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Effect of substrate pretreatment on particle size distribution in a full-scale research biogas plant

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HIGHLIGHTS

- The particle size distribution in fermenting substrate was measured.
- Mechanically pretreated and untreated substrate high in fiber was fed.
- Fine fraction of particles were measured to a large extent.
- The disintegration had an effect on larger particles, not on smaller particle sizes.
- A uniform distribution is not achieved and no indications for stagnant were found.

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ABSTRACT

The objective of this study was to investigate the pretreatment effects of high-fibre substrate on particle size distribution in a full-scale agricultural biogas plant (BGP). Two digesters, one fed with pretreated material and one with untreated material, were investigated for a period of 90 days. Samples from different positions and heights were taken with a special probe sampling system and put through a wet sieve. The results show that on average 58.0 ± 8.6% of the particles in both digesters are fine fraction (<0.063 mm). A higher amount of particles (13.1%) with a length >4 mm was measured in the untreated digester. However, the volume distribution over all positions and heights did not show a clear and uniform distribution of particles. These results reveal that substrate pretreatment has an effect on particle size in the fermenting substrate, but due to the uneven distribution mixing, is not homogeneous within the digester.

1. Introduction

In biogas production, the active stirring of the fermenting mixture must be implemented to uniformly distribute the nutrients in the continuously stirred tank reactor (CSTR) biogas digester. This process forms a suspension of liquid and solid parts, which avoids sedimentation or floating of particles, enables gas lift, ensures uniform heat distribution and prevents foam formation (Hennig et al., 2011; Hopfner-Sixt and Amon, 2006; Reinecke et al., 2012; Weiland, 2010; Wu, 2012). As a result, the consumption of electric energy by stirring accounts for approximately 50% of the electric energy consumption in agricultural BGP fed with energy crops, thus having a direct impact on the profitability of the BGP operation (Naegele et al., 2012). An increase in the use of substrates, such as energy crops with high fiber content, caused the dry matter (DM) content in the digester to increase significantly (Lemmer et al., 2013). In light of limited agricultural resources, the discussion of food versus fuel lead to an increase in the use of non-food substrates for biogas production, such as horse manure (Mönch-Tegeder et al., 2013) or waste materials from landscape management. In order to generate the best possible biogas yield and to avoid problems with the process technology, substrate pretreatment is applied at many BGP. Pretreatment of materials with a high fiber content results in a smaller particle size and therefore increases the substrate surface to provide more access for microbial degradation, hence the rate and degree of degradation increases after size reduction (Palmowski and Müller, 2003; Zhang and Banks, 2013). The literature provides many examples about the positive effect of pre-treatment on biogas production. Mechanical pretreatment is one of the main processes and it has been shown that methane production in ley crop silage increases

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by 43–59% after grinding. An ongoing interest in scientific research on different pretreatment systems can also be noted. Current research is mainly focusing on lab- or pilot-scale research, while full-scale experience is limited (Carlsson et al., 2012). An overview on the fundamentals and different approaches of substrate pretreatment for anaerobic digestion is given by several authors (Agbor et al., 2011; Fernandes et al., 2009; Hendriks and Zeeman, 2008; Mosier et al., 2005).

To increase the efficiency of the mixing process, several studies in the field of intrusive (e.g., experimental research) and non-invasive (computational fluid dynamics, computed tomography, and computer automated radioactive particle tracking) have been carried out and found that in some cases up to 15–40% of the digester may be dead zones. Dead zones are zones with no organic matter degradation leading to an accumulation of organic matter or zones with no supply of organic matter indicated by extremely low dry-matter contents. In practice, however, it was found challenging to apply those results to the biogas formation process (Lemmer et al., 2013). A core factor of this obstacle is that the properties, e.g. rheology, of the fermenting substrate cannot be sufficiently described as it is an opaque and multiphase system (Vesvikar et al., 2005). Multiphase describes the fact that the fermenting substrate contains temperatures ranging from 40 °C to 53 °C, liquids, solids, diluted minerals, fibrous material of different lengths and biogas (Lemmer et al., 2013; Wu and Chen, 2008). Furthermore, it is reported that with increasing the total solids concentration, the fermenting substrate shows non-Newtonian pseudoplastic behavior and viscosity (Wu and Chen, 2008). It is also known that the shear viscosity is not consistently linear dependent to the shear rate, thus a defined value for substrate viscosity cannot be given.

Many researchers are trying to simulate the mixing processes in the digester by "assuming" the rheological properties. The available research about measuring those properties show unsatisfactory results and lead to incorrect assumptions. The preferred theoretical chopping length of renewable energy crops is 5 cm, on average. It is known that substrates of this length will have a strong influence on rheology. In practical application, many biogas farmers report the problem of floating layers in digesters, caused by very long particles. Pretreatment methods to break down large particles are becoming more common, e.g. if fibrous material is available. Research on slurry showed that the biological degradation in the digester will also lead to a general shift in distribution towards larger sizes due to the degradation of small and easily degradable particles (Marcato et al., 2008). At present, no full-scale research has been undertaken about this specific topic. Our study aims to fill that gap and describe the fermenting substrate in more detail.

Although the complexity of the material is subject to research and the effects of different particle lengths on substrate properties are described in the literature, there is no information available about the real particle length in fermenting substrate. Despite all the efforts in research that focus on substrate pretreatment, mixing efficiency and description substrate rheology, the literature still lacks information about the effect of substrate pretreatment on particle size distribution in biogas digesters. In a unique approach, the full-scale research BGP of Hohenheim University was used to study the particle size distribution in two similar digesters, one fed with pretreated and one with untreated material. The results will provide novel and useful information for researchers studying this topic, as it shows previously unknown results from a practical application for the first time. This will help to improve the technical design of mixing devices and thereby to promote energy and mixing efficiency.

2. Methods

2.1. Research biogas plant

The experiments were carried out in full-scale at the research BGP of Hohenheim University, located at the "Lindenhof" agricultural research estate in Eningen unter Achalm (Germany). The setup, the mass and flow schemes of the research BGP have been described in full detail by various authors (Lemmer et al., 2008; Naegele et al., 2012; Naegele et al., 2013a; Naegele and Lemmer, 2011; Naegele et al., 2013b; Thomas and Wyndorps, 2012). The two digesters used for the experiment are made of concrete and are covered with insulated concrete. Each digester has a diameter of 14 m and a height of 6 m resulting in a maximum volume of 923 m^3. To ensure a constant process temperature (40 ± 1 °C), digester one is equipped with a floor and a wall heating system, whereas digester 2 is fitted with only a wall heating system (Fig. 1). The process temperature is measured and recorded with six PT 100 temperature sensors, three fitted on the wall and three on the pillar in the middle of the digester at the heights of bottom, center and surface. For solid substrate supply, every digester is equipped with a separate solid substrate feeding system, consisting of a vertical mixer. Within the project "Horse manure – further development of technologies for the efficient use of horse manure" (FKZ 03KB064) that aimed to use fiber-rich organic waste from agriculture for biogas production, a cross-flow grinder (Bio-QZ, MeWa, Gechingen, Germany) was set up and integrated between the vertical mixer and digester 1. The technical description, as well as the workflow for this decomposing device, is given by Mönch-Tegeder et al. (in press). The treatment leads to a significant increase in particle surface area and defibration of lignocellulosic materials. In this trial, the treatment time was set to 15 s and the filling of the cross flow grinder finished when the current draw reached 65% of the maximum. This setup was chosen according to Mönch-Tegeder et al. (2014b) who achieved the best pretreatment efficiency in his trials. The substrate was supplied to the digester every 120 min. To ensure the gas lift and a uniform distribution of the feed and heat, all digesters are equipped with a submersible motor mixer. Furthermore, digester 1 is set up with a propeller incline shaft agitator (Fig. 1b), whereas digester 2 is fitted with a paddle incline agitator unit (Fig. 1c). These two different mixing systems were installed over the course of a previous research project. The submersible motor mixer (13 kW) is directly driven by an electric motor and the incline propeller agitator (14 kW) is driven via a frequency converted electric motor for energetic speed control at 60% of its maximum power (Lemmer et al., 2013). During the experiment, a mixing time of one minute prior and two minutes post feeding was set. During the feeding process, permanent mixing was applied. Intermittent mixing was applied in between the feeding cycles, and the agitator positions were unchanged during the experimental period. Although no scientifically proven method for describing the mixing quality currently exists, we used indicators such as bad process performance, process failure or a low biogas production rate as parameters. Under mesophilic conditions (40.5 °C), approximately 96 m^3/h [standard temperature and pressure (STP)] of biogas are produced, with a composition of approximately 52% CH_4, 48% CO_2 and 500 ppm hydrogen sulfide (H_2S). All substrates fed into the biogas process are weighed by the feeding systems or measured with a flow meter. Samples of input substrates and fermenting substrate were taken on a fortnightly basis and analyzed for DM, organic dry matter (oDM), pH, volatile organic acids/total inorganic carbon (VOA/TAC) and volatile fatty acids (VFA) content in the biogas laboratory of Hohenheim University according to the standard methods of the Federation of German Agricultural