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Key success factors in discontinuously operated dry digestion

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1. Introduction

Digestion with an elevated content of total solids (TS) is widely used to treat municipal solid waste. Since 1993, what are called dry digestion plants have been constructed more often than wet digestion plants in Europe /Bolzonella et al., 2003/. As municipal authorities were in charge of mainly solid organic materials, implementation of technical processes especially designed to be able to cope with solid substrates was a logical step. Continuous one-stage processes are most common, though some discontinuous (batch-operated) plants do exist and have demonstrated reliability (e.g. systems Bekon, Biocel).

In agriculture, during the last century liquid manure was the predominant substrate for biogas production in Europe. Therefore, mainly what are called "wet digestion" plants (TS content < 15 % in the digester /Bilitewski et al., 2004/) were built. The rising interest to use solid agricultural substrates such as energy crops or solid manure evokes searches for technologies appropriate for digestion at elevated TS contents ("dry digestion"). In full scale, digestion of solid biomass is limited in conventional slurry-plants, due to technical restrictions (e.g. related to mixing and feeding devices).

Due to the fact that smaller throughputs are sought in agriculture in general, direct transfer of expensive municipal dry digestion systems (in general continuous processes) is difficult. Discontinuously operated digesters with percolation (sprinkling of process water over the stacked biomass) are considered to be one possible option, as technology is rather robust and flexibility is high. In these batch systems, the whole substrate load is filled at once into the digester and is digested over several weeks. There is no substrate mixing during the digestion process. Degradation begins anew with each filling of the reactor.

Solid-phase digestion of agricultural substrates in discontinuously operated digesters was researched at the University of Hohenheim within a project financed by the Ministry of Nutrition and Agriculture of Baden-Württemberg. Results were published in a PhD thesis /Kusch, 2007/.

2. Material and Methods

Experiments in laboratory and in full scale were carried out; details were published /Kusch, 2007/Kusch et al., 2006/. Laboratory experiments were conducted using 10 solid-phase digesters (thermostatted at 35 °C, solid material content around 50 L, Figure 1). Leachate was collected in a liquid-phase reservoir at the base and sprinkled discontinuously over the biomass (in general, leachate recirculation was twice daily for 15 min). Full-scale experiments were performed at a farm plant consisting of four concrete digestion boxes of 130 m³ each (Figure 2, solid material content of each box around 100 to 110 m³). Process water was sprinkled over the biomass bed and leachate of all four boxes was collected in one tank. Prior to filling solid material into a reactor, substrate windrows were formed and homogenized with a compost windrow turner. Pre-aeration was carried out to reduce the anaerobic heat requirement by using the temperature increase resulting from the composting step. The plant had been built mainly for the digestion of green cut and was operated for around two years.

Figure 1 Solid-phase digestion laboratory with ten reactors

Figure 2 Full-scale farm plant with four solid-phase digestion boxes

3. Selected results

Biogas yields were found to be comparable to the yields obtained in liquid-phase digestion if process conditions were optimal. Besides economic viability, successful implementation of dry digestion on-farm 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

3.1 Process conditions

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.

In a farm-scale trial a mixture of around 60 % v/v fresh grass and 40% horse dung with straw was digested with discontinuous percolation (around 6 percolation intervals per day during the first two weeks, afterwards reduction of process water recirculation to twice daily). Samples from the digested substrate (solid residue) were taken in a three-dimensional body profile. Although TS was within a favourable range (< 25 %) in the whole stack, VS was found to vary much and to be very high in some samples (Figure 3). Samples from the inner core of the stack had high VS contents, while those from the outside had lower values. Colour of the residue was brownish in the outsides of the stack, but it was greenish inside the substrate body and a sour smell was noticed. This corresponds to low pH values along with high VFA concentrations (up to nearly 30,000 ppm) in those samples. Leachate from the reactor was regularly sampled throughout the experiment. After eight weeks no VFA were detectable anymore in the leachate (despite abovementioned presence of VFA in the substrate body). This indicates that further wash-out of acids by sprinkled process water was insignificant. The inhomogeneous and incomplete degradation in this experiment indicates the risk of inactive zones in the substrate body.

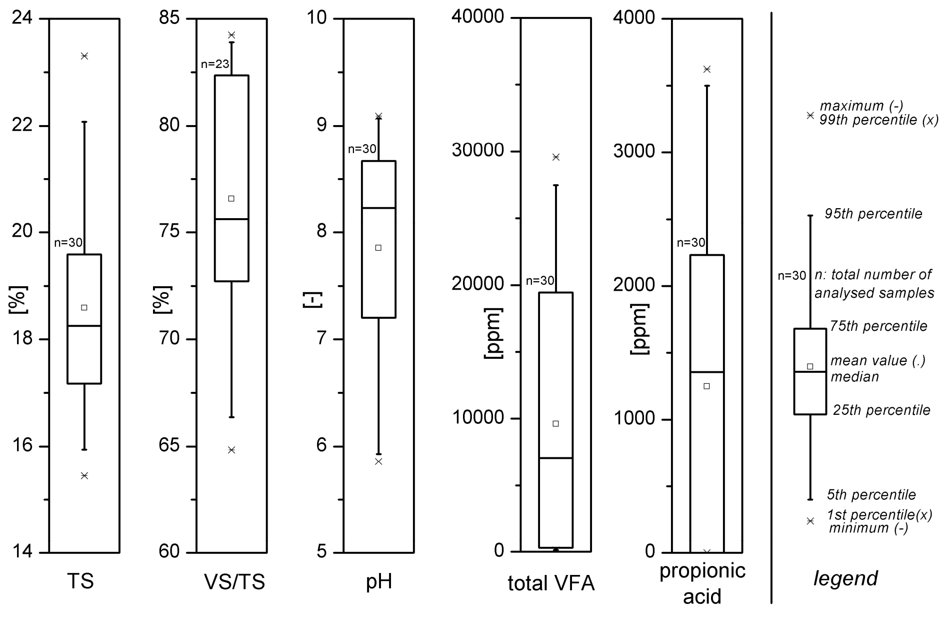

Figure 3 **TS, VS, pH and VFA concentrations in solid residue of digested mixture of fresh grass with horse dung in farm-scale experiment (digestion time: 8 weeks)**

In order to avoid too strong acidification during digestion, in the percolation process fresh substrate can be mixed with solid inoculum (already digested material). 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; municipal green cut: around 20 % w/w TS) /Kusch, 2007/. Further experimental results demonstrate that fractions should be carefully mixed prior to being filled in the reactor /Kusch, 2007/. Digestion (with discontinuous process water recirculation) was found more stable (reduced risk of acidification) when fresh biomass and solid inoculum had not been mixed, but were placed into the reactor in layers /Forster-Carneiro et al., 2004/Kusch et al., 2006/. However, biogas generation was significantly slower, thus requiring longer retention times in the digester /Kusch, 2007/. A high degree of homogeneity within the stacked substrate body minimizes the risk of inactive zones. This not only ensures high methane yields, but it also prevents discharge of material that has only partly degraded.

At least three digesters need to be run offset in order to equalize gas production of the system. In systems with several solid-phase digesters that are functionally coupled through the recirculated liquid phase (leachate collected from all reactors and reused for percolation of all reactors), gas production from one digester cannot be assessed with precision. Organic material is partly washed out from the substrate stack and metabolized either in the liquid tank or in other solid-phase digesters. Only part of the total methane production actually occurs in the substrate itself. Moreover, liquefied organic matter from other fermenters is poured in with the recirculated process water and mineralized in the biomass bed. Especially with easily degradable substrate, significant proportions of the total organic matter will be washed out from the stacked biomass. In experiments with ensiled maize, up to 2/3 of the total methane production occurred outside the actual substrate stack (in the process water tank and in other solid-phase digesters) /Kusch, 2007/. Gas production from the process water tank must be collected.

The main disadvantages of batch operated dry digestion are the high ratio of seeding material needed to prevent irreversible acidification at the start-up of the process and long retention times in the reactor /Veeken and Hamelers, 2000/. In order to reduce the necessary amount of solid inoculum, in alternative systems intensified percolation with wash-out of acids might be envisaged. Promising research data from laboratory experiments have been published /Kausch et al., 2005/Kusch, 2007/Zielonka et al., 2007/. It needs to be taken into account that this actually is a different concept (biogas production in the biomass stack is no longer the main purpose). Washed-out acids need to be metabolized either in a separate methanisation reactor (which itself needs optimization) or they can be sprinkled over ‘older’ (already stabilised) biomass stacks (this is possible for example with source-separated biowaste, but other substrates such as energy crops do not result in sufficient solid digestate which could be used for this purpose). Prior to a full-scale implementation further research on such systems is advantageous. A successful implementation will even more necessitate that the liquid actually trickles through the whole substrate stack in order to wash out the hydrolysed organic material and the result will therefore depend on the individual material characteristics. The concepts are highly susceptible to appearance of inactive zones. While in digestion processes where fresh biomass is seeded with sufficient solid inoculum, methanogenic areas expand from the seed bodies throughout the whole digester /Kalyuzhnyi et al., 2000/Martin, 1999/Vavilin et al. 2002/, wash-out of organics plays the key role in these alternative concepts without or with reduced solid inoculum. Any inhomogeneous conditions over the substrate stack height will result in reduced process efficiency.

3.2. Choosing discontinuous solid-phase digestion among alternative systems

Choosing one process type among several alternative systems should depend on the specific characteristics of the available materials. Easily hydrolysable biomasses with high energy density, e.g. ensiled maize or grass, are especially suitable for continuous digestion. 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. A sufficient structure is also important regarding the pre-aeration (composting step) /Membrez, 2002/. Fibrous material, which in general is regarded as unsuitable for running a continuous digestion at elevated TS-contents (e.g. sheep dung /Shan, 1992/, horse dung /Kalia and Singh, 1998/), does not cause any problem in batch-operated solid-phase digestion with percolation. In order to maximize gas production per reactor volume, mixtures of fractions with high energy content and structure-rich fractions are advisable. Possible mixtures are maize with municipal green cut or with solid dung containing straw. Experimental results on the performance of horse dung in solid-phase digestion systems have been published /Kusch et al., 2008/.

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. Therefore, compared to digestion of waste materials, special care should be taken so as to avoid inactive zones with inhibited degradation.

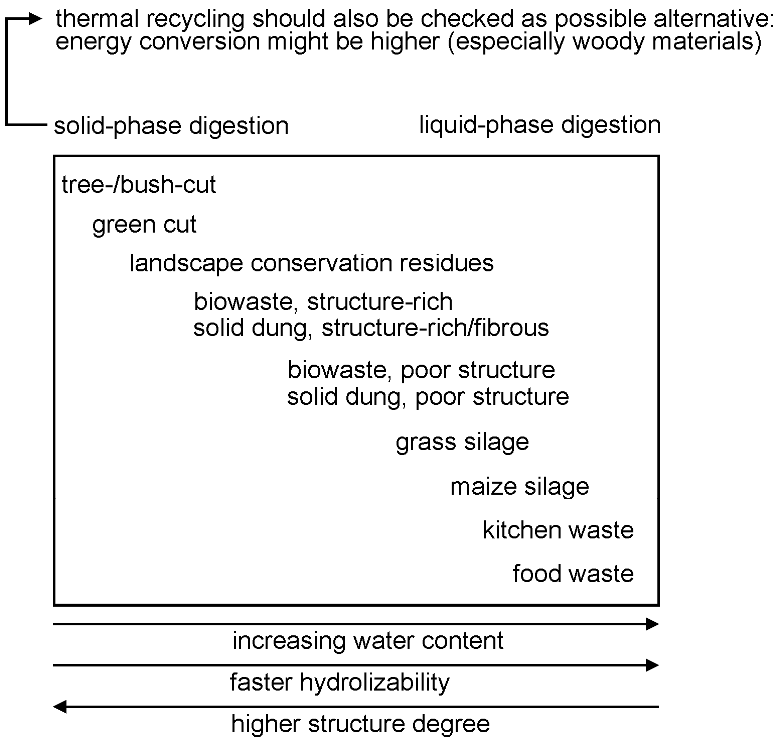

Figure 4 **Suitability of different organic fractions in terms of their energetic use in discontinuous solid-phase digestion systems (dry digestion) or their preferential use in liquid-phase digestion systems (wet digestion)**

Discontinuous systems are more appropriate with smaller throughputs. In contrast to continuous systems, no process automation is possible. The amount of effort and labour required is constantly increasing with higher numbers of digestion boxes. The volume of one reactor is limited /Weiland, 2006/; therefore for higher throughputs high numbers of digestion boxes would be necessary.

Regional structures may be favourable when the implementation of decentralized solid-phase digestion systems is considered. For example it was reported that straw represents a significant part within the Ukrainian energy potential from biomass /Dubrovin et al., 2005/, but until now hardly any of this potential is actually used for energy production.

Advantages have been claimed for two-phase digestion systems /Cho et al., 1995/Ghosh et al., 2000/Llabrés-Luengo and Mata-Alvarez, 1988/Raynal et al., 1998/, although in large scale only 11 % of the total available digestion capacity is offered by two-phase digestion systems /De Baere, 2000/, probably because one-phase systems are cheaper regarding investment and maintenance /Mata-Alvarez et al., 2000/. In dry digestion systems the first step might be set up as a continuous or a discontinuous reactor, both types have already been studied in full-scale /Linke et al., 2006/Schäfer et al., 2006/. With systems in which leachate trickles through a biomass bed, phase separation may be more difficult to achieve than with stirred digesters due to lack of mixing and low ion diffusion in a non-flooded matrix /O'Keefe and Chynoweth, 2000/. In general, phase separation appears to be more difficult for slowly hydrolysable substrates /Chanakya et al., 1992/. For solid materials with slow degradability, single-phase digestion was recommended /Christ, 1999/Wechs, 1985/. For easily degradable materials, a two-phase system was considered more advisable /Mata-Alvarez et al., 2000/Pavan et al., 2000/. In general two-stage concepts are highly efficient and more stable but also more complex and more expensive /Lissens et al., 2001/, and therefore, less suitable for smaller throughputs.

5. Conclusions

Due to associated benefits, e.g. robust techniques, high flexibility and applicability when no liquid manure is available, solid-phase digestion (dry digestion) is of increasing interest in agriculture. More and more box type fermenters with sprinkling of process water over the stacked biomass can be found in Germany. Sustainable decisions in support of, or against, the use of such a process type require an adequate process evaluation during the planning of a new biogas plant.

Experimental results from a research project carried out at the University of Hohenheim show that, if process conditions are optimal, digestion of solid substrates in discontinuous solid-phase systems can achieve substrate specific methane yields that are comparable to those in common, slurry-based liquid-phase digestion installations. A higher risk of inactive zones with inhibited biodegradation was, however, observed at farm-scale. This may be explained as result of lack of mixing during fermentation and due to inhomogeneous conditions over the substrate stack height.

Choosing one process type among several alternative systems should depend on the specific characteristics of the available materials. Easily hydrolysable biomasses with high energy density, e.g. ensiled maize or grass, are especially suitable for continuous digestion. 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.

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