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Anaerobic Treatment and Biogas Production from Organic Waste

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1. Introduction

Organic wastes under consideration are of natural origin that possess biochemical characteristics ensuring rapid microbial decomposition at relatively normal operating conditions. When considering the organic waste treatment we have generally in mind organic mineralization, biological stabilisation and detoxification of pollutants. Most common organic wastes contain compounds that are mainly well biodegradable. They can be readily mineralized either through biological treatment (aerobic or anaerobic), or thermo chemical treatment such as incineration, pyrolysis and gasification. The latter will not be treated in this work. Most organic wastes produced today originate in municipal, industrial and agricultural sector. Municipal waste (as well as municipal wastewater sludge) is generated in human biological and social activities and contains a large portion of organic waste readily available for treatment. Agricultural waste is common in livestock and food production and can be utilised for biogas production and therefore contribute to more sustainable practice in agriculture. Industrial wastes arise in many varieties and are the most difficult for biological treatment, depending of its origin. Namely, many industries use chemicals in their production in order to achieve their product quality and some of these chemicals are present in the waste stream, which is consequently difficult to treat. Recently, organic waste treatment has had a lot of attention, due to possibilities of energy recovery from these wastes as well as to prevent their adverse environmental effects. Energy recovery is possible through controlled release of chemically bound energy of organic compounds in waste and can be retrieved through chemical and biochemical processes. Most of the organic wastes appear in solid form; however contain up to 90% of moisture, therefore thermo-chemical treatment such as incineration cannot be applied. To address sustainability in the treatment of organic wastes, environmental aspect, energy aspect and economical aspect of the treatment processes should be considered.

Biodegradable organic waste can be treated with or without air access. Aerobic process is composting and anaerobic process is called digestion. Composting is a simple, fast, robust and relatively cheap process producing compost and CO_2 (Chiumenti et al. 2005, Diaz et al. 2007). Digestion is more sophisticated, slow and relatively sensitive process, applicable for selected input materials (Polprasert, 2007). In recent years anaerobic digestion has become a prevailing choice for sustainable organic waste treatment all over the world. It is well suited for various wet biodegradable organic wastes of high water content (over 80%), yielding methane rich biogas for renewable energy production and use.

Table 1 shows typical solid and organic substance contents and biogas yields for most frequent organic wastes, treated with anaerobic digestion.

Organic waste	**TS[1] [%]**	**VS[2] in TS [%]**	**Biogas yield (SPB) [m^3kg^{-1} of VS]**
Municipal organic waste	15-30	80-95	0.5-0.8
Municipal wastewater sludge	3-5	75-85	0,3-0,5
Brewery spent grain	20-26	80-95	0.5-1.1
Yeast	10-18	90-95	0.5-0.7
Fermentation residues	4-8	90-98	0.4-0.7
Fruit slurry (juice production)	4-10	92-98	0.5-0.8
Pig stomach content	12-15	80-84	0.3-0.4
Rumen content (untreated)	12-16	85-88	0.3-0.6
Vegetable wastes	5-20	76-90	0.3-0.4
Fresh greens	12-42	90-97	0.4-0.8
Grass cuttings (from lawns)	20-37	86-93	0.7-0.8
Grass silage	21-40	87-93	0.6-0.8
Corn silage	20-40	94-97	0.6-0.7
Straw from cereals	~86	89-94	0.2-0.5
Cattle manure (liquid)	6-11	68-85	0.1-0.8
Cattle excreta	25-30	75-85	0.6-0.8
Pig manure (liquid)	2-13	77-85	0.3-0.8
Pig excreta	20-25	75-80	0.2-0.5
Chicken excreta	10-29	67-77	0.3-0.8
Sheep excreta	18-25	80-85	0.3-0.4
Horse excreta	25-30	70-80	0.4-0.6
Waste milk	~8	90-92	0.6-0.7
Whey	4-6	80-92	0.5-0.9

[1]TS – total solids

[2]VS – volatile (organic) solids

Table 1. Types of organic wastes and their biogas yield

2. Basics of anaerobic digestion

This section deals with anaerobic waste treatment methods only, as the most advanced and sustainable organic waste treatment method. Anaerobic digestion (WRAP 2010) is "*a process of controlled decomposition of biodegradable materials under managed conditions where free oxygen is absent, at temperatures suitable for naturally occurring mesophilic or thermophilic anaerobic and facultative bacteria and archaea species, that convert the inputs to biogas and whole digestate*". It is widely used to treat separately collected biodegradable organic wastes and wastewater sludge, because it reduces volume and mass of the input material with biogas (mostly a mixture of methane and CO_2 with trace gases such as H_2S, NH_3 and H_2) as by-product.

Thus, anaerobic digestion is a renewable energy source in an integrated waste management system. Also, the nutrient-rich solids left after digestion can be used as a fertilizer.

2.1 Biochemical reactions in anaerobic digestion

There are four key biological and chemical stages of anaerobic digestion:

1. Hydrolysis
2. Acidogenesis
3. Acetogenesis
4. Methanogenesis.

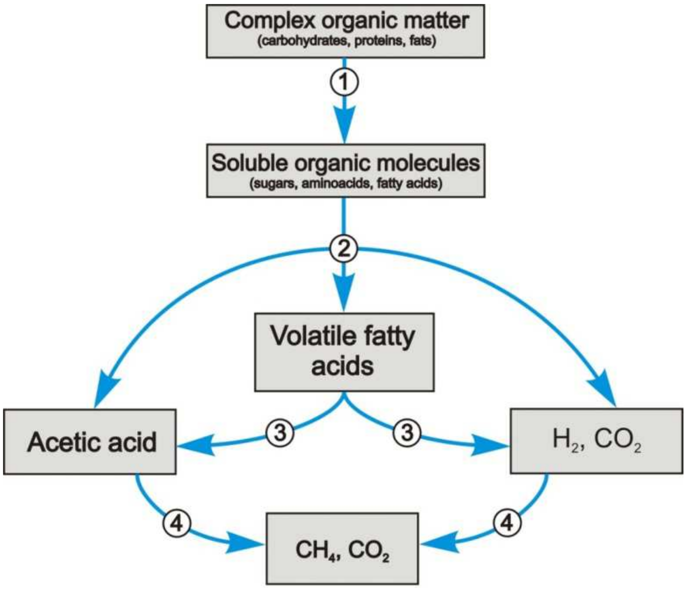

Fig. 1. Anaerobic pathway of complex organic matter degradation

In most cases biomass is made up of large organic compounds. In order for the microorganisms in anaerobic digesters to access the chemical energy potential of the organic material, the organic matter macromolecular chains must first be broken down into their smaller constituent parts. These constituent parts or monomers such as sugars are readily available to microorganisms for further processing. The process of breaking these chains and dissolving the smaller molecules into solution is called hydrolysis. Therefore hydrolysis of high molecular weight molecules is the necessary first step in anaerobic digestion. It may be enhanced by mechanical, thermal or chemical pretreatment of the waste. Hydrolysis step can be merely biological (using hydrolytic microorganisms) or combined: bio-chemical (using extracellular enzymes), chemical (using catalytic reactions) as well as physical (using thermal energy and pressure) in nature.

Acetates and hydrogen produced in the first stages can be used directly by methanogens. Other molecules such as volatile fatty acids (VFA's) with a chain length that is greater than acetate must first be catabolised into compounds that can be directly utilised by methanogens. The biological process of acidogenesis is where there is further breakdown of the remaining components by acidogenic (fermentative) bacteria. Here VFA's are generated along with ammonia, carbon dioxide and hydrogen sulphide as well as other by-products.

The third stage anaerobic digestion is acetogenesis. Here simple molecules created through the acidogenesis phase are further digested by acetogens to produce largely acetic acid (or its salts) as well as carbon dioxide and hydrogen.

The final stage of anaerobic digestion is the biological process of methanogenesis. Here methanogenic archaea utilise the intermediate products of the preceding stages and convert them into methane, carbon dioxide and water. It is these components that makes up the majority of the biogas released from the system. Methanogenesis is – beside other factors - sensitive to both high and low pH values and performs well between pH 6.5 and pH 8. The remaining, non-digestible organic and mineral material, which the microbes cannot feed upon, along with any dead bacterial residues constitutes the solid digestate.

2.2 Factors that affect anaerobic digestion

As with all biological processes the optimum environmental conditions are essential for successful operation of anaerobic digestion (Table 2). The microbial metabolism processes depend on many parameters; therefore these parameters must be considered and carefully controlled in practice. Furthermore, the environmental requirements of acidogenic bacteria differ from requirements of methanogenic archaea. Provided that all steps of the degradation process have to take place in one single reactor (one-stage process) usually methanogenic archaea requirements must be considered with priority. Namely, these organisms have much longer regeneration time, much slower growth and are more sensitive to environmental conditions then other bacteria present in the mixed culture (Table 3). However, there are some exceptions to the case:

Parameter	Hydrolysis/ Acidogenesis	Methanogenesis
Temperature	25-35°C	Mesophilic: 30-40°C Thermophilic: 50-60°C
pH Value	5.2-6.3	6.7-7.5
C:N ratio	10-45	20-30
Redox potential	+400 to -300 mV	Less than -250 mV
C:N:P:S ratio	500:15:5:3	600:15:5:3
Trace elements	No special requirements	Essential: Ni, Co, Mo, Se

Table 2. Environmental requirements (Deublein and Steinhauser 2008)

- With cellulose containing substrates (which are slowly degradable) the hydrolysis stage is the limiting one and needs prior attention.
- With protein rich substrates the pH optimum is equal in all anaerobic process stages therefore a single digester is sufficient for good performance.
- With fat rich substrates, the hydrolysis rate is increasing with better emulsification, so that acetogenesis is limiting. Therefore a thermophilic process is advised.

In aspiration to provide optimum conditions for each group of microorganisms, a two-stage process of waste degradation has been developed, containing a separate reactor for each stage. The first stage is for hydrolysis/acidification and the second for acetogenesis/methanogenesis. The process will be discussed in detail in section 3.

Microorganisms	Time of regeneration
Acidogenic bacteria	Less than 36 hours
Acetogenic bacteria	80-90 hours
Methanogenic archaea	5-16 days
Aerobic microorganisms	1-5 hours

Table 3. Regeneration time of microorganisms

2.2.1 Temperature

Anaerobic digestion can operate in a wide range of temperature, between 5°C and 65°C. Generally there are three widely known and established temperature ranges of operation: psychrophilic (15-20°C), mesophilic (30-40°C) and thermophilic (50-60°C). With increasing temperature the reaction rate of anaerobic digestion strongly increases. For instance, with ideal substrate thermophilic digestion can be approx. 4 times faster than mesophilic. However using real waste substrates, there are other inhibitory factors that influence digestion, that make thermophilic digestion only approx. 2 times faster than mesophilic.

The important thing is, when selecting the temperature range, it should be kept constant as much as possible. In thermophilic range (50-60°C) fluctuations as low as ±2°C can result in 30% less biogas production (Zupančič and Jemec 2010). Therefore it is advised that temperature fluctuations in thermophilic range should be no more than ±1°C. In mesophilic range the microorganisms are less sensitive; therefore fluctuations of ±3°C can be tolerated.

For each range of digestion temperature there are certain groups of microorganisms present that can flourish in these temperature ranges. In the temperature ranges between the three established temperature ranges the conditions for each of the microorganisms group are less favourable. In these ranges anaerobic digestion can operate, however much less efficient. For example, mesophilic microorganisms can operate up to 47°C, thermophilic microorganisms can already operate as low as 45°C. However the rate of reaction is low and it may happen that the two groups of microorganisms may exclude each other and compete in the overlapping range. This results in poor efficiency of the process, therefore these temperatures are rarely applied.

2.2.2 Redox potential

In the anaerobic digester, low redox potential is necessary. Methanogenic archaea need redox potential between -300 and -330 mV for the optimum performance. Redox potential can increase up to 0 mV in the digester; however it should be kept in the optimum range. To achieve that, no oxidizing agents should be added to the digester, such as oxygen, nitrate, nitrite or sulphate.

2.2.3 C:N ratio and ammonium inhibition

In microorganism biomass the mass ratio of C:N:P:S is approx. 100:10:1:1. The ideal substrate C:N ratio is then 20-30:1 and C:P ratio 150-200:1. The C:N ratio higher than 30 causes slower microorganisms multiplication due to low protein formation and thus low energy and structural material metabolism of microorganisms. Consequently lower substrate degradation efficiency is observed. On the other hand, the C:N ratio as low as 3:1 can result in successful digestion. However, when such low C:N ratios and nitrogen rich substrates are applied (that is often the case using animal farm waste) a possible ammonium inhibition must be considered. Ammonium although it represents an ideal form of nitrogen for microorganisms cells growth, is toxic to mesophilic methanogenic microorganisms at concentrations over 3000 mgL^{-1} and pH over 7.4. With increasing pH the toxicity of ammonium increases (Fig. 2).

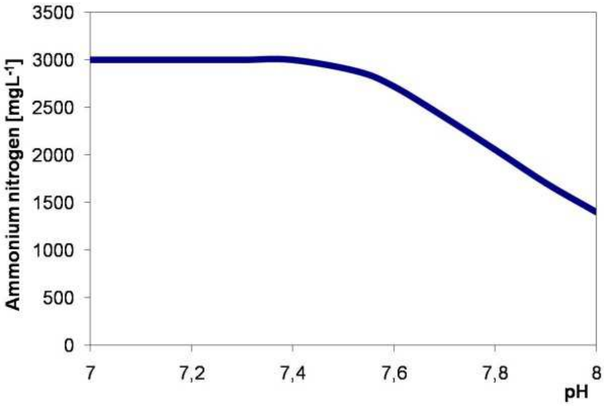

Fig. 2. Ammonium nitrogen toxicity concentration to methanogenic microorganisms

Thermophilic methanogenic microorganisms are generally more sensitive to ammonium concentration. Inhibition can occur already at 2200 mgL^{-1} of ammonium nitrogen. However the ammonium inhibition can very much depend on the substrate type. A study of ammonium inhibition in thermophilic digestion shows an inhibiting concentration to be over 4900 mgL^{-1} when using non-fat waste milk as substrate (Sung and Liu 2003).

Ammonium inhibition can likely occur when digester leachate (or water from dewatering the digested substrate) is re-circulated to dilute the solid substrate for anaerobic digestion. Such re-circulation must be handled with care and examined for potential traps such as ammonium or other inhibitory ions build up.

To resolve ammonia inhibition when using farm waste in anaerobic digestion several methods can be used:

- First possibility is carefully combining different substrates to create a mixture with lower nitrogen content. Usually some plant biomass (such as silage) is added to liquid farm waste in such case.
- Second possibility is diluting the substrate to such extent, that concentration in the anaerobic digester does not exceed the toxicity concentration. This method must be handled with care. Only in some cases dilution may be a solution. If the substrate requires too much dilution, a microorganisms washout may occur, which results in process failure. Usually there is only a narrow margin of operation, original substrate causes ammonium inhibition, when diluted to the extent necessary to stop ammonia inhibition, and already a washout due to dilution occurs.
- It is also possible to remove ammonium from the digester liquid. This method is usually most cost effective but rarely used. One of such processes is stripping ammonia from the liquid. It is also commercially available (GNS 2009).

2.2.4 pH

In anaerobic digestion the pH is most affecting the methanogenic stage of the process. pH optimum for the methanogenic microorganisms is between 6.5 and 7.5. If the pH decreases below 6.5, more acids are produced and that leads to imminent process failure. In real digester systems with suspended biomass and substrate containing suspended solids, normal pH of operation is between 7.3 and 7.5. When pH decreases to 6.9 already serious actions to stop process failure must be taken. When using UASB flow through systems (or other systems with granule like microorganisms), which utilize liquid substrates with low suspended solids concentration normal pH of operation is 6.9 to 7.1. In such cases pH limit of successful operation is 6.7.

In normally operated digesters there are two buffering systems which ensure that pH persists in the desirable range:

- Carbon dioxide - hydrogen carbonate - carbonate buffering system. During digestion CO_2 is continuously produced and release into gaseous phase. When pH value decreases, CO_2 is dissolved in the reactor solution as uncharged molecules. With increasing pH value dissolved CO_2 form carbonic acid which ionizes and releases hydrogen ions. At pH=4 all CO_2 is in form of molecules, at pH=13 all CO_2 is dissolved as carbonate. The centre point around which pH value swings with this system is at pH=6.5. With concentrations between 2500 and 5000 mgL^{-1} hydrogen carbonate gives strong buffering.
- Ammonia - ammonium buffering system. With decreasing pH value, ammonium ions are formed with releasing of hydroxyl ions. With increasing pH value more free ammonia molecules are formed. The centre point around which pH value swings with this system is at pH=10.

Both buffering systems can be overloaded by the feed of rapidly acidifying (quickly degradable) organic matter, by toxic substances, by decrease of temperature or by a too high loading rate to the reactor. In such case a pH decrease is observable, combined with CO_2 increase in the biogas. Measures to correct the excessive acidification and prevent the process failure are following:

- Stop the reactor substrate supply for the time to methanogenic archaea can process the acids. When the pH decreases to the limit of successful operation no substrate supply should be added until pH is in the normal range of operation or preferably in the upper portion of normal range of operation. In suspended biomass reactors this pH value is 7.4 in granule microorganisms systems this pH value is 7.0.
- If procedure from the point above has to be repeated many times, the system is obviously overloaded and the substrate supply has to be diminished by increasing the residence time of the substrate.
- Increase the buffering potential of the substrate. Addition of certain substrates which some contain alkaline substances to the substrate the buffering capacity of the system can be increased.
- Addition of the neutralizing substances. Typical are slaked lime ($Ca(OH)_2$), sodium carbonate (Na_2CO_3) or sodium hydrogen carbonate ($NaHCO_3$), and in some cases sodium hydroxide (NaOH). However, with sodium substances most precaution must be practiced, because sodium inhibition can occur with excessive use.

2.2.5 Inhibitory substances

In anaerobic digestion systems a characteristic phenomenon can be observed. Some substances which are necessary for microbial growth in small concentrations inhibit the digestion at higher concentrations. Similar effect can have high concentration of total volatile fatty acids (tVFA's). Although, they represent the very substrate that methanogenic archaea feed upon the concentrations over 10,000 mgL^{-1} may have an inhibitory effect on digestion (Mrafkova et al., 2003; Ye et al., 2008).

Inorganic salts can significantly affect anaerobic digestion. Table 4 shows the optimal and inhibitory concentrations of metal ions from inorganic salts.

	Optimal concentration [mgL^{-1}]	**Moderate inhibition [mgL^{-1}]**	**Inhibition [mgL^{-1}]**
Sodium	100-200	3500-5500	16000
Potassium	200-400	2500-4500	12000
Calcium	100-200	2500-4500	8000
Magnesium	75-150	1000-1500	3000

Table 4. Optimal and Inhibitory concentrations of ions from inorganic salts

In real operating systems it is unlikely that inhibitory concentrations of inorganic salts metals would occur, mostly because in such high concentrations insoluble salts would precipitate in alkaline conditions, especially if H_2S is present. The most real threat in this case is sodium inhibition of anaerobic digestion. This can occur in cases where substrates are wastes with extremely high salt contents (some food wastes, tannery wastes…) or when excessive use of sodium substances were used in neutralization of the substrate or the digester liquid. Study done by Feijoo et al. (1995) shows that concentrations of 3000 mgL^{-1} may already cause sodium inhibition. However, anaerobic digestion can operate up to concentrations as high as 16,000 mgL^{-1} of sodium, which is close to saline concentration of seawater. Measures to correct the sodium inhibition are simple. The high salt substrates must be pre-treated to remove the salts (mostly washing). The use of sodium substances as neutralizing agents can be substituted with other alkaline substances (such as lime).

Heavy metals also do have stimulating effects on anaerobic digestion in low concentrations, however higher concentrations can be toxic. In particular lead, cadmium, copper, zinc, nickel and chromium can cause disturbances in anaerobic digestion process. In farm wastes, e.g. in pig slurry, especially zinc is present, originating from pig fodder which contains zinc additive as an antibiotic. Inhibitory and toxic concentrations are shown in Table 5.

Other organic substances, such as disinfectants, herbicides, pesticides, surfactants, and antibiotics can often flow with the substrate and also cause nonspecific inhibition. All of these substances have a specific chemical formula and it is hard to determine what the behaviour of inhibition will be. Therefore, when such substances do occur in the treated substrate, specific research is strongly advised to determine the concentration of inhibition and possible ways of microorganisms adaptation.

Metal	Inhibition start[1] [mgL^{-1}]	Toxicity to adopted microorganisms[3] [mgL^{-1}]
Cr^{3+}	130	260
Cr^{6+}	110	420
Cu	40	170
Ni	10	30
Cd	70	600
Pb	340	340
Zn	400	600

[1]As inhibitory concentration it is considered the first value that shows diminished biogas production and as toxic concentration it is considered the concentration where biogas production is diminished by 70 %.

Table 5. Inhibitory and toxic concentrations of heavy metals

3. Anaerobic digestion technologies

Block scheme of anaerobic digestion (Fig. 3) shows that technological process of typical anaerobic digestion. It consists of three basic phases: i) substrate preparation and pre-treatment, ii) anaerobic digestion and iii) post treatment of digested material, including biogas use. In this section all of the processes will be elaborated in detail.

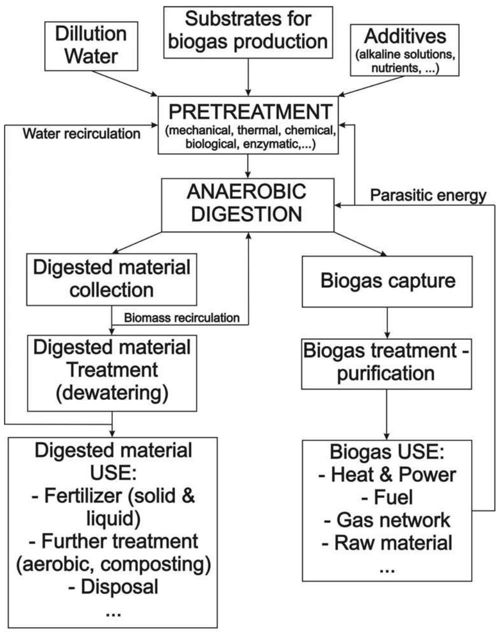

Fig. 3. Block scheme of anaerobic digestion and biogas/digestate utilisation

3.1 Pretreatment

In general, all types of biomass can be used as substrates as long as they contain carbohydrates, proteins, fats, cellulose and hemicellulose as main components. It is however important to consider several points prior to considering the process and biomass pre-treatment. The contents and concentration of substrate should match the selected digestion process. For anaerobic treatment of liquid organic waste the most appropriate concentration is between 2 - 8 % of dry solids by mass. In such case conventional single stage digestion or two stage digestion is used. If considering the treatment of solid waste using solid digestion process, the concentration substrate is between 10 and 20 % by mass. Organic wastes can also contain impurities which usually impairs the process of digestion. Such materials are:

- Soil, sand, stones, glass and other mineral materials
- Wood, bark, card, cork and straw
- Skin and tail hair, bristles and feathers
- Cords, wires, nuts, nails, batteries, plastics, textiles etc.

The presence of impurities in the substrate can lead to increased complexity in the operating expenditure of the process. During the process of digestion of liquid manure from cattle the formation of scum layer on the top of the digester liquid can be formed, caused by straw and muck. The addition of rumen content and cut grass (larger particles than silage) can contribute to its formation. If the substrate consists of undigested parts of corn and grain combined with sand and lime the solid aggregates can be formed at the bottom of the digester and can cause severe clogging problems.

In all such cases the most likely solution is pre-treatment to reduce solids size. Naturally, that all the non-digestible solids (soil, stones, plastics, metals...) should be separated from the substrate flow in the first step. On the other hand grass, straw and fodder residue can contribute to the biogas yield, when properly pretreated, so they are accessible to the digestion microorganisms. Pretreatment can be made by physical, chemical or combined means.

Physical pretreatment is the most common. The best known disintegration methods are grinding and mincing. In grinding and mincing the energy required for operation is inversely proportional to the particle size. Since such energy contributes to the parasitic energy, it should be kept in the limits of positive margin (the biogas yield increased by pre-treatment is more than energy required for it). In the case of organic waste the empirical value for such particle size is between 1 and 4 mm.

Chemical pre-treatment can be used when treating ligno-cellulosic material, such as spent grains or even silage. Very often chemical treatment is used combined with heat, pressure or both. It is common to use acid (hydrochloric, sulphuric or others) or an alkaline solution of sodium hydroxide (in some cases soda or potassium hydroxide). Such solution is added to the substrate in quantities that surpass the titration equilibrium point and then it is heated to the desired temperature and possibly pressurized. Retention times are generally short (up to several hours) compared to retention times of the anaerobic digesters. The pretreated substrate is then much more degradable. The shortage of this pretreatment is low energy efficiency and the cost of chemicals required. It rarely outweighs the costs of building a bigger digester. Therefore it is used mostly in treating industrial waste (such as brewery) where there is plenty of waste lye or acid present and waste heat can be regenerated from the industrial processes as well. Fig. 4 presents the results of our research done on spent brewery grain, where up to 70% of organic matter could be, by means of proper pretreatment, extracted from solid to liquid form, ready for flow-through anaerobic digestion. The research revealed that higher temperatures of pretreatment (120-160°C) enabled finishing of the pretreatment process in 1-2 hours; however the need for a pressurised vessel in such case did not outweigh the time saving.

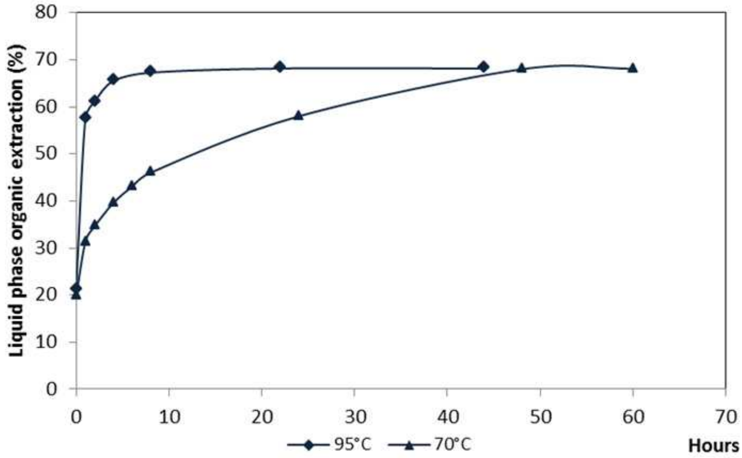

Fig. 4. Effectiveness of thermo-chemical pretreatment

Thermal pretreatment rewards with up to 30 % more biogas production if properly applied. This process occurs at temperature range of 135-220°C and pressures above 10 bar. Retention times are short (up to several hours) and hygienisation is automatically included. Pathogenic microorganisms are completely destroyed. The process runs economically only with heat regeneration. When heat is regenerated from outflow to inflow of the pre-treatment process, it takes only slightly more heat than conventional anaerobic digestion. Such process is very appropriate for cellular material such as raw sewage sludge.

It is also possible to use biological processes as pretreatment. They are emerging in the world. Disintegration takes place by means of lactic acid which decomposes complex components of certain substrates. Recently also disintegration with enzymes has been quite successful, especially using cellulose, protease or carbohydrases at a pH of 4.5 to 6.5 and a retention time of at least 12 days, preferably more (Hendriks and Zeeman 2009).

3.2 Anaerobic digestion

For anaerobic digestion several different types of anaerobic processes and several different types of digesters are applicable. It is hard to say in advance, which digester type is most appropriate for treating the selected organic waste. Digestion of farm waste, for example, should be carried out in decentralized plants to serve each farm separately, to make it an economic and technological unit combined with the farm. In the same sense a town may be a unit in treatment of organic municipal waste. It is important to study the waste of each such unit carefully to be able to determine optimal conditions for substrate digestion. Organic waste can differ very much even in same geographical areas, therefore it is strongly recommended to conduct laboratory and pilot scale experiments before design of the full scale digester is made. Considering the costs of the full scale digester, conducting pilot scale experiments is a minor item, especially if you have no preceding results or experience. The biggest economic setback is when a digester is constructed and it does not perform as expected and consequently requires reconstruction.

There are several processes available to conduct anaerobic digestion. Roughly, the digestion process can be divided into solid digestion and wet digestion processes. Solid digestion processes are in fact anaerobic composters. In this process substrate and biomass are in pre-soaked solid form, containing. 20 % of dry matter and 80 % water. Such processes have several advantages. The main advantage is reducing the reactor volume due to much less water in the system. Four times more concentrated substrate equals approximately four times less reactor volume. It is also possible that some inhibitors (such as ammonium) can have less inhibitory effects in solid digestion process. The biggest disadvantage of solid digestion process is the substrate transport. Substrate in solid form requires more energy for transport in and out of the digesters. It is also a stronger possibility of air intrusion into the digesters, which poses a great risk to process stability and safety. It has been only recently that such processes have gained ground for a wider use. A fine example is the Kompogas® process (Kompogas 2011).

A much larger variety represents wet digestion processes. They operate at conventional concentration up to 5 % of dry solids by mass of the digester suspension. There are several reactor technologies available to successfully conduct anaerobic digestion. Roughly, they can be divided into batch wise (Fig. 5 and Fig. 6) and continuous processes. Furthermore continuous processes can be divided into single stage (Fig. 7) or two-stage processes (Fig. 8). In most of the wet digestion processes microorganisms are completely mixed and suspended with substrate in the digester. The suspended solids of substrate and microorganisms are impossible to separate after the process. If the substrate contains little solids and is mostly dissolved organics liquid, we can apply flow-through processes. In these processes microorganisms are in granules and granules are suspended in liquid which contains dissolved organic material. In such anaerobic processes microorganisms granules are easily separated from the exhausted substrate. Typical representative of such process is the UASB (Upflow Anaerobic Sludge Blanket) process (Fig. 9).

3.2.1 Batch processes

In the batch process all four steps of digestion as well as four stages of treatment process happen in one tank. Typically the reaction cycle of the anaerobic sequencing batch reactor (ASBR) is divided into four phases: load, digestion, settling and unload (Fig. 5). A stirred reactor is filled with fresh substrate at once and left to degrade anaerobically without any interference until the end of the cycle phase. This leads to temporal variation in microbial community and biogas production. Therefore, batch processes require more precise measurement and monitoring equipment to function optimally. Usually these reactors are built at least in pairs, sometimes even in batteries. This achieves more steady flow of biogas for instant use. Between the cycles the tank is usually emptied incompletely (to a certain exchange volume), which is up to 50% of total reactor volume. The residue in the tank serves as microbial inoculum for the next cycle. This makes batch reactors volume larger than of the conventional continuous reactors; however they do not require equalization tanks and the total reactor volume is usually less than in conventional processes. They can be coupled directly to the waste discharge; however this limits the use to more industrial processes (for example food industry) and less to other waste production. Typical cycle time is one day.

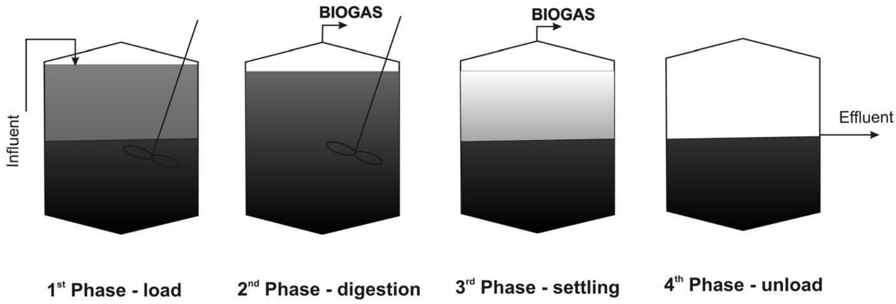

Fig. 5. Schematic picture of the batch ASBR process

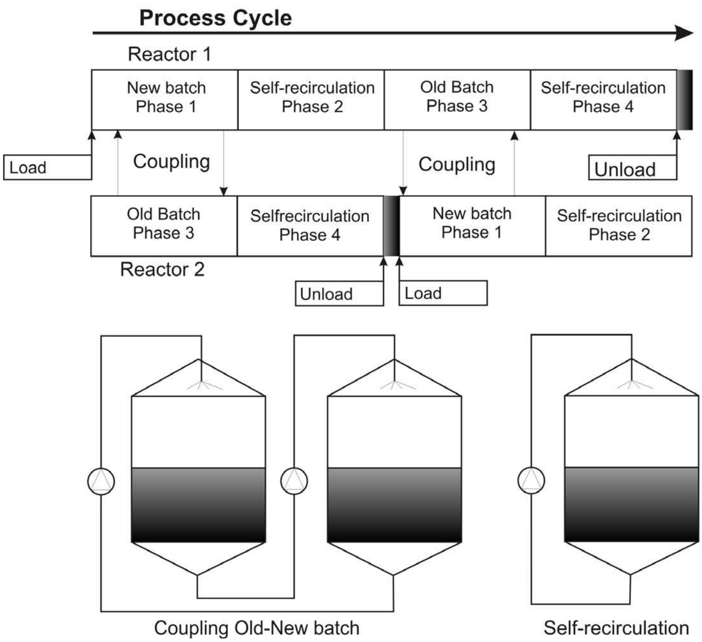

Fig. 6. Batch solid anaerobic digestion

Alternative processes that treat wet organic waste in solid state is reported in literature as SEBAR - Sequential Batch Anaerobic Digester System (Tubtong et al., 2010). In this case the cycle is also divided into four phases, however somehow different than in an ASBR process. This process requires digesters always to be in pairs. The reactor is almost completely emptied between cycles therefore it requires inoculation through leachate exchange between the two digesters (from the one in the peak biogas production to the one at the start of the process). In the other phases leachate is self-circulated (Fig. 6). Typical cycle time is between 30 and 60 days. Although solid substrate reduces the reactor volume, the volume is still rather large due to long cycle times compared to conventional digesters that process liquid substrates. The advantage of this type of digesters is less complicated monitoring equipment so they are applicable in smaller scale.

3.2.2 Continuous processes

Most of the commercial biogas plants use conventional continuous anaerobic digestion process. By conventional it is meant fully mixed, semi-continuous or continuous load and unload reactor at mesophilic temperature range (35-40°C) - Fig. 7. In majority of the cases, the substrate is loaded to the reactor once to several times a day, rarely is it loaded continuously. Continuous load can lead to short circuit, which means that fresh load can directly flow out of the reactor if mixing is too intense or input and output tubes are located improperly. The digester is usually single stage, although they are built in pairs, they do not function as a stage separated process. Usually digesters are equipped with a preparation tank, where various substrates are mixed and prepared for the loading, which also serves as a buffer tank. In many cases also a post-treatment tank is added (it is also called post-fermenter), where treated substrate is completely stabilized and prepared for further treatment. The post-treatment tank can also serve as a buffer towards further treatment steps of the substrate. Generally post-fermenters do not contribute much to overall biogas yield (up to 5 %) if the digester operates optimally. The size of the preparation and post-treatment tanks are determined according to the necessary buffer capacity for continuous operation. The size of the digester is determined with the necessary Hydraulic Retention Time (HRT) and with Organic Loading Rate (OLR) that should be determined in pilot tests. HRT is defined as digester volume divided by substrate flow rate and represents time (in days) in which a certain unit volume of the substrate passes through the reactor. For mesophilic digesters the usual values are between 20 - 40 days, depending on the substrate bio-degradability. In thermophilic digesters to achieve the same treatment efficiency HRT is smaller (between 10 and 20 days).

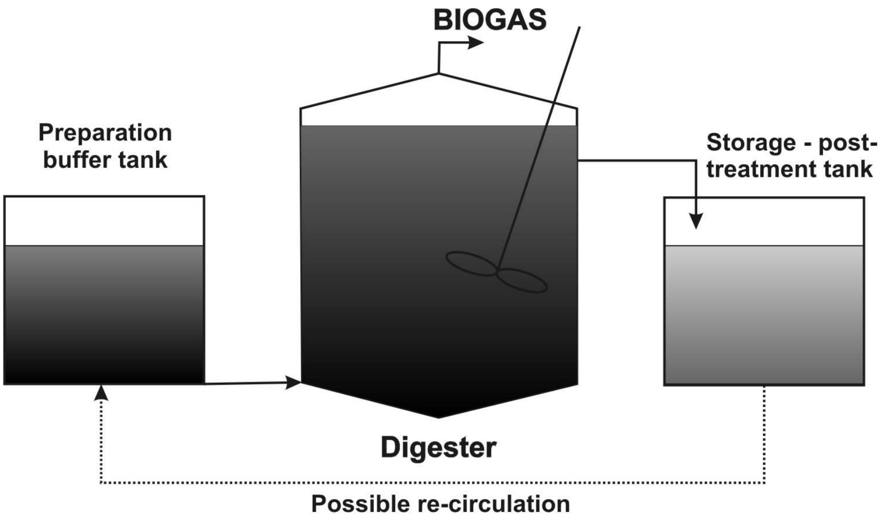

Fig. 7. Conventional single stage anaerobic digestion process

Organic load rate OLR (sometimes also called volume load) is defined as mass of organic material fed to the digester per unit volume per day. Typical value for mesophilic digesters is 2.0-3.0 $kgm^{-3}d^{-1}$. Typical value for thermophilic digesters is 5.0 $kgm^{-3}d^{-1}$. Maximum OLR depends very much of the substrate biodegradability; mesophilic process can rarely achieve higher loads than 5.0 $kgm^{-3}d^{-1}$ and thermophilic 8.0 $kgm^{-3}d^{-1}$. Locally in the digester for a short period of time higher loads can be achieved, however due to inherent instability it is not advisable to run continuously on such high loads.

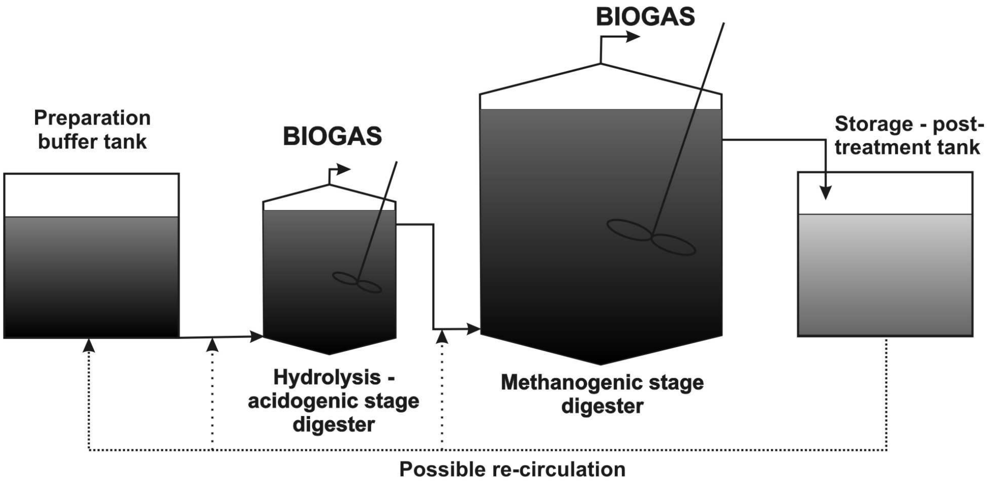

Fig. 8. Two stage anaerobic digestion

To achieve better biodegradation efficiency and higher loads stage separated process can be applied (Fig. 8). In this case the whole substrate or just portions of the substrate which are not easily degradable are treated first in hydrolysis-acidogenic stage reactor and after that in the methanogenic reactor. By separating the biological processes in two separate tanks each can be optimised to achieve higher efficiency with respect to one tank, where all stages of the digestion processes occur simultaneously. Many research data have been published giving considerable attention to this kind of processes (Dinsdale et al., 2000; Song et al., 2004; De Gioannis et al., 2008; Ponsá et al., 2008). Both stages can be either mesophilic or thermophilic, however it is preferred that the hydrolysis-acidogenic reactor is thermophilic and methanogenic is mesophilic. Typical HRT for the thermophilic hydrolysis-acidogenic reactor is 1-4 days, depending on the substrate biodegradability. Typical HRT for the methanogenic reactor is 10 - 15 days (mesophilic) and 10 - 12 days (thermophilic). Advantages of this process beside shorter HRTs are higher organic load rate (20 % or more). Many authors also report slightly better biogas yields (Messenger et al., 1993; Han et al., 1997; Roberts et al., 1999; Tapana and Krishna, 2004). The only disadvantage is more sophisticated equipment and process control, yielding the operation more expensive.

3.2.3 Flow-through processes

The flow-through processes, such as UASB process (Fig. 9) are used only for substrates where most of the organic material is in dissolved form with solids content at maximum 1-5 gL^{-1}. In this substrate category are highly loaded wastewaters of industrial origin (e.g. from beverage industry).

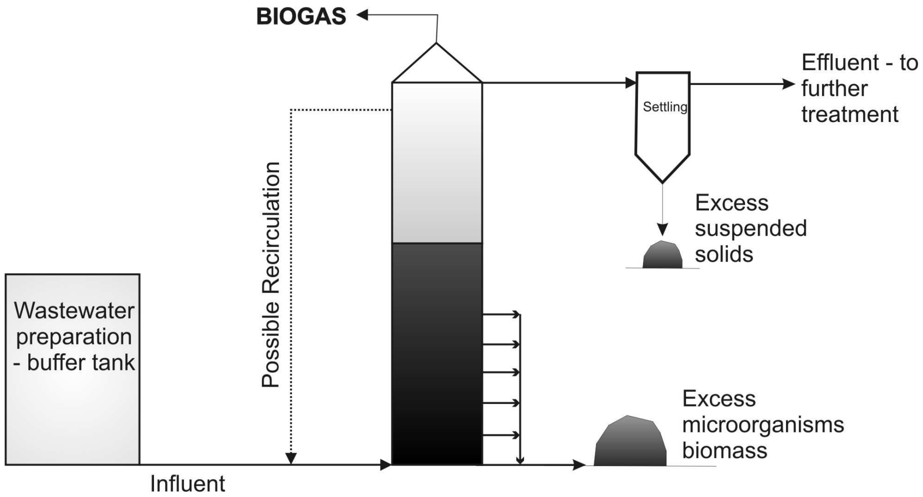

Fig. 9. The UASB process

3.3 Post-treatment and substrate use

After the substrate has been digested, it usually needs additional treatment. There are several possibilities of digested substrate utilisation. Most often, especially in the case of farm waste treatment, the digested substrate is used as a fertilizer. It can be used in liquid state or dewatered. Liquid substrate (total solids concentration 1-5 % by mass) is pumped from the post-treatment tank and spread on the fields. However it must be considered that fertilizing is possible only in certain periods of the year (once or twice). The post-treatment container must be designed accordingly. A possible solution is a lagoon, where digested substrate is stored and additionally stabilized and mineralized during the storing time. When using solid substrate (total solids concentration 20-30 % by mass), the digested substrate is mechanically dewatered first (by belt press or centrifuge) and then liquid and solid parts are used separately. Solid digestate after dewatering can be used fresh as a fertilizer, or it should be stabilized by composting (see further section).

Liquid part of the separated digestate can be used in the new substrate preparation as dilution water, however great caution must be given to nutrients or salts build-up and consequently possible inhibition in the anaerobic digestion. Usually only a portion of that liquid is used in the substrate preparation; the rest must be further treated as a wastewater. Typical concentration of the liquid part of digestate is 200-1000 mgL^{-1} of COD.

3.4 Biogas production, storage, treatment and use

When operating a biogas plant, biogas is the main product and considerable attention must be given to its production, storage, treatment and use. Biogas production completely depends on the efficiency of the anaerobic digestion and its microorganisms. Previous sections have shown what conditions must be met to successfully operate anaerobic digestion. There are two distinct parameters that describe the biogas production:

1. Specific Biogas Productivity - SBP (it's also called biogas yield). It is defined as volume of biogas produced per mass of substrate inserted into digester (m^3kg^{-1}). There are variations; SBP can be expressed in m^3 of gas per kg of substrate: i) (wet) mass, ii) total solids, iii) volatile organic solids or iv) COD. SBP tells us how much biogas was produced from the chosen unit of substrate. Maximum possible SBP for certain substrate is called biogas potential. Biogas potential can be determined by a standard method (ISO 1998).
2. Biogas Production Rate – BPR. It is defined as volume of biogas produced per volume of the digester per day ($m^3m^{-3}d^{-1}$). BPR tells us how much biogas we can gain from the active volume of a digester in one day.

SBP values of an optimally operating digester reach 80-90 % of the biogas potential. Typical values of SBP for farm waste are shown in Table 1. Typical values of BPR for mesophilic digesters are from 0.9 to 1.3 $m^3m^{-3}d^{-1}$. Lower values indicate the digester is oversized; higher values are rare or impossible, due to anaerobic process failure. For thermophilic or two stage digesters the typical BPR values are from 1.3 to 2.1 $m^3m^{-3}d^{-1}$, respectively. UASB reactors are much less volume demanding and can achieve a BPR of up to 10 $m^3m^{-3}d^{-1}$.

Biogas production is rarely constant; it is prone to fluctuations due to variation of loading rates, inner and outer operating conditions, possible inhibitions etc... Therefore, a buffer volume is required for the biogas storage. This enables the biogas user to get a constant biogas flow and composition. Most of the modern biogas plants are equipped with co-generation units (named also combined heat and power units – CHP) which require constant gas flow for steady and efficient operation. There are several possibilities of biogas storage; roughly they can be divided into low pressure (10-50 mbar) and high pressure storage (over 5 bar). Low-pressure storage is used in on-site installations and for gas grid delivery; high pressure storage is used for long term storage, for transport in high pressure tanks and in installations with scarce space for volume extensive low pressure holders.

Low pressure biogas holders arise in many variations. It is possible to include biogas holder in the design of the digester. The most known is the digester with a movable cover. These digesters are less common, because a movable cover requires increased investment and operating expenditure. More common are external biogas holders that are widely commercially available. An example of a modern biogas holder is presented in Fig. 10.

Low pressure biogas holders require an extensive volume of 30 to 2000 m^3 (Deublin and Steinhauser, 2008). Usually the pressure is kept constant and the volume of the bag is varied. High pressure biogas holders are of constant volume and made of steel, they are subject to special safety requirements. They do require more complex equipment for compression and expansion of the gas and are more cost-effective for operation and maintenance.

Biogas contains methane (40-70% by volume) and carbon dioxide. There are also components, present in low concentrations (below 1 %) such as water vapour, substrate micro particles and trace gases. Therefore biogas treatment is necessary to preserve equipment for its storage, transport and utilisation. Solid particles can be filtered out by candle filters, sludge and foam is separated in cyclones. For removal of trace gases, where hydrogen sulphide (H_2S) is the most disturbing one due to its corrosion properties, processes like scrubbing, adsorption and absorption are used. In some cases also drying is required (usually to the relative humidity of less than 80 %).

After cleaning, biogas is used to produce energy. The most common way is to us all biogas in cogeneration plant in CHP unit to produce power and heat simultaneously (Fig. 11). In this case we can achieve maximum power production and enough excess heat to run the digesters. The energy required for heating the digester is also called parasitic energy. The anaerobic digesters require heat to bring the substrate to operating temperature and to compensate the digester heat losses. The digester also requires energy for mixing, substrate pumping and pre-treatment. The largest portion of heating demands in the digester operation is substrate heating. It requires over 90 % of all heating demands, and only up to 10 % is required for heat loss compensation (Zupancic and Ros 2003). In mesophilic digestion a CHP unit delivers enough heat for operation, while in thermophilic digestion additional heat is required. This additional heat demand can be covered by heat exchange between substrate outflow to substrate inflow -

Usually a conventional counter-currant heat exchanger is sufficient; however a heat pump can be applied as well.

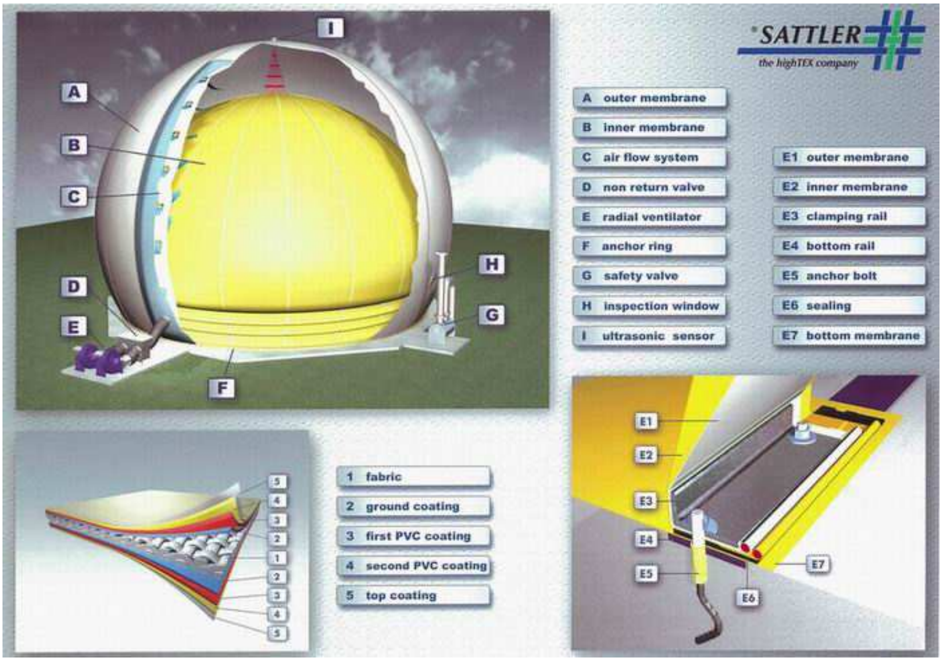

Fig. 10. An example of commercially available biogas holder (Sattler 2011)

Electric energy is also required in digester operation for pumping, mixing and process control and regulation. In practice, no more than 10-15 % of electric energy produced should be used for internal demands.

The pre-treatment process may also require electric or thermal energy. Pre-treatment improves anaerobic digestion and its biogas production. However implications of pre-treatment methods must be carefully considered. The golden rule is that pre-treatment should not spend more energy that it helps to produce. If the energy use and production balances out, pre-treatment may have benefits such as more stable digested substrate, smaller digesters, pathogen removal etc. There are substrates that require extensive pre-treatment; especially this is the case for ligno-cellulosic material (like spent brewery grains, Sežun et al. 2011) that require energy intensive pre-treatment to be successfully digested. In such cases the energy need for pre-treatment must be accounted in the energy production. In many cases it cannot outweigh the economy of the process; it may well happen that the parasitic energy demand is too high.

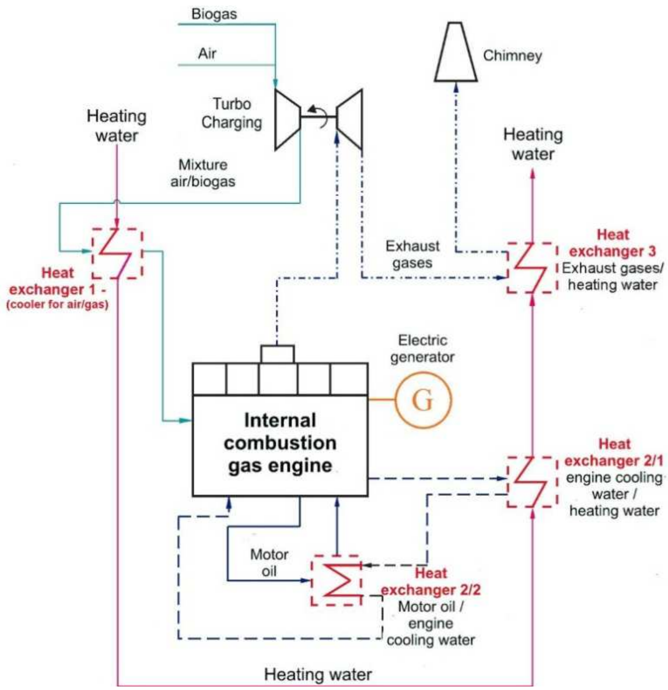

Fig. 11. Schematic of a combined heat and power units (CHP) unit

In recent years great interest was taken to biogas injection into natural gas grid. Mainly due to the fact, that global energy efficiency in such cases is usually far greater that at CHP plants. Namely in warmer periods of the year, heat produced in the CHP is largely wasted and therefore unused. Injecting the biogas into natural gas grid assures more than 90% energy efficiency, due to the nature of the use (heat production), even in warmer periods. Consequently the whole biogas production process can be more economic, in some cases even without considerable subsidies as well as more renewable energy is put to the energy supply. Also in most cases, the investment costs of biogas plants may be less, since there is no CHP plant. In order to be able to inject the biogas into natural gas as biomethane (Ryckebosch et al., 2011) grid certain purity standards must be fulfilled, which in EU are determined by national ordinances (a good example is the German ordinance for Biogas injection to natural gas grids from 2008), where responsibilities of grid operators and biogas producers are determined (Fig. 13) as well as quality standards are prescribed (DVGW, 2010). When injecting biomethane into the natural gas grid some biogas must be used for the reactors self-heating. It is advisable to use regeneration (Fig. 12), even in mesophilic temperature ranges, to minimize this expenditure, which on annual basis can contribute to 10-20 % of all biogas production (Pöschl et al., 2010).

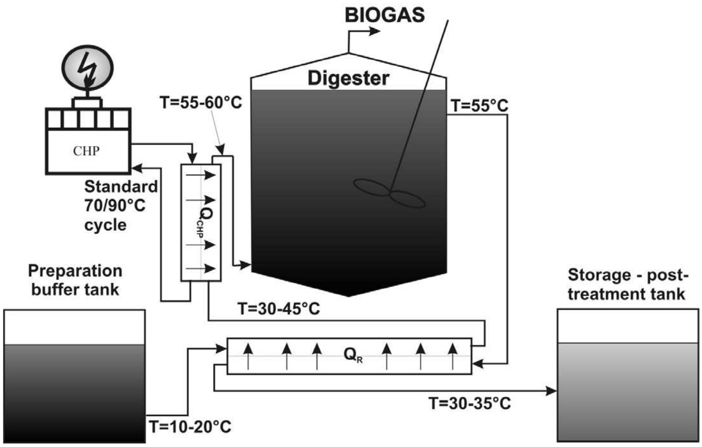

Fig. 12. Scheme of the heat regeneration from output to input flows.

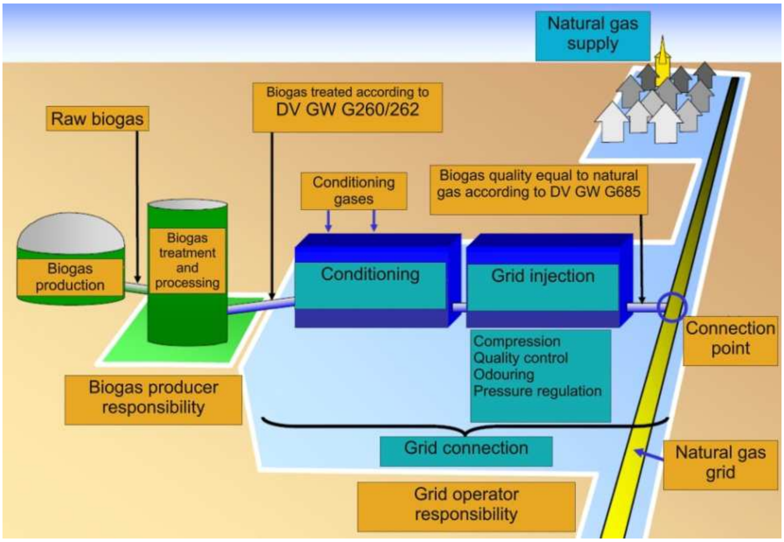

Fig. 13. Injection of biogas into natural gas grid (Behrendt and Sieverding 2010)

3.5 Anaerobic digestion residue management

Environmental impact assessment of an anaerobic digestion plant (a biogas station) should take into consideration both the plant emissions and the digestate management. The first aspect mainly relates to flue gas and odour emissions. The exhaust gases from gas motors must fulfil emission limit values, which is not a problem when appropriate gas pretreatment (sulphide and ammonia removal) has been applied. Unpleasant odours mainly originate from storage, disintegration and internal transport of organic waste. These should be carried over in a closed system, equipped with an air collection system fitted with a biofilter or connected with the gas motor air supply.

3.5.1 The anaerobic digestion residue management

A quality management system (QMS) specific to a defined digestion process and its resulting whole digestate or any separated liquor and separated fibre, should be established and maintained. Anaerobically digested slurry or sludge contains 2-12 % of solids; wet waste from solid state digestion contains 20-25 % solids. The digestate contains not degraded organic waste, microorganism cells and structures formed during digestion, as well as some inorganic matter. This is potentially an alternative source of humic material, nutrients and minerals to the agricultural soil (PAS, 2010). It may be used directly or separated into liquid and solid part. The liquid digestate is often recycled to the digestion process; some pretreatment may be required to reduce nitrogen or salt content.. Freshly digested organic waste is not stable under environmental conditions: it has an unpleasant odour, contains various noxious or corrosive gases such as NH_3 and H_2S, and still retains some biodegradability. In certain periods of a year it may be used in agriculture directly, in most cases however it must be stabilized before being applied to the fields.

Aerobic treatment (composting) is an obvious and straightforward solution to this problem. The composting procedure has several positive effects: stabilization of organic matter, elimination of unpleasant odours and reduction of pathogenic microorganisms to an acceptable level. Composting, applied prior to land application of the digested waste, contributes also to a beneficial effect of compost nitrogen availability in soil. (Zbytniewski and Buszewski, 2005; Tarrasón et al., 2008)

The simplest way is composting of the dehydrated fresh digestate in a static or temporarily turned-over pile. A structural material is necessary to provide sufficient porosity and adequate air permeability of the material in the pile. Various wood or plant processing residues may be used as a structural material like woodchips, sawdust, tree bark, straw and corn stalks provided that the sludge : bulk agent volume ratio is between 1:1 and 1:4 (Banegas et al., 2007). The majority of organic material is contributed by the bulking agent, but significant biodegradation of the digestate organic material also occurs, by means of natural aerobic microorganisms.

The final compost quality depends on the content of pollutants such as heavy metals, pathogenic bacteria, nutrients, inert matter, stability etc. in the mature compost. Typical quality parameters are presented in Table 6. The properties of the compost standard leachate may also be considered. Heavy metals and persistent organic pollutants accumulate in the compost and may cause problems during utilization. Compost quality depends on quality of the input material, which should be carefully controlled by input analysis. Pathogenic bacteria may originate from the mesophilic digestates or from infected co-composting materials, if applied (e.g. food waste). If thermophilic phase period of the composting process has lasted at least few days, the compost produced may be considered sanitized and free of pathogens such as *Salmonella, Streptococci* and *coliforms.*

The third important factor is presence of nitrogen. Several authors have reported that the optimal C/N ratio is between 25/1 and 30/1 although operation at low C/N ratios of 10/1 are also possible. With such low C/N ratios the undesirable emission of ammonia can be significant (Matsumura et al., 2010). Characteristic values of organic matter content and total nitrogen in the digested sludge are 50-70% and 1.5-2.5%, respectively. In the first week of the digested sludge composting the total carbon is reduced by between 11% and 27% and total nitrogen is reduced by between 13% and 23% (Pakou et al., 2009; Yañez et al., 2009).

Parameter	Test method	Limit value
1. Pathogens		
Escherichia coli	ISO 16649-2	1000 CFU/g fresh matter
Salmonella sp.		Absent in 25 g fresh matter
2. Toxic elements		
Cd	EN 13650	1.5 mg/kg d.m.
Cr	EN 13650	100 mg/kg d.m.
Cu	EN 13650	200 mg/kg d.m.
Hg	ISO 16772	1.0 mg/kg d.m.
Ni	EN 13650	50 mg/kg d.m.
Pb	EN 13650	200 mg/kg d.m.
Zn	EN 13650	400 mg/kg d.m.
3. Stability		
Volatile faty acids	GC	-
Residual biogas potential		0.25 l/gVS
4. Physical contaminants		
Total glass, metal, plastic and other man-made fragments		0.5 $\%_{m/m}$ d.m.
Stones >5 mm		8 $\%_{m/m}$ d.m.
5.Parameters for declaration		
Total nitrogen	EN 13654	
Total phosphorus	EN 13650	
Total potassium	EN 13650	
Water soluble chloride	EN 13652	-
Water soluble sodium	EN 13652	
Dry matter	EN 14346	
Loss on ignition	EN 15169	
pH	EN 13037	

Table 6. Control parameters of digestate quality for application in agriculture (WRAP 2010)

Highest degradation rates in the compost pile are achieved with air oxygen concentration above 15% which also prevents formation of anaerobic zones. The quality of aeration depends primarily on structure and degree of granulation of the composting material; finer materials generally provide better aeration of the compost pile (Sundberg and Jönsson, 2008). In the first stages of degradation, acids are generated, and these tend to decrease the pH in the compost pile. The optimum pH range for microorganisms to function is between 5.5 and 8.5. Elevated temperature in the compost material during operation is a consequence of exothermic organic matter degradation process. The optimum temperature for composting operation, in which pathogenic microorganisms are sanitised, is 55-70°C. In the initial phases of composting the prevailing microorganisms are fungi and mesophilic bacteria, which contribute to the temperature increase and are mostly sanitised in the relevant thermophilic range. When temperature falls many of the initial mesophilic microorganisms reappear, but the predominant population are more highly evolved organisms such as protozoa and arthropods (Schuchard, 2005). For optimum composting operation the correct conditions must be established and are determined by particle size distribution and compost pile aeration have shown that the air gaps in the compost pile can be reduced from an initial 76.3% to a final 40.0%. The optimum moisture content in the compost material is in the range of 50-70%.

In the recent years the composting practice for anaerobic digestate has been thoroughly studied for many different types of substrates, for co-composting and with many different bulk agents (Nakasaki et al., 2009; Himanen et al., 2011).

From various reasons the composting of the digestate residue is sometimes not possible (lack of space, problems with compost disposal etc.). Alternatively the digestate may be treated by thermal methods, which require higher solid content. Mechanical dehydration by means of continuous centrifuges provides solid content about 30 % with positive calorific value. Incineration may be carried out in a special kiln (most often of fluidized bed type) or together with municipal waste in a grit furnace. Co-incineration in industrial kilns usually require drying of sludge to 90 % dryness, that gives calorific value of about 10 MJ/kg. Thermal methods are more expensive than composting due to high energy demand for dehydration and drying, sophisticated processes invplved and strict monitoring requirements. Good review of the modern alternative processes of anaerobic sludge treatment is presented by Rulkens (2008).

4. Conclusions

The chapter entitled "Sustainable Treatment of Organic Wastes" presents principles and techniques for treatment of wet biodegradable organic waste, which can be applied in order to achieve environmental as well as economic sustainability of their utilisation.

The chapter mostly focuses on organic wastes generated in the municipal sector; however it may well apply to similar wastes from agriculture and industry. The main focus is aimed at matching the anaerobic treatment process to the selected type of waste in order to maximize the biogas production, a valuable renewable energy resource. The chapter also focuses on technological aspects of the technology used in such treatments and presents and elaborates several conventional treatments (such as semi-continuous processes, two stage processes, sequencing batch processes, etc.) as well as some emerging technologies which have only recently gained some ground (such as anaerobic treatment in solid state). The basic conditions are presented which are required to successfully design and operate the treatment process. Organic loading rates, biogas production rates, specific biogas productivity, biogas potentials and specific concerns for certain technologies and waste substrates are presented. The main influencing factors such as environmental conditions (pH, temperature, alkalinity, etc.) have been addressed as well as inhibitors that can arise in such processes (heavy metals, ammonia, salts, phenolic compounds from lignocellulosic degradation, organic overload etc.). The biogas treatment and use, such as power production and natural gas grid injection, have been presented as well as the use of parasitic energy, options for biogas production enhancement through waste pre-treatment (mechanical, chemical, physical, etc.) and treatment of residues of anaerobic digestion, which may have an important impact on the environment. Special attention is given to further treatment of digested solid residues as well. Due attention is paid to aerobic stabilization processes (open and closed composting), taking into account physical form of the waste, its composition, pollution, degradability and final deposition and use.

5. Acknowledgment

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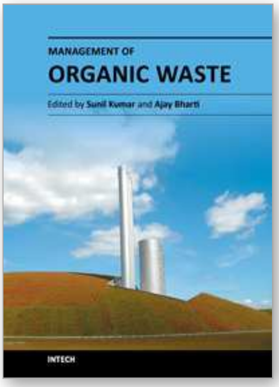

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This book reports research on the utilization of organic waste through composting and vermicomposting, biogas production, recovery of waste materials, and the chemistry involved in the processing of organic waste under various processing aspects. A few chapters on collection systems and disposal of wastes have also been included.