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# Dry Digestion of Organic Residues

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## 1. Introduction

Sustainable development closely links to the context of energy. Replacing fossil fuels with sustainably produced biomass or organic residues will not only be a way to cope with the depletion of fossil fuel resources but also to reduce the $CO_2$ emissions into the atmosphere and therefore minimise the risk of global warming. A large variety of methods of biomass energy conversion are available today. Some technologies produce secondary fuel such as methanol or biomass oil which then can be utilized for various purposes. Especially for electricity generation efficient processes might be direct combustion, thermal gasification or the production of biogas.

Anaerobic digestion (AD) with biogas production, including utilisation of the organic fraction of waste materials and of residues, is a particularly promising choice and experiences increasing interest worldwide. AD does not only supply a clean and versatile energy carrier, thus displacing other energy sources such as fossil energy, but is well suited to contribute towards appropriate waste management schemes in urban areas and in agriculture. Biogas production has high potential worldwide, and it is in particular digestion of solid materials which is of increasing interest. As a result, it is to be expected that so-called dry digestion systems, operated with an elevated content of total solids (TS) in the reactor, will experience more widespread implementation.

Agricultural residues in general are left on field or are brought back to field in order to supply fertilizers and to improve soil quality. Anaerobic digestion offers the possibility to produce renewable energy, and at the same time generates a digestate with an improved fertilizer value.

Currently the most common strategy for management of municipal solid waste (MSW) worldwide is still landfill. As a result of higher environmental awareness, and often based on favourable legislative backgrounds, more and more emphasis is given to recycling and recovery, and in particular to efficient use of organic materials. Composting and anaerobic digestion are state-of-the-art for treating organic substrates.

Germany today is leading in the area of biogas production. Around 6,000 AD plants are in operation, and the number is further increasing. Most plants are in the agricultural sector, but currently at least 100 plants are run solely on the organic fraction of MSW, a direct result

of introduction of source-segregation schemes for household waste. Due to favourable frameworks the number of AD plants in the municipal field will significantly rise in the coming years (along with more agricultural plants to be build).

## 2. Anaerobic digestion: basics

Different types of biomass can be used for biogas production, including organic waste from gastronomy/food waste, the organic fraction of MSW, organic waste from industry/commercial waste, sewage sludge, excreta, agricultural residues, and for energy generation purposes grown energy crops. This book chapter focuses on biogas production with solid waste materials. The main principles are common in digestion of all materials, though solid substrates require adaptation of the processes. Separate collection of organic fractions and diversion from landfill is among the main success criteria.

### 2.1 Principles and products of the AD process

Biogas is produced in the absence of oxygen (anaerobic digestion) through biological activity of different microorganisms if the environment is friendly for the microbes (water content, temperature, nutrients). The substrate must provide all components necessary for the metabolic processes (C, N, O, H, S, P, K, Ca, Mg), including micronutrients such as nickel, iron, zinc, manganese, copper, molybdenum, selenium, wolfram. Material should not have inhibiting substances (e.g. disinfectants, antibiotics, heavy metals). Inhibitory or toxic effects are in general related to concentration and process conditions. As metabolic (intermediate) products can also have inhibitory effects ($NH_3$, $H_2S$, volatile fatty acids, $H_2$), process conditions need to be controlled.

Anaerobic digestion with biogas production is the result of an anaerobic reaction chain with several steps. Each of the steps hydrolysis, acidification, acetogenesis, methanogenesis involves specific groups of microorganisms with individual requirements. Efficient biogas production necessitates that process conditions are favourable (or at least tolerable) for each of the groups. Microbiology, together with different characteristics of manifold potential substrates, is one explanation for the large variety of technical solutions to be found in full-scale applications.

During anaerobic digestion a large part of the energy contained in the biomass is transformed into methane, an energy carrier which then can be used for example to produce electricity. Anaerobic digestion of glucose for example leads to biogas which contains 85 % of the energy content of glucose (2868 kJ/mol contained in glucose after having been formed in the photosynthesis pathway), see Fig. 1.

Biogas has a wide variety of possible applications, the most common ones are:

- Direct use for cooking and lighting (small-scale AD plants at household level)
- Utilisation for heat generation
- Generation of electricity (several engine types can be fuelled with biogas; electricity generation is often accompanied by heat generation in combined heat and power plants/ CHP)
- Fuel for cars/vehicles
- Feeding into the natural gas grid (after upgrading to natural gas quality; now one standard in industrialized countries when produced at large scale; different upgrading technologies exist)

Compared to other renewable energies, it is one advantage of the energy carrier biogas that it can be stored to be used according to fluctuating demands or to availability of alternative energies. Biogas can be a particularly advantageous choice e.g. in hybrid power systems for electricity supply in remote areas or islands (Borges Neto at al., 2010). It is not necessary to make use of biogas directly at the production site. Local biogas grids can be an intelligent solution to provide biogas to where it can be used at highest efficiency (Panic et al., 2011).
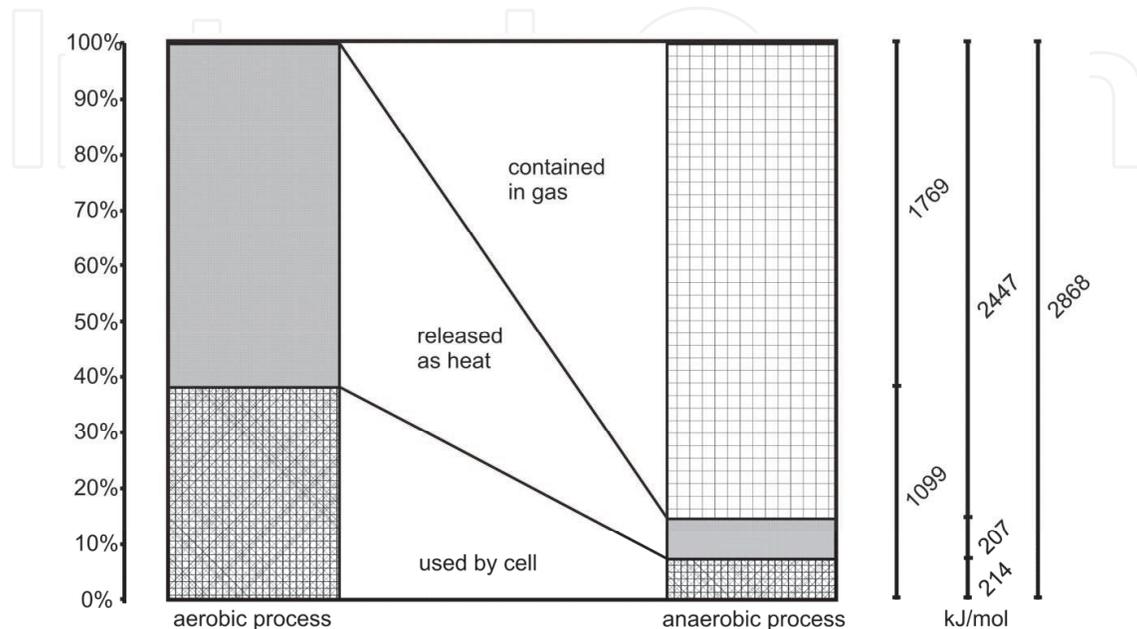


Fig. 1. Energy balance of aerobic and anaerobic degradation of glucose (based on Kranert, 1989)

During digestion, the amount of organic material is reduced in the substrate whereas nutrients like nitrogen are conserved in the biomass. AD residue therefore is an efficient fertilizer. Especially with regard to nitrogen biogas residues have excellent nutritional properties as digestion encourages transformation into bioavailable ammonia. The extent of nutrient uptake by plants depends on the time of application and there is always the possibility that nutrients will be leached from the soil when plants are unable to take them up. While in the organic form nitrogen must be first mineralised, AD converts much of the organic N into ammonia, yielding a digestate with 60-80% of the total nitrogen content in the form of ammonia (Banks et al., 2007). This makes it highly predictable, minimises leaching losses and is in line with the development of good agricultural practices. Ammonia can be converted to nitrate for plant uptake, while some plants may use ammonia directly.

The improved fertilizer value of AD digestate is to be considered as economic advantage of the AD unit. Other fertilizers are displaced and higher biomass yields are possible, as has been reported for napa cabbage, cauliflower (Jian, 2009). Digestate which is not fit for landspreading (e.g. due to contamination with heavy metals) must be disposed of.

## 2.2 AD plant types

Many different AD plant types have been developed and are to be found in full-scale for various applications and in different regions. The following overview is restricted on types typically implemented for digestion of solid waste materials, agricultural substrates and household wastes. Table 1 provides an overview on different technology concepts.

| | |
|---|---|
| Operation of mode: batch, fed-batch or continuous | In *batch systems* the whole substrate is filled at once into the reactor and is digested over a pre-defined period. When digestion is complete material is removed and the process is started with a fresh load. In batch systems digestion and methane production start anew with each filling of the reactor and biogas supply therefore is not continuous. For commercial operation it is in general necessary to have several reactors run off-set (alternative loading and unloading), at least three reactors should be operated. |
| | In *fed-batch mode* material is added to the digester by and by until the space is used up. Then all material is removed and the emptied digester provides new reactor volume. |
| | In a *continuous* system (or more precise semi-continuous) substrate is regularly fed into the reactor, and at the same time effluent is unloaded. Biogas production is continuous. Such a system in most cases is judged to be better suited for large-scale operations (Suryawanshi et al., 2010), drastic changes of input composition should be avoided. |
| Transport of material, homogeni-sation in reactor | The most common types of AD plants are based on the concept *continuously stirred tank reactor* (CSTR). Plants are equipped with facilities for stirring the digester content (continuously, or in most cases semi-continuously), resulting in homogenization of reactor content but also in differing retention times for different particles, with part of the material leaving the reactor after very short digestion. |
| | *Plug flow digesters* are long narrow reactors (typically 5 times as long as the width) with inlet and outlet at opposite ends. Feeding is carried out semi-continuously and typically with a thick substrate (~15% TS). In general there is no internal stirring device, material advances whenever new substrate is added and in theory the reactor content does not mix longitudinally on its way towards the outlet (but actually material does not remain as a plug and portions advance faster than others – but minimum retention time is assured far better than in CSTR concepts, thus allowing for better hygienisation). |
| Total solids content (TS) | So-called *wet digestion plants* are most common in agriculture, they are operated at TS < 12%. When digesting higher amounts of solid materials, water content needs to be adjusted (addition of liquid substrates, water or recirculation of digester effluent). |
| | For digestion of organic materials available mainly in solid form, implementation of technical processes designed for higher TS contents was a logical step (e.g. municipal bio waste). So-called *dry digestion plants* are typically operated at TS > 20%, water content often is not adjusted to a specific value but is a result of the digesting substrates. |
| | It needs to be mentioned that no final definition based on TS content exists; in literature other TS limits can be found. Occasionally a third type is introduced in order to characterise processes operated between 12 to 20% TS: *semi-dry digestion.* |
| Digestion temperature | Most AD plants are operated in the *mesophilic range*, optimally around 30-38 °C. Especially in tropical countries AD plants are operated without |

| | |
|---|---|
| | temperature control with digestion at ambient temperatures (~20-45 °C). Mesophilic processes are more stable than thermophilic, the greater number of mesophile microorganisms makes the process more tolerant to changes in environmental conditions. |
| | Besides mesophilic AD, *thermophilic digestion* is a conventional operational temperature, optimally around 48-57 °C. The increased temperature results not only in better hygienisation, but in faster reaction rates, and consequently faster biogas production (shorter retention times, higher degradation rates). However, the process is less stable and requires higher energy input for reactor heating. |
| | AD plants operated at *psychrophilic temperature* (<20 °C) are less common, they are restricted to low-tech applications. Degradation of organic material and biogas production are very slow, resulting in long retention times. |
| One-, or two-stage (multi-stage) systems | In *two-stage systems* (or multi-stage systems, which however are very rare) process conditions can be optimized for the different groups of microorganisms in order to improve overall efficiency. While during the first phase conditions can be optimized in order to achieve a rapid liquefaction, the second phase converts soluble matter into biogas. Compared to single-stage systems the process is more rapid and more stable, but investment and maintenance costs are considerably higher. |
| | By far the most AD plants are *one-stage processes*, with one single reactor for the digestion process (in general followed by a storage tank). |

Table 1. Types of digesters

## 2.3 Digestion at elevated TS contents

In agriculture, continuously operated reactors processing materials with high water contents are most common. This is to be explained by the fact that slurry was the predominant substrate for agricultural biogas plants throughout many decades. However, the use of solid substrates such as yard manure and especially energy crops is becoming more attractive (Amon et al., 2007; Weiland, 2006). In full scale, digestion of solid biomass is limited in conventional slurry-plants, due to technical restrictions in particular related to mixing and feeding devices, and technologies appropriate for operation with elevated content of total solids (TS) are imperative.

In general, the term 'dry fermentation' describes digestion with higher TS content. Since lack of moisture limits bacteriological activity in all anaerobic systems, no digestion can actually be 'dry'. Therefore, the terms 'solid-state' digestion (Martin, 1999; Martin et al., 2003) or 'solid-phase' digestion (Anand et al., 1991; Chanakya et al., 1997; Kusch et al., 2008) are used as equivalents to 'dry digestion'. Similarly, the term 'liquid-phase digestion' is used as equivalent to 'wet digestion' for processes operated with low TS content.

Dry digestion is still uncommon in agriculture, but to treat municipal solid waste so-called dry digestion processes with > 20% TS are implemented to at least a similar extent than wet digestion processes (Bolzonella et al., 2003; Forster-Carneiro et al., 2008), in general one-stage processes are favoured (Forster-Carneiro et al., 2008). As MSW is a solid material, development of technological concepts adapted to high TS contents was a logical step. While MSW is mainly processed continuously, batch processing of solid material prevails in agricultural dry digestion systems.

Both, single-stage (Kusch et al., 2008; Svensson et al., 2006) and two-stage approaches (Andersson & Björnsson, 2002; Linke et al., 2006; Parawira et al., 2002) are the subject of research for both, batch and continuous processing. Section 3 of this Chapter describes in detail a full-scale application and experimental results of one-stage batch dry digestion, and Section 4 focuses on two-stage continuous processing.

Dry digestion reduces the risk that process problems will occur due to fibrous materials floating on top of the liquid, a phenomenon often observed in wet digestion of lignocellulosic substrates such as straw or straw-containing dung, e.g. from horses (Kalia & Singh, 1998). Some further advantages associated with dry digestion systems are as follows (Hoffmann, 2001; Köttner, 2002): lower reactor volume, less process energy, lower transport capacity, less water consumption.

Monitoring results of 61 full-scale AD plants revealed that in particular continuously operated dry digestion plants are comparable to wet digestion in terms of general efficiency, methane productivity (methane generation per net reactor volume and day) and methane yield (FNR, 2009). It was however pointed out that demands on technical equipment (stirring devices, pumps) are much higher, due to the elevated viscosity of the digester content. In addition, there is a higher risk for shortage of micronutrients, and as a result addition of micronutrients is common. Discontinuous dry digestion in box type digesters was found to have a higher risk for lower gas yields and for increased odour emissions due to handling of material outside the digestion boxes (see Chapter 3), but the monitoring project confirmed that plants are robust and failure rarely occurs.

## 2.4 Degradability of solid residues

Lignocelluloses comprise a large fraction of solid biomass such as MSW, crop residues, animal manures, woodlot arisings, forest residues or dedicated energy crops (Sims, 2003). Global crop residues alone were estimated at about 4 billion Mg for all crops and 3 billion Mg per annum for lignocellulosic residues of cereals (Lal, 2009). Biogas production from lignocellulosic biomass is a slow (without pre-treatment having been applied to the substrate prior to digestion) but steady process. Methane originates mostly from hemicellulose and cellulose, but not from lignin which cannot be degraded by anaerobic microorganisms. As in other biochemical conversion pathways, in the anaerobic digestion of this substrate type, enzymes must first break the lignin barrier in order to gain access to the degradable components. In order to make these biomasses better available to anaerobic degradation, various physical or chemical pre-treatment technologies are known, including thermochemical or ultrasonic pre-treatment, use of different additives or steam pressure disruption (Liu et al., 2002; Petersson et al., 2007; Yadvika et al., 2004). Though potentially applicable on larger scale, for lignocellulosic materials contained within solid manure sophisticated expensive pre-treatment procedures seem inappropriate for utilisation on single farms. Two-stage digestion with hydrolysis is feasible (see Chapter 4.2).

The actual methane yield depends on the total methane potential, the digestion time and degradation kinetics (influenced by substrate characteristics and process conditions). The total methane potential $G_{pot} = G(t \rightarrow \infty)$ can be determined by optimized batch testing, which should include extrapolation of the experimental findings (Kusch et al., 2008; 2011). The exploitation degree $q_t = G_t/G_{pot}$ indicates the proportion of $G_{pot}$ released at a specific point in time (t). Table 2 lists selected experimental results.

| | $q_{26}$ | $q_{28}$ | $q_{42}$ | $q_{49}$ | $q_{74}$ | |
|---|---|---|---|---|---|---|
| Oat husks | 0.61 | 0.65 | 0.84 | 0.90 | | Kusch et al., 2011 |
| Horse dung with straw | | 0.52 | 0.62 | | 0.74 | Kusch et al., 2008 |
| Wheat straw | 0.49 | | 0.61 | | | based on Møller et al., 2004 |

Table 2. Exploitation degree $q_t = G_t/G_{pot}$ for different digestion times

## 2.5 Legislative background for diversion of MSW fractions from landfill to AD

The organic fraction of MSW is most suitable for biogas production through AD, and as mentioned above dry digestion is particularly well suited and most common. Among the key factors towards more widespread implementation of AD for organic MSW fractions, is waste segregation at source. The existence of legal frameworks resulting in authorities being liable to promote source-segregation in order to avoid landfilling of biodegradable waste is one of the main drivers to dissemination of AD in a country. Since several decades, legislation in the area of treatment of MSW has placed increasing emphasis on recycling and recovery in Europe and in many other countries.

The effect of legislation can be shown on the example Germany. Today the country has one of the highest recycling rates in the European Union (EU) and worldwide, and a significant amount of energy is recuperated via combustion by waste to energy treatment facilities (WtE), with generation of electricity and heat. In 2009 ~67% of MSW was recycled, incineration was applied to ~32%, while only 0.4% of total MSW was landfilled (2 kg per capita, compared to 216 in 1997) (Fig. 2).
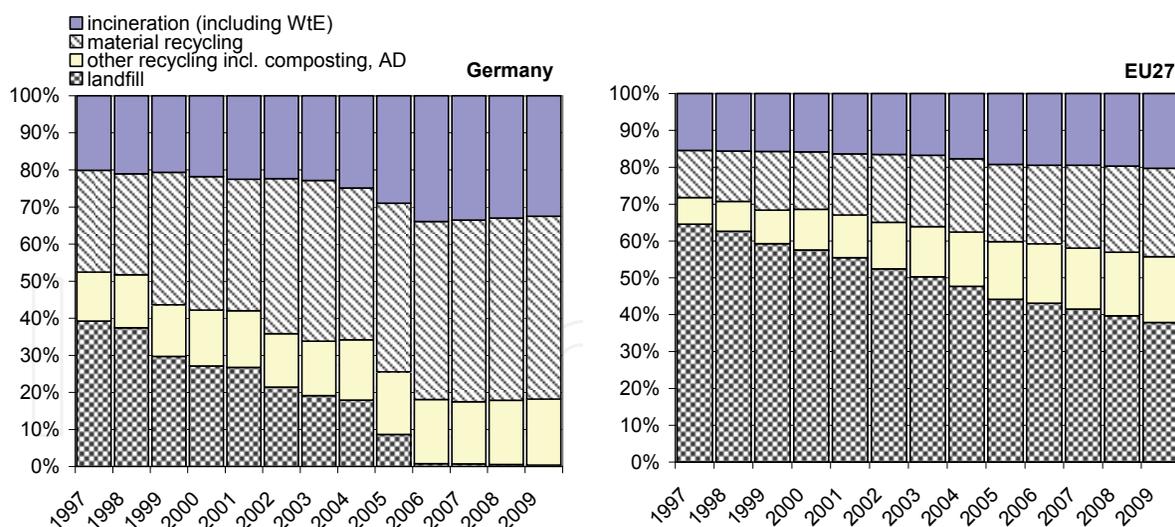


Fig. 2. MSW treatment in Germany and the 27 EU member states (based on data from Eurostat, 2011)

Germany is subject to EU regulations and has aligned its legislation according to demands on EU level, and often more stringent targets were set. Within the key focus of the EU Landfill Directive (1999) is to reduce negative effects of landfilled waste on the environment. According to the set EU objectives waste disposal is to be reduced by 20% by 2010 and by 50% by 2050 compared to 2000, and it is in particular the amount of biodegradable MSW

going to landfill which is gradually to be reduced (75% of biodegradable MSW going to landfill by 2006, 50% by 2009 and 35% by 2016 compared to a 1995 baseline).

Three legislation schemes have had highest impact on the high recycling rates in Germany (Mühle et al., 2010): (i) a refund system for cans and bottles ("Ordinance on the avoidance and recovery of packaging wastes", 1998), (ii) introduction of kerbside collection in the early 1990s (following the "Act for promoting closed substance cycle waste management and ensuring environmentally compatible waste disposal") and (iii) severe restriction of landfilling of non-pretreated MSW since 2005 by the commencement of the "Technical instructions on MSW" (replaced by the "Landfill Ordinance", which came into force in 2009). Landfill of non-pretreated MSW is now practically impossible, and it is in particular reduction of the organic fraction which needs to be ensured by pre-treatment.

## 3. Batch anaerobic dry digestion

Batch-wise digestion of stacked biomass represents a particularly simple system. More and more box type fermenters with percolation (sprinkling of process water over the stacked biomass) are to be found in full scale. The box type reactors process mainly agricultural solid substrates. Some more facilities digest municipal biowaste and have proven reliability (e.g. systems Bekon, Biocel).

### 3.1 Principles

Substrate is filled at once into the reactor and is digested over a pre-defined period. The addition of an appropriate ratio of solid inoculum accelerates methanisation and prevents digester failure (Ten Brummeler & Koster, 1989). The sprinkled liquid assures favourable biomass moisture content.

In order to equalise gas production at least three batch-operated dry digestion reactors need to be run offset. In general all digesters are functionally coupled through the recirculated liquid: leachate of all reactors is collected in a common process water tank and reused for percolation. It is not possible to operate the system without a separate process water tank, since the total volume of liquid varies in time and depends on water content, water holding capacity and degradation kinetics of the solid materials. Due to the water movement through the stack of solids, organic material is partly washed out from the substrate stack and is metabolised either in the liquid tank or in other solid-phase digesters, while only part of the total methane production actually occurs in the substrate itself.

Experimental results demonstrate that in batch-operated dry digestion with percolation significant amounts of biogas can originate from methanogenic activity in the process water tank. This gas volume is not to be neglected and represents a valuable energy source. If not valorised, the negative effect lies not only in the fact that the energy content is not utilised but also in the fact that any methane released to the atmosphere will function as greenhouse gas. There is a general tendency to keep this plant type as simple as possible. Experimental results suggest that gas capture not only from the digesters but also from the process water tank should be considered as a standard. Dimensioning of the process water tank is not of decisive influence on methane generation in the liquid phase. Even when deciding in favour of a small process water tank, equipment for catching generated biogas from the tank needs to be foreseen. Especially when digesting easily hydrolysable biomass, special attention needs to be given to biogas generated in the liquid phase (Kusch et al., 2009).

### 3.2 Description of a selected full-scale plant

Within a research project, full-scale experiments have been performed at a farm plant located in the southern area of Germany on a farm with organic farming (Bioland). The plant consists of four concrete digestion boxes of 130 m³ each (Fig. 3). Process water was sprinkled over the biomass bed and leachate of all four boxes was collected in one tank to be reused for percolation. Digestion temperature was in the mesophilic range. Percolation (not automated) was around twice daily in routine plant operation. The full-scale farm plant has been described in previous publications (Kusch, 2007).

Though other materials (solid dung, grass, energy crops) were added as well, the AD plant was built especially for the digestion of green cut collected by the local authority. This material is not suited for conventional wet digestion due to the presence of stones and a high proportion of woody biomass. Green cut was chopped to <10 cm before digestion.



Fig. 3. Full-scale farm plant with four solid-phase digestion boxes

The fermenters were filled and emptied by using a wheel loader. Before the filling, substrate was mixed with solid inoculum (digested material from the previous cycle). For the mixing, a windrow was formed of fresh substrate and of solid inoculum and mixed with a compost windrow turner. A short period of pre-composting ensured that temperature of the substrate increased so that pre-heated material was brought into the reactor.

### 3.3 Experimental results

A combination of laboratory and farm scale experiments was conducted. The farm scale plant is described in Chapter 3.2. A dry digestion laboratory with 10 reactors (50 L each) was build (described in detail by Kusch (2007)).

Experiments showed that the necessary amount of inoculum strongly depends on specific substrate characteristics and may vary within a wide range (ensiled maize: around 70 % w/w based on TS; ensiled grass: around 70 % w/w TS; horse dung with straw: 10 to 20 % w/w TS; cattle dung: 0 %, but augmentation of gas yield in mixture with structure material). It was found that both in laboratory and full-scale achieved biogas yields were comparable to the yield obtained in liquid-phase digestion, if process conditions were optimal. However, suboptimal conditions resulted in an inhomogeneous and incomplete degradation at farm-scale (Kusch, 2007). Optimal conditions are difficult to be determined

and to be fulfilled at farm-scale, which increases the risk of incomplete degradation in this simple fermenter type with no substrate mixing.

It has been demonstrated that during process initiation discontinuous leachate recirculation is more favourable than continuous watering (Kusch et al., 2012; Martin, 1999; Vavilin et al., 2002, 2003; Veeken and Hamelers, 2000), which is assumed to be the result of encouraging methanogenic areas to expand throughout the whole digester, while continuous watering bears the risk to spread acidification. In addition, it was demonstrated that for the process type discussed here there is no beneficial effect of continuous water circulation compared to discontinuous watering throughout the whole digestion process (Kusch et al., 2012).

Experimental results (at laboratory scale) clearly indicate that methane formation within the recirculated liquid significantly adds to the total methane production of the process. In testing, up to 21% of the total methane generation originated from the recirculated liquid. This suggests that methane generation from the liquid phase is not to be neglected and needs to be recuperated. The process water tank should be equipped with gas collection facilities. Experimental results further indicate that higher ratios of easily hydrolysable substrates increase the proportion of methane from the liquid phase while slowly hydrolysable material encourages biogas generation in the decomposing biomass bed itself (Kusch et al., 2009).

The successful implementation of processes with percolation necessitates that liquid actually trickles through the whole substrate stack. Therefore, process water with low viscosity must be used as should substrate with sufficient structure. Liquid manure (slurry) is not suitable for percolation, as it will not ensure a leachate flow through the solid biomass bed. If no process water is available, fresh water (e.g. rain water) can be used to start the process.

Materials with poor structure should be mixed with structure material such as straw or green cut before digestion. In order to facilitate homogeneous digestion and avoid excessive tightening during the process, the fresh biomass stack should not exceed a height of 3 m.

Operation of the full-scale plant has proven to be robust and flexible, which are the main advantages associated with this process type. It needs to be taken into consideration that – in contrast to continuous process types – no process automation is possible, and as a result the necessary amount of effort and labour increases drastically for higher throughputs and higher numbers of reactors (the volume of one reactor is limited).

Choosing one process type among several alternative systems should depend on the specific characteristics of the available materials. If biogas generation is envisaged exclusively with energy crops, continuously operated process alternatives should be given special consideration. Discontinuous digestion with stacked biomass and sprinkling of process water is not the optimal choice for such substrates due to their poor structure and the high inoculum proportion required. Especially for materials such as energy crops with high costs for cultivation and conservation, incomplete degradation may have critical effects on the profitability of a biogas plant (a factor which is less relevant for digestion of organic residues). Therefore, compared to digestion of waste materials, special care should be taken so as to avoid inactive zones with inhibited degradation.

For discontinuous digestion with stacked biomass and percolation, structure-rich biomass, e.g. green cut or solid dung, is especially advantageous choice when considering process technology. Mixtures of structure-rich biomass and energy rich materials are well suited both in terms of material characteristics and energy production.

Successful implementation of discontinuous dry digestion is the result of two main factors:

- Favourable process conditions during digestion
- Appropriate choice of dry or wet digestion depending on the specific characteristics of the available substrates

## 4. Continuously operated dry digestion

Continuously operated reactors are commonly used in municipal waste digestion, they are state-of-the art. There are several manufacturers offering large scale plants.

| Process | Waste | Capacity | TS in reactor | Retention | Biogas yield | | | CH$_4$ content |
|---------|-------|----------|---------------|-----------|--------------|--|--|----------------|
| | | Mg/year | % | days | Nm³/Mg TS | Nm³/Mg VS | Nm³/Mg Input | % |
| 3A | BW | | | 45-50 | 410 | 285 | 100 | 55 |
| BEKON | BW | | ≤50 | 28-35 | 240-530 | 170-370 | 60-130 | 55-60 |
| KOMPOGAS | BW | 20,000 | 35 | 15-20 | 380 | 245 | 85 | 50-63 |
| ATF | BW | 1,000 | 35-50 | 15-25 | 120-400 | 96-320 | 30-96 | 55-65 |
| DRANCO | BW | 20,000 | 18-26 | 20-30 | 550-780 | 390-550 | 120-170 | 50-65 |
| DRANCO | OR | 13,500 | 56 | 25 | 460-490 | 240-250 | 133-144 | 55 |
| VALORGA | BW | 52,000 | 30-35 | 24 | 390-410 | 175-185 | 80-85 | 55-60 |

BW: biowaste; OR: organic residues (municipal); TS: total solids; VS: volatile solids

Table 3. Technical parameters of large-scale organic waste disposal dry fermentation plants (as compiled by Kraft, 2004)

Though wet digestion prevails in the agricultural area, farm scale continuously operated dry digestion plants operated on organic residues are known as prototype or single farm specific solutions. The following focuses on innovative solutions for continuous dry digestion of agricultural organic residues.

### 4.1 Principles

One of the first prototypes for continuous dry digestion of agricultural substrates was developed in Switzerland (Baserga et al., 1994). It was a pilot plant of 9.6 m³ capacity for continuous digestion of solid beef cattle manure on-farm. The solid manure was pressed via a pipe into the top of an upright standing cylinder. The pipe was heated to ensure that the material reaches the fermenter at suitable temperature. For discharging a scraper floor filled a discharge screw and the digesting residue was separated by a screw press. The liquid fraction was used as inoculum sprayed on the top of the reactor.

This principle was further developed by a prototype designed by Timo Heusala and implemented at Agrifood Research Finland (MTT) in Sotkamo, Finland (Virkkunen et al., 2010). Metener Ltd delivered the measuring equipment and modifications. The size of the screw stirred fermenter is 4.5 m³ and the liquid volume is about 3 m³, Fig. 4. A feeder screw charges solid manure from beef cattle. The manure is a mixture of excreta, peat, and straw or reed canary grass. The fermenter is discharged by a screw.

Also in Switzerland at FAT, a channel pilot reactor was developed. Baskets filled with solid manure pass through a slurry filled airtight fermentation channel. This solution did not find its way into praxis yet.

A continuously two stage two phase pilot plant was developed by Lars Evers in Järna, Sweden (Schäfer et al., 2005). This biogas plant is a suitable tool not only for renewable

energy production but also for designing organic fertilisers by varying anaerobic process parameters like load rate of the reactor, retention time and mechanical treatment before, within and after the anaerobic process. This plant is described in the following chapter.
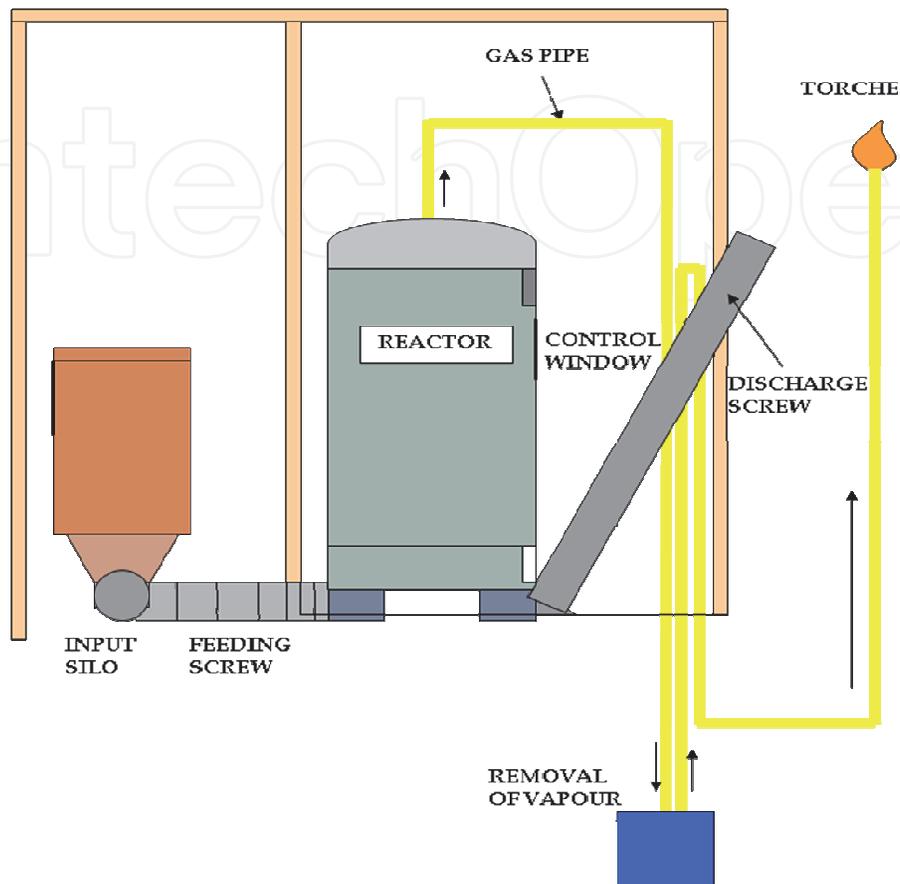


Fig. 4. Prototype of a solid manure fermenter in Sotkamo, Finland; picture courtesy Heidi Kumpula

## 4.2 Description of a selected full-scale plant

The local association of farms, horticulture enterprises, food processing units, food stores, and consumers in Järna aims to recycle organic waste. The goal is reduced use of non-renewable energy and use of the best-known ecological techniques in each part of the system, to reduce consumption of limited resources and minimize harmful emissions to the atmosphere, soil, and water. The biogas plant described here served as reference plant for nutrient recycling solutions within the BERAS-project of "The Baltic Sea Region INTERREG III B Neighbourhood Programme 2000-2006" of the European Union. Presently the biogas plant digests dairy cattle manure and organic residues originating from the farm and the surrounding food processing units.

The prototype plant is situated on farm close to the stall. Figure 5 shows the block diagram of the material flow of the two reactors. The blue boxes describe the processes, the white boxes the input and output, and the yellow boxes digestion residues within the process.

Both reactors are made of CORTEN-steel cylinders of 2.85 m inner diameter. They are coated by 20 cm pulp isolation and corrugated sheet. The steel cylinders were formerly used as smokestack.
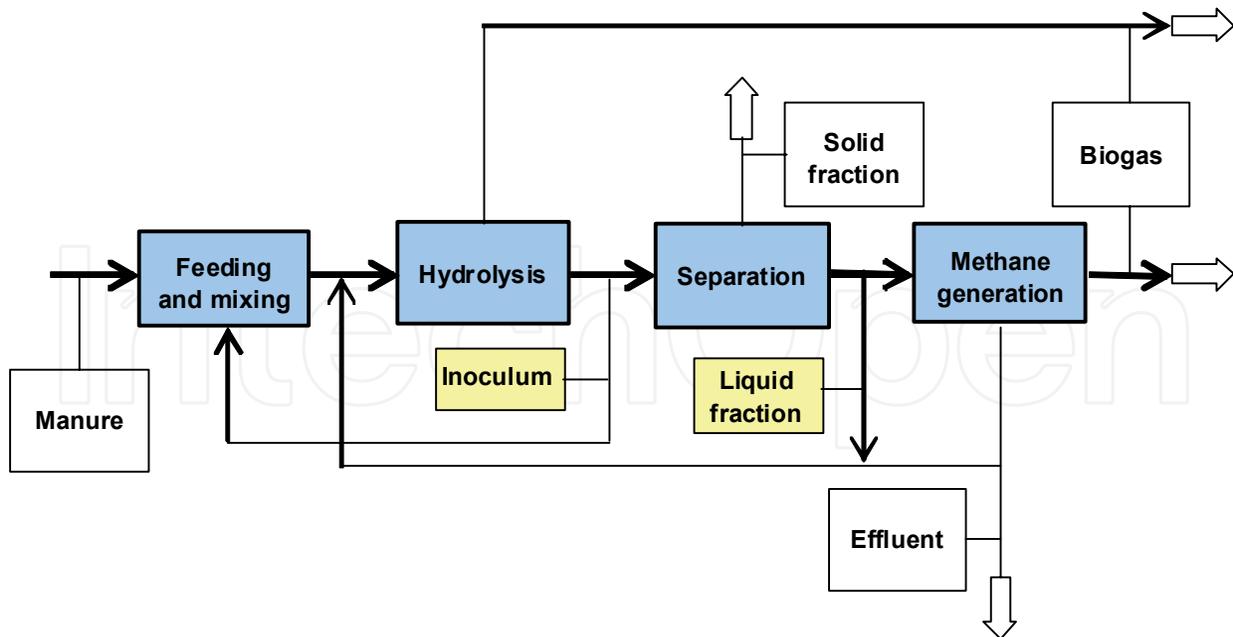
Fig. 5. Block diagram of the material flow of the prototype plant in Järna, Sweden

In a two-phase process, the hydrolysis reactor is continuously filled and discharged automatically. The output from the hydrolysis reactor is separated into a solid and liquid fraction. The solid fraction is composted. The liquid fraction is further digested in a methane reactor and the effluent is used as liquid fertiliser. The different process steps are described according to Figure 6.
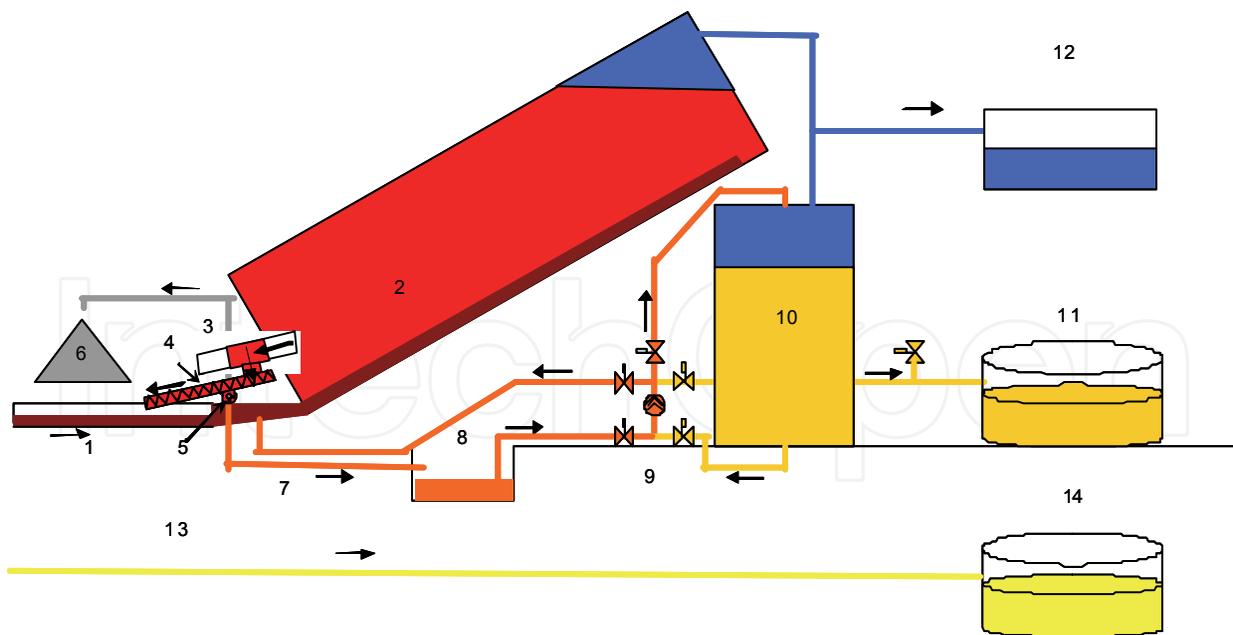


Fig. 6. Principle of operation of the prototype biogas plant at Yttereneby farm, Järna, Sweden. 1 feeder channel, 2 first or hydrolysis reactor, 3 drawer, 4 drawer discharge screw, 5 solid residue separation screw, 6 solid residue after hydrolysis, 7 drain pipe of liquid fraction, 8 liquid fraction buffer store, 9 pump and valve, 10 second or methane reactor, 11 effluent store, 12 gas store, 13 urine pipe, 14 urine store

A hydraulic powered scraper shifts manure of a dairy stanchion barn into the feeder channel (1) of the hydrolysis reactor (2). The manure is a mixture of faeces, straw and oat husks. The urine (13) is separated in the stall via a perforated scraper floor and stored separately (14). From the feeder channel the manure is pressed via a feeder pipe to the top of the 30° inclined hydrolysis reactor of 53 m³ capacity. The manure mixes with the substrate sinking down by gravity force. After 22 to 25 days retention at 38 °C, a bottomless drawer (3) from the lower part of the reactor discharges the substrate. Every drawer cycle removes about 0.1 m³ substrate from the hydrolysis reactor to be discharged into the transport screw (4) underneath. From the transport screw, the substrate partly drops into a down crossing extruder screw (5) where it is separated into solid (6) and liquid (7) fractions. The remaining material is conveyed back to the feeder channel and inoculated into the fresh manure.

The solid fraction from the extruder screw is stored at the dung yard for composting. The liquid fraction is collected into a buffer store (8) and from there pumped into the methane reactor (10) with 17 m³ capacity. The methane reactor is 4 m high and filled with about 10,000 filter elements offering a large surface area for methane bacteria settlement. Liquid from the buffer and from the methane reactor partly returns into the feeder pipe to improve the flow ability. After 15 to 16 days retention at 38 °C the effluent is pumped into slurry store (11) covered by a floating canvas. A screw pump (9) conveys all liquids, directed by four pressurized air-driven valves. The gas generated in both reactors is collected and stored in a sack (12).

A compressor generates 170 mbar pressure to supply the burners of the process and estate boiler with biogas for heating purposes. A programmable logic controller regulates the biogas plant automatically.

## 4.3 Experimental results

The plant produced in average 52 m³ biogas per day. Maximum yield was 91 m³ biogas per day or 0.17 m³ CH4/kg VS. From oat husks and straw, originate 53 to 70% of the organic dry matter of the input material. In the solid fraction remained 70 to 75% of the total solids, in the effluent 10 to 15% and within the biogas 14.8 to 14.9%. Because the solid fraction is removed after digestion of the manure in the first reactor, the loading rate and the yield rate cannot be calculated for the whole plant. This methodical problem makes it difficult to compare this plant with one-stage plants.

The volume efficiency of the plant is slightly better than the average of common slurry fermenters. An evaluation of on farm biogas plants (Bundesforschungsanstalt für Landwirtschaft (FAL), 2006) reported that 70% of the evaluated plants achieved a volume efficiency of 250 to 750 L biogas per m³ and day. Up to 305 kWh per day or 56% of the produced energy was available for heating the farm estate. Composted solid fraction and effluent together contained 70 to 81% of the total input nitrogen and 94 to 111% of input $NH_4$.

The two-phase prototype biogas plant in Järna is suitable for digestion of organic residues of the farm and the surrounding food processing units. The plant works full-automatically. However, the two-phase process consumes much energy and the investment costs are high. There is still a lack of appropriate technical solutions in terms of handling organic material of high dry matter content, and process optimisation. The innovative continuously feeding and discharging technique is appropriate for the consistency and the dry matter content of

the organic residues of the farm. It is probably not suitable for larger quantities of unchopped straw or green cut.

| Reactor | | R1 | R2 | R1 + R2 | R1 | R2 | R1 + R2 |
|---|---|---|---|---|---|---|---|
| Observation period | | | spring | | | autumn | |
| Effective capacity | m³ | 53 | 18 | 71 | 53 | 18 | 71 |
| Fresh mass input | kg/day | 2,000 | 1,045 | 2,000 | 2,430 | 1,184 | 2,430 |
| Specific weight input | kg/m³ | 946 | 968 | | 989 | 1,015 | |
| Organic dry matter VS | kg/day | 340 | 61 | 340 | 375 | 35 | 375 |
| Organic dry matter | % | 17 | 5.8 | 17 | 15 | 3 | 15 |
| Retention time | days | 25 | 16 | | 22 | 15 | |
| Loading rate | kg/(m³ day) | 6 | 3 | | 7 | 2 | |
| Biogas yield | L/kg VS | 85 | 313 | 141 | 125 | 147 | 139 |
| Methane yield | L/kg VS | 48 | 204 | 85 | 71 | 96 | 80 |
| Volume efficiency | L/(m³ day) | 544 | 1,093 | 681 | 887 | 297 | 740 |

Table 4. Performance parameters of the biogas prototype plant in Järna

Further pros and cons of the presented AD plant in Järna are compiled in Table 5 (it needs to be taken into account, that optimization was not yet fully completed).

| Pros | |
|---|---|
| Operating | Full-automatically digestion of solid manure, no mixing required |
| Heat energy | Up to 1.7 kWh / kg organic dry matter, up to 57% energy surplus |
| $N_{tot}$ losses | Up to 39% reduced compared to aerobic treatment |
| $NH_4$ losses | Up to 93% reduced compared to aerobic treatment |
| $CH_4$ generation | Up to 64% from oat husks (residues from the food processing unit) and straw |
| Cons | |
| Gas production | Average gas yield too far from the maximum yield |
| Heat consumption | Organic material must be heated twice |
| Investment costs | >2000 € per m³ reactor volume |

Table 5. Pros and cons of the prototype biogas plant in Järna, Sweden

Up to now, the technique of the prototype does not offer competitive advantages in biogas production compared to slurry based technology as far as only energy production is concerned. The results show that the ideal technical solution is not invented yet. This fact may be a challenge for farmers and entrepreneurs interested in planning and developing future competitive biogas plants on-farm suitable for solid organic matter.

## 5. Conclusions

Dry digestion of organic residues is particularly well suited and state-of-the art for treating the organic fraction of MSW. Segregation at source is among the main factors towards wider dissemination of this technology, and therefore regulatory frameworks are most important.

Dry digestion is less common in the agricultural sector, but the technology has experienced increasing interest in the last years, and it is to be expected that more dry digestion plants will be build.

Development of new prototype biogas plants requires appropriate compensation for environmental benefits like closed nutrient cycle and production of renewable energy to improve the economy of biogas production. The prototype in Järna described in Section 4 of this book chapter meets the set objectives since - beside renewable heat energy - a new compost product from the solid fraction is generated. However, the two-phase process consumes much energy and the investment costs are high.

Batch anaerobic dry digestion in box type fermenters promises further application in agriculture and for treatment of municipal solid waste, especially with smaller substrate throughputs. Methane yields can be achieved which are at the same level than the yields in wet digestion systems. A higher risk of inactive zones with inhibited biodegradation was, however, observed at full scale. This may be explained as result of lack of mixing during fermentation and due to inhomogeneous conditions over the substrate stack height.

For discontinuous digestion with sprinkling of process water, structure-rich biomass, e.g. green cut, landscape conservation residues or solid dung, is especially advantageous choice when considering process technology. In order to maximize gas production per reactor volume, mixtures of fractions with high energy content and structure-rich fractions are advisable.

## 6. Acknowledgements

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