

Evaluation of Biogas Production from the Co-Digestion of Municipal Food Waste and Wastewater Sludge at Refugee Camps Using an Automated Methane Potential Test System

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Abstract: The potential benefits of the application of a circular economy—converting biomass at Za'atari Syrian refugee camps into energy—was investigated in this study. Representative organic waste and sludge samples were collected from the camp, mixed in different ratios, and analyzed in triplicate for potential biogas yield. Numerous calorific tests were also carried out. The tangential benefit of the co-digestion that was noticed was that it lowered the value of the total solid content in the mixture to the recommended values for wet digestion without the need for freshwater. To test the potential methane production, the automated methane potential test system (AMPTS) and the graduated tubes in the temperature-controlled climate room GB21 were utilized. Also, calorific values were determined for the organic waste and sludge on both a dry and a wet basis. The maximum biogas production from 100% organic waste and 100% sludge using AMPTS was 153 m³ ton⁻¹ and 5.6 m³ ton⁻¹, respectively. Methane yield reached its maximum at a $V_{\text{sub}}/V_{\text{inoculum}}$ range of 0.25–0.3. In contrast, the methane yield decreased when the $V_{\text{sub}}/V_{\text{inoculum}}$ exceeded 0.46. The optimum ratio of mixing of municipal food waste to sludge must be carefully selected to satisfy the demands of an energy production pilot plant and avoid the environmental issues associated with the sludge amount at wastewater treatment plants (WWTPs). A possible ratio to start with is 60–80% organic waste, which can produce 21–65 m³ biogas ton⁻¹ fresh matter (FM). The co-digestion of organic waste and sludge can generate 38 Nm³/day of methane, which, in theory, can generate about 4 MW in remote refugee camps.

Keywords: organic waste; MSW (Municipal Solid Waste); sludge; anaerobic digestion; methane; circular economy; Jordan

1. Introduction

Jordan is a semi-arid country with scarce fresh water resources and relatively limited agricultural activities [1,2]. Currently, Jordan is ranked second in the world in water scarcity [3–5]. Therefore, the biomass availability in arid and semi-arid regions can be considered to be relatively low compared with non-arid regions [6]. Biomass residues available in Jordan may be derived from localized agriculture-related activities, the organic fraction of municipal solid waste (OFMSW), animal manure, and organic industrial wastes [7]. However, the utilization of biomass energy is still

limited to the direct combustion process for space heating, and currently has no real industrial utilization.

Jordan is a non-oil producing country, which imports 96% of its energy supplies [8]. Moreover, Jordan is an upper-middle-income country with a population of 9.53 million inhabitants. Thirty percent of the population are non-Jordanians, and 30% are registered as refugees. Approximately 80% of Syrian refugees in Jordan live in urban areas in the north of Jordan; the remaining 20% live in the Za'atari, Marjeb al-Fahood, Cyber City, and Al-Azraq camps [9–11]. The influx of refugees into Jordan has significantly increased the demand for energy and water resources, and caused an adverse economic burden in Jordan [12,13].

Due to the Syria crisis, Jordan has issued a response plan for 2016–2018. It is stated in the plan that there will be a gap between the landfill capacity and the total volume of waste produced on a daily basis, which was determined to be 1698 tons per day (indicating that 19% of organic waste will not be landfilled due to lack of landfill capacity) [14]. Also, the high generation rates of waste (i.e., 55% organic waste) and its disposal to non-sanitary landfills pose environmental, economic, and social problems [15,16], which is the case at the refugee camps. Consequently, this indicates the necessity of reassessing the way Jordan deals with its municipal solid waste (MSW); i.e., to treat it as a resource and not as a burden. Saidan et al. in 2017 analyzed the waste composition generated at the refugee camps and showed that the OFMSW represents the main waste category, with 53% of the total MSW [10]. However, Saidan et al. focused only on potential recyclable materials, such as plastics, paper, and cardboard, without investigating the potential of converting organic waste into energy opportunities [10].

Anaerobic digestion (AD) is a viable and cost-effective technology for waste management [17,18]. However, the co-digestion of OFMSW and sewage sludge has been proposed to overcome the operational obstacles of having high organics and volatile fatty acid accumulation in the sole digestion of sewage sludge [18–23], with relatively less environmental impact compared with other waste management systems reported in some case studies [24].

The circular economy has been defined in the literature as an alternative to a traditional linear economy (make, use, dispose), where the resources are used for as long as possible, the maximum value is extracted from them whilst in use, and then the products and materials are recovered and reused [25,26]. In this context, biogas is a renewable energy that is worth promoting based on the circular economic model [27–29]. Moreover, the waste-to-biogas supply chain ensures that environmental impacts are reduced to a minimum and natural resources are used more efficiently [30,31].

The main objective of the present paper is to study the potential benefits of the application of a circular economy in terms of biomass at refugee camps. To do so, samples of OFMSW and sludge were taken from a camp, mixed in different ratios, and analyzed for their potential biogas yield using an automated methane potential test system.

2. Materials and Methods

2.1. Study Area

For the purpose of this research, the Za'atari Syrian Refugee Camp (ZSRC) was selected as the study area, which is located approximately 8 miles from the Syrian border (32°17'44.4"N 36°19'25.5"E). ZSRC is the largest refugee camp in the Middle East, and the second-largest refugee camp in the world [32]. The ZSRC has on average 80,000 residents, and regularly generates 28–50 tons of unsegregated municipal waste per day (40 tons/day on average). The ZSRC's waste management is fully described in the work undertaken by Saidan et al in 2017. However, it is now considered to be the fourth-largest city in Jordan and is gradually evolving into a permanent settlement [33]. Running the ZSRC tends to be expensive due to the high costs of waste treatment and energy supply [34]. In this context, the introduction of a biogas production and energy-producing plant would help to minimize the cost of running the refugee camp. As a result of that, progress towards sustainability and better living conditions in the camp can be ensured [35].

2.2. Waste Sampling and Preparation in the ZSRC

Due to restrictions on, and control of, access to the ZSRC, the ZSRC's managing personnel provided representative MSW samples over a period of one week together with sludge from the Za'atari wastewater treatment plant (WWTP). However, in order to achieve representative samples, guidelines were provided to the ZSRC's technical personnel. The weight of the sample was 15 kg, and it was delivered as a composite sample.

The MSW sample was harvested for its organic fraction, then the organic fraction was milled down to achieve a particle size of less than 10 mm. This size distribution ensures the homogeneity and repeatability of the test.

2.3. Preliminary Testing of Waste Samples

All experiments were conducted in the biogas lab located at the German Jordanian University. The room temperature and humidity in the lab were controlled using an air conditioning system with a set value of 24 °C and 60% relative humidity. Within the lab, a climate-insulated room is installed where the temperature is kept at 36 °C.

As a preliminary and an important step in setting up the experiment, detailed information on the volatile solids (VS) and the total solids (TS) in all the experimental content was estimated. This importance arises from the impact of the ratio between the VS of the inoculum and the VS of the substrate on the bio-methane production rates. All experiments were carried out at least in triplicate for each tested parameter, and the corresponding statistical variation is shown.

TS and VS were calculated for the OFMSW, the sludge from the Za'atari WWTP, and the inoculum used in the experiment. The inoculum used in the experiment was received from an anaerobic digester located at the Shallalah WWTP; its TS and VS values were $(1.08 \pm 0.02)\%$ and $(72.22 \pm 11.45)\%$, respectively. The measurement of the VS and TS for all constituents in the experiments was carried out in accordance with DIN 38 414-S2 [36]. For the determination of TS, three crucibles were heated at 105 °C (the tests were done in triplicate) for an hour, then they were cooled down in a desiccator to room temperature. After that, the crucibles were filled with a sample and weighed. Subsequently, it was placed in the oven overnight at 105 °C, then left to cool down to the ambient temperature. Eventually, the sample's corresponding weight was taken, and the TS in the crucible were calculated. Similarly, after that, VS measurement was conducted using the dried sample from the TS measurement. The dried sample was ground to a particle size of less than 0.25 mm according to DIN 38 409 [37]. Then, the sample was weighed and placed in crucibles, and the sample was heated at 200 °C, 300 °C, and 500 °C for 20 min, 30 min, and 5 h, respectively.

After acquiring the TS and VS values for all constituents, the ratio of volatile solids in the substrate to the volatile solid in the inoculum was determined. Then, weight calculations for the different percentages of mixing between the OFMSW and the WWTP sludge were performed. Setting up the reactors for both the GB21 experiment and the automated methane potential test system (AMPTS) is performed in a similar manner; however, the tests operate differently. While the AMPTS operates automatically for both mixing and measurements, the climate room GB21 test requires the readings to be taken, and the mixing to be performed, manually. The experiments were conducted in controlled conditions regarding temperature and environment. The AMPTS has a water bath that self-regulates temperature, and each reaction chamber is submerged in the water bath and closed off to the surrounding environment. Moreover, the climate room is tightly sealed with self-regulating heaters.

Based on the VS values, different co-digestion ratios were selected between the OFMSW and the WWTP sludge and tested accordingly. These ratios were then analyzed by GB21 [38] using the standardized graduated glass tubes in the temperature-controlled climate room and in the AMPTS as well.

2.4. Experimental Setup for Aerobic Digestion

AMPTS equipment (Bioprocess Control, Sweden), due to its accuracy and high throughput, was employed for the on-line measurements of biogas and biomethane flows, which were then used in the determination of the biogas potential of various substrates on a laboratory scale [39]. AMPTS consists of three main components: a digester, a carbon dioxide (CO₂) fixing unit, and a gas enumerator. The digester is a batch system with automated mixing motors, and each digester is connected through plastic lines to the CO₂ fixing unit then to the gas flow enumerator [40,41]. Each of these batch reactors (digesters) were kept at a constant 37 °C throughout the experiment's duration. The volume readings are automatically logged, standardized, and tabulated wirelessly by the system. AMPTS is further described in McEniry et al. (2014) [42] and Bioprocess Control Sweden AB (2014) [43].

The GB21 method was implemented in the present study in the climate room using the eudiometer system. The system consists of 500-ml reactors, where each of them is connected to a eudiometer tube and filled with a buffer solution (The buffer solution consisted of 200 g NaCl/L and 5 g/l of citric acid), which traps all biogas produced in the reactors. The climate room was kept at a constant temperature of 36 °C, and the pressure measurements were recorded on a reading basis. The total volume of the gas was measured by measuring the displacement of the buffer solution due to the gas production. Then, the total volume reading was standardized based on the climate room's pressure reading and temperature. The generated biogas volume was collected and eventually analyzed for its composition.

3. Results and Discussion

3.1. Waste Analysis and Characterization

The TS and VS parameters of the OFMSW, the sludge, and the inoculum were characterized, and the results were considered as a preliminary step to both the AMPTS and the climate room GB21 method test. The TS and VS for the OFMSW samples collected from the ZSRC are shown in Table 1. The TS and VS values for the inoculum are $(1.08 \pm 0.02)\%$ and $(72.22 \pm 11.45)\%$, respectively; the TS and VS values for the sludge are $((1.37 \pm 0.31)\%$ and $(72.99 \pm 14.28)\%$, respectively.

Table 1. The total solid (TS) and volatile solid (VS) content of the organic fraction of municipal solid waste (OFMSW) samples.

Sample	Water Content (%)	TS (%)	VS (% of Dry Matter (DM))	Ash Content %
1	81.85	18.15	86.1	13.9
2	88.81	11.19	85.5	14.5
3	77.85	22.15	86.5	13.5
4	79.65	20.35	85.4	14.5
5	79.98	20.02	84.4	15.6
mean	81.63 ± 4.26	18.37 ± 4.26	85.6 ± 0.8	147.8 ± 11.1

To investigate biogas generation potential, it is unnecessary to measure the calorific values of an OFMSW and WWTP sludge, since the calorific value should not be equal to the anaerobic fermentation ability. However, this was done in the present work in order to assess different waste-to-energy options, such as incineration and anaerobic co-digestion. The calorific values of both the OFMSW and the WWTP sludge on a dry basis are shown in Table 2. These values were acquired in accordance with DIN 51900 [44]. It is clear that the calorific values of the OFMSW and the WWTP sludge are relatively low even on a dry basis. The situation is worsened due to the fact that both the WWTP sludge and the OFMSW have a high water content; hence, incineration is not a feasible option in comparison with the biogas production option.

Table 2. The dry-basis calorific values of the OFMSW and the wastewater treatment plant (WWTP) sludge.

WWTP Sludge Sample	Weight	Dry Basis Calorific Value
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	(g)	(J/g)
1	0.6941	12,738
2	0.7972	12,656
3	0.7707	12,591
4	0.6549	12,291
5	0.5803	12,170
Mean value \pm SD		12489 \pm 219

OFMSW Sample	Weight (g)	Dry Basis Calorific Value (J/g)
1	0.6837	19,205
2	0.4762	18,853
3	0.5180	19,174
4	0.5690	18,543
5	0.5176	18,578
Mean value \pm SD		18,870 \pm 281

3.2. Evaluation of the Biogas Production and Performance of AMPTS

Table 3 and Figure 1 show the yields of bio-methane production from the OFMSW mixed with the Za'atari WWTP's sludge at different ratios. The production volumes are presented in Normal milliliter per gram of volatile solids. The production volume showed a strong correlation with the amount of organic fraction: the greater the percent of OFMSW, the greater the bio-methane yield.

Further, it is clear that most of the biogas production occurred in the first 10 days. Thereafter, a small amount of bio-methane was cumulatively produced (i.e., 4–12% of the total production).

Table 3. Bio-methane production at different mixing ratios.

Sample	$\frac{VS_{\text{substrate}}}{VS_{\text{inoculum}}} *$	Bio-Methane Production (Nml/g VS)
Inoculum	-	5.2 \pm 2.3
Reference	0.24	314.4 \pm 6.1
100% OFMSW	0.22	383.3 \pm 21.7
80% OFMSW	0.22	344.9 \pm 14.6
60% OFMSW	0.22	337.9 \pm 17.1
40% OFMSW	0.21	357.9 \pm 21.7
20% OFMSW	0.22	316.6 \pm 17.5

$$* \text{ loading ratio} = \frac{\text{mass}_{\text{substrate}} \times TS_{\text{substrate}} \times VS_{\text{substrate}}}{\text{mass}_{\text{inoculum}} \times TS_{\text{inoculum}} \times VS_{\text{inoculum}}}$$

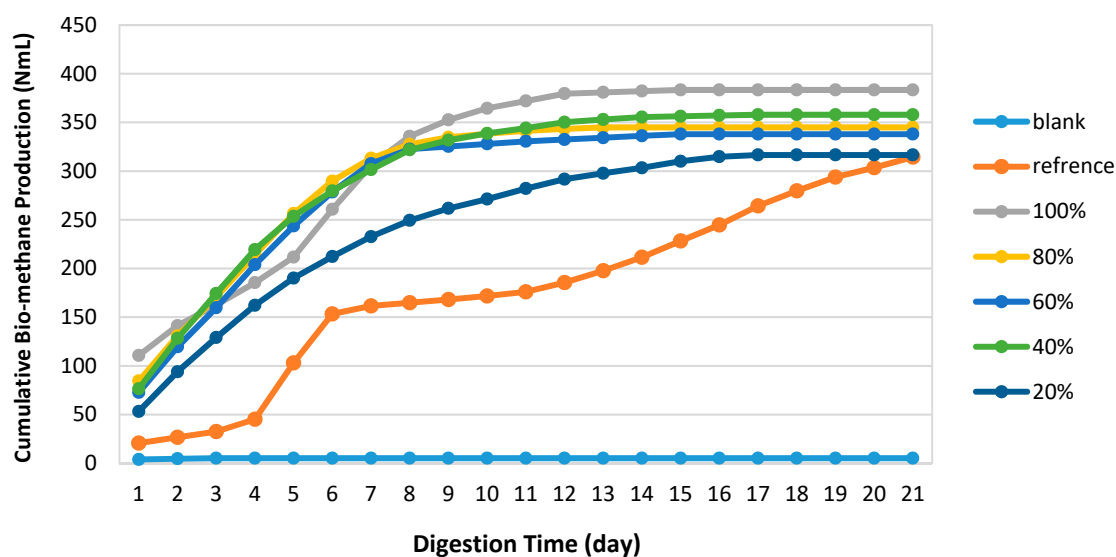


Figure 1. The cumulative bio-methane production volumes per gram of VS (total volumes were recorded by the automated methane potential test system (AMPTS), then divided by the VS values).

The AMPTS contains a CO₂ fixation unit (where the gas produced in the climate room is trapped in the void between the reactor and the buffer solution). Therefore, it only provides bio-methane production values. Table 4 and Figure 2 show the production volume of biogas. As stated before, the production volume is directly proportional to the amount of OFMSW used.

Based on the highest methane yield produced as shown in Table 4, it could be considered that a Vs sub/ Vs inoculum range of 0.25–0.3 is the ideal ratio for methane yield. Some offsets can be noticed in Table 4, where two values of Vs sub/ Vs inoculum are higher than 0.3: 0.457 at a lower mixing ratio (20–80%) and 0.462 at a higher mixing ratio (80–20%). In Figure 2, the cumulative methane trend showed no delay (the lag phase) in all experiments. However, for 0.457 at the lower mixing ratio (20–80%) and 0.462 at the higher mixing ratio (80–20%), the biogas ceased after 23 days, while the volume of methane production was slightly lower than that of the 0.25–0.3 Vs sub/ Vs inoculum range. This indicates that the amount of micro-organism required for an anaerobic reaction to take place is not enough for the biodegradation process [45,46].

Table 4. The biogas production at different mixing ratios attained from the climate room system.

	Mixing Ratio	Fresh Matter		$\frac{VS_{substrate} *}{VS_{inoculum}}$	Total Production (NmL/g VS)
	OFMSW–WWTP Sludge	OFMSW (g)	WWTP Sludge (g)		
1	10–90	0.37	55	0.277	261 ± 43
2	20–80	1.34	80	0.457	291 ± 37
3	30–70	1.2	43	0.278	375 ± 28
4	40–60	1.95	25	0.246	520 ± 22
5	50–50	1.98	31	0.275	512 ± 52
6	60–40	2.37	25	0.274	562 ± 36
7	70–30	3.51	13	0.296	605 ± 25
8	80–20	5.5	20	0.462	455 ± 44
9	90–10	3.56	6	0.267	884 ± 51
10	100% OFMSW	3.97	0	0.267	824 ± 34
11	100% WWTP sludge	0	62	0.284	269 ± 46

$$* \text{ loading ratio} = \frac{\text{mass}_{\text{substrate}} \times \text{TS}_{\text{substrate}} \times \text{VS}_{\text{substrate}}}{\text{mass}_{\text{inoculum}} \times \text{TS}_{\text{inoculum}} \times \text{VS}_{\text{inoculum}}}$$

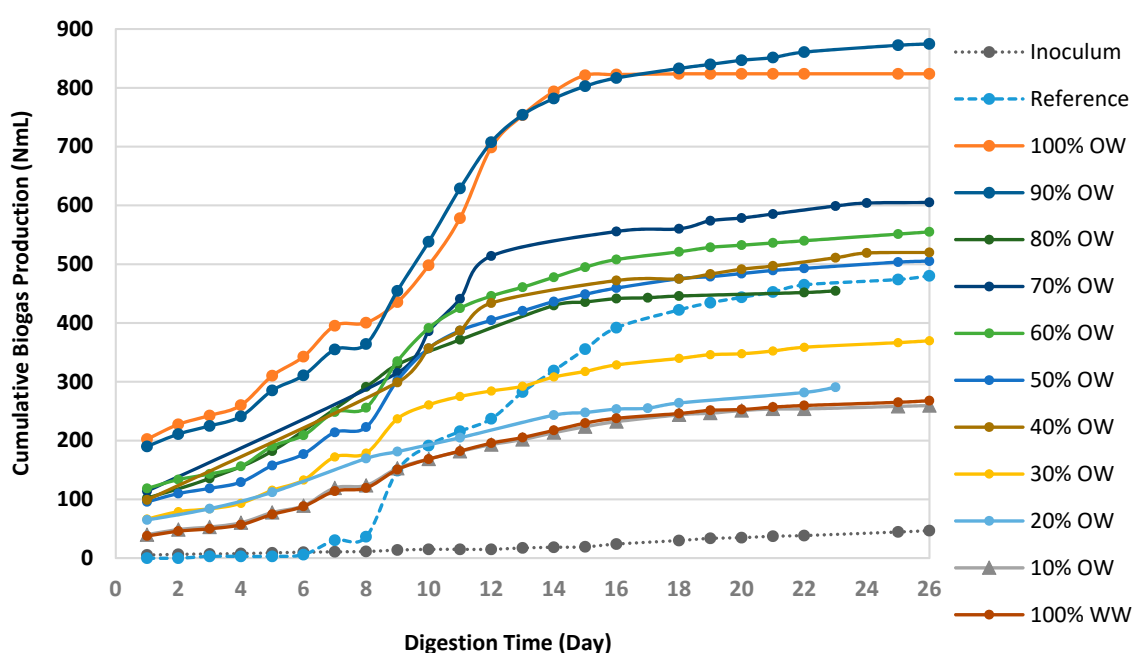


Figure 2. The cumulative biogas production volumes per gram of VS (total volumes were recorded in the climate room system, then divided by the VS values).

Unlike the AMPTS, the biogas production from the climate room system includes other gases in addition to methane, which is CO₂. Therefore, the biogas produced from the climate room system was analyzed for its composition as shown in Table 5, which shows the percentages of CH₄ and CO₂ in the biogas. Multiplying the percentage of CH₄ with the total produced amount of biogas yields CH₄ volumes that are relatively close to those found in the AMPTS test, despite the fact that both tests were performed under different (VS substrate/VS inoculum) ratios.

Table 5. The biogas composition at different mixing ratios.

Sample	CH ₄ (%)	CO ₂ (%)
Reference	72	28
Inoculum	59	41
0%	66	34
10%	61	39
20%	67	33
30%	66	34
40%	67	33
50%	67	33
60%	65	35
70%	66	34
80%	62	38
90%	67	33
100%	65	35

The obtained biogas production reported in this work reflects previously reported values for similar substrates. Elbeshbishy et al. investigated in 2012 the bio-methane potential from food wastes and primary sludge, and reported that 400–1400 L_{methane}/kg VS can be produced depending on the used inoculum [47]. Pavi et al. investigated in 2017 the biogas potential of the co-digestion of an OFMSW and fruit and vegetable wastes at different ratios. They found that the best mixing ratio was 1:3 OFMSW to the fruit and vegetables, with an approximate production of 396 Nml/g VS methane [48]. Fiore et al. studied in 2016 the biogas potential from industrial food-processing waste [49]. In their work, they reviewed several potential types of industrial waste. The results vary from 180 L_{methane}/kg VS for apple pulp to 300 L_{methane}/kg VS for Glycerol [49,50]. Moreover, fruit and vegetable waste has been reported to produce 320–630 L_{biogas}/kg VS [51].

3.3. Biogas Plant Potential and Analysis

Based on the experimental results, it is recommended to undertake co-digestion of the feed for the pilot biogas plant. The feed should comprise sludge from the ZSRC's WWTP and the organic waste portion of the municipal waste generated at the ZSRC.

For the calculations, and as stated before, the ZSRC has an average population of 80,000, and generates an average of 0.8 kg/capita per day of daily waste. The MSW composition generated at the ZSRC contains 50% organic waste. Moreover, the WWTP produces approximately 2000 m³ of sludge on a daily basis.

In summary, the conducted biogas potential test indicates the following: 1): the organic portion of the municipal waste was about 40–50%, with the TS and VS being 20% and 15% of the total amount of solid, respectively; and 2) the total solid in the sludge was about 2–6% (depending on the sampling location), and the volatile solid was 0.3–3% of the fresh matter.

The maximum production of biogas from the APMTS system was found for the 100% organic waste, with an approximate value of 81 m³ of bio-methane per ton of fresh organic waste, while the smallest quantity was for sludge from the WWTP only, with an approximate value of 1.6 m³ of bio-methane per ton of fresh sludge.

One possible scenario to operate a large-scale biogas plant is to use 11% of the residues as feed to the biogas plant. For that, 500 kg of the sludge should be mixed with about 280 kg of organic municipal waste per day. The biogas potential test indicates that about 38 Nm³/day of biogas can be generated. However, the potential percentage of methane that can be generated in the biogas is about 62%. Using a combustion engine to generate heat and electricity with an efficiency of 40%, and taking into consideration the calorific value of methane, 38 Nm³/day can generate about 98,000 kWh/day as electricity, 98,000 kWh/day as thermal energy, or about 4 MW in theory. For that, four digesters are needed, each with a capacity of about 20,000 m³.

4. Conclusions

In the present study, it was demonstrated that laboratory-scale testing provides a good basis for the anaerobic co-digestion of the OFMSW and wastewater treatment sludge generated at ZSRC. In addition, the results of AMPTS and climate room testing could be valuable in optimizing critical parameters for the further implementation of anaerobic digestion/co-digestion under continuous operation. Co-digestion of organic waste and sludge increases the dissolved nutrients and water content in the wet fermentation process (88–95%). The maximum production of biogas from the APMTS system was from 100% organic waste, with an approximate value of 81 m³ bio-methane·ton⁻¹ fresh organic waste. The smallest quantity was for sludge from the WWTP only, with an approximate value of 1.6 m³ bio-methane ton⁻¹ fresh sludge. The results from the climate room system experiments were found to be in good agreement with those of the APMTS system experiments, with slight deviations. The maximum production was found to be from 100% organic waste, with an approximate production of 153 m³ bio-gas ton⁻¹ fresh organic waste and only 5.6 m³ bio-gas ton⁻¹ fresh sludge. Optimization of the Vs sub/ Vs inoculum ratios plays a vital role in a batch digester's operation. The results indicated that Vs sub/ Vs inoculum ratios ranging from 0.25 to 0.3 produce the maximum methane yields. The average composition of the bio-methane in the biogas was 65%, and the remainder was mainly carbon dioxide. The ratio of mixing between the municipal organic waste and the sludge from the WWTP should be chosen carefully to satisfy the demands of an energy production pilot plant and the environmental problems associated with the sludge amount at WWTPs. A possible ratio to start with is 60–80% organic waste, which can produce 21–65 m³·ton⁻¹ fresh matter (FM). Finally, having a biogas plant at the ZSRC to co-digest organic waste and sludge could generate 38 Nm³/day of methane, which could potentially produce about 4 MW in theory. This represents a potential application of a circular economy at the ZSRC and at other similar camps and small communities.

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Abbreviations

AMPTS	automated methane potential test system
AD	Anaerobic digestion
DM	Dry matter
FM	Fresh matter
kWh	Kilo watt hour
MSW	Municipal solid waste
MW	Mega watt
OFMSW	Organic fraction of municipal solid waste
TS	Total solids
VS	Volatile solids

WWTP wastewater treatment plant
 ZSRC Za'atari Syrian refugees camp

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