage 2.

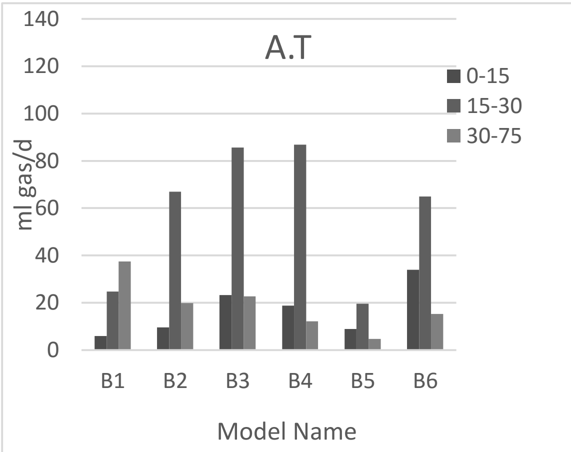
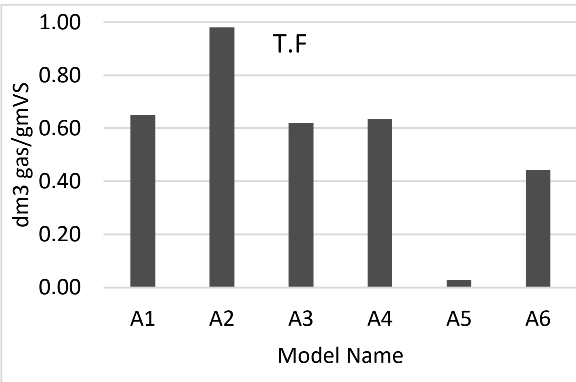
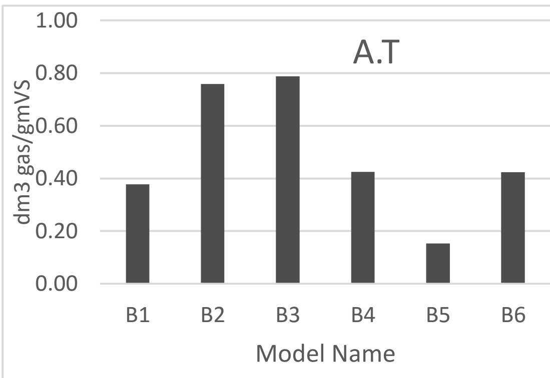


Figure (3-d) Gas production rate of A.T sludge source tests at stage 2.



Figures (3-e) Gas produced / VS destroyed for T.F sludge models in stage 2



Figures (3-f) Gas produced / VS destroyed for A.T sludge models in stage 2

Table (3-a) The measured parameters at the end of the experiments of stage 1.

Stage 1		T.F sludge type models						1 A.T sludge type models					
Parameter	Unit	A1	A2	A3	A4	A5	A6	B1	B2	B3	B4	B5	B6
pH	---	7.8	7.7	7.7	7.5	7.5	7.6	7.6	7.6	7.6	7.5	7.6	7.5
COD	mg/l	24000	26000	28000	18000	28000	21000	29000	31000	29000	28000	27000	14000
VFA	mg/l	73.82	16.24	10.34	9.54	6.09	13.58	4.40	3.40	12.31	4.60	4.35	41.08
W/C	%	96.9	97.2	96.9	97.4	98.1	97.5	96.6	96.6	96.7	96.9	97.8	97.1
TS	mg/l	30250	27900	29100	24100	17850	23950	32250	31950	30150	29700	29200	27300
VS	mg/l	18300	16400	17250	14450	10000	12950	18250	17800	17800	17250	15700	14400
VS/TS	---	0.60	0.59	0.59	0.60	0.56	0.54	0.57	0.56	0.59	0.58	0.54	0.53

Table (3-b) The measured parameters at the end of the experiments of stage 2.

Stage 2		T.F sludge type models						2 A.T sludge type models					
Parameter	Unit	A1	A2	A3	A4	A5	A6	B1	B2	B3	B4	B5	B6
pH	---	7.58	7.44	7.38	7.38	7.38	7.41	7.44	7.76	7.48	7.44	7.41	7.41
COD	mg/l	13000	13000	12500	11000	10000	10000	13000	18000	18500	16000	14000	13000
VFA	mg/l	24.2	32.2	69.5	117.8	109.2	112.4	28.1	52.9	91.1	250.4	245.4	253.4
W/C	%	98.6	98.5	98.8	98.6	98.5	98.7	99.0	98.6	98.6	99.4	98.6	98.8
TS	mg/l	13600	15050	11350	14200	14800	13200	10000	13750	14050	12950	14200	12000
VS	mg/l	8450	10200	7550	8350	8550	7850	6550	10950	9900	7250	8650	7200
VS/TS	---	0.62	0.68	0.67	0.59	0.58	0.59	0.66	0.80	0.70	0.56	0.61	0.60

Table (4) Values of C/N ratio for digested sludge of stage 2 models.

Parameter	A1	A2	A3	A4	A5	A6	B1	B2	B3	B4	B5	B6
3 C %	30.41	32.79	35.13	34.74	41.7	34.84	33.76	32.64	40.59	19.47	25.95	32.24
N %	2.97	2.81	2.7	3.4	3.1	3.17	3.84	3.89	3.79	3.66	3.46	3.64
C/N	10.24	11.67	13.01	10.22	13.45	10.99	8.79	8.39	10.71	5.32	7.50	8.86

4. Conclusions

All curves of stage one are closer to reverse L shaped while curves of stage two are closer to S shaped. TS &VS reduction % in stage 2 is higher than reduction % of stage 1. Gas produced amount in stage 1 is higher than stage 2, and this has been attributed to the fact that using an inoculum value at the beginning of stage 1. However, the methane ratio in the second stage is higher than the first stage. Gas produced in T.F sludge tests is higher than gas produced of A.T sludge tests, and this is normal due to the high biodegradability of T.F humus sludge. Co digestion of SS & OFMSW shows more effectiveness with the A.T sludge type. Generally, for both types of sludge the optimum mixing ratio is 60% SS: 40% OFMSW in gas production and C/N ratio improvement as a good fertilizer. On the contrary, the ratio 40% SS: 60% OFMSW where it was more exposed to anaerobic digestion inhibitors.

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