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Biogas Production: Evaluation and Possible Applications

Venko Beschkov

Abstract

Biogas is an excellent example of renewable feedstock for energy production enabling closure of the carbon cycle by photosynthesis of the existing vegetation, without charging the atmosphere with excessive carbon dioxide. The present review contains traditional as well as new methods for the preparation of raw materials for biogas production. These methods are compared by the biogas yield and biogas content with the possible applications. Various fields of biogas utilization are discussed. They are listed from simple heating, electricity production by co-generation, fuel cell applications to catalytic conversions for light fuel production by the Fischer-Tropsch process. The aspects of carbon dioxide recycling reaching methane production are considered too.

Keywords: biogas, raw materials, pre-treatment, production, utilization

1. Introduction

The extensive economic growth in the developed countries imposed a severe impact on the air and water quality. The impact on the air quality consists in the enormous emissions of greenhouse gases from many sources: energy production, burning fossil fuels, transport and household. The emission rate of resulting carbon dioxide in the atmosphere is too high to enable its assimilation by the present vegetation. Therefore, the concept of the use of renewable energy sources became so important during the last decades. Besides wind and solar energy, an important place occupies the biomass, namely biogas, bioethanol, biodiesel. The main reason is the replacement of fossil fuels by carbon-containing biomass that can be easily assimilated by the present vegetation. Hence, the carbon cycle is closed. Another option of use of biomass is its application as raw material for chemical productions thus replacing, at least partially the oil as the main feedstock for organic synthetic products [1–3].

Biogas is the simplest renewable fuel in comparison with bioethanol and biodiesel. Besides its use as a fuel, it can be converted into other products, like light fuels and chemical products after dry reforming and consequent catalytic conversions, like the Fischer-Tropsch process [4]. Many countries adopted programs for biogas applications in energy production [5, 6]. The comparison between the biofuels produced by different biomass as the substrate is shown below.

Biogas is produced by anaerobic digestion of organic materials from the natural origin [7–9]. Normally it contains methane (50–75% vol.). The rest is carbon dioxide with small amounts of nitrogen, hydrogen, ethane and traces of sulfur

compounds (hydrogen sulfide and mecaptanes). The calorific value of biogas is between 20 and 32 MJ/m^3. Its production became popular in the first half of the twentieth century. It became more important after the growth of the oil and gas prices in the 1970s. On the other hand, its importance is steadily maintained in the developing countries in Asia and Africa where a lot of low-scale anaerobic digesters are developed and used in the household [10, 11]. Currently, biogas production is popular in Europe and North America as a tool for simultaneous treatment of waste in agriculture and food industry and energy production at the same time to maintain these activities [10, 12, 13]. Landfill gases containing methane are also the reason for concern, since the emitted methane has a 25 times stronger greenhouse effect than carbon dioxide. There are also practical applications for the utilization of these gases for energy production thus reducing their harmful greenhouse effect.

The global energy production from biogas in the year 2000 was about 280,000 TJ, growing to almost 1.3 million TJ by 2014. As a volume, the annual world production of biogas was about 59 billion cubic meters in 2013. Almost half of this amount was produced in the European Union [10, 12, 14, 15] and it is growing considerably during the last decade [13].

The classical substrate for biogas production is manure (cattle, pig), poultry litter and activated sludge. However, there are other carbon sources to be treated by anaerobic digestion, like lingo-cellulosic residues, waste from the food industry, like stillage from ethanol distilleries, vegetable and meat industries, etc. In some cases, these substrates must be pre-treated to be converted into digestible form [14–16].

In the present chapter different substrates for biogas production will be considered along with their pre-treatment and mode of operation. Different applications of biogas will be outlined below.

2. Substrates and biogas yields

The traditional substrate for biogas production is manure, poultry litter, lingo-cellulose, activated sludge, as well as residues from the food industry (stillage from alcohol beverage production, vegetable waste, etc.). The gas yield per unit mass of substrate is an important indicator for further decisions for process development and plant construction. There are various data for this indicator but here we shall present some of them as average figures, cf. **Table 1** [17].

The best methane yield per unit of total solids can be attained by grass as a substrate. In general, the choice of substrate depends on various factors: its availability and the problems it may cause; the economic issues, as the price of energy and waste treatment; the equipment for anaerobic digestion, etc. For example, the

Substrate	Biogas yield, m^3/kg TS	Methane content, %vol.	Specific methane yield, m^3/kg TS	Reference
Cattle manure	0.29	62.8	0.182	[16]
Pig manure	0.43	66.9	0.288	[17, 18]
Poultry litter	0.47	57.9	0.277	[19]
Grass	0.55	77	0.423	[17]
Straw	0.34	58.0	0.197	[17]
Corn stalks	0.42	53.0	0.226	[17]

Table 1.
Experimentally estimated biogas yields per unit total solids (TS) from different agricultural waste.

use of grass gives the best results but requires additional pre-treatment to facilitate the conversion of non-soluble lignocellulose into soluble and biodegradable oligosaccharides. More detailed survey on the waste potential for biogas production is given in [17–20].

3. Pretreatment of substrates

The pretreatment methods of biomass for biogas production depend on the type of substrate and it is associated with the main scheme of consecutive steps of AD. [21].

The pretreatment method is related closely to the first step in the technology, i.e., the hydrolysis of insoluble organics. As a result, the macromolecules, i.e., carbohydrates, proteins, lipids are converted into soluble and digestible compounds of lower molecular mass.

The main groups of pretreatment methods of organic substrates for biogas production are mechanical, chemical methods [22] and microbial ones [8].

Milling is an inevitable step in substrate pretreatment reducing the size of the material particles. It can improve susceptibility to enzymatic hydrolysis of lignocelluloses [23].

3.1 Chemical methods

The chemical methods are based on acid or alkaline hydrolysis of the natural polymers.

The biggest problems are met with the pre-treatment of lingo-cellulosic substrates. The main problem is the removal of lignin. Alkaline hydrolysis is used for this purpose. Sodium hydroxide, lime or ammonia are applied with a substantial increase of biogas production, up to 16% vol. [24, 25].

Another chemical method is the treatment of substrates by calcium hypochlorite, combining chemical oxidation with alkaline action. There are new data for the treatment of waste-activated sludge by $Ca(ClO)_2$ thus increasing the methane yield up to 60% [26].

The acid hydrolysis of ligno-cellulose substrates consists of the treatment of the substrate by sulfuric acid [27], but hydrochloric acid and nitric acid also have been used [22]. The acid hydrolysis is usually accomplished at higher temperatures (120-180°C) and pressure. Under these conditions hemicellulose is completely degraded, cellulose to a higher extent. However, lignin is only partially degraded.

A serious disadvantage of these two kinds of chemical treatment is the necessity of pH adjustment because of the sensitivity of the methanogenics toward pH. It is known they can successfully produce methane in the pH range of 6–8.

Best results of chemical treatment are obtained by H_2O_2 in alkaline media combined with microwave treatment [28]. However, the price of H_2O_2 makes this method unpractical.

There are also some efforts for pretreatment by ozonolysis [29, 30], ionic liquids [31–33]. But they are too costly for large-scale practical application.

3.2 Thermal methods and steam explosion

3.2.1 Thermal pretreatment

Besides the thermochemical methods (acid and alkaline hydrolysis) thermal pretreatment consist of purely thermal treatment. First, it is treatment by hot water at elevated pressure so keep water at liquid state [34].

This kind of pretreatment facilitates the further enzymatic digestibility of cellulose with better sugar yield and almost no fermentation inhibitor [35]. An advantage of this method is the lack of chemicals and additional waste streams and it is eco-friendly because it does not need neutralization of liquid streams and conditioning chemicals saving time and energy for it.

A number of chemical reactions takes place during hot water pretreatment. The thermal destruction of hemicellulose results in the production of organic acids. They act as catalysts to promote the hydrolysis of carbohydrate polysaccharides into oligosaccharides and monosaccharides. These processes resemble dilute acid hydrolysis.

3.2.2 Steam explosion

The method of steam explosion consists of the action of saturated steam at high pressure on the biomass for some time. Afterwards the pressure is released abruptly causing the explosive breakdown of the macromolecules in the biomass and the bonds between them [36]. It is a widely used method of biomass pretreatment for various purposes (ethanol fermentation, biogas production, etc.). It is considered a catalyzed and uncatalyzed steam explosion. In the first case, some acidic chemicals (SO_2, H_2SO_4, CO_2) are used as catalysts to mix with biomass before steam-explosion. The commonly used temperature range is 160–260°C for short period of time at pressures up to 4.8 MPa [37].

During uncatalyzed steam, explosion hemicellulose is degraded and lignin structure is altered. The cellulose digestibility during steam explosion followed by enzymatic hydrolysis is enhanced [38, 39]. However, the catalyzed steam explosion is considered more efficient because of the deeper transformation of the biomass into mode digestible intermediates but in some cases neutralization of the mixture is required, e.g., when sulfuric acid is applied.

Certain limitations associated with the steam explosion method are: (1) incomplete disruption of fibers, (2) generation of inhibitory components to microbial growth, enzymatic hydrolysis and fermentation [40]. Because inhibitory degradation products are formed pretreated biomass needs to be washed with water to remove the inhibitory materials along with water-soluble hemicelluloses [41]. The apparent increase of lignin content during heat treatment has been observed due to hemicelluloses degradation product, furfural and lignin polymerization [41].

The more profound removal of lignin is a key-step in biomass pre-treatment before anaerobic digestion and therefore special attention is paid to it, cf. Timilsena [42].

3.2.3 Enzyme methods

This group of methods is essential for biomass pre-treatment. It can be applied in combination with other ones, as mentioned above or separately. Usually, it is relied on enzymes existing in the very biomass, for example in cattle manure [43]. Otherwise, isolation and application of certain hydrolases for the aims of biogas production are not economically acceptable.

The main microbial species, capable to convert the insoluble substrates into soluble ones are from the genera *Pseudomonas, Cellulomonas, Streptomyces, Bacillus*, etc. and white-rot fungi (like *Trichoderma, Aspergillus, Penicillium*) as well [9].

There are data about the capability of certain fungi to degrade lignin, thus enabling further cellulose hydrolysis, see Lee et al. [44].

Anyway, the enzyme methods are naturally incorporated into the overall hydrolytic process of biomass preparation for further acidogenesis, cf. **Figure 1**.
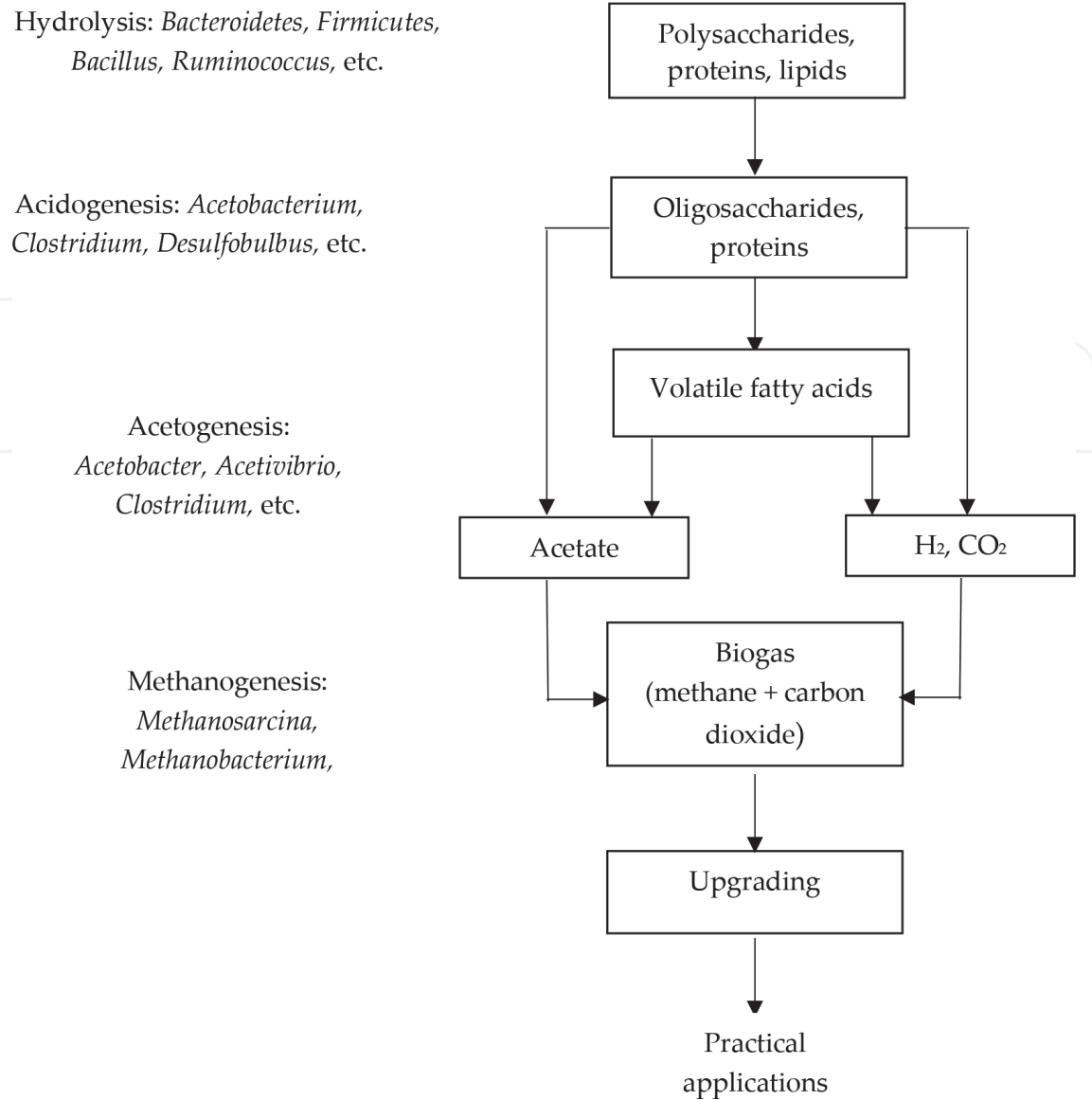
Hydrolysis: *Bacteroidetes, Firmicutes, Bacillus, Ruminococcus,* etc.

Acidogenesis: *Acetobacterium, Clostridium, Desulfobulbus,* etc.

Acetogenesis: *Acetobacter, Acetivibrio, Clostridium,* etc.

Methanogenesis: *Methanosarcina, Methanobacterium,*

Polysaccharides, proteins, lipids

Oligosaccharides, proteins

Volatile fatty acids

Acetate

H_2, CO_2

Biogas (methane + carbon dioxide)

Upgrading

Practical applications

Figure 1.
Scheme of the consecutive processes of biogas formation in anaerobic process, according to Garcia-Heras [21].

3.2.4 Other methods

There are also some physical methods, including pretreatment by γ-irradiation [45], by ultrasonication [46], pulsed electric field [47] with electric field intensity of up to 20 kV/cm. The main disadvantage of these methods is that they are high energy-consuming and therefore very costly.

Microwave treatment has been also considered [48–50]. Our experience with microwave treatment of corn stalks and grass hey did not give better results for biogas yield compared to the treatment by acid hydrolysis or simple enzyme treatment.

Recently a constant electric field was applied after the steam explosion of activated sludge to remove or destroy the inhibitors formed during the steam explosion. A very high methane yield was observed. The same approach was also applied to other substrates, like cattle manure, coniferous needles, glycerol and their mixtures [51]. Some results are shown below, cf. **Figure 2**.

In the conducted experiments, we have found out that, the treatment of the waste material with electric current leads to improvement in the ingredients of produced biogas, expressed mainly in higher methane content (reaching 95–98% (vol.) in experiment E4 in a comparison with most commonly observed 50–75%).
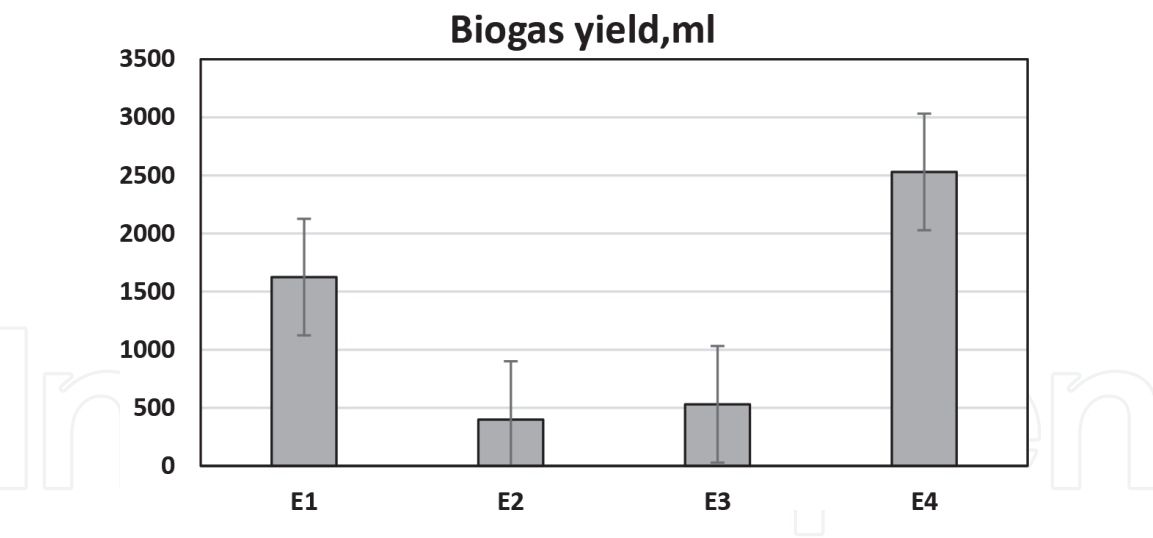
Biogas yield, ml

Figure 2.
Cumulative biogas yield for ca. 110 days under different pre-treatment conditions at different amounts of added glycerol, manure and sulfuric acid at different anode potential. Mesophilic process..E1–16 g coniferous material +200 ml 1% H_2SO_4 + 8 g glycerol +600 g manure. Treated by constant anode potential 0.77 V/S.H.E. for 30 minutes. E2–32 g coniferous material +400 ml 1% H_2SO_4 + 16 g glycerol +1200 g manure. Treated by constant anode potential 0.77 V/S.H.E. for 30 minutes. E3–16 g coniferous material +100 ml 1% H_2SO_4 + 8 g glycerol +300 g manure. Treated by constant anode potential 0.25 V/ S.H.E. for 30 minutes. E4–16 g coniferous material + + 100 ml 1% H_2SO_4 + 8 g glycerol +300 g manure. Treated by constant anode potential 0.5 V/ S.H. E. for 30 minutes. Original data reported in [51].

One can see that moderate amounts of glycerol and manure with the low amount of sulfuric acid are preferable (experiment E4). We have observed that applying electrical current to cattle manure leads to the intensification of the digesting process, more biogas and higher methane content. The importance of the anode potential is visible after a comparison of the results from experiments E3 and E4. Under similar initial components of the reactive mixtures, the anode potential of 0.5 V/S.H.E. is superior to the one at E3, namely 0.25 V/S.H.E.

Generally, the decision for selection of the certain method of pretreatment has its technological and economic backgrounds and the cheapest one must be chosen depending on the very conditions. For example, simple microbial hydrolysis by cellulases contained in the cattle manure could be sufficiently effective compared to the sophisticated physical and thermochemical processes.

4. Biogas production

The mesophilic anaerobic digestion with biogas production follows the steps described in **Figure 1**.

The operation conditions for the production of biogas are associated with the selected substrate. Generally, the first choice is to decide whether the process will be mesophilic (30-40°C) or thermophilic one (50–60°C) [9].

The thermophilic process seems to be preferable because of the higher biogas production rate. Another reason is the sterilization of the sludge destroying pathogens and parasite microbial cultures. Next, undesirable seeds of various weeds contained in the manure are also destroyed thus protecting the soil from weeds at further fertilization by the residual sludge and wastewater. However, the thermal balance of the produced energy and the energy input to maintain a higher temperature must be made carefully. Another unexpected obstacle is the higher sensitivity of the thermophilic microbes to pH variation than the mesophilic ones. From this point of view, the mesophilic process seems to be more promising.

The effectiveness of microbes involved in anaerobic digestion determines the rate of substrate decomposition and biogas production [52]. The naturally formed microbial consortia are quite sensitive to pH variations and unbalanced operation may lead to strong inhibition and process failure. At mesophilic processes, the hydrolysis is usually performed by bacteria from the genera *Bacillus, Streptococcus, Klebsiella*, etc. After hydrolysis, the following acidogenesis, acetogenesis and methanization take place, performed by different specific bacteria and archae.
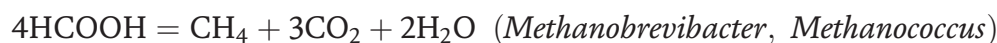
Acidification is usually performed by bacteria from the genera *Acetobacterium, Clostridium, Desulfobulbus, Eubacterium,* etc. [52]. At a higher feeding rate of the substrate in the acidification phase, an excessive production of volatile fatty acids (formic, acetic, propionic, butyric ones) may occur thus decreasing pH below the optimum value for methanogens (i.e., between 7 and 8). It usually provokes stopping the process of biogas production. High volatile fatty acid (VFA) concentrations inhibit the growth of acid-producing bacteria thus reducing also rate of acidogensis. Fermentation of sugar is inhibited by total concentrations of volatile fatty acids above 4 g/l [15, 53]. The long-chain fatty acid concentration of about 30–300 mg/l was found as appropriate for anaerobic decomposition [9]. Some of the possible acidogenic reactions are listed below.

$$C_6H_{12}O_6 + 2H_2 = 2CH_3CH_2COOH + 2H_2O \tag{1}$$

$$C_6H_{12}O_6 + 2H_2O = 2CH_3COOH + 2CO_2 + 4H_2 \tag{2}$$

The last one is an acetogenic one too. Formic acid is formed by acetogenesis and it is carried out by bacteria from the genera *Syntrophomonas, Syntrophobacter, Clostridium, Syntrophospora, Acetobacter* [9]. Acetate is formed from propionate, bicarbonate too:

$$CH_3CH_2COO^- + 3H_2O = CH_3COOH + HCO_3^- + 3H_2 \tag{3}$$

$$2HCO_3^- + 4H_2 + H^+ = CH_3COO^- + 4H_2O \tag{4}$$

Further VFA is decomposed to methane and carbon dioxide following the reactions (5):

$$4HCOOH = CH_4 + 3CO_2 + 2H_2O \quad (Methanobrevibacter, \ Methanococcus)$$

$$CH_3COOH = CH_4 + CO_2 \quad (Methanosarcina) \tag{5}$$

$$C_2H_5COOH + 2H_2O = CH_4 + 2CO_2 + 3H_2$$
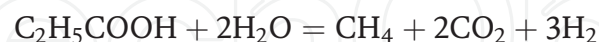
Other schemes for methane formation from carbon dioxide and hydrogen is accomplished by *Methanobacterium, Methanobrevibacter, Methanothermus* [54]:

$$CO_2 + 4H_2 = CH_4 + 2H_2O \tag{6}$$

In this case the content of methane in the biogas is much higher. A molar (or volumetric yield) of biogas, richer of methane more than 50% is a clear indication for the pathway, shown in Eq. (6).

The method of carbon isotopes was extensively used to establish the pathway of methane production, as summarized by Conrad [55].

4.1 Single stage and multi-stage systems

It is well, in any case, to manage biogas production in a continuous or fed-batch mode. The latter is preferable because of the low process rate and the menace of wash-out (at high dilution rates) or accumulation of inhibitors (at high substrate dosage).

The anaerobic digestion systems are classified as single stage and multi-stage systems based on the different steps of digestion, cf. **Figure 1**. The simple single stage systems are used for many decades. They are available in the simplest design. The most used type of anaerobic digestion is the UASB (upflow anaerobic sludge blanket) digester used extensively for wastewater treatment and biogas production [56].

The substrate is introduced in the lower end of the bioreactor and passed through a layer of sludge, where granules of microbes are formed. The treated water leaves the digester from the upper side where the produced biogas is also released.

All phases of anaerobic digestion are carried out in a single apparatus with batch or continuous mode. In a single digester, all steps of anaerobic digestion take place in one space and as a result process fluctuations or low biogas production occurs because of the accumulation of inhibitors (volatile fatty acids or ammonia in some cases) at hydrolysis and acidogenesis. As a result, the pH in the digester goes out of the optimum limits for successful methanogenesis. Better and more stable operation is possible when the steps in **Figure 1** are carried out simultaneously, but separated in consecutively situated reactors. Multi-stage cascades of bioreactors with the separated acidogenesis and methanogenesis show better gas production. The main advantage of the consecutive scheme consists in the higher stability of each unit in the cascade at the undesired fluctuation of feed, substrate content, pH, temperature, etc. That is why the separation of each of the four stages of biogas production will improve substrate degradation as well as biogas/methane production. This approach was proposed by Grobicki & Stuckey [57] and later applied in a series of studies on stillage conversion to biogas [58] and glycerol utilization [59]. Microbial analysis showed that different microbial cultures were developed in the different steps, corresponding to the content of volatile fatty acids in the step [58, 60].

4.2 Biogas production with glycerol addition

Crude glycerol is the main waste product from biodiesel manufacturing. It is released in the amount equivalent to the methanol used and exceeds the market demands. This waste product contains water and it is contaminated by the catalyst and residual methanol. The demand for pure glycerol and its price makes the purification of this waste product not economically feasible. That is why the use of this glycerol for the production of value-added chemicals was sought [61–63]. Such products are propylene glycol, 1,3-propanediol, epichlorohydrin. Some of its derivatives are suitable as additives to gasoline and diesel.

There are some efforts for waste glycerol utilization as a substrate for biogas production [64–66]. There is also a study on glycerol addition to enhance the mutual production of biohydrogen and methane by crude glycerol addition [67]. It was established that glycerol and microalgal biomass as co-substrates had an antagonistic effect on hydrogen production and a synergistic effect on methane fermentation.

A hinder for this application is the rapid accumulation of VFA leading to strong inhibition of the methanogenesis and shift to production of gas with very low methane content [64, 65]. It is because in comparison to the traditional substrates glycerol has a very simple molecule and therefore it quickly yields intermediates and final products as organic acids and alcohols. If the initial amount of glycerol is high, the resulting pH drop leads to inhibition of methanogenesis. However, that small amounts of glycerol can boost biogas production based on traditional substrates, see Wohlgemut [68] and Fountoulakis & Manios [69].

When the digestate of bioethanol production was supplemented with 15% and 25% g/L of glycerol (as COD), the cumulative methane and biogas yield was increased to 318 Nml/gCOD and 196 Nml/gCOD which was approximately 6 times higher compared to digestion of the single substrate [66].

In our studies, we have shown that besides the biogas production some other valuable chemical products are obtained (2,3-butanediol, 1,3-propanediol) [60].

A multi-stage cascade bioreactor of eight consecutive compartments was used for anaerobic digestion of stillage with small controlled amounts of glycerol. The latter has been added in a fed-batch mode.

A specific microbial profile is formed along with the compartments, cf. **Table 2**. The bacteria of the strain *Klebsiella* are capable to digest glycerol to 1,3-propane diol and 2,3-butanediol. They can also produce formic acid to yield carbon dioxide and hydrogen. The microbial analysis showed that methane was produced mostly by the pathway of CO_2 reduction by hydrogen, cf. Eq. (7). It is also seen that the methanogens prevail in the second compartment and further.

In the next **Figure 3** the VFA profile, the pH profile and the concentrations of 2,3-butanediol along the bioreactor compartments are shown, see [60]. The VFA

Compartment No.	Genera	Pathway of methane production
1	Molds, *Bacillus*	None
2	*Klebsiella, Methanosarcina*	Acetate, Eq. (5); $CO_2 + H_2$, Eq.(6)
3	*Klebsiella, Methanobacterium*	$CO_2 + H_2$, Eq.(6)
4	*Klebsiella, Methanobacterium*	$CO_2 + H_2$, Eq.(6)
5	*Klebsiella, Methanobacterium*	$CO_2 + H_2$, Eq.(6)
6	*Klebsiella, Methanobrevibacter*	$CO_2 + H_2$, Eq.(6)
7	*Klebsiella, Methanobrevibacter*	$CO_2 + H_2$, Eq.(6)
8	*Klebsiella Methanobrevibacter*	$CO_2 + H_2$, Eq.(6)

Table 2.
Microbial profile in a multistage bioreactor with glycerol as a supplement. Microbial identification is taken from [60].
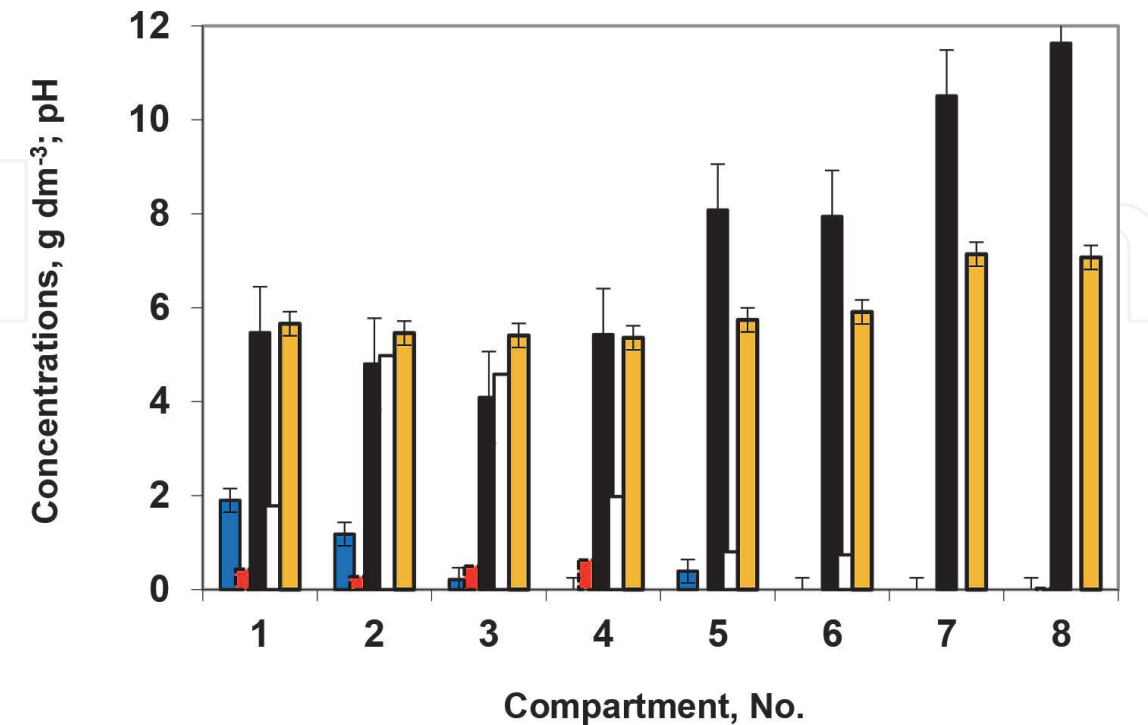

Figure 3.
Profiles of the substrate, intermediate products and pH on the 12th day after a feed with glycerol; (blue) – Glycerol; (red) – Acetic acid; (white) – Propionic acid; (black) – 2,3-butanediol; (yellow) – pH. Feed 1 kg crude glycerol, cf. ref. [60].

concentrations reach maximum values in compartments 2 and 3 and decrease along the bioreactor to zero in compartments 7 and 8. Obviously, acetic acid is converted more rapidly than the propionic one. The pH profile along the compartments correlates reasonably with the VFA variations.

The target product, i.e., 2,3-butanediol is accumulated in practically interesting concentrations, up to 12 g/l.

4.3 Biogas applications

The first and the simplest mode of application of biogas is direct combustion for heating and lighting, as it was adopted in developing countries. The next more sophisticated application is its use for power generation, so-called co-generation. Co-generation is the simultaneous production of electricity and heat by the combustion of biogas. This is the so-called "combined heat and power" process (CHP). Such applications are well spread, using municipal solid waste [70], activated sludge from wastewater treatment plants. The co-generation unit is composed of an engine that actuates as an alternator. The electricity efficiency of the co-generation units reaches 35%. The heat recovery makes it possible to reach a total output of 85% of all produced heat is utilized [71].

The flexibility of biogas systems can support electricity production to follow the temporal local electricity demand, thus facilitating grid stability. It is a decentralized component of the overall energy system and it can serve as a distribution hub in rural areas [72].

Besides CHP, another approach is the "power to gas" (PtG) where the surplus renewable electricity is used for the production of hydrogen by electrolysis [72]. It was proposed for utilization of energy surplus produced by traditional power stations when the electricity demand is low. There are proposals for carbon dioxide recycling by using the released hydrogen for the reduction of carbon dioxide to methane.

Biogas has already broad applications in transport. After upgrading, i.e., separation of carbon dioxide and the sulfur-containing impurities, it competes for natural gas in transport and it is also injected in the gas distribution grids [72].

4.4 Fuel cell applications

A very attractive application of biogas for electricity production is its use in fuel cells [73]. Before gas feed, biogas must be upgraded after the removal of carbon dioxide and sulfur compounds. The classic methane-driven fuel cells convert catalytically methane into a mixture of carbon monoxide and hydrogen. Hydrogen is separated and used as a fuel in a traditional hydrogen/oxygen fuel cell to generate electricity.

The advantages of fuel cell applications with methane consist in their higher efficiency compared to combustion and co-generation [74]. Next, the released heat can be utilized for maintaining the temperature regime in the fuel cell. A disadvantage of this method is the necessity of carbon monoxide removal and the subsequent charging of the atmosphere by carbon dioxide. More attractive is to convert methane (or biogas) into electricity in one step [74–76] in solid oxide fuel cells. However, the power density is still low for practical use.

Besides these applications biogas can be used also for chemical production using dry reforming to produce synthesis gas (a mixture of carbon monoxide and hydrogen) which is further used for light hydrocarbon production by the Fischer-Tropsch process [77].

4.5 Biogas upgrading

Biogas upgrading means the removal of carbon dioxide, partially or completely, and the traces of sulfur compounds. The produced gas is reach of methane and it is competitive to the natural gas in the gas distribution grid. It is suitable for domestic purposes and for transport as well.

Once separated, the resulting methane can be mixed at a desired ration of produce other chemicals via synthesis gas.

The most direct method for biogas upgrading is the membrane separation [78–80]. There is information about commercial equipment for biogas upgrading. Some of them is based on membrane separation [81], or by pressure-swing adsorption to reach capacity from about 500 to 5000 Nm³/h methane [82].

There are also proposals to recycle CO_2 into methane using bioelectrochemical systems [83]. Although, it seems attractive, energy input is required with the release of carbon dioxide. That is why the use of the PtG approach as mentioned above based on energy surpluses, or other renewable energies, like solar or wind ones are recommended.

4.6 Feasibility of biogas production and use

The feasibility of a biogas equipment depends on different factors. First, it is the amount and generation rate of feedstock (manure, straw, activated sludge, etc.) and its threat to the environment. Next, it is the need of heat or electricity for the considered location. Then, it could be assumed to use biogas as alternative fuel for transport purposes, to be injected in the gas distribution grid or electricity production by co-generation. Biogas upgrade is required if is supposed for transport purposes or for mixing with natural gas in the grid.

It is apparent that different substrates require different approaches. Heating is beneficial because it used to maintain temperature even at mesophilic process. It is possible to maintain it using the heat from a cogeneration (CHP) system after combustion of biogas.

An innovative method is the Power to Gas method integrating the electricity grid with the gas [72].

After selection of biogas as appropriate option for waste treatment with energy recovery, there is necessity to try to select the best method of application for the present community. There are various factors that can affect the rate and amount of produced, namely.

- Type of digester and its capacity

- Temperature (mesophilic or thermophilic process)

- Retention time with the corresponding digester size

- The necessity of pH maintenance

- The presence of certain chemicals in the substrate.

At times of surplus of variable renewable electricity production, hydrogen may be produced via electrolysis, thus storing energy.

5. Conclusions

The biogas has various applications, starting with the simple combustion. Important applications are electricity production by co-generation, by fuel cell applications, as a fuel for transport purposes and as a feedstock for production of chemicals like light hydrocarbons. Prior to its use as a fuel or for chemical purposes, upgrading of biogas with removal of carbon dioxide is desirable. A promising approach is "power to gas" process after electricity production for recycling of carbon dioxide into methane. The biogas yield and quality depend either by the pre-treatment, or the operation mode (substrate dosage, choice of anaerobic digester, etc.). It seems that simple enzyme pre-treatment is good enough compared with more sophisticated methods, like ultrasonic or microwave treatment, even steam explosion. The choice of methods and scale of application depends on the regional raw material access, the energy demands and climate peculiarities.

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