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ORIGINAL ARTICLE

# Experimental evaluation and optimization of the anaerobic digestibility of two new desert weeds for biogas production

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**Abstract**

Today, the energy crisis, increasing emissions, and global warming have been crucial challenges in the world, especially in developing countries, and the use of renewable energies can be a good solution for these problems. Biogas is a renewable energy that has numerous benefits, including the production of fertilizers, increasing public health, control of diseases, and especially the production of clean energy. Therefore, methane production from weeds can be an attractive method to supply renewable fuel. The present study aimed to evaluate the potential of producing biogas from two new desert weeds, *Sophora alopecuroides* and *Alhagi maurorum*, on a lab-scale in four 2.4 L digestion tanks at room temperature (33 ± 2 °C) in two stages. Also, the effects of various parameters such as pH and different biomass:water ratios on methane production have been investigated. The produced gas compositions were analyzed using gas chromatography-thermal conductivity detector (GC-TCD). The quantities of biogas produced from both plants were determined at different biomass to water ratios and finally, the optimal ratio for each plant was determined. The quantity of optimal cumulative biogas production in 10 days was 2324 and 3099 ml for *A. maurorum* (biomass:water ratio = 1:5) and *S. alopecuroides* (biomass:water ratio = 1:6), respectively. The results proved that *S. alopecuroides* produced 33.34% more biogas compared to *A. maurorum*. The presence of high volatile solids and low dry solids, and higher carbon:nitrogen ratio (three times) in *A. maurorum* compared to *S. alopecuroides* are the effective factors in the production of the lower amount of biogas in this plant.

**Keywords** Biogas · Biomass · Desert weed · *Sophora alopecuroides* · *Alhagi maurorum* · Methane

**Abbreviations**

| | |
|---|---|
| SA | *Sophora alopecuroides* |
| AM | *Alhagi maurorum* |
| MC | Moisture content |
| TS | Total solid |
| VS | Volatile solids |
| B/W | Biomass to water ratio |
| H | Hydrogen |
| N | Nitrogen |
| C | Carbon |
| S | Sulfur |
| C/N | Carbon to nitrogen ratio |

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## 1 Introduction

Today, fossil fuels supply a majority of the world's energy requirements [1, 2] while fossil fuels are limited and lead to the production of various pollutants such as sulfur oxide, NOx, and carbon dioxide (the major cause of global warming) [3]. In 2010, world's total electricity generation capacity was 20 terawatt hour (TWh), 81% contributed by thermoelectric (fossil fuel and nuclear), 17% by hydropower, and 2% by renewable energy sources. In 2035, global electricity demand is expected to increase 70% to 34 TWh as compared to 2010 consumption [4]. Also each country faces unique environmental challenges, its steps vary, but they all eventually aim to reduce negative environmental impacts and attain carbon neutrality [5]. Therefore, in recent years, the tendency to use different sources of renewable energy has increased [6, 7]. Biomass is one of the most important sources of renewable energy so that it supplies at least 8%, and up to 35% of total primary energy supply by 2050 in all the baseline and mitigation scenarios presented, with its contribution increasing in mitigation scenarios [8]. One of the main ways of converting biomass to energy is anaerobic digestion [9, 10], i.e., the process through which organic matter is decomposed in the absence of oxygen, leading to the production of methane, carbon dioxide, and ammonia, as well as low-molecular-weight organic acids [11]. Today, anaerobic digestion is utilized to control pollution of wastewater [12], industrial waste [13], and municipal waste [14] and has become a major process of renewable energy production like biogas and hydrogen. Moreover, anaerobic digestion is the main method of converting agricultural waste and weeds into biomass.

Many investigations have evaluated the potential for gas production from agricultural wastes [15]. Studying the biomethane potential (BMP) test is a relatively easy and reliable method used to show the potential methane yield of organic matter, and is valuable for the design and operation of anaerobic digesters [16]. However, the raw materials generally used to produce biogas are consumed directly by humans as food or animal feed, so they cannot be considered a stable source of raw materials for the production of biogas [17]. Lignocellulosic-based biomass (e.g., weeds) can be used to produce biogas because these plants can grow in different climates (except in very hot or cold areas) and so, is globally an inexpensive and abundant source for the production of a large amount of dry matter using a very little amount of water [18]. The high cellulose content and availability have made weeds a very attractive raw material for the production of biogas. However, the very low efficiency and the ratio of the volume of biogas produced to the mass of biomass used for anaerobic digestion has limited their use [19].

Sinha et al. [20] studied isolate cellulolytic bacteria from termite-gut and soil, optimizing their cellulase production to enhance biogas generation. The result shows maximum cellulase activity of 1.26 ± 0.044 U/ml and 1.31 ± 0.052 U/ml for DSB1 and DSB12 was observed at pH 7 and 7.2 under 35°C and 37°C, respectively. Jomnonkhaow et al. [21] investigated the production of biogas from Napier grass and Napier silage and reported that size reduction accompanied by thermal-assisted hydration significantly improved biogas production. In another study, Eshore et al. [17] combined sugarcane bagasse with plant waste with the ratios of 0, 25, 50, 75, and 100% to produce biogas and observed that the ratio of 50% led to the production of the highest amount of biogas. In Uzbekistan, the chemical composition of several halophytes was investigated and their potential to produce biogas was compared. The results showed that Suaeda and Kochia were the most valuable plants [22, 23]. Turcios et al. [23] analyzed the potential use of the facultative halophyte *Chenopodium quinoa* Willd. as a substrate for biogas production. In the first approach, *C. quinoa* was cultivated with different concentrations of sodium chloride under hydroponic conditions and used as a substrate for biogas production. The results showed that the higher the NaCl in the culture medium, the higher the amount of sodium, potassium, crude ash, and hemicellulose, and the lower the amount of calcium, sulfur, nitrogen, and carbon in the biomass. According to this study, high yields of methane can be produced using *C. quinoa* biomass.

Many studies have used the combination of weeds and animal dung to increase the efficiency of biogas production. Ahn et al. [24] investigated the biogas production potential from switchgrass mixed with swine and poultry manure, separately in 1 L reactors. The results showed that in the 62-day period, the swine manure test units produced the highest amount of methane gas (0.337 L/g VS), while the poultry manure test unit produced the lowest amount of gas (0.002 L/gr VS). Xi et al. [25] investigated the effect of adding six plants on the production of biogas and methane from wheat straw. The results showed that the addition of 10% pseudo-ginseng residues led to the highest biogas and methane productivity (337 ml/g TS of biogas and 178 ml/g TS of methane, respectively). In the study of Andre et al. [26], to produce biogas, anaerobic digestion of dry weed was performed using the combination ratios of 25, 40, and 50% with cattle manure. The results showed that 40:60% ratio of weed:cattle manure led to the highest yield of biogas production. Zhao et al. [27] performed anaerobic co-digestion of food waste and *Sophora flavescens* residues at different co-substrate ratios of 5:5, 7:3, 3:7, 0:10, and 10:0. The composition ratios of 7:3 and 5:5 had the highest biogas yields, which were 8.85% and 57.25% higher than those of the single food waste and single *Sophora flavescens* residues. The final biogas yield in group 0:10 (plant) was about 44.53% lower than group 10:0 (food waste).

### 1.1 Novelty

Not many studies have been conducted on the use of desert weeds for biogas production. Besides, due to the high volume of weeds in different countries, including Iran, there is great potential in using them to produce biogas. Accordingly, the present study aimed at the experimental use of two plants, *Sophora alopecuroides* and *Alhagi maurorum*, as desert weeds in biogas production. To do this, after physicochemical analyses, the plants were combined with cow manure in four different biomasses to water ratios and then placed in the digestion tanks. The value of the biogas produced and the pH were daily measured for each ratio. The optimization of parameters in biogas production is complex because it involves a large number of permutations and combinations of temperatures, heating rates, and pressures [28] but in this study some effective parameters such as pH and water ratio have been investigated experimentally.

The major novelty of the present study are as follows:

- *S. alopecuroides* and *A. maurorum* have been used as new weeds for producing biogas.
- Evaluation of the important parameters in the anaerobic process (pH and C/N ratio) for each weed.
- Evaluation of different biomass to water ratios for each weed.
- Investigating the effect of volatile and solid substances on the value of biogas production for each weed.
- Introducing the optimal ratio of biomass to water for each weed.
- Determining the maximum amount of biomass produced for each weed.
- Investigation of the effect of plant compounds on biogas production.

## 2 Materials and methods

### 2.1 Physicochemical analysis of weeds

Figure 1 shows the plants *S. alopecuroides* and *A. maurorum* collected from the plains of Sabzevar City in northeastern Iran. The plants were separately dried in the open air and then ground using a mill. According to American Public Health Association (APHA) standard, the mass of *S. alopecuroides* and *A. maurorum* samples was measured for biomass to water ratios of 1:2, 1:4, 1:5, and 1:6 and then put in the oven (Fig. 2a) at 110 °C for 10 h and the total solid (TS) content was measured. In the next step, to measure the volatile solid (VS) mass, the samples were burned and their mass was measured again. In addition, the moisture content (MC) of the plants was measured according to ASTM D 2216-19 standard [29]. The amounts of carbon, hydrogen, nitrogen, and sulfur of the plants were measured in the comprehensive central laboratory of Ferdowsi University of Mashhad using CHNS elemental analyzer (Fig. 2b and Table 1). The oven is generally used to measure the amount of moisture or TS and the CHNS is used to measure the other elements listed in Table 1.

### 2.2 Procedure

In the present study, 2.4 L containers were used as a digestion tank. Four outlets were installed on each tank, two of which for installing the pressure gauge and temperature sensor to measure the pressure and temperature, respectively, and the other two outlets for connecting to a manometer and a gas tank. A hot water bath was used

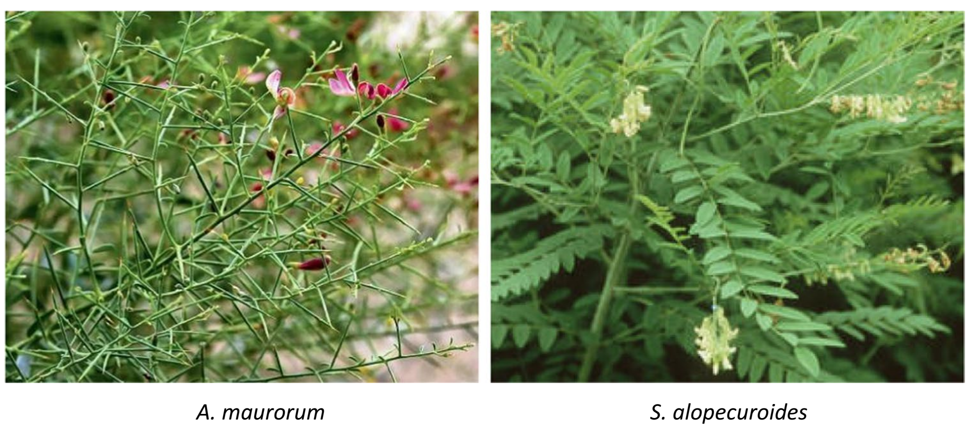


**Fig. 1** *S. alopecuroides* and *A. maurorum*

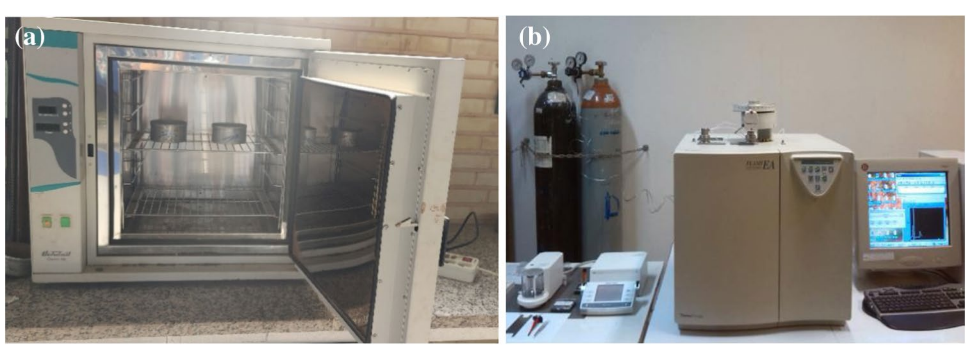


**Fig. 2** **a** Oven. **b** CHNS elemental analyzer

**Table 1** Physicochemical characteristics of *S. alopecuroides* and *A. maurorum*

| Parameters | SA | AM |
|---|---|---|
| MC% | 8.1 | 3.6 |
| TS% | 92.48 | 96.52 |
| **VS**[a]% | 94.2 | 91.24 |
| **C**[a]% | 44.88 | 44.93 |
| **H**[a]% | 6.26 | 5.84 |
| **N**[a]% | 4.19 | 1.44 |
| **S**[a]% | 0.12 | 0.18 |
| C/N | 10.71 | 31.2 |

[a]% of TS

to make a constant temperature. The digestion tanks were put in a container equipped with a heating element with an automatic cut-off at 30–35 °C, and the output numbers of K-type thermocouples were recorded in a 4-channel data logger using XH-W1315 digital display. The pressure of the digester was measured using a pressure gauge and gas mass was measured using an EK-600H scale with an accuracy of 0.01 g. Also, the water displacement method was used to measure the volume of biogas. The digestion tanks were also stirred daily with an interval of 6 h for 2–3 min. Gas compositions were characterized using GC-TCD. Figure 3a and b show the experiment conditions and schematic conditions of the experiment, respectively.

Table 2 shows the characteristics, applications, and error percentage of the equipment used in the experiment. The plant samples were ground, mixed with water and also cow manure (10% of the dry mass) in different ratios, and placed in sealed digesters. Also, the results obtained from different biomass to water ratios are compared.

## 3 Results and discussion

### 3.1 Optimal biomass to water ratio

Figure 4 shows the cumulative volume of biogas produced from *S. alopecuroides* and *A. maurorum* mixed with cow

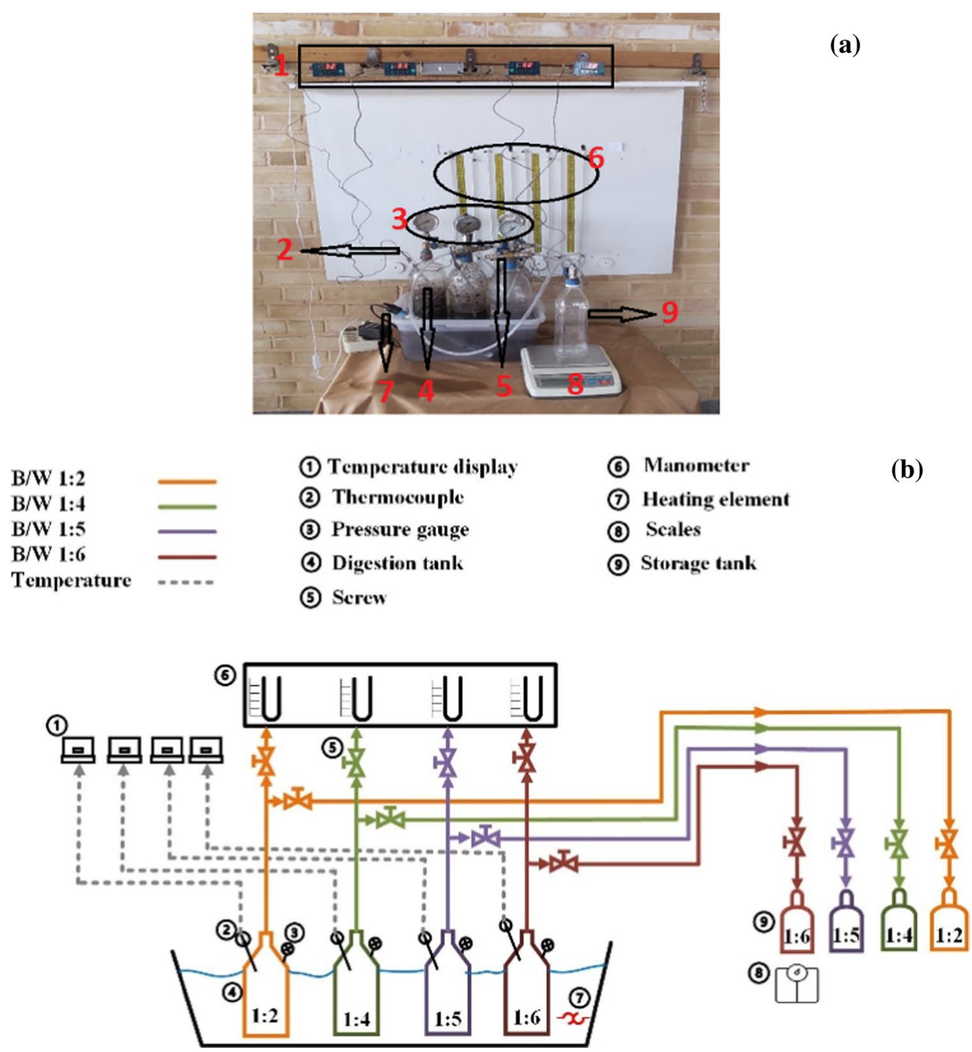


**Fig. 3** **a** The experiment conditions and (**b**) schematic conditions of the experimental

manure, at biomass to water ratios of 1:2, 1:4, 1:5, and 1:6. The optimal biomass to water ratio was 1:6 and 1:5 for *S. alopecuroides* and *A. maurorum*, respectively. According to previous studies, lower TS% and higher VS% are effective factors in the amount of biogas [29]. As shown in Table 1, lower TS and higher VS in *S. alopecuroides* were the main

**Table 2** Components, application, and error percentage of equipment used in the experiment

| | Components | Application | Error (%) |
|---|---|---|---|
| 1 | XH-W1315 | Temperature display | ±2°C |
| 2 | K-type thermocouple | Temperature measurement | ±2°C |
| 3 | Pressure gauge model INDUMART CANADA | Measuring pressures of >1 bar | ±0.125 bar |
| 4 | 2.4 L digestion tank | Sample storage | ±0.1 ml |
| 5 | Screw | Disconnect and reconnect the gas flow | - |
| 6 | Manometer | Measuring pressures of <1 bar | ±0.001 bar |
| 7 | Heating element AQ-1500/300W | Raising the water bath temperature to 33° | ±2°C |
| 8 | Scale model EK-600H | Measurement of the gas mass | ±0.01 gr |
| 9 | 1 L gas tank | Collecting the produced gas | ±0.1 ml |

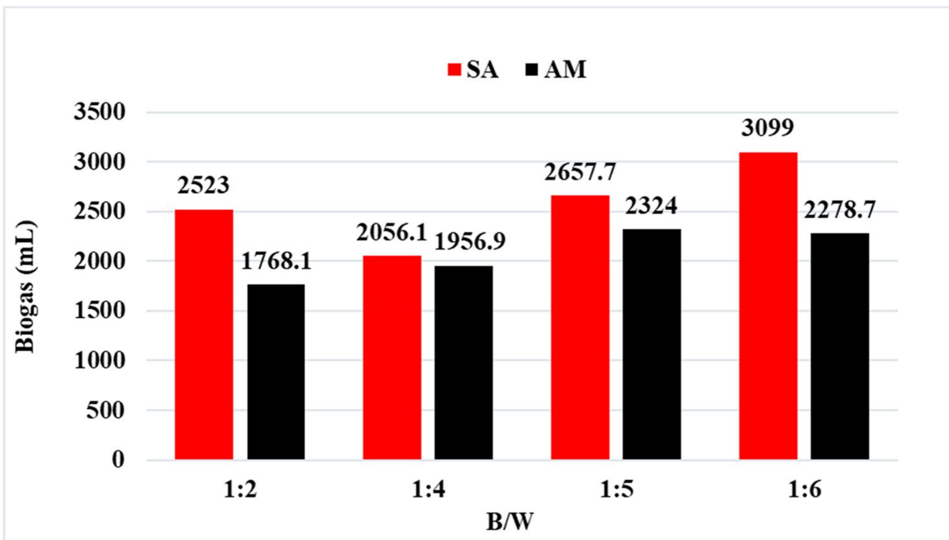


**Fig. 4** Biogas produced from *S. alopecuroides* and *A. maurorum* at different biomass to water ratios

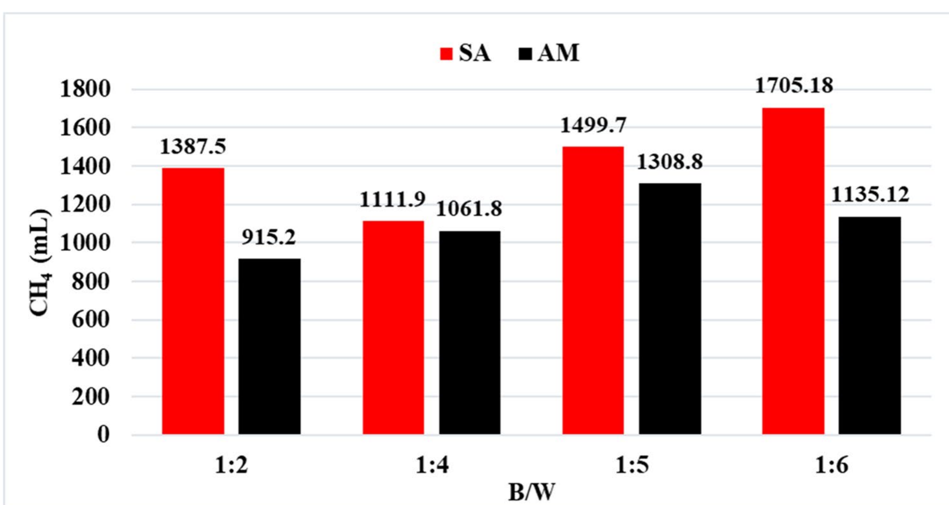


**Fig. 5** Methane production from *S. alopecuroides* and *A. maurorum* at different biomass to water ratios

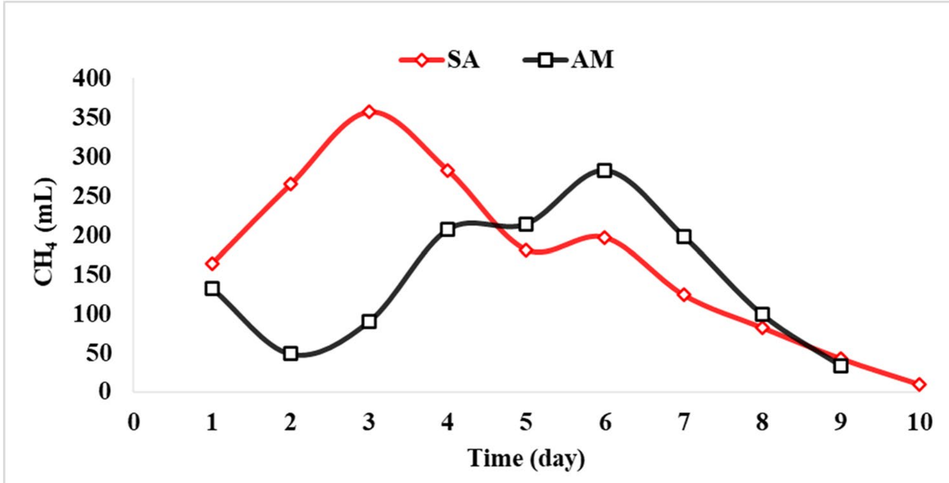


**Fig. 6** The variation of methane production from *S. alopecuroides* and *A. maurorum* at the optimal ratios of 1:6 and 1:5

causes of higher biogas production compared to *A. maurorum*. Figure 5 shows the amount of cumulative methane gas produced in a 10-day period using two desert weeds *S. alopecuroides* and *A. maurorum* in different biomass to water ratios. The results showed that *S. alopecuroides* led to the production of higher amounts of methane compared to *A. maurorum*. One of the main factors in the amount of methane produced in anaerobic digestion is the C/N (carbon to nitrogen ratio) parameter. Bacteria do not consume equal amounts of carbon and nitrogen and carbon is consumed about 30 to 35 times faster than nitrogen. If the carbon to nitrogen ratio is too high, the nitrogen will run out and there will be more carbon in the environment. Under this condition, many bacteria release nitrogen stored in their cells and die. If the carbon to nitrogen ratio is low and there is a lot of nitrogen in the environment, the fermentation process will stop due to the lack of carbon and the available nitrogen will be released as ammonia gas [30]. According to Table 1, the high C/N level in *A. maurorum* (almost three times) compared to *S. alopecuroides* caused rapid nitrogen consumption and less methane production.

### 3.2 Evaluating the trend of changes in the amount of methane produced

According to the results, 1:6 and 1:5 were the optimal ratios for *S. alopecuroides* and *A. maurorum*, respectively. The trend of changes in the amount of methane produced from *S. alopecuroides* and *A. maurorum* in the optimal ratios of 1:6 and 1:5, respectively, in 10 days has been compared in Fig. 6. The highest amount of methane produced from *S. alopecuroides* was observed in the first 3 days of the experiment, while in the following 7 days, it had a downward and uneconomical trend. *A. maurorum* between days 3–6 produced the highest amount of methane. Methane-producing bacteria are very sensitive to pH and do not have acceptable enzymatic activity at pH less than 6.2. According to Samani et al. [31] results, the optimum pH is 6.2–8.5,

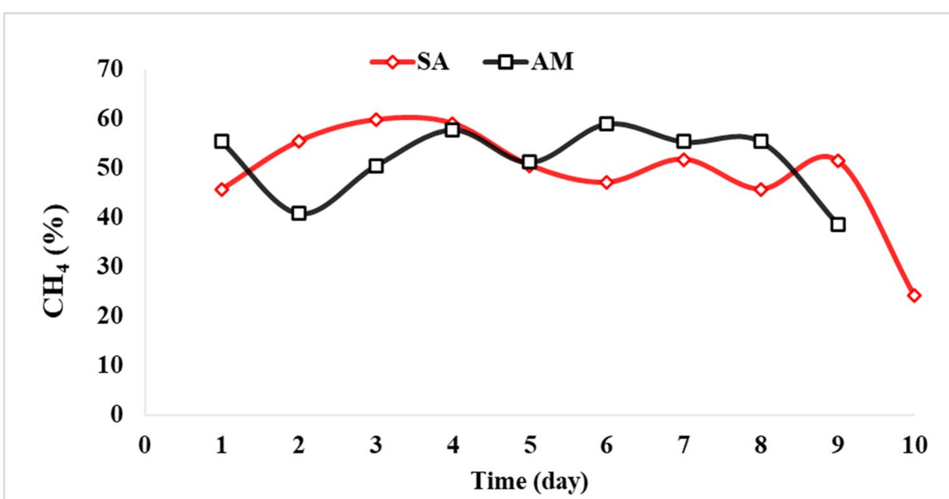


**Fig. 7** The variation of volumetric percentage of methane production from *S. alopecuroides* and *A. maurorum* during 10 days

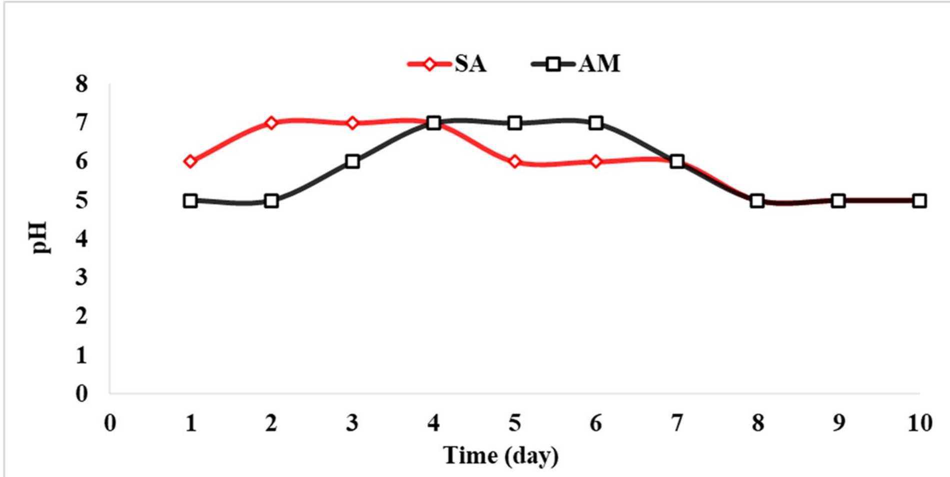


**Fig. 8** The variation pH for *S. alopecuroides* and *A. maurorum* within a 10-day period

therefore where pH is suitable (Fig. 8), anaerobic bacteria grew rapidly. Methane-producing bacteria for *S. alopecuroides* and *A. maurorum* were active on days 1–3 and 3–6, respectively. The amount of methane produced during this period increased and then decreased.

Figure 7 shows the V%/day of methane produced from *S. alopecuroides* (optimal ratio 1:6) and *A. maurorum* (optimal ratio 1:5). The production of methane from *S. alopecuroides* had an increasing trend from day 1 to 3 and reached its maximum on day 3. Regarding *A. maurorum*, the V%/

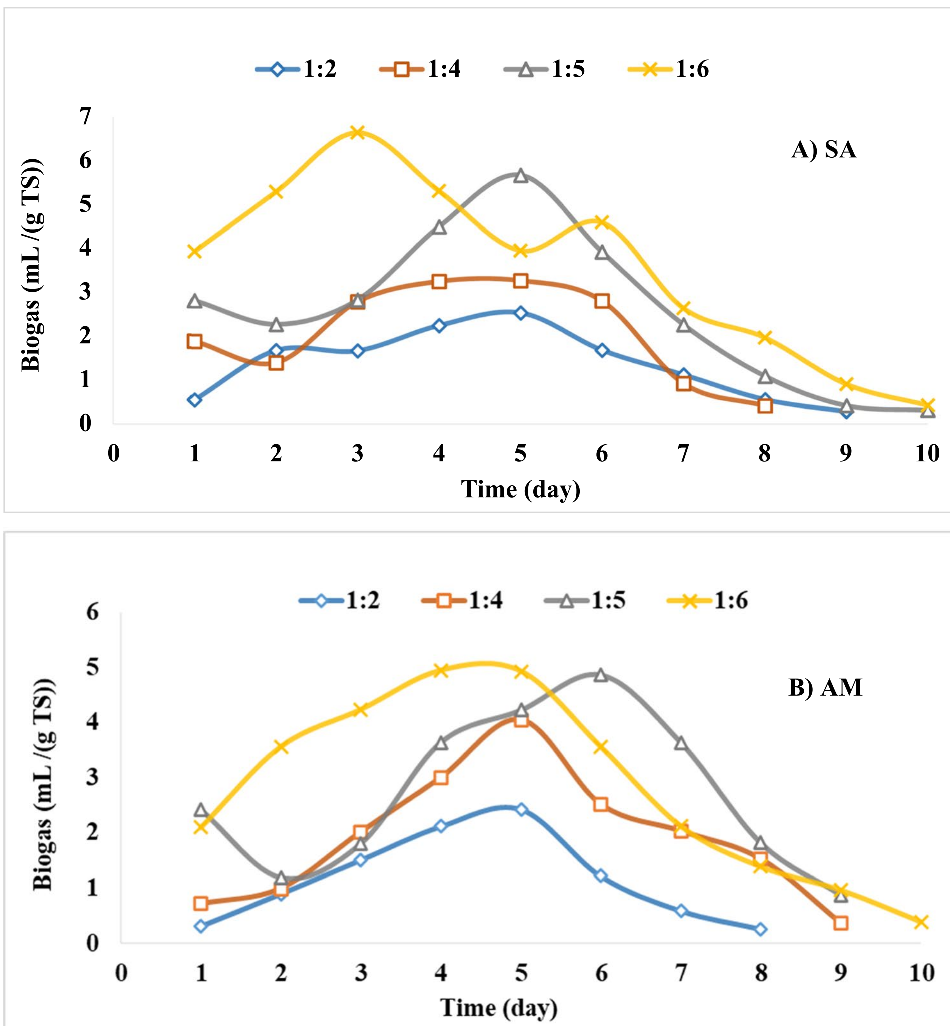


**Fig. 9** The variation of biogas production of (**A**) *S. alopecuroides* and (**B**) *A. maurorum* in ratios of 1:2, 1:4, 1:5, and 1:6

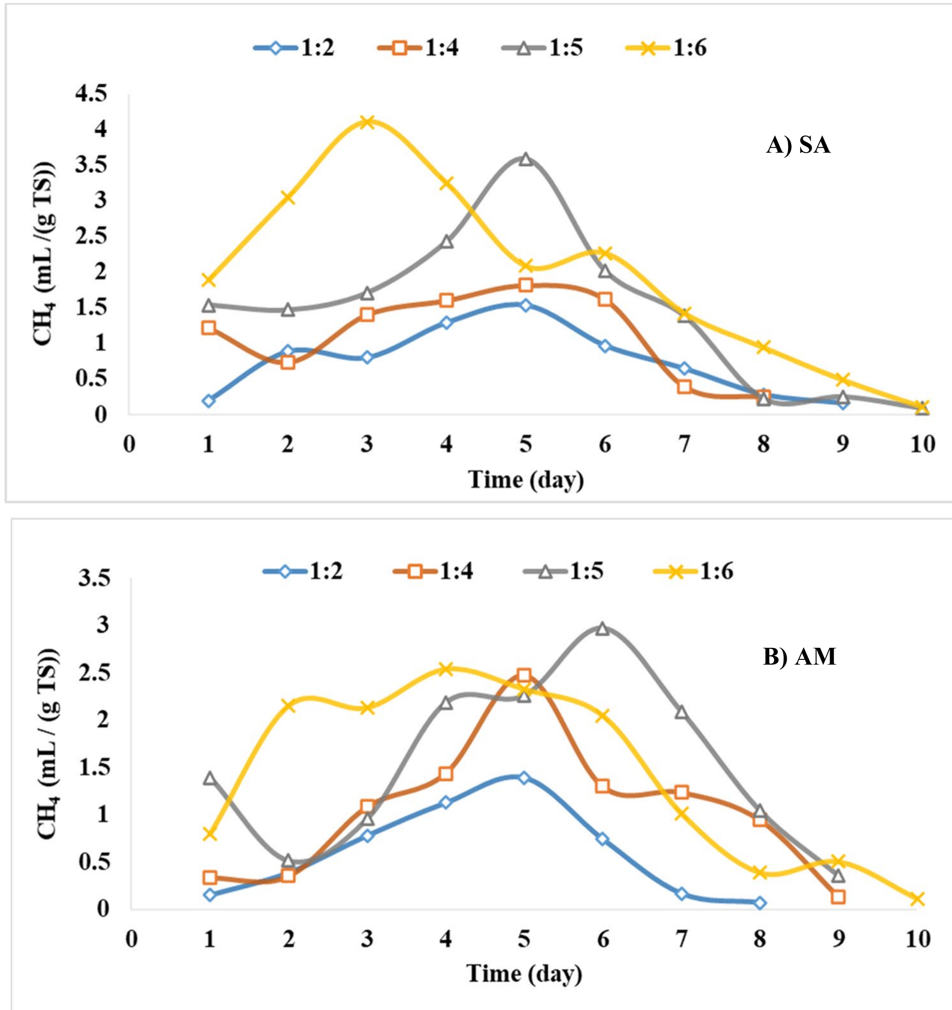


**Fig. 10** The variation of methane production of (**A**) *S. alopecuroides* and (**B**) *A. maurorum* in ratios of 1:2, 1:4, 1:5, and 1:6

day of methane produced decreased by 15% on day 2, then increased and reached its maximum on day 6. As shown in Fig. 7, the percentage of methane produced over a period of 2–8 days varied between 40 and 60% and then decreased. Changes in C/N and pH in the digester are among the reasons for daily changes in methane production.

### 3.3 Evaluation of pH changes in the digester

The pH plays an important role in the performance of an anaerobic digester. Proper alkalinity is one of the most important factors in proper pH control. Alkalinity is a buffer solution that prevents rapid changes in pH. Buffer solutions are able to neutralize small amounts of added acid or base, thus maintaining the pH of the solution relatively stable. The acid-producing bacteria have acceptable enzymatic activity at pH >5, but methane-producing bacteria do not have an acceptable activity at pH <6.2. Most obligate anaerobe bacteria, including methane-producing bacteria, have optimal activity at pH 6.8–7.2 [32]. The pH value decreases with the production of volatile acids and increases with their consumption and methane production. Figure 8 shows the pH changes for the two plants during different days. The pH level for *S. alopecuroides* was 6 on the first day and increased to 7 on the second day. This rate remained constant until the fourth day and then decreased. In *A. maurorum*, the pH level was constant until the second day, then increased and reached 7 on the fourth day, and this value continued until the sixth day, and after that, it decreased. From the seventh day to the last day, the pH level in both plants had the same trend. Moreover, as shown in Fig. 6, the pH range was more desirable on days 1 to 3 for *S. alopecuroide* and on days 3 to 6 for *A. maurorum*, which led to higher methane production.

### 3.4 Evaluation of biogas and methane production efficacy

In addition to proper fertilizer [33], maximum biogas production is also very important. Figure 9 shows the biogas

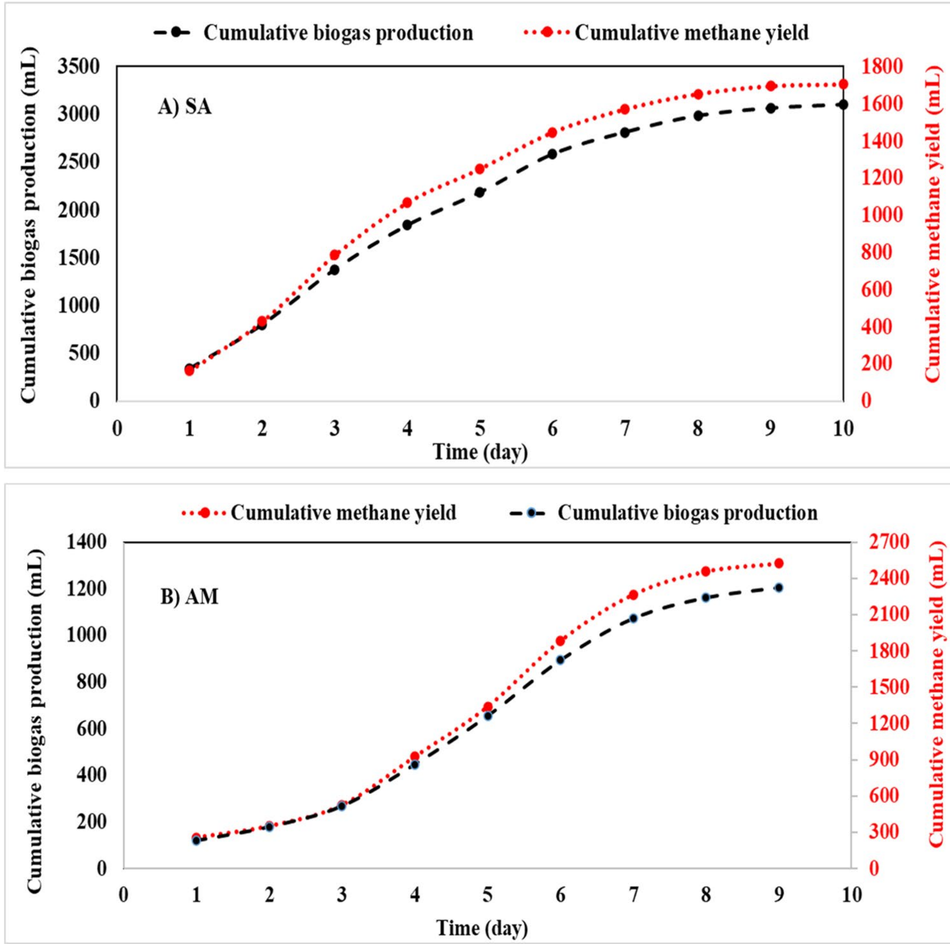


**Fig. 11** The variation of cumulative biogas production and cumulative methane yield for (**A**) *S. alopecuroides* and (**B**) *A. maurorum*

production efficiency (ratio of biogas volume to biomass mass) from *S. alopecuroides* and *A. maurorum* at different biomass to water ratios. The present study was carried out in a 10-day period. Various factors such as temperature, carbon to nitrogen ratio, acidity, proper mixing, material concentration, and type of materials identify as key parameters in biogas production [30]. As mentioned in Section 3.1, lower TS percentage and higher VS percentage are a factor in the amount of biogas produced. Figure 9 shows the difference between daily biogas produced at different biomass to water ratios. The amount of biogas produced in all ratios from both plants gradually decreased after day 6. Moreover, the highest biogas production was 6.6 and 4.9 ml/g TS for *S. alopecuroides* and *A. maurorum*, respectively.

Figure 10 shows the diagram of methane gas yield for *S. alopecuroides* and *A. maurorum* in different ratios vs days. One of the main factors in the amount of methane produced in anaerobic digestion is the C/N parameter. The higher the C/N ratio, the faster the nitrogen consumption and the lower the gas production. As shown in Fig. 5, the highest amount of methane produced from *S. alopecuroides* was on day 3 and at the optimal biomass to water ratio of 1:6 (4.1 mL/g TS) and from *A. maurorum*, it was on day 6 and at the optimal biomass to water ratio of 1:5 (2.9 mL/g TS); these data are consistent with Table 1. The production of methane in the last days gradually decreased and reached its lowest amount in the last day, which was due to the reduced activity of methane-producing bacteria.

Figure 11 shows the cumulative biogas production and cumulative methane yield from *S. alopecuroides* and *A. maurorum* at optimal biomass to water ratios. As can be seen, for *S. alopecuroides*, the slope of the chart is steep in the early days, which gradually decreases after day 3. Regarding *A. maurorum*, the slope of the diagram is slow in the first and last days, but on days 3 to 6, it has a steeper slope; these data are consistent with the results obtained about the pH (Section 3.3). Also, it was found that 56.3% and 55% of the biogas produced by *A. maurorum* and *S. alopecuroides*, respectively, were methane, meaning that the biogas produced by *A. maurorum* had better quality compared to that of *S. alopecuroides*.

## 4 Conclusion

The present study assessed the simultaneous anaerobic digestion of the two desert weeds *S. alopecuroides* and *A. maurorum* in different biomass to water ratios and most important results obtained are as follows:

- The highest quantity of cumulative biogas production within 10 days was 2324 and 3099 ml for *A. maurorum* (biomass:water ratio = 1:5) and *S. alopecuroides* (biomass:water ratio = 1:6), respectively.
- The high C/N level in *A. maurorum* (almost three times) compared to *S. alopecuroides* caused rapid nitrogen consumption and less methane production.
- The increasing trend of methane production at pH 6.8–7.2 was due to the proper activity of methane-producing bacteria in this range.
- *S. alopecuroides* produced 33.34% more biogas compared to *A. maurorum*.
- Biogas produced from *A. maurorum* had a better quality due to the higher percentage of methane.

**Author's contribution** Mohammad Gholizadeh: conceptualization, writing–reviewing and editing
Mahdi Deymi-Dashtebayaz: conceptualization, writing–reviewing and editing, supervision
Abolfazl Mehri: data curation, software, writing–original draft preparation
Alireza Zameli: writing–original draft preparation, writing–original draft preparation
Daryoush Dadpour: writing–reviewing and editing

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## Declarations

**Conflict of interest** The authors declare no competing interests.

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