Journal of Achievements in Materials and Manufacturing Engineering
VOLUME 37
ISSUE 2
December
2009

# Analysis of different substrates for processing into biogas

**B. Mursec [a,*], P. Vindis [a], M. Janzekovic [a], M. Brus [a], F. Cus [b]**
[a] Faculty of Agriculture and Life Sciences, University of Maribor, Pivola 10, 2311 Hoce, Slovenia
[b] Faculty of Mechanical Engineering, University of Maribor, Smetanova 17, 2000 Maribor, Slovenia
* Corresponding author: E-mail address: bogomir.mursec@uni-mb.si

Received 28.09.2009; published in revised form 01.12.2009

**Manufacturing and processing**

## ABSTRACT

**Purpose:** The main target is to produce as much biogas as possible with highest possible biomethane content from crops representing the principal fuel for driving the gas motors and electric generators and, consequently, production of electricity.

**Design/methodology/approach:** The biogas production was measured by a mini digester according to the German standard DIN 38414, Part 8. It was effected in the mesophilic temperature range. The biogas production from six different energy crops and pig slurry was measured in the laboratory of the Faculty of Agriculture and Life Sciences. In six trial fields the monocultures such as maize, sorghum, amaranth, sunflower, Jerusalem artichoke and sugar beet were grown.

**Findings:** The highest biomethane production was achieved with the sunflower substrate (283 Nl/kgVS), followed by the sorghum substrate (188 Nl/kgVS) and maize (187 Nl/kgVS). The amaranth substrate produced 225 Nl/kgVS and the Jerusalem artichoke 115 Nl/kgVS. The least amount of biomethane was produced from the sugar beet (95 Nl/kgVS).

**Research limitations/implications:** The basic structure of the laboratory device is welded from stainless steel (inox) and is limited by the following dimensions: 2500 mm length, 1000 mm height and 350 mm width. The device consists of twelve units of fermentors ensuring four tests simultaneously with three replications and assuring high accuracy of results.

**Practical implications:** The test fermentors serve to test the biogas production from different energy crops and other materials of organic origin. The results reached serve to plan the electricity production in the biogas production plant.

**Originality/value:** The mini digesters simulated in laboratory the actual state from the biogas production plant. Anaerobic fermentation was introduced and the biogas to be processed into electricity was produced.

**Keywords:** Technological devices and equipment; Energy plants; Biogas production; Fermentor

**Reference to this paper should be given in the following way:**
B. Mursec, P. Vindis, M. Janzekovic, M. Brus, F. Cus, Analysis of different substrates for processing into biogas, Journal of Achievements in Materials and Manufacturing Engineering 37/2 (2009) 652-659.

## 1. Introduction

The 21st century faces the problem of growing energy consumption and diminishing supplies of fossil fuels, which has led to researches of the use of renewable energy sources and, consequently, the development of new technological processes of energy production. One of the most efficient energy sources is the biogas produced from green energy crops and organic waste matters. The biogas has a very positive impact on the environment, since less $CO_2$ is formed during its combustion than used for photosynthesis by the plants from which it is produced [1, 2, 3, 4].

The biogas is formed during anaerobic fermentation of organic matters such as: farmyard manure, liquid manure, energy crops, organic waste materials, slaughter-house waste etc. In case the degradation process takes place in accurately specified conditions, the biogas is released. In the biogas device it is possible to use any organic-biological matters whose composition changes due to the effect of microorganisms and does not contain more than 15% of dry matter. With less than 5% of dry matter the degradation process still takes place, but is economically not justified. The top limit of the dry matter is the limitation, where the substrate can still be pumped and mixed. It often happens that the substrate must be thinned with water as a preparatory measure, which increases the cost of operation. After completion of fermentation a separator of the liquid and solid phase of the fermented mass is used as recourse. By the return of the liquid phase a great quantity of water is saved, the transport cost is reduced and the freshly supplied substrate is enriched with the bacterial flora. The methane bacteria cannot process the fats, proteins, carbohydrates in pure form. For processing they need nitro-compounds and microbic compounds which abound in the manure and animal slurry. Materials such as straw, long grass and other biological waste must be crushed, otherwise the fermentation process takes too much time (the retention time in the fermentor is prolonged very much) and the sediments on the fermentor bottom and the fragments on the surface of the fermenting mass accumulate [5, 6, 7].

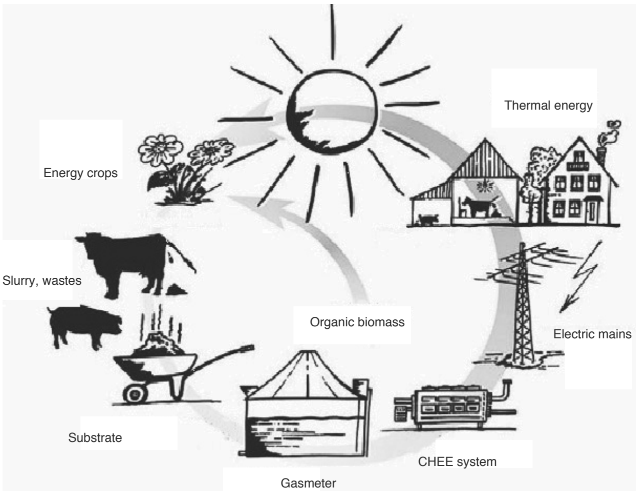


Fig. 1. Diagram of device for production and utilization of biogas from cattle-breeding, representing a natural energy circle [11]

The biogas production from animal droppings and green mass of energy crops is shown in Figure 1. The substrate consists of a mixture of animal droppings and several ensiled energy crops on which the gas profitability relies. The conditions for optimum production are limited by the anaerobic process at 35 °C (mesophilic range) and steady mixing of substrate in the digester. A covered gas-tight roof, i.e., the so-called geometer is provided at the digester top, where the biogas produced is stored. Electric energy is produced through constant supply of the biogas into the gas motor driving the electric generator. The generator must be connected to public electric mains for the purchase of the electric energy. During internal combustion of the water-cooled motor the heat is created which can be used for heating of the digester and other devices CHEE (co-generation of heat and electric energy) [8, 9, 10].

Operation of the installed laboratory device for biogas production and measuring was tested with the use of pig slurry mixtures and various co-substrates of energy and alternative crops.

The substrate, filled into fermentors, is connected with the eudiometer and levelling bulb with which it is possible to read the quantity of the biogas produced. Composition of the biogas produced was measured by Geotechnical Instruments GA 45 gas meter and the content of different present gases, produced by the decomposition and/or putrefaction of the substrate, was analysed.

The gas meter measures three principal component gases:

- $CH_4$ – methane,
- $CO_2$ – carbon dioxide,
- $O_2$ – oxygen.

By calibrated measurements it is possible to determine and calculate the quantity of the biogas produced from the composed substrate in accordance with standard DIN 38414.

The biogas contains combustible and non-combustible matters shown in Table 1. The composition largely depends on the organic matters formed during the fermentation process.

Table 1 shows the usual chemical composition of the biogas. Quality of the biogas from the point of view of energy utilization is governed by the percentage of the methane concentration, however, it can be improved by reducing the share of non-combustible matters. Usually, this implies the removal of carbon dioxide and sulphuretted hydrogen. In reaction with water the sulphuretted hydrogen forms the corrosive sulphuric acid ($SO_2$ + $H_20$ = $H_2SO_3$ - sulphuric acid).

Table 1.
Combustible and non-combustible ingredients of biogas [11]

| Biogas composition | |
|---|---|
| Combustible ingredients of biogas | Concentration (%) |
| Methane ($CH_4$) | 50 – 70 |
| Hydrogen ($H_2$) | < 1 |
| Sulphuretted hydrogen ($H_2S$) | 2 |
| | |
| Non-combustible ingredients of biogas | Concentration (%) |
| Carbonic hydrogen ($CO_2$) | 25 – 50 |
| Water steam ($H_2O$) | 2 – 7 |
| Oxygen ($O_2$) | 0 – 0,5 |
| Ammonia ($NH_3$ ) | 0 – 2 |

The calorific value of 1 $m^3$ of biogas from the mixture of pig slurry and maize is about 4 to 7 $kWh/m^3$ of electric energy depending on the methane content and substrate preparation.

## 2. Description of the approach, work methodology, materials for research, assumptions, experiments etc.

The co-substrate consists of several types of different crops which were tested one by one for methane production and/or profitability. Those crops are: maize, sorghum, amaranth, Jerusalem artichoke, sunflower and sugar beet.

Figure 2 shows the pig slurry inoculum.

Fig. 2. Pig slurry inoculum

Figure 3 shows the production of gas from various substrate samples.

Fig. 3. Production of gas from various substrate samples

### 2.1. Eudiometr

The eudiometer is a laboratory glass gas tube, closed on one side, with scale measuring the volume of biogases in the chemical reaction.

Eudiometer construction:

For execution of the test the apparatus shown in Figure 4 is used. It consists of the eudiometer tube (B) of 300 to 400 ml volume graduated from the top down (the scale for the division of the value is 5 ml) and placed onto an upright bottle with a ground joint-fermentor (A) of 500 ml volume. A connecting tube (C), allowing the entry of the putrefied gas in the upright bottle into the measuring tube, runs through the eudiometer bottom. The connecting tube remains in fixed position due to glass sticks fitted on four sides (E). The glass fermentor from which a sufficiently long dosed connecting pipe (F) runs to the levelling bulb (G), made of glass or synthetic material (at least 750 ml volume) is located at the eudiometer lower end. A tap cock (H) is provided at the eudiometer top end for gas sampling and for adjustments of the zero point.

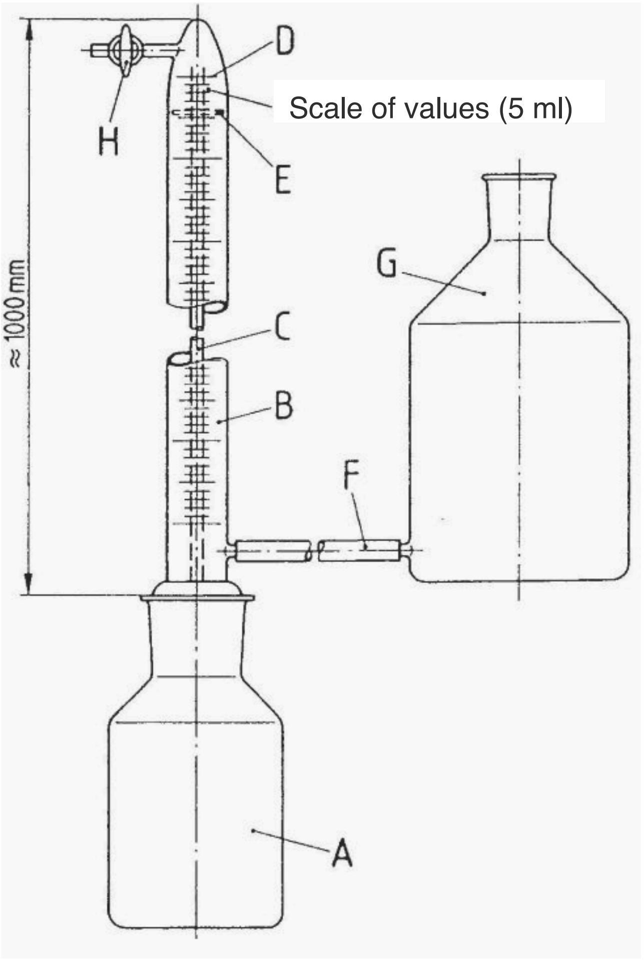


Fig. 4. Eudiometer for determination of gas from substrate charged [12]

## 2.2. Materials used

The mini digester consists of several units [13, 14, 15]:

- Water thermostat and heating pump.
- Thermometer for measuring the room and water bath temperature.
- Barometer.
- Equipment for gas analysis (carbon dioxide, methane, oxygen, hydrogen, nitrogen, e.g., Geotechnical Instruments GA 45 gas meter or gas-phase chromatograph.
- Confining liquid: 30 ml of sulphuric acid $H_2SO_4$ is added to 1 l of distilled water; in this mixture 200 g of $Na_2SO_4 \cdot 10\ H_2O$ are separated through light heating.
- A few drops of methyl orange solution (0,1 g of methyl orange sodium salt dissolved in 100 ml of distilled water) are added to the solution and the solution turns orange. The confining liquid is then stored at room temperature.
- Water bath for fermentors.
- Levelling bulb with connecting pipe up to eudiometer of up to 400 ml volume.
- Fermentor bottle of 500 ml volume.
- Appropriate energy crops and animal slurry for substrate mixture.
- Sealing compound to prevent ingress of oxygen into fermentors and gas evaporation.
- Weighing device for precise weighing of mixture quantity.

Fig. 5. Series of tests of biogas production

## 2.3. Preparation of test

At the beginning of test the residual dry matter and the organic matter of the inoculum were determined. Prior to the beginning of test, except in exceptional cases, the pH value of the inoculum was adjusted to 7 to 8 pH, if possible, with simultaneous adding of inorganic depressors, e.g., sodium hydrogen carbonate; the inoculum was tempered to about 35 °C.

In extreme cases, the optimization of the offer of nutritive substances by adjusting the C: N: P ratio of the mass to about 100: 6:1 is required. This is affected by adding ammonium chloride $NH_4Cl$ or sodium hydrogen phosphate $NaH_2PO_4$. Additional tests depend on specific problems and on the manner of initial processing of the sample. The test (Figure 5) comprised two check samples of the pig slurry inoculum producing the minimum biogas quantity, followed by three series of tests with three replications from which the biogas yield from crops was evident. Additional equipment: heating pump, digital thermometer and barometer, well covered fermentor in water bath is of key significance for successful process of biogas production.

## 2.4. Implementation

The test was carried out in water bath at 35 °C (+/-1). Reaction vessels (standard bottles A), necessary for the series of tests, were filled with a great quantity of substrate (Table 2), only the current thinning ratio varied.

Table 2.
Recommended ratio for execution of test

| Masses of inoculum and trial inoculum in mixture in g | | | |
|---|---|---|---|
| Test No. | Inoculum sample | Inoculum | Mixture |
| 0 | 0 | 400 | 400 |
| 1 | 15 | 385 | 400 |
| 2 | 20 | 380 | 400 |

For the beginning of the test series the recommended mixing ratio is as indicated in Table 2. The reference inoculum should have similar organic matter content as the inoculum used. The upright bottle-fermentor (A) was filled with the specified inoculum content (Figure 6); the air in the bottle was supplanted bay nitrogen and the eudiometer (B) was placed in position. By means of the levelling bulb (G), with eudiometer cock (H) open, the confining liquid level was adjusted to the mark 0. The confining liquid must not enter into the connecting tube (C) and, consequently into the trial inoculum. The levelling bulb should be filled up to one fourth. Then the cock (H) was closed.

The upright bottle (A) with inoculum mixture should be kept in the dark. The volume of the gas released lowered with the level equality of the confining liquid with the eudiometer tube and levelling bulb. At the beginning, the developed gas volume was let out every day (if necessary, more frequently); later on, with decreasing gas formation it was let out in many time intervals and was entered into the table of values. The test continued, until a relatively small volume of putrefied gas had been formed (1% of the total volume produced until that moment every day).

The major quantity of putrefied inoculum is, usually, biologically degraded during the first week of the test. After 40 days, usually, a very low gas formation is observed. On each reading of the gas volume in the eudiometer tube the temperature and the air pressure are determined so that the gas volume can be re-calculated into normal conditions. The level of the confining liquid is to be adjusted, too, depending on the gas formation, after each individual reading or after several readings with open cock (H), supposing that the air must not enter into the tap cock (H). In many cases the established volume of the gas formed is enough large.

Fig. 6. Fermentor filled with substrate

# 3. Description of achieved results of own researches

## 3.1. Biogas production from maize

The maize (˝*Zea mays*˝ *L.*) of Nexos variety was sown during the 1st decade of May and was harvested by ensiling the complete plant at the beginning of October in the stage of full maturity. After harvesting it was stored in anaerobic conditions and after certain conservation time the average maize sample was taken for measurements and chemical analysis specified by the laboratory. The mixture consisted of 15 g of ensiled maize mass and 385 g of inoculum. The test with measurements proceeded in three replications of the same substrates during 35 days [16]. The biogas production was accompanied by daily measurements with reading of the biogas volume produced from the substrate. The gas production from maize proceeded normally as shown in Figure 7. The final result of the biogas production was the average value of three replications and amounted to 362 Nl/kgVS. During the test the daily concentration of methane in the sample was measured; its content was 53.47% out of which the average calculated amount of methane was 187 Nl/kgVS.

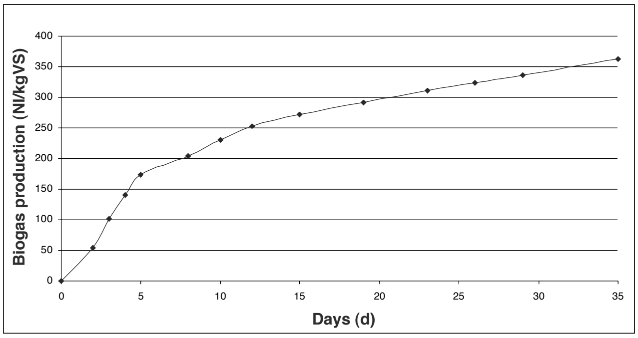


Fig. 7. Biogas production from maize substrate

## 3.2. Biogas production from sorghum

The sorghum (˝*Sorghum*˝ *L.*) of Autan variety was sown during the 1st decade of May and harvested by ensiling the complete plant at the beginning of October in the stage of full maturity. After harvesting it was stored in anaerobic conditions and after certain conservation time the average sorghum sample was taken for measurements and chemical analysis specified by the laboratory. The mixture consisted of 15 g of ensiled sorghum mass and 385 g of inoculum.

The test with measurements proceeded during 35 days in three replications with the same substrates. The gas production from sorghum proceeded partly normally as shown in Figure 8. After the fifth day of the test the biogas production lowered and lagged behind until the 15th day. This phenomenon may be caused by trouble in the fermentor due to presence of major concentration of carbon dioxide and oxygen. The final result of the biogas production was the average value of three replications and amounted to 350 Nl/kgVS. During the test the daily concentration of methane in the sample was measured, its content was 51.81% out of which, the average calculated amount of methane was 188 Nl/kgVS.

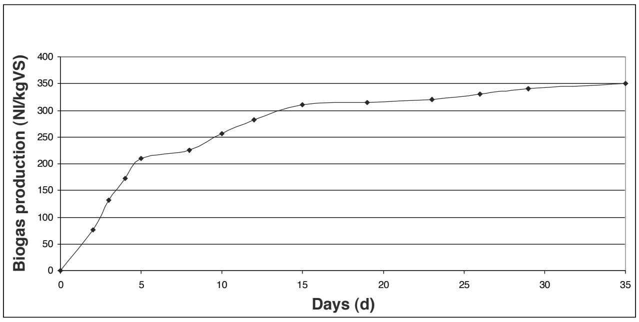


Fig. 8. Biogas production from sorghum substrate

## 3.3. Biogas production from amaranth

The amaranth (˝*Amaranthus sp.*˝ *L.*) of Acruentus G6 variety was sown during the 1st decade of May and harvested by ensiling the complete plant at the beginning of October. After harvesting it was stored in anaerobic conditions and after certain conservation time the average amaranth sample was taken for measurements and chemical analysis specified by the laboratory. The mixture consisted of 15 g of amaranth and 385 g of pig slurry inoculum. The test with measurements proceeded during 35 days with three replications of the same substrates. The biogas production was accompanied by daily measurements with reading of the biogas volume produced from the substrate. The gas production from amaranth proceeded normally as shown in Figure 9. The final results of the biogas production were the average value of three replications and amounted to 280 Nl/kgVS. During the test the daily concentration of methane in the sample was measured; its content was 44.56% out of which the average calculated amount of methane was 125 Nl/kgVS.

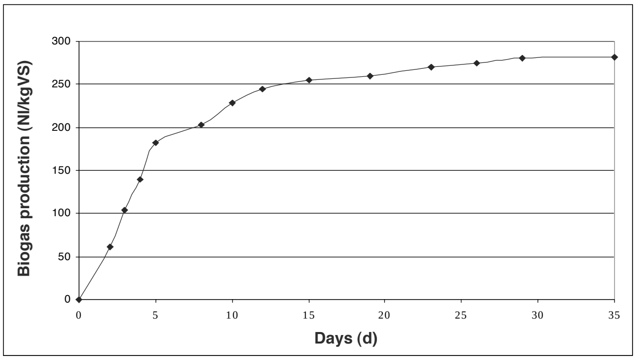


Fig. 9. Biogas production from amaranth substrate

## 3.4. Biogas production from sunflower

The common sunflower (″*Helianthus annuus*″ *L*.) was sown during the 1st decade of May and harvested by ensiling the complete plant at the beginning of September. After harvesting it was stored in anaerobic conditions and after certain conservation time the average sunflower sample was taken for measurements and chemical analysis specified by the laboratory. The mixture consisted of 15 g of ensiled sunflower mass and 385 g of inoculum. The test with measurements proceeded in three replications with the same substrates during 35 days. The biogas production was accompanied by daily measurements with reading of the biogas volume produced from the substrate. The gas production from sunflower proceeded normally as shown in Figure 10. The final result of the biogas production was the average value of three replications and amounted to 451 Nl/kgVS. During the test the daily concentration of methane in the sample was measured; its content was 62.85% out of which the average calculated amount of methane was 283 Nl/kgVS. Due to its high energy potential the sunflower produced the highest biogas yield, which could not be reached by other crops.

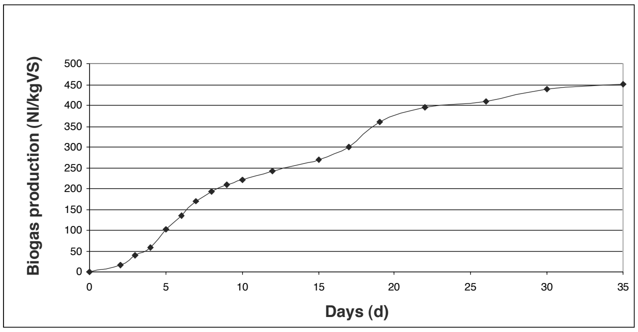


Fig. 10. Biogas production from common sunflower substrate

## 3.5. Biogas production from Jerusalem artichoke

The alternative crop Jerusalem artichoke (″*Helianthus tuberosus*″ *L*.) was sown during the 1st decade of May and harvested by ensiling the complete upper part of the plant at the beginning of October. After harvesting it was stored in anaerobic conditions and after certain conservation time the average Jerusalem artichoke sample was taken for measurements and chemical analysis specified by the laboratory. The mixture consisted of 15 g of Jerusalem artichoke mass and 385 g of inoculum. The test with measurements proceeded in three replications with the same substrates during 35 days. The biogas production was accompanied by daily measurements with reading of the biogas volume produced from the substrate. The progress of gas production from the Jerusalem artichoke was hindered, i.e., the production was delayed and the gas formation was hindered as shown in Figure 11. The final result of the biogas production was the average value of three replications and amounted to 217 Nl/kgVS. During the test the daily concentration of methane in the sample was measured; its average content was 52.56% out of which the average calculated amount of methane was 115 Nl/kgVS.

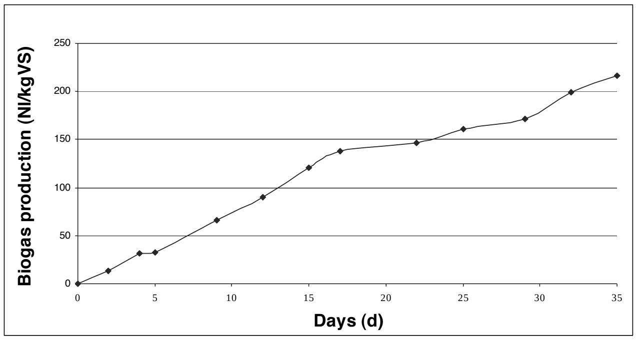


Fig. 11. Biogas production from Jerusalem artichoke substrate

## 3.6. Biogas production from sugar beet

The sugar beet (″*Beta vulgaris sp. L*″.), which was previously one of the principal crops for sugar production, can be also used for biogas production. It was sown during the 1st decade of May and harvested in October by ensiling the complete plant - root and green top part of the plant above ground. After harvesting it was stored in anaerobic conditions and after certain conservation time the average sugar beet sample was taken for measurements and chemical analysis specified by the laboratory the mixture consisted of 15 g of sugar beet mass and 385 g of inoculum. The test with measurements proceeded in three replications with the same substrates during 35 days. The biogas production was accompanied by daily measurement with reading of the biogas volume produced from the substrate. The progress of gas production from the sugar beet was hindered, i.e., the production was delayed and the gas formation was hindered due to the presence of water formation as shown in Figure 12.

The final result of the biogas production was the average value of three replications and amounted to 106 Nl/kgVS. During the test the daily concentration of methane in the sample was measured; its average content was 55.82% out of which the average calculated content of methane was 95 Nl/kgVS.

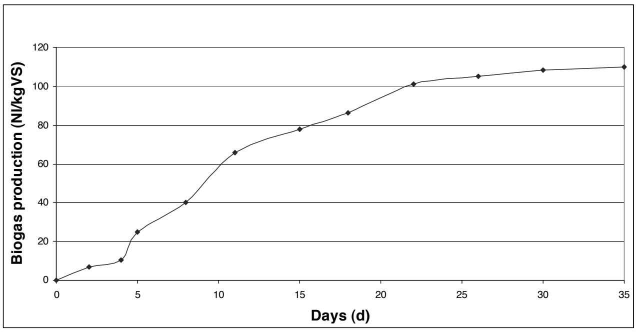


Fig. 12. Biogas production from sugar beet substrate

## 3.7. Final results of production and explanation

The final result of the biogas production and methane produced from crops is shown in Table 3, where the average calculated values of biogas production are indicated.

Table 3.
Data on calculated production of biogas and methane from crops

| | Methane (Nl/kgVS) | Biogas (Nl/kgVS) |
|---|---|---|
| Maize | 187 | 362 |
| Sorghum | 188 | 350 |
| Amaranth | 125 | 280 |
| Sunflower | 283 | 451 |
| Jerusalem artichoke | 115 | 217 |
| Sugar beet | 95 | 106 |

In Figure 13 the quantities of the produced biogas in comparison with the methane yield are graphically shown. During the tests of various alternative crops it was estimated that the sunflower has the highest energy potential and results in the highest methane production and concentration.

In case of sunflower the methane concentration reached about 62.85%; it means that out of 451 Nl/kgVS the methane quantity was 283 Nl/kgVS which was useful for utilization of the fuel. Two universally useful crops are maize and sorghum which are predominant animal feed as mixture or singly. The maize and sorghum are also suitable for the biogas production because they contain much proteins and carbohydrates, which is a high energy potential.

The amount of the biogas produced from sorghum is about 350 Nl/kgVS, the methane content concentration is 50 - 60%, i.e., about 180 - 205 Nl/kgVS.

Other alternative crops such as Jerusalem artichoke and amaranth, which also have a high protein supply but cannot compete with predominant crops such as maize, produced considerably less gas and methane. The methane concentration in the amaranth sample was not excessively low, since it amounted to about 50% on an average.

The biogas and methane yield was in strong contrast with the value of the dry matter and moisture percentage in the sample, since it varied round 180 - 280 Nl/kgVS of biogas and 120 Nl/kgVS of methane.

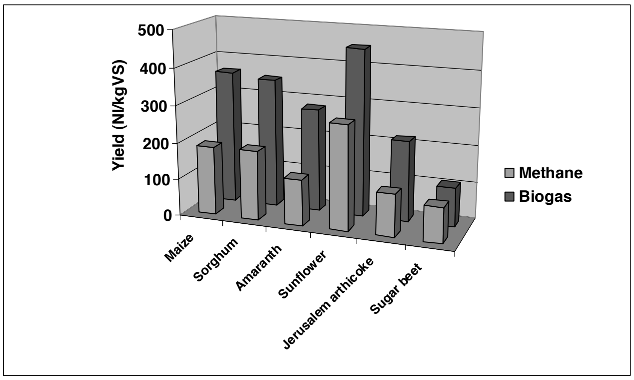


Fig. 13. Comparison of results of production between methane and biogas

The average methane concentration percentages in the substrate, shown in Figure 14, represent the percentages of the methane amount present in the crop, which is of key importance for the biogas yield.

The effects on the methane production in the biogas depend on the preparation of the substrate which must not contain undesirable inorganic matters which would hinder the fermentation process.

The key factors for the fermentation process are the pressure in the fermentor and the percentage of moisture in it. In this way the biogas yield and the methane concentration percentage can be considerably larger.

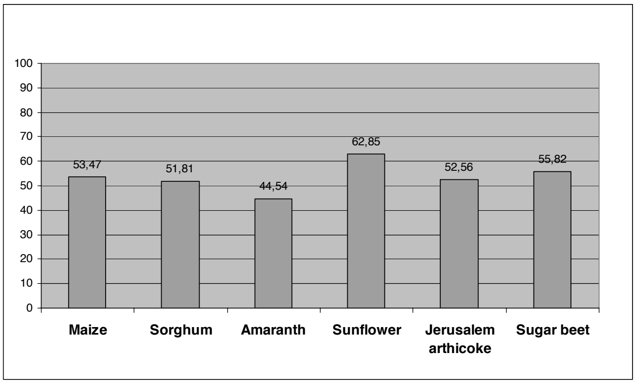


Fig. 14. Average methane concentration in substrate

## 4. Conclusions

The following conclusions have been reached by test:

- The biogas production continued during 35 days in 0.5 l fermentor at 35 °C.
- Analysis comprised six different tests with three replications from which the methane yields were evident.

- The biogas production proceeded in a slightly alkaline range; it means that the substrate contained the optimum pH between 7 and 7.5.
- The process of production depends on the parameters such as: anaerobic condition of production, temperature in fermentor, pH value of substrate, uniform pressure in fermentor and mixing of substrate in fermentor..
- The highest biomethane production has been reached with the sunflower substrate, followed by substrates of sorghum, amaranth and Jerusalem artichoke, while sugar beet produced least biomethane.
- For higher biogas yields the substrate must contain high-quality and degradable organic matters, from which a higher percentage of the methane concentration is produced.

## References

[1] K. Navickas, Biogas for farming, energy conversion and environment protection, International symposium, Biogas, technology and environment, University of Maribor, Faculty of Agriculture, (2007) 25-29.

[2] P. Weiland, Production and energetic use of biogas from energy crops and wastes in Germany, Applied Biochemistry and Biotechnology 109 (2003) 263–274.

[3] D. P. Chynoweth, Biomethane from energy crops and organic wastes, Proceedings of the 10th World Congress on Anaerobic Digestion, Montreal, Canada, 2004, 525-530.

[4] A. Ploj, B. Mursec, F. Cus, U. Zuperl, Characterization of machines for processing of waste materials, Journal of Materials Processing Technology 175/1-3 (2006) 338-343.

[5] A. Tiehm, K. Nickel, M. Zellhorn, U. Neis, Ultrasonic waste activated sludge disintegration for improving anaerobic stabilization, Water Research 35 (2001) 2003-2009.

[6] F.P. Gene, Fundamentals of anaerobic Environmental engineering 112 (1986) 867-920.

[7] E.J. Cook, Anaerobic sludge digestion: Manual of practice No. 16, Alexandria VA: Water pollution control federation: Task force on Sludge stabilization, 1986.

[8] H. Fredriksson, A. Baky, S. Bernesson, L. Nordberg, O. Noren, P. Hansson, Use of on-farm produced biofuels on organic farms - Evaluation of energy balances and environmental loads for three possible fuels, Agricultural Systems 89 (2006) 184-203.

[9] A. Bonmati, X. Flotats, L. Mateu, E. Campos, Study of thermal hydrolysis as a pretreatment to mesophilic anaerobic digestion of pig slurry, Water Science Technology 4/44 (2001) 109-116.

[10] B. Mursec, M. Janzekovic, F. Cus, U. Zuperl, Comparison of rollers after sowing of buckwheat, Journal of Achievements in Materials and Manufacturing Engineering 17 (2006) 269-272.

[11] J. Garvas, Biogas, http://www.ee.uni-lj.si /VOOVE/ekskurzija_2007/system/bioplin.pdf, University of Ljubljana, Faculty of Mechanical Engineering.

[12] DIN 38 414, Determination of digestion behaviour ‘‘sludge and sediments’’, Beuth Verlag, Berlin, 1985 (in German).

[13] P. Vindis, B. Mursec, C. Rozman, M. Janzekovic, F. Cus, Biogas production with the use of mini digester, Journal of Achievements in Materials and Manufacturing Engineering 26 (2008) 99-102.

[14] D. Stajnko, M. Brus, M. Hocevar, Estimation of bull live weight through thermographically measured body dimensions, Computers and Electronics in Agriculture 2/61 (2008) 233-244.

[15] B. Mursec, F. Cus, Integral model of selection of optimal cutting conditions from different databases of tool makers, Journal of Materials Processing Technology 133 (2003) 158-165.

[16] T. Amon, B. Amon, V. Kryvoruchko, W. Zollitsch, K. Mayer L. Gruber, Biogas production from maize and dairy cattle manure - Influence of biomass composition on the methane yield, Agriculture, Ecosystems and Environment 118 (2007) 173-182.