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Foam formation in biogas plants caused by anaerobic digestion of sugar beet

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HIGHLIGHTS

- Anaerobic digestion of sugar beet is often accompanied by foam formation.
- Foaming caused by sugar beet is intensified by the presence of divalent ions.
- Foam caused by pectin is stabilized by sucrose and divalent ions.
- Roughly disintegrated sugar beet forms less foam than sugar beet processed to mush.
- Sugar beet-based foaming is reduced by addition of urea and ammonium chloride.

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ABSTRACT

The use of sugar beet in anaerobic digestion (AD) during biogas production can lead to process upsets such as excessive foaming in fermenters. In the present study, foam formation in sugar beet-fed digestates was studied in foaming tests. The increasing disintegration grade of sugar beet was observed to have a promoting effect on foaming in the digestate but did not affect the biogas yield. Chemical analysis of foam and digestate from sugar beet silage AD showed high concentrations of pectin, other carbohydrates and N-containing substances in the foam. Both pectin and sucrose showed little foaming in AD. Nevertheless, sucrose and calcium chloride had a promoting effect on foaming for pectin AD. Salts of divalent ions also enhanced the foam intensity in the case of sugar beet silage AD, whereas ammonium chloride and urea had a lessening effect on sugar beet-based foaming.

1. Introduction

The presence of sugar beet in the substrate mix brings many advantages. This substrate is very digestible and has a methane yield of 419 m^3/t VS, which is higher than 360 m^3/t VS in the case of maize (Gissén et al., 2014). On the other hand, the use of sugar beet in biogas production is accompanied by specific problems such as ensuring suitable storage and foam formation in fermenters. Storage and conservation of sugar beet has been extensively discussed and there are diverse approaches such as ensiling in the form of sugar beet pulp in liquid silos (Weiland, 2003) or ensiling of ground beet in large plastic bags (Weißbach et al., 2011).

Foam formation in the course of anaerobic digestion (AD) often represents a serious problem for biogas plant operators because the foam can plug gas pipes and lead to losses in biogas yield (Pagilla et al., 1997). Research into foaming causes had been mainly focused on anaerobic digesters of municipal wastewater sludge until recently (e.g., Ganidi et al., 2009; Westlund et al., 1998; Pagilla et al., 1997). Foam formation in other AD systems for biogas production has only recently begun to attract research attention. Surveys by Moeller et al. (2012b) and Kougias et al. (2014) showed the high percentage of biogas plants that suffered from foam formation: 12 out of 15 waste treating biogas plants in Germany (Moeller et al., 2012b) and 15 out of 16 full-scale biogas plants in Denmark had experienced foaming in fermenters or substrate storage/pre-digesters (Kougias et al., 2014).

Excessive foaming mainly causes operational problems such as plugging of gas pipes, foam binding of recirculation pumps, inversion of digester solids profiles (Pagilla et al., 1997), and structural

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damage to the digester roof in extreme cases (Moeller et al., 2012b).

Formation of foam can also decrease digestion efficiency and digester gas production (Pagilla et al., 1997). As a consequence, excessive foaming causes financial losses due to decreased biogas production (Westlund et al., 1998), increased deployment of staff and costs for foam-suppressing measures such as anti-foaming agents (Moeller et al., 2012b). Sometimes, plant components may have to be replaced after a foaming event (Moeller et al., 2012b).

Foam is a dispersion of a gas in a liquid consisting of a large proportion of gas (Vardar-Sukan, 1998). The prerequisite for foam formation is the presence of surface active substances such as volatile fatty acids (VFA), oil, grease, detergents and proteins (Ganidi et al., 2009). Foam can further be stabilized by proteins, suspended particles (Ganidi et al., 2009) and filamentous microorganisms that occur mainly in waste activated sludge (Pagilla et al., 1997; Lienen et al., 2014). The rumen bloat-causing foam that has many parallels to biogas foam (Moeller et al., 2012b) is formed especially by soluble plant proteins, bacterial slime and fine plant particles (Wang et al., 2012). Foam formation is thus often a result of loading the biogas reactor with specific substrates that contain high concentrations of the above-mentioned compounds.

Sugar beet root consists of 76.8% water, 14% sucrose and 5.5% fiber (pulp) (FAO/EBRD, 1999). The pulp is water insoluble and contains 26–32% hemicellulose, 22–24% cellulose, 21.5–23% uronic acids (pectins), 1–2% lignin, 7–8% protein and 7.5–12% ash (Michel et al., 1988). The chemical composition of sugar beet includes proteins and pectins, which are among the foam-causing compounds mentioned above. Proteins are surface active agents that have both hydrophilic and hydrophobic properties and thus have an impact on the surface tension of a solution (Ganidi et al., 2009). However, the mode of action of pectins lies in their ability to form three-dimensional stable structures and gels and, as a consequence, in the enhancement of the solution viscosity (Clarke and Reid, 1974). Furthermore, they are able to strongly enhance the stability of protein foams (Dickinson, 2003).

Two publications have been published this year on foam formation and control in the AD of sugar beet pulp. Suhartini et al. (2014) compared mesophilic and thermophilic modes of operation in laboratory biogas reactors at two different organic loading rates (OLR) of 4 and 5 g volatile solids (VS) L^{-1} day^{-1}. They found that the foaming potential in mesophilic-operated fermenters rose with ascending OLR. In contrast, thermophilic fermenters showed no foam formation at both organic loading rates (Suhartini et al., 2014). The authors suggested that foam formation in mesophilic fermenters was caused by extracellular polymer substances (EPS).

Stoyanova et al. (2014) compared the one- and two-stage mono fermentation of sugar beet press pulp at mesophilic conditions in a continuous stirred tank reactor. It was found that the two-stage AD led to reduction of the overall hydraulic retention time and higher OLRs were possible in this mode of operation with reduced risk of foaming. The authors discussed the effect of substrate composition on the digestate viscosity. They considered the pectin fraction to be one of the factors that influence viscosity in the digestate (Stoyanova et al., 2014). Nevertheless, no conclusions were drawn regarding the causes of foaming in fermenters. Although both studies presented a good overview of the conditions leading to foam formation and suppression by AD of sugar beet pulp, the foam composition and, thus, the real cause of foam formation still remains unclear. For this reason, the aim of this study was to investigate background foam formation and stabilization caused by co-digestion of sugar beet under mesophilic conditions. The problem of foam formation in the course of anaerobic digestion of sugar beet was first considered theoretically by means of two full-scale biogas plants that seasonally utilize sugar beet as substrate. Based on the comparison of the case examples, two main topics for laboratory research on this phenomenon were formulated. Firstly, the effect of sugar beet root disintegration grade on foaming intensity was considered. Secondly, the formation of foam by sugar beet silage AD and its destabilization/stabilization by additives and other chemicals in AD were studied.

2. Methods

2.1. Case examples of sugar beet AD in full-scale biogas reactors

Two biogas plants that co-ferment sugar beet at a high percentage were compared as case examples (their main characteristics are shown in Table 1).

The biogas plant BP A was constructed in 2006, is located on the site of an agricultural cooperative and utilizes the manure of the local cattle. Sugar beet has been seasonally used as a co-substrate since 2007. The daily sugar beet amount accounts for up to 16.5% of the substrate fresh matter. After sugar beet was introduced into the substrate mix, only slight foam formation was observed in the fermenter. Three years later, however, the situation changed after the modification of the manure collecting system. The foam layer was temporarily so high that action was necessary in order to prevent process upsets and damage to equipment. The plant operator tried several empirical methods of combatting foam (e.g., addition of anti-foaming agents, plant oils and acetate, and the prolongation of the stirring cycle). However, the only effective measure was continuous stirring. According to the operator, the foam appeared only when sugar beet mush was added and when cleaning of the cattle barns was carried out more than once a week. The cleaning process included the disinfection of the cattle barn by spreading dolomitic lime on the rubber mats.

The fermenter of BP A was sampled twice. The first sampling was carried out during the period of sugar beet co-digestion and enhanced foaming. The second sampling occurred in the post-foaming period when no sugar beet was digested. The fresh samples were transported to the laboratory and analyzed immediately as described in Section 2.3.

Table 1
Operational data of a foaming biogas plant (BP A) and of a foam-free biogas plant (BP B).

Biogas plant	BP A	BP B
Foam formation in biogas reactor	YES	NO
Agitation cycle	Six minutes per hour	Continuous
Agitation devices	Digester: horizontal paddle agitator and submersible mixer Secondary digester: two submersible mixers	Three digesters: horizontal paddle agitator Three secondary digesters: reeling agitator
Feeding cycle	Once per hour	Continuous feeding
Dry matter content of digestate	7%	13%
Daily substrate composition	30 m^3 cattle manure, 8 t sugar beet, 6 t corn silage, 1 t grass silage, 2 t rest feed, 1.5 t coarse wheat	49 t corn silage, 32 t crop silage, 20–40 t sugar beet, 16 t grass silage, 3 t coarse rye
Additives	None	Urea, iron hydroxide
Sugar beet pre-treatment	Processed to mush once a week using a wood shredder	Coarsely crushed using sugar industry machinery