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Enhancing biogas production through optimized organic loading rate and temperature in anaerobic digestion of municipal solid waste: A study from Aleppo

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Abstract
Background: Aleppo produces large amounts of municipal solid waste, making environmentally safe disposal essential. Dry anaerobic digestion is a promising method for treating the organic fraction of municipal solid waste (OFMSW) while generating renewable energy. Key parameters such as pH, hydraulic retention time (HRT), organic loading rate (OLR), and temperature strongly affect biogas yield.
Methods: This study examined semi-continuous dry anaerobic digestion of OFMSW from Aleppo using two digesters operated at 35 °C and 45 °C. The substrate contained 25.03% total solids (TS) and 23.32% volatile solids (VS). The digesters were run for 70 days with OLRs of 4.66, 6.99, and 9.33 kg VS/m^3·day.
Results: The best performance was observed at 45 °C and an OLR of 6.99 kg VS/m^3·day, producing 0.431 m^3/kg VS of biogas with a VS removal efficiency of 76.34%. Compared to 35 °C, digestion at 45 °C increased VS removal efficiency and biogas yield by 14.34% and 19.25%, respectively. However, raising OLR to 9.33 kg VS/m^3·day reduced both efficiency and productivity at both temperatures.
Conclusion: Higher temperatures enhanced both VS removal and biogas production, but excessive OLR negatively impacted performance. The study identifies 45 °C and 6.99 kg VS/m^3·day as optimal conditions, providing guidance for improving OFMSW treatment and maximizing energy recovery. These results highlight the potential of dry anaerobic digestion as a sustainable solution for managing organic waste in Aleppo and similar contexts.
Keywords: Solid waste, Biofuels, Temperature, Anaerobic digestion, Methane
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Introduction

Rapid population growth and urbanization have led to a significant increase in the generation of municipal solid waste (MSW), particularly in urban areas. According to the Solid Waste Directorate of Aleppo City, the city produces approximately 1500 to 1700 tons of municipal solid waste daily, with organic materials comprising 65–85% of the waste.

Currently, this waste is collected at an intermediate transfer station and then transported to landfills without undergoing a sorting process. Consequently, the organic components biodegrade under anaerobic conditions in landfills, leading to the release of gases and the formation of leachate containing both organic and inorganic pollutants, which poses a risk of groundwater contamination. Therefore, it is crucial to implement effective treatment technologies that enable resource recovery from municipal solid waste and support the development of a sustainable bioeconomy.

Dry anaerobic digestion is a biological process where organic matter is decomposed by a consortium of microorganisms, producing biogas as a byproduct (1). This technology is especially suited for treating high-solid-content materials, such as the organic fraction of municipal solid waste (OFMSW) and agricultural waste, where the total solid content ranges between 20% and 40% (2). The methane yield in such processes varies from 0.2 to 0.6 m^3/kg of volatile solids (VS), depending on the feedstock and system configuration (2).

Biogas yield is primarily determined by the characteristics of the OFMSW, with specific biogas production ranging from 200 to 600 m^3/ton of waste treated and methane production ranging between 0.13 and 0.4 m^3/kg VS (2).

Operational parameters such as pH, mixing, temperature, and organic loading rate (OLR) significantly impact digester performance (3). Temperature, in particular, plays a crucial role in microbial activity and the decomposition of waste. Higher temperatures generally accelerate decomposition and enhance biogas production (4). In continuous systems, biogas and methane production are influenced by the OLR, which must be carefully adjusted to maintain process stability (2). OLR is one of the key design parameters in dry anaerobic digestion, defined as the amount of volatile solids loaded per unit volume of digester per day (2).

Previous studies, such as that by Nguyen et al., have examined semi-continuous dry anaerobic digestion of food waste under mesophilic and thermophilic conditions in South Korea (1). Their findings showed that increasing OLR led to improved gas production and reduced volatile solids, with the highest VS removal efficiency at 79.67% and a maximum biogas production of 162.14 m^3/ton. The methane content was 61.89% at an OLR of 8.62 ± 0.34 kg VS/m^3·day with a hydraulic retention time of 25 days under thermophilic conditions (1). Similarly, thermophilic conditions outperformed mesophilic conditions, with increases of 6.88% and 16.4% in VS removal and biogas production, respectively (1).

Liu et al. also investigated food waste in China as a feedstock for semi-continuous anaerobic digestion (5). Their results indicated that the optimal OLR under thermophilic conditions was 2.5 g VS/L·day, yielding 541 mL CH_4/g VS. Under mesophilic conditions, the optimal OLR was lower, at 1.5 g VS/L·day. Notably, at the same OLR, methane yields were 33–49% higher under thermophilic conditions compared to mesophilic conditions (5).

Babaei and Shayegan reported a reduction in VS removal efficiency and biogas yield as OLR increased. Their study on semi-continuous anaerobic digestion of vegetable waste at 34 °C found the optimal OLR to be 1.4 kg VS/m^3·day, with a methane yield of 0.25 m^3/kg VS and a VS removal efficiency of about 88% (6).

Zhen et al. used agricultural organic waste straw and cow dung as raw materials in a vertical continuous push-flow dry anaerobic digestion reactor on a controlled laboratory scale. The experimental results showed that the system was in low-stress operation at an organic load rate (OLR) of 3 g VS/L·day, the VS methane production rate was located at 225 ~ 272 mL CH_4/g VS. They also reported that when the OLR reached 25 g VS/L·day, the content of VFAs all began to climb rapidly above 8000 mg/L, with the acetic acid content increasing most significantly because the activity of acetic acid-type methanogenic bacteria was the first to be inhibited (7).

Given that the application of dry anaerobic digestion for municipal solid waste (MSW) in Syria is still in its early stages, there is a notable lack of research data on the development and adaptation of this technology to local conditions for potential energy recovery and sustainable waste management. This research aims to study the effect of organic loading rate (OLR) and temperature on the biogas yield from semi-continuous dry anaerobic digestion of MSW from Aleppo city.

Materials and Methods

Organic Fraction of Municipal Solid Waste (OFMSW) and Inoculum

The substrate used in this study was the organic fraction of municipal solid waste (OFMSW), which was collected from various locations within Aleppo city, Syria. Prior to its use, the OFMSW was mechanically shredded to a particle size of less than 2 mm. For the digester startup phase, cow dung was employed as an inoculum (8).

This inoculum was sourced from a private farm located in the rural outskirts of Aleppo. The characteristics of the OFMSW and the inoculum are summarized in Table 1. The critical factors in the anaerobic digestion process include the total organic carbon (TOC) and total nitrogen (TN) of the feedstock, as well as their ratio. The optimal C/N ratio is generally reported to range between 20 and 30 (2). In some studies, a C/N ratio between 15 and 35 is considered ideal for anaerobic digestion (9). It was found that the C/N ratio in the residues used as a reactant falls within the optimal range.

Experiments were conducted using a semi-continuous dry anaerobic digestion system. Two locally made galvanized iron digesters were used, each with a total volume of 60 L and an adequate volume of 30 L. Each digester was equipped with inlet and outlet ports for reactants, a gas outlet with an open/close valve, and an independent electrical control system. A mixer with an arm and a motor running at 45 RPM was used, with mixing time controlled by a timer. Temperature control was achieved using a water bath system with a temperature

Table 1. OFMSW and inoculum characteristics

Analysis	OFMSW	Inoculum	Mixture of inoculum and OFMSW at a ratio of (1:1)
TCOD (g/L)	154	59	120
TKN (%)	1.64	1.88	1.65
TOC (%)	50.11	38.77	42.50
C/N	30.56	20.62	25.76
TS (%)	25.03	15.68	20.39
TS (g/L)	273.60	158.4	219.2
VS (%)	23.32	11.3	16.1
VS (g/L)	254.85	114.15	173.16
Moisture content	74.97	84.32	79.61
pH	5.7	7.93	6.09

sensor, and pressure inside the digesters was monitored using a pressure gauge. As shown in Figure 1, the gas produced by each digester was collected through a flexible tube connected to a gas meter and a gas collection bag.

Experimental Procedure

The startup phase for each digester was initiated by filling both with a mixture consisting of 15 liters of OFMSW and 15 liters of inoculum.

The inoculum is added at the beginning of the digestion process to accelerate the startup period. This method is effective in providing the necessary microorganisms for the new reactants. Many researchers recommend using 50% of the digester components as inoculum during the startup phase (2).

Once filled, the digesters were sealed tightly to create anaerobic conditions. The temperature was maintained at 35 °C and 45 °C for the two digesters using water baths, and the reactors were referred to as R1 and R2, respectively.

Mixing was performed intermittently, operating in half-hour intervals—on for 30 minutes and off for 30 minutes—over 11 hours each day. The digestion process was continuously monitored until the volatile solids (VS) removal efficiency reached a stable level. The startup phase lasted 65 days for R1 (35 °C) and 50 days for R2 (45 °C).

High TS content in dry anaerobic digestion processes results in increased OLR values, which can reach a range of 12–15 kg VS/m³·day in continuous systems. In contrast, wet anaerobic digesters cannot operate at OLR values higher than 5 kg VS/m³·day (3).

It is essential to carefully select the OLR to maximize the efficiency of waste treatment in the digester, without reaching values that could jeopardize the stability of the digestion process (2).

Following the startup, the digesters were fed daily with OFMSW, and digestate was withdrawn at equivalent amounts of 600, 900, and 1200 g per day. These feeding rates corresponded to organic loading rates (OLR) of 4.66, 6.99, and 9.33 kg VS/m³·day, respectively, with hydraulic retention times (HRT) of approximately 50, 33, and 25 days, respectively.

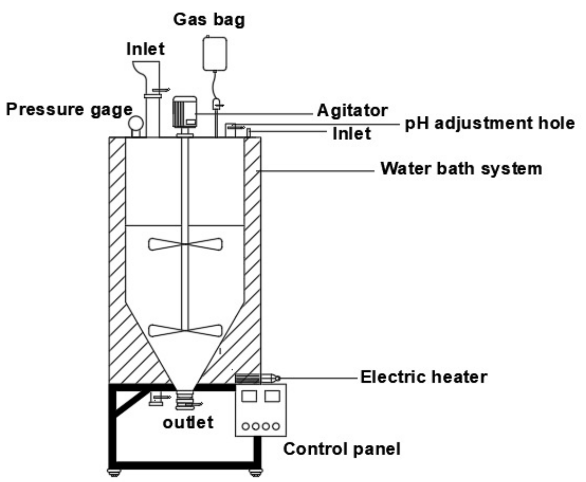

Figure 1. The schematic diagram of an anaerobic digester

The efficiency of the anaerobic digestion process was monitored until the stabilization of biogas production and VS removal. The phase studying the effect of changing OLR took 20 days at OLRs of 4.66 and 6.99 kg VS/m³·day, while it took 30 days at an OLR of 9.33 kg VS/m³·day.

The pH values were adjusted to the range of 7.2–8 (4) by adding a 3N NaOH solution using a chemical dosing pump (Microdose, Type: ME1-PH).

Analytical Methods

Throughout the study, daily samples of both influent (feed) and effluent (digestate) sludge, as well as biogas, were collected and analyzed to assess the performance of the digesters. The following parameters were measured:

• *Total solids (TS)*
Determined by drying and weighing the samples.
• *Volatile solids (VS)*
Measured using the drying and incineration-weighing method.
• *Total nitrogen (TN)*
Analyzed using the Kjeldahl method.
• *Total organic carbon (TOC)*
Calculated based on total organic matter, as determined by ignition losses from drying and incineration, with the assumption that TOC comprises 53.8% of the organic matter in municipal solid organic waste (10).
• *Total chemical oxygen demand (TCOD)*
Measured using an LH-C55 colorimeter for COD and HACH reagents.
• *pH*
Monitored using an inspected pH meter.

The volume of biogas produced was recorded using a CX-WGFM-XMF-1 biogas flow meter (Shanghai Cixi Instrument Co., Ltd., China). The composition of the biogas (CH_4, CO_2, H_2S) was analyzed using a biogas analyzer (CM1791101, Beijing Shi'An Technology Instrument Co., Ltd.). This device utilizes the infrared optical principle to detect the concentration of methane and carbon dioxide gases, leveraging the wavelength characteristics of these gases. The H_2S sensors used in this device operate on an electrochemical principle. The internal electrode will react with the gases being detected, acting as a catalyst to facilitate the directional movement of electrons between electrodes. This process amplifies the electrical signal and displays it using amplification circuit technology and other existing technologies, thereby enabling the detection of concentration.

Results

Performance of Anaerobic Digestion in R1

The biogas production and its composition when OLR changes are presented in Table 2 and Figure 2(A). Biogas production decreased at the beginning of each stage due to the change in organic load as the organisms needed time to adapt to the new conditions. Subsequently, biogas

Table 2. Biogas production, composition, VS concentration, and removal efficiency in R1

Operation time (day)	Gas volume (L)	CH_4 (%)	CH_4 volume (L)	CO_2 (%)	CO_2 volume (L)	H_2S (ppm)	Biogas yield (m^3/kg VS)	Methane yield (m^3/kg VS)	VS (g/L)	VS removal efficiency (%)
OLR = 4.66 kg VS/m³·day										
1	34.14	49	16.73	30	10.24	55	0.325	0.159	79.95	68.63
2	34.54	47	16.23	29	10.02	96	0.335	0.158	83.10	67.39
3	35.54	47	16.70	31	11.02	132	0.351	0.165	85.91	66.29
4	36.51	57	20.81	34	12.41	131	0.361	0.206	86.24	66.16
5	37.49	57	21.37	35	13.12	132	0.372	0.212	86.69	65.98
6	37.46	58	21.73	33	12.36	95	0.385	0.223	92.83	63.57
7	37.73	59	22.26	33	12.45	58	0.402	0.237	98.41	61.39
8	37.85	59	22.33	32	12.11	85	0.393	0.232	94.24	63.02
9	37.39	58	21.69	34	12.71	99	0.394	0.228	96.54	62.12
10	37.95	59	22.39	32	12.14	68	0.387	0.229	91.55	64.08
11	37.94	60	22.76	32	12.14	85	0.395	0.237	94.81	62.80
12	38.58	58	22.38	35	13.50	73	0.385	0.224	87.99	65.47
13	37.85	59	22.33	33	12.49	88	0.384	0.226	90.37	64.54
14	38.08	57	21.71	39	14.85	63	0.399	0.228	95.96	62.35
15	38.05	58	22.07	40	15.22	70	0.382	0.222	88.80	65.16
16	38.94	54	21.03	33	12.85	86	0.395	0.213	90.65	64.43
17	39.34	55	21.64	35	13.77	166	0.402	0.221	91.73	64.01
18	39.58	56	22.16	34	13.46	178	0.403	0.226	91.19	64.22
19	39.75	57	22.66	33	13.12	145	0.401	0.229	89.61	64.84
20	39.33	58	22.81	35	13.77	160	0.395	0.229	88.91	65.11
OLR = 6.99 kg VS/m³·day										
Operation time (day)	Gas volume (L)	CH_4 (%)	CH_4 volume (L)	CO_2 (%)	CO_2 volume (L)	H_2S (ppm)	Biogas yield (m^3/kg VS)	Methane yield (m^3/kg VS)	VS (g/L)	VS removal efficiency (%)
21	35.06	48	16.83	42	14.73	55	0.233	0.112	87.95	65.49
22	38.28	46	17.61	49	18.76	133	0.258	0.119	90.10	64.65
23	42.49	47	19.97	41	17.42	138	0.296	0.139	95.35	62.59
24	50	55	27.50	43	21.50	133	0.353	0.194	97.64	61.69
25	59.3	56	33.21	38	22.53	143	0.417	0.233	96.72	62.05
26	59.39	59	35.04	37	21.97	142	0.407	0.240	92.77	63.60
27	64.33	58	37.31	38	24.45	144	0.437	0.253	91.21	64.21
28	65.78	57	37.49	32	21.05	187	0.444	0.253	90.08	64.65
29	67.2	57	38.30	35	23.52	195	0.452	0.258	89.72	64.79
30	64.19	58	37.23	33	21.18	200	0.426	0.247	87.54	65.65
31	64.83	56	36.30	36	23.34	198	0.432	0.242	88.19	65.40
32	65.1	60	39.06	39	25.39	202	0.430	0.258	86.73	65.97
33	66.33	58	38.47	34	22.55	201	0.442	0.256	87.96	65.49
34	67.1	58	38.92	34	22.81	197	0.445	0.258	87.19	65.79
35	66.99	57	38.18	35	23.45	203	0.439	0.250	85.23	66.56
36	67.59	57	38.53	33	22.30	203	0.435	0.248	82.25	67.73
37	67.83	57	38.66	32	21.71	205	0.435	0.248	81.43	68.05
38	69	55	37.95	33	22.77	207	0.445	0.245	82.41	67.66
39	68.58	55	37.72	31	21.26	195	0.441	0.243	82.10	67.78

Table 2. Continued.

40	68.08	58	39.49	32	21.79	198	0.436	0.253	81.55	68.00
OLR = 9.33 kg VS/m^3·day										
Operation time (day)	Gas volume (L)	CH_4 (%)	CH_4 volume (L)	CO_2 (%)	CO_2 volume (L)	H_2S (ppm)	Biogas yield (m^3/kg VS)	Methane yield (m^3/kg VS)	VS (g/L)	VS removal efficiency (%)
41	60.94	46	28.03	47	28.64	103	0.313	0.144	92.61	63.66
42	60.41	45	27.18	48	29.00	101	0.312	0.140	93.42	63.34
43	63.72	46	29.31	46	29.31	103	0.327	0.150	92.53	63.69
44	59.85	48	28.73	46	27.53	117	0.319	0.153	98.31	61.42
45	41.01	49	20.09	45	18.45	139	0.228	0.112	104.84	58.86
46	54.70	52	28.44	42	22.97	116	0.295	0.153	100.13	60.71
47	60.72	53	32.18	41	24.90	162	0.322	0.171	97.69	61.67
48	58.65	55	32.26	39	22.87	148	0.306	0.168	95.24	62.63
49	61.49	56	34.43	38	23.37	215	0.321	0.180	95.29	62.61
50	67.46	55	37.10	39	26.31	201	0.361	0.199	99.16	61.09
51	65.72	57	37.46	37	24.32	307	0.350	0.200	98.51	61.35
52	68.41	50	34.21	44	30.10	126	0.351	0.176	92.52	63.70
53	69.57	54	37.57	40	27.83	166	0.353	0.190	90.41	64.52
54	71.98	56	40.31	38	27.35	337	0.375	0.210	95.03	62.71
55	74.28	53	39.37	41	30.45	552	0.383	0.203	93.24	63.41
56	72.84	55	40.06	41	29.86	722	0.413	0.227	107.88	57.67
57	74.69	58	43.32	39	29.13	861	0.407	0.236	102.00	59.98
58	73.80	57	42.07	41	30.26	619	0.412	0.235	105.41	58.64
59	71.88	50	35.94	46	33.06	773	0.394	0.197	102.96	59.60
60	73.08	51	37.27	44	32.16	933	0.388	0.198	97.88	61.59
61	72.33	52	37.61	44	31.83	618	0.381	0.198	96.78	62.02
62	75.02	51	38.26	46	34.51	784	0.390	0.199	94.63	62.87
63	74.14	50	37.07	48	35.59	828	0.393	0.196	97.56	61.72
64	78.59	56	44.01	39	30.65	818	0.416	0.233	97.45	61.76
65	75.83	61	46.26	32	24.27	1005	0.390	0.238	92.89	63.55
66	72.80	60	43.68	36	26.21	1006	0.387	0.232	98.23	61.46
67	72.28	58	41.92	40	28.91	1005	0.382	0.222	97.16	61.88
68	71.36	59	42.10	36	25.69	1005	0.376	0.222	96.79	62.02
69	73.78	59	43.53	38	28.04	1005	0.393	0.232	98.23	61.46
70	72.82	58	42.24	38	27.67	1005	0.387	0.225	98.20	61.47

production increased until it reached a stable level. We also observed an increase in biogas production with increasing OLR. The average volume of biogas produced was 37.7, 60.87, and 68.14 L/day, and the average biogas production per kilogram of OFMSW was 62.84, 69.07, and 56.78 L/kg in digester R1 at OLR values 4.66, 6.99, and 9.33 kg VS/m^3·day, respectively.

The variation in methane production resulting from changes in the OLR in digester R1 is presented in Figure 2(B). An increase in methane production was noted with increasing OLR. The average methane volume produced was 21.19, 34.19, and 36.73 L/day at OLR values of 4.66, 6.99, and 9.33 kg VS/m^3·day. The average methane production per kilogram of OFMSW was 35.32, 37.99, and 30.61 L/kg at OLR values of 4.66, 6.99, and 9.33 kg VS/m^3·day, respectively. The biogas yield in R1 when the OLR value changed is presented in Table 2 and Figure 3(A).

An increase in biogas yield was observed when the OLR increased from 4.66 kg VS/m^3·day to 6.99 kg VS/m^3·day, with average biogas yields of 0.382 and 0.405 m^3/kg VS, respectively. However, it decreased to 0.361 m^3/kg VS at an OLR of 9.33 kg VS/m^3·day. Figure 4 shows the methane yield in digester R1 when the OLR value changed. An increase in methane productivity was observed when the OLR increased from 4.66 kg VS/m^3·day to 6.99 kg VS/m^3·day, with average values of 0.215 and 0.227 m^3/kg VS, respectively. It then decreased to 0.195 m^3/kg VS at the OLR value of 9.33 kg VS/m^3·day.

Figure 5(A) shows the change in the VS values when the

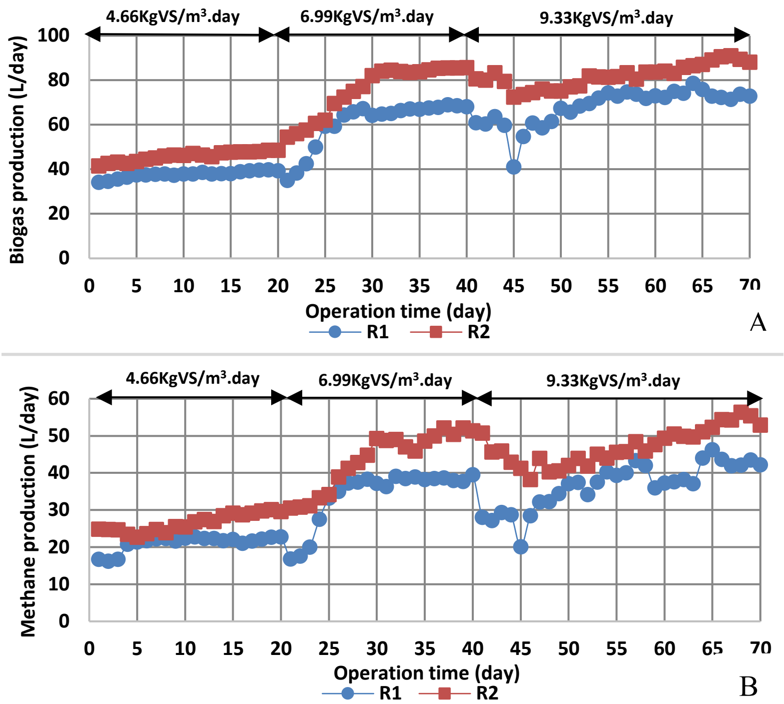

Figure 2. **(A)** Daily biogas production in R1 and R2; **(B)** Daily methane production in R1 and R2

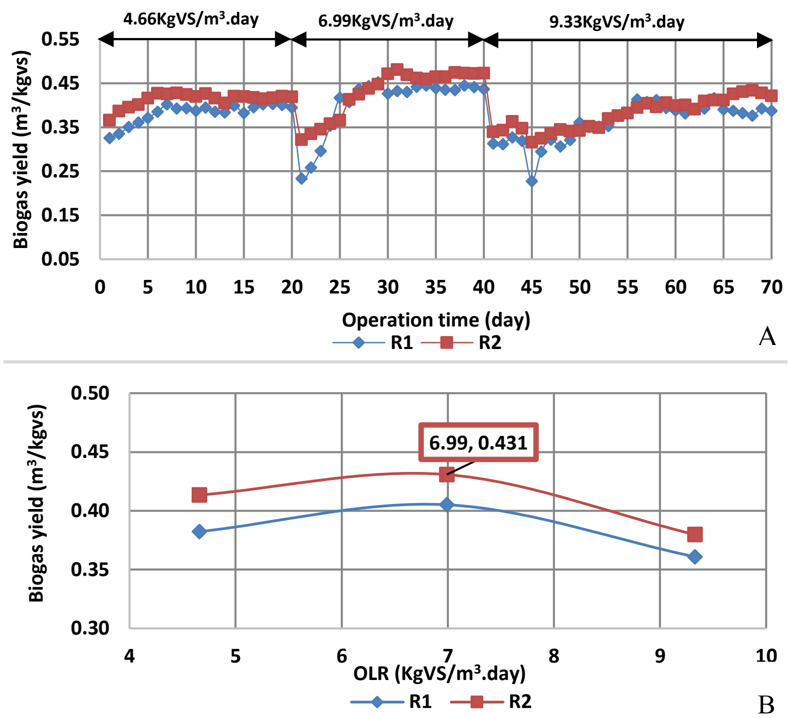

Figure 3. **(A)** Daily biogas yield in digesters R1 and R2; **(B)** Biogas yield vs. OLR in R1 and R2

OLR changed in R1. It is worth noting that the removal of the VS was unstable at the beginning of each digestion stage in the digester. The VS removal ratios when the OLR changed in R1 are presented in Figures 5(B) and (C). An increase in the biological decomposition of organic matter can be observed when the OLR increased from 4.66 kg VS/m^3·day to 6.99 kg VS/m^3·day, with average VS removal percentages of 64.58% and 65.39%, respectively. However, VS removal efficiency decreased to 61.77% when the OLR increased to 9.33 kg VS/m^3·day.

Performance of Anaerobic Digestion in R2

Biogas production and its composition during different phases of the experiment in R2 are presented in Table 3

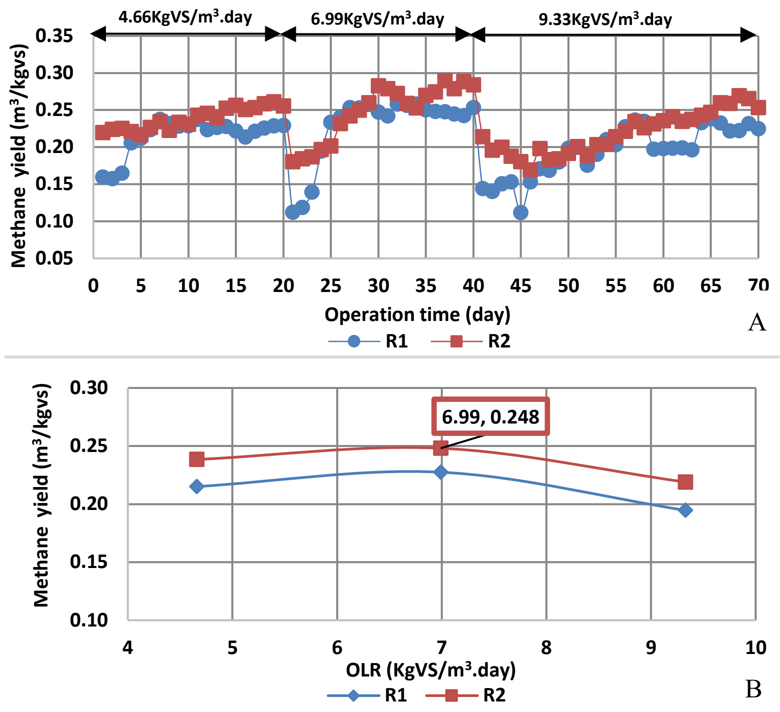

Figure 4. **(A)** Daily methane yield in R1 and R2; **(B)** Methane yield vs. OLR in R1 and R2

and Figure 2(A). The average volume of biogas produced was 45.86, 75.68, and 81.9 L/day, and the average biogas production per kilogram of OFMSW was 76.43, 85.54, and 68.25 L/kg in digester R2 at the OLR values 4.66, 6.99, and 9.33, respectively.

The variation in methane production due to the change in the OLR in digester R2 is presented in Figure 2(B). An increase in methane production was noted with an increase in OLR. The average methane volume produced was 26.49, 43.61, and 47.19 L/day, and the average methane production per kilogram of OFMSW was 44.15, 48.46, and 39.32 L/kg at OLR values of 4.66, 6.99, and 9.33 kg VS/m^3·day, respectively.

The biogas yield in R2 when the OLR value changed is presented in Table 3 and Figure 3. Biogas productivity increased when the OLR increased from 4.66 kg VS/m^3·day to 6.99 kg VS/m^3·day, with average values of 0.413 and 0.431 m^3/kg VS, respectively. However, it decreased to 0.38 m^3/kg VS at an OLR value of 9.33 kg VS/m^3·day. Figure 4 shows the methane yield in digester R2 when the OLR value changed. An increase in methane productivity was noted when the OLR increased from 4.66 kg VS/m^3·day to 6.99 kg VS/m^3·day, with average values of 0.238 and 0.248 m3/kg VS, respectively. It then decreased to 0.219 m3/kg VS at an OLR of 9.33 kg VS/m^3·day.

Figure 5(A) shows the change in the VS values when the OLR changed in R2. It is worth noting that the removal of VS was unstable at the beginning of each digestion stage in the digester. Figures 5 (B) and (C) show the change in the VS removal ratios when the OLR changed in R2. The average removal percentage of VS in digester R2 increased when the OLR increased from 4.66 kg VS/m^3·day to 6.99 kg VS/m^3·day, with average removal percentages of 72.55% and 76.34%, respectively. However, it decreased to 70.75% when the OLR increased to 9.33 kg VS/m^3·day.

Discussion

Careful selection of the organic loading rate (OLR) is crucial to enhance the efficiency of waste treatment in anaerobic digesters without causing the accumulation of inhibitory substances. Both digesters demonstrated an increase in biogas yield with rising OLR, followed by a decrease. The optimal OLR was identified at 6.99 kg VS/m^3·day, as indicated in Figure 3(B).

The observed decline in biogas and methane yield at an OLR of 9.33 kg VS/m^3·day in both digesters can be attributed to the high organic load and short hydraulic retention time (HRT). Additionally, the increased withdrawal rates resulted in insufficient microbial populations for the effective breakdown of organic matter. These findings align with those of Jiang et al. (9), who studied the impact of OLR on OFMSW at temperatures of 35 °C and 55 °C. Their research showed that increasing the OLR from 0.75 to 7.5 kg VS/m^3·day resulted in biogas productivity increasing from 381 to 495 mL/g VS at 35 °C, and from 377 to 544 mL/g VS at 55 °C. However, when the OLR increased from 7.5 to 9 kg VS/m^3·day, biogas productivity decreased to 348 mL/g VS and 479 mL/g VS at temperatures of 35 °C and 55 °C, respectively. At an OLR of 11 kg VS/m^3·day, biogas productivity fell to 346 mL/g VS and 377 mL/g VS at the two respective temperatures, resulting in operational difficulties due to overloading.

The volatile solid (VS) removal rates were unstable at

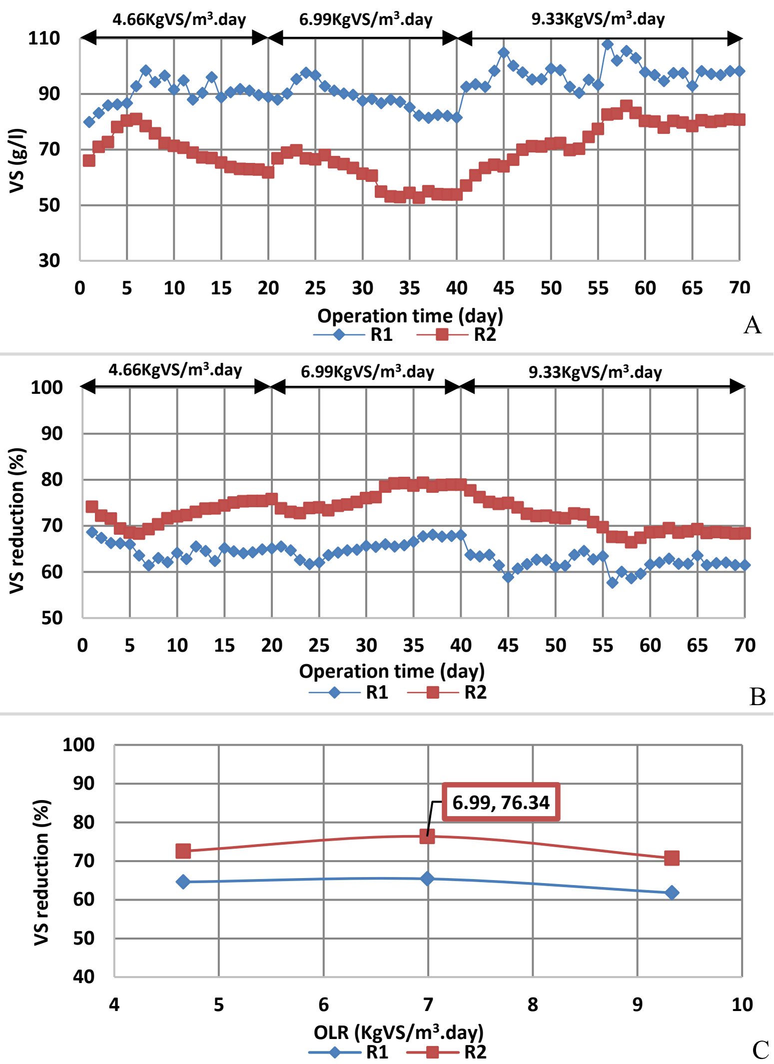

Figure 5. **(A)** Daily VS concentration in R1 and R2; **(B)** Daily VS removal efficiency in R1 and R2; **(C)** VS removal efficiency vs. OLR in digesters R1 and R2.

the beginning of each digestion stage in both digesters due to sudden OLR changes, necessitating an adaptation period for the microorganisms. This adaptation phase was shorter during the first two stages compared to the third stage due to the increased organic load.

This finding is consistent with Nguyen et al. (1), who observed an increase in the biodegradation of organic matter and, consequently, an increase in VS removal efficiency when the organic loading rates were increased from 2.16 kg VS/m^3·day to 8.62 kg VS/m^3·day. Higher organic loading rates were not studied.

The highest VS removal efficiency was achieved at an OLR of 6.99 kg VS/m^3·day and an HRT of 33 days in both digesters. Gou et al. also noted a decrease in VS removal efficiency when the OLR increased from 1 to 8 kg VS/m^3·day while co-digesting activated sludge waste with food waste (11).

Biogas productivity in digester R2 was notably higher than in R1, attributed to increased microbial metabolic activity at elevated temperatures. Operating at 45 °C resulted in faster stabilization and higher VS removal rates compared to 35 °C. This effect is due to higher temperatures creating a more conducive environment for the growth and activity of anaerobic microorganisms (1).

Conclusion

The study results demonstrate that as the OLR increases from 4.66 kg VS/m^3·day to 6.99 kg VS/m^3·day, both biogas and methane productivity improve at temperatures of 35 °C and 45 °C, alongside an increase in VS removal efficiency conversely, when the OLR is raised to 9.33 kg VS/m^3·day, both VS removal efficiency and biogas and methane productivity decline at the two studied temperatures.

Additionally, increasing the temperature leads to enhanced biogas and methane productivity, along with improved VS removal efficiency. The highest average biogas and methane productivity were observed at 0.431 m^3/kg VS and 0.248 m^3/kg VS, respectively. Meanwhile, the peak VS removal efficiency of 76.34% occurred at 45 °C and an OLR of 6.99 kg VS/m^3·day.

The research findings can be applied to treat organic

Table 3. The results of biogas production, composition, VS concentration, and removal efficiency with changes in the OLR value in digester R2

Operation time (day)	Gas volume (L)	CH_4 (%)	CH_4 volume (L)	CO_2 (%)	CO_2 volume (L)	H_2S (ppm)	Biogas yield (m^3/kg VS)	Methane yield (m^3/kg VS)	VS (g/L)	VS removal efficiency (%)
OLR = 4.66 kg VS/m^3·day										
1	41.45	60	24.87	36	14.92	1006	0.366	0.219	65.95	74.12
2	42.64	58	24.73	33	14.07	1006	0.386	0.224	70.90	72.18
3	43.23	57	24.64	26	11.24	1006	0.395	0.225	72.61	71.51
4	42.61	55	23.44	25	10.65	1006	0.402	0.221	78.04	69.38
5	43.59	52	22.67	24	10.46	1006	0.416	0.217	80.39	68.46
6	44.56	53	23.62	25	11.14	1006	0.427	0.226	80.93	68.24
7	45.07	55	24.79	23	10.37	1006	0.426	0.234	78.41	69.23
8	46.02	52	23.93	25	11.51	1006	0.428	0.223	75.73	70.28
9	46.47	55	25.56	24	11.15	1006	0.424	0.233	72.34	71.61
10	46.24	55	25.43	27	12.48	1006	0.420	0.231	71.25	72.04
11	47.13	57	26.86	25	11.78	1006	0.426	0.243	70.61	72.29
12	46.45	59	27.41	33	15.33	1006	0.416	0.245	68.79	73.01
13	45.68	59	26.95	36	16.44	1006	0.405	0.239	67.07	73.68
14	47.45	60	28.47	39	18.51	1007	0.421	0.252	66.85	73.77
15	47.76	61	29.13	35	16.72	1007	0.420	0.256	65.30	74.38
16	47.88	60	28.73	31	14.84	1006	0.417	0.250	63.65	75.02
17	47.79	61	29.15	32	15.29	1006	0.415	0.253	62.93	75.31
18	48.02	62	29.77	32	15.37	1006	0.417	0.258	62.87	75.33
19	48.51	62	30.08	32	15.52	1006	0.421	0.261	62.78	75.37
20	48.55	61	29.62	33	16.02	1006	0.419	0.256	61.71	75.79
OLR = 6.99 kg VS/m^3·day										
Operation time (day)	Gas volume (L)	CH_4 (%)	CH_4 volume (L)	CO_2 (%)	CO_2 volume (L)	H_2S (ppm)	Biogas yield (m^3/kg VS)	Methane yield (m^3/kg VS)	VS (g/L)	VS removal efficiency (%)
21	54.48	56	30.51	31	16.89	1006	0.322	0.180	66.82	73.78
22	56.03	55	30.82	32	17.93	1006	0.335	0.184	68.90	72.96
23	57.63	54	31.12	30	17.29	1005	0.346	0.187	69.61	72.69
24	60.59	55	33.32	37	22.42	1005	0.358	0.197	66.74	73.81
25	62.08	55	34.14	32	19.87	1005	0.366	0.201	66.39	73.95
26	69.52	56	38.93	33	22.94	1005	0.413	0.231	67.93	73.35
27	72.43	57	41.29	33	23.90	1005	0.425	0.242	65.41	74.33
28	75.02	57	42.76	35	26.26	1005	0.438	0.250	64.74	74.60
29	77.15	58	44.75	34	26.23	1006	0.448	0.260	63.34	75.15
30	82.11	60	49.27	33	27.10	1006	0.471	0.283	61.25	75.97
31	84.04	58	48.74	35	29.41	1005	0.481	0.279	60.61	76.22
32	84.54	58	49.03	32	27.05	1005	0.470	0.272	54.79	78.50
33	83.92	56	47.00	37	31.05	1005	0.462	0.259	53.07	79.18
34	83.54	55	45.95	35	29.24	1005	0.460	0.253	52.86	79.26
35	83.84	58	48.63	36	30.18	1005	0.465	0.269	54.30	78.69
36	84.62	59	49.93	37	31.31	1005	0.465	0.274	52.65	79.34
37	85.41	61	52.10	34	29.04	1005	0.475	0.290	54.93	78.45
38	85.48	59	50.43	35	29.92	1005	0.473	0.279	53.87	78.86
39	85.5	61	52.16	34	29.07	1005	0.472	0.288	53.78	78.90
40	85.61	60	51.37	34	29.11	1005	0.473	0.284	53.71	78.92
OLR = 9.33 kg VS/m^3·day										

Table 3. Continued.

Operation time (day)	Gas volume (L)	CH_4 (%)	CH_4 volume (L)	CO_2 (%)	CO_2 volume (L)	H_2S (ppm)	Biogas yield (m^3/kg VS)	Methane yield (m^3/kg VS)	VS (g/L)	VS removal efficiency (%)
41	80.61	63	50.78	31	24.99	1005	0.340	0.214	57.03	77.62
42	80.02	57	45.61	33	26.41	1006	0.343	0.196	60.63	76.21
43	83.40	55	45.87	36	30.02	1005	0.363	0.200	63.32	75.15
44	79.42	54	42.89	38	30.18	1005	0.348	0.188	64.47	74.70
45	72.44	57	41.29	37	26.80	1005	0.316	0.180	63.91	74.92
46	73.52	52	38.23	32	23.53	1005	0.325	0.169	66.35	73.97
47	74.43	59	43.91	32	23.82	1005	0.335	0.198	69.86	72.59
48	76.02	53	40.29	33	25.09	1005	0.345	0.183	71.14	72.09
49	75.15	54	40.58	35	26.30	1005	0.341	0.184	71.03	72.13
50	75.11	56	42.06	38	28.54	1004	0.342	0.192	72.01	71.74
51	77.04	57	43.91	35	26.96	1005	0.352	0.200	72.31	71.63
52	77.54	54	41.87	35	27.14	1006	0.349	0.189	69.77	72.62
53	81.92	55	45.06	32	26.21	1006	0.370	0.203	70.19	72.46
54	81.54	54	44.03	37	30.17	1006	0.377	0.203	74.46	70.78
55	81.42	56	45.60	38	30.94	1005	0.382	0.214	77.39	69.63
56	81.62	56	45.71	40	32.65	1005	0.395	0.221	82.58	67.60
57	83.41	58	48.38	37	30.86	1005	0.404	0.234	82.86	67.49
58	80.48	57	45.87	41	33.00	1005	0.396	0.226	85.65	66.39
59	83.62	57	47.66	32	26.76	1005	0.406	0.231	83.11	67.39
60	83.61	59	49.33	34	28.43	1005	0.399	0.235	80.22	68.52
61	84.11	60	50.47	33	27.76	1005	0.401	0.241	80.03	68.60
62	83.14	60	49.88	36	29.93	1005	0.391	0.235	77.79	69.48
63	85.75	58	49.74	33	28.30	1005	0.409	0.237	80.27	68.50
64	86.53	59	51.05	32	27.69	1005	0.411	0.243	79.61	68.76
65	87.13	60	52.28	35	30.50	1005	0.412	0.247	78.41	69.23
66	89.15	61	54.38	36	32.09	1006	0.426	0.260	80.47	68.42
67	90.50	60	54.30	38	34.39	1006	0.431	0.259	79.94	68.63
68	90.93	62	56.38	36	32.73	1005	0.434	0.269	80.29	68.50
69	89.35	62	55.40	35	31.27	1005	0.428	0.265	80.83	68.28
70	88.12	60	52.87	36	31.72	1004	0.422	0.253	80.70	68.33

municipal solid waste in Aleppo city using a semi-continuous dry anaerobic digester at a specific organic loading rate and temperature, eliminating the need for water addition. This approach enables the utilization of waste as a sustainable resource, rather than disposing of it in environmentally harmful ways. Additionally, this method can be extended to study other types of organic raw materials, such as agricultural waste.

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Resources: Roaa Salem and Nahed Farhoud
Supervision: Nahed Farhoud
Validation: Roaa Salem and Hussain Saleh
Visualization: Roaa Salem
Writing–original draft: Roaa Salem
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Competing interests

The authors declare that they have no competing interests.

Ethical issues

The authors hereby certify that all data collected during the study are stated in this manuscript, and no data from the study has been or will be published elsewhere separately.

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