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Disintegration in the biogas sector – Technologies and effects

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HIGHLIGHTS

- Recent data about disintegration technologies (German biogas market 2011/2012).
- Overview on energy demand of selected physical disintegration technologies.
- Evaluation of technologies by reference to the Technology Readiness Assessment Guide.
- Data of the prevalence of disintegration technologies on German biogas plants (2012).
- BMP-tests with un-/treated barley straw (TPH) and calculations of conversion rates.

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ABSTRACT

Pretreatment of organic material prior to anaerobic digestion is seen as an option to increase the overall efficiency of the process. An overview of physical, chemical, and biological disintegration (DT) of substrates in the biogas sector is given. The energy demands DT were surveyed. The technologies were evaluated by reference to the Technology Readiness Assessment Guide of the U.S. Department of Energy. The evaluation focuses on ligno-cellulosic substrates like straw. Data of a survey among biogas plant operators were analyzed regarding the prevalence of disintegration technology classes in Germany. Furthermore, biochemical methane potential tests were conducted in laboratory scale to determine the specific methane yields of un-/treated barley straw (thermal pressure hydrolysis (TPH)). A methane potential of 228 ml CH_4/g VS was measured for untreated barley straw; and of 251 ml CH_4/g VS for TPH-straw (190 °C, 30 min). The reaction rates in BMP were calculated between 0.0976 and 0.1443 d^{-1}.

1. Introduction

Due to the growing interest in substrates like straw or other fibrous substrates in the biogas sector, the number of disintegration-technology-brands rose during the last years in Germany (Daniel-Gromke et al., 2012) and will probably further increase in the future.

Disintegration in this case means the (pre-)treatment of substrates for biogas plants or the treatment of the output of anaerobic digesters for the purpose of re-digestion. Disintegration aims to destruct the cell walls of the substrate and to release the cells‘ matter. In fact, disintegration technologies (DT) are applicable to increase the particle surface area or to change the quality of the substrate for a faster and easier microbial use. DT can accelerate or enhance the degradation of substrates. Hence, the whole process chain of biogas with regards to energy production could run more efficiently.

DT enable biogas plants to decompose highly fibrous substrates (high in ligno-cellulosic compounds) like straw. The microbial degradation of cellulose requires much more time than the degradation of easy available substrates as e.g. starch (Czepuck et al., 2006).

Lignin is only degradable in the presence of oxygen in aerobic processes and thus without the generation of methane as an energy carrier (composting) or without the possibility of nutrient recovery (combustion). However, if the lignin does not hamper the microbiological consortium to a greater extent, the share of hemicellulose and cellulose of the ligno-cellulosic complex is degradable in an anaerobic process, which produces biogas for energy use and simultaneously a bio-fertilizer.

The technologies can be distinguished into physical, chemical, and biological methods of disintegration. In general also combinations of these methods are applicable. Further details are given in

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chapter 3.1. The objectives of the utilization of disintegration technologies in the biogas sector are

(a) Increase of the biogas yield due to disintegration of cells and enlargement of the particle surface,
(b) Acceleration of the degradation of substrates for an higher capacity utilization of the digester,
(c) Avoiding of floating and sinking layers, or
(d) Enhancement of the management and automation of the feed-in (stirring, pumping).

However, the challenges for designer, manufacturer and operator of disintegration units are to raise its efficiency in energy and costs.

There are several options of disintegration for an agricultural biogas plant. Four major points for possible intervention were identified: harvest of the substrate, conservation/storage of substrate, feed-in of the digester, or outlet of the main digester. Aside from harvest the other three options are also practicable for biogas plants, in which waste or residues are treated.

The effect of an accelerated formation of biogas (due to disintegration) can be observed very often (Sapci et al., 2013; Kusch et al., 2011) in discontinuous anaerobic digestion tests (BMP-tests). However, the effect of acceleration becomes less important with increasing retention times realized in continuous systems. In practice it is very difficult to make a distinction between a true increase of yield (activation of substrate, which is not available without DI technology) and an acceleration of the degradation. Both would show an increasing biogas output of the CSTR. In case of an increased yield, most likely acceleration can also be observed. The aim of this study was to compile data on available or potentially applicable pre-treatment technologies for the biogas sector in Germany and to evaluate their effects.

2. Methods

2.1. Market analysis, dissemination and evaluation of technologies

The presented overview of physical, chemical and biological disintegration technologies (DT) is based on a market and literature research in Germany in the years 2011 and 2012. The energy demands in kWh/m^3 or kWh per kg total solids (TS) of selected physical DT were also surveyed, e.g. thermal pressure hydrolysis and various mills. The DT were evaluated by reference to the Technology Readiness Assessment Guide of the U.S. Department of Energy (DOE, 2011). While physical pre-treatment technologies mostly lead to an enlargement of the particle surface, no effects on the chemical composition (exception: addition of water) of the substrate can be observed. In contrast chemical or biological pre-treatment can effect the chemical composition in other words the substrate's quality.

Furthermore data from another DBFZ-project, which includes a biogas plant operatoŕs survey, were analyzed regarding the prevalence of disintegration technology classes operated on German biogas plants. Approximately 7500 biogas plants were in operation in Germany in 2012. Out of 980 questionnaires answered by plant operators 140 applications of DT were identified, installed on 123 biogas plants.

2.2. Disintegration, BMP-tests, nutritional value and theoretical calculations

Barley straw was chopped and spliced simultaneously in a full scale cutting mill (STZ Strohmühle, Company: Himel, Melchingen, Germany) on a farm to a maximal length of appr. 10 mm. Afterwards the chopped straw was thermal pressure hydrolyzed in a pilot plant of the company VENTURY GmbH Energieanlagen (Dresden, Germany). The thermal-pressure-hydrolysis was fed with 2 kg straw and 6 L of water for every trial and heated with steam. The steam and wet straw was released explosively. The temperatures chosen were 130 °C, 160 °C or 190 °C and the retention time was set at 5 or 30 min.

A biochemical methane potential (BMP) test in laboratory scale was conducted with AMPTS-device (Company: Bioprocesscontrol, Lund, Schweden) to determine the specific methane yields of un-/treated barley straw to reveal the two effects of disintegration: acceleration and enhancement. The basis for the BMP was the guideline VDI 4630 (2006). The samples consisted of 400 g inoculum and 1.2–1.8 g volatile solids (VS) of the un-/treated barley straw, each in 3 replications. The pure inoculum was measured to determine its methane yield and to subtract it from the other samples. The inoculum consisted of 50% v/v digestates of an agricultural biogas plant (fed with cattle manure and fodder residues) and 50% v/v digestate of a municipal sewage sludge treatment plant. The test was terminated after 34 days and operated under mesophilic conditions (38 °C); microcrystalline cellulose was used as reference substrate. The methane yields were standardized (273.15 K, $1.01325\ 10^5$ Pa). Total solids (TS) and volatile solids (VS) were determined on the base of DIN EN 12880 (2001) and DIN EN 12879 (2001).

The nutritional values of untreated barley straw and one sample of thermal-pressure-hydrolyzed straw (190 °C, 30 min) were determined according to Schmidt (2011), in order to calculate the theoretical methane yield stoichiometrically. As model substances the following was assumed: palmitin ($C_{16}H_{32}O_2$; 1005.2 ml CH_4/g VS) for lipids, 21 amino acids ($C_{13}H_{25}O_7N_3S_1$; 396.5 ml CH_4/g VS) for proteins and glucose ($C_6H_{12}O_6$; 373.2 ml CH_4/g VS) for fiber and nitrogen-free extracts. The model substances were chosen in accordance to the draft VDI 4630 (2004), due to the fact that the current version VDI (2006) does not contain model substrates formulae. The calculated values were compared with the measured values.

Assuming a first order kinetic for the degradation (see Eq. (1)) reaction rates (k) [d^{-1}] were calculated based on the data of the BMP-tests. Starting from the biogas produced during the batch test the substrate conversion was calculated (assuming the obtained biogas yield equals the initial substrate). The graph of the substrate conversion was used to fit a first order kinetic to the data. In order to eliminate the lag-phase and use only the part of the test, which represents the first order kinetics the best, the data between day 5 and 20 of the BMP-tests (all together 34 days) were selected. The high values of the coefficient of determination for the k-calculation (between 0.96 and 0.99) show the congruence of model and experimental data (Table. 3).

3. Results and discussion

3.1. Market analysis, dissemination and evaluation of technologies

Pre-treatment technologies can be distinguished into physical, chemical, and biological methods of disintegration. One result of the market and literature research is that for mechanical comminution mills like agitator bead mill, hammer mills, colloid mills, and cutting mills or other technologies like Gorator, Kreis-Dissolver, jet impact reactor as well as Bio-QZ are available in Germany (Schumacher et al., 2013). Other mechanical technologies are Bioextrusion, ultrasound, cavitation generator, and high pressure homogenizer. As electrical pre-treatment methods can be listed BioCrack, shock wave, and electroporation. Also chemical or biological additives like enzymes are available (Schumacher et al., 2013). The list is neither completely nor conclusively, due to the dynamic development of the market, the variety of technical