

The energy balance in farm scale anaerobic digestion of crop residues at 11–37 °C

Irene Bohn*, Lovisa Björnsson, Bo Mattiasson

Department of Biotechnology, Lund University, Box 124, 22100 Lund, Sweden

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Abstract

Crop residues can be used for biogas production in farm scale reactors. Use of a process temperature below mesophilic conditions reduces the need for heating as well as investment and operating costs, although it may also reduce the methane yield. In the present study the effect of temperature on net energy output was studied using sugar beet tops and straw as substrates for two pilot-scale reactors. Digestion was found to be stable down to 11 °C and optimal methane yield was obtained at 30 °C. The methane yield and process performance was studied at 15 °C and 30 °C as organic loading rates were increased. It was found that the highest net energy production would be achieved at 30 °C with a loading rate of 3.3 kg VS m⁻³ day⁻¹. Running a low-cost process at ambient temperatures would give a net energy output of 60% of that obtained at 30 °C. © 2006 Elsevier Ltd. All rights reserved.

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1. Introduction

Agricultural residues, including manure and energy crops, represent an important source of biomass that can serve as a substrate in anaerobic digestion, resulting in the production of renewable energy. Within EU, these types of biomasses could amount to 1545 million tonnes per year, if 760 tonnes of energy crops were produced each year [1]. Sugar beet tops are one example of such a crop residue, of which quite a million tonnes is produced each year in Sweden alone [2]. In some parts of Sweden on-farm production of biogas from crop residues is preferable to digestion in centralized plants because the production of these substrates is distributed at low density over wide areas [3]. In such cases digestion of the biomass on the farm reduces the transport needs. Plant nutrients are retained in the digested residue, making it valuable as fertilizer [4,5]. Recycling the residues as biofertilizers thus adds value to the biogas system. The use of biofertilizers is facilitated when digestion is restricted to the farm because it reduces the risk for spreading of plant diseases, which may be a problem for a centralized biogas plant [2]. Traditionally it is primarily manure that is digested in farm-scale digesters. However, in Germany,

where substantial subsidies are provided for electricity produced from biogas which is produced on a farm scale, energy crops are used as co-substrates in more than 90% of the digesters to increase the gas yield [6].

High investment costs [1] and high operating costs and costs of producing and handling the substrate [7] limit and may possibly preclude the feasibility of farm scale digestion in Sweden unless subsidies are provided. Energy prices in Sweden are low and one cannot count on receiving subsidies, making a highly cost-efficient system important. Solid-digestion processes have been found to be cost-effective for the farm-scale digestion of energy crops and of crop residues with a high content of solids, [6,7]. However, the methane yield obtained may be lower due to inefficient degradation [8]. High-solid digestion also eliminates the possibility of co-digestion with liquid manure. Another possibility of decreasing costs is that of operating the process at low temperatures. In farm-scale digestion under mesophilic conditions up to 1/3 of the energy produced may be needed for heating [9], and operating at ambient or decreased temperature rather than heating the system has been found to reduce investment costs and maintenance and operation costs [10–12]. Low-cost systems operated at temperatures below mesophilic conditions have shown to be successful in on-farm manure treatment, although the degradation efficiency achieved is lower and the retention times required are higher than in mesophilic systems [12–14].

* Corresponding author. Tel.: +46 46 222 8347; fax: +46 46 222 4713.

E-mail address: irene.bohn@biotek.lu.se (I. Bohn).

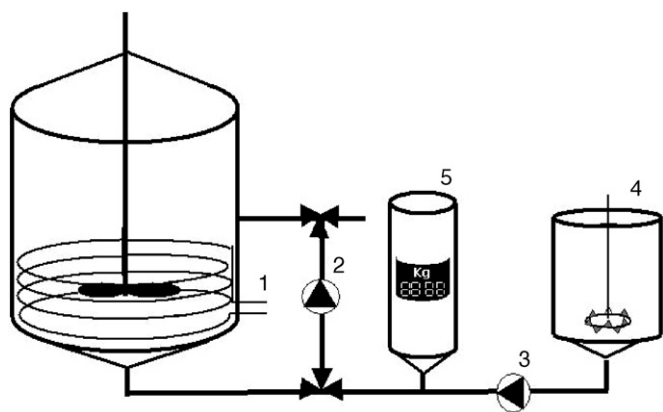


Fig. 1. Schematic view of the pilot-scale reactor (reactor 2) after installation of the new feeding system, where a weighing cell is used to control the amount of feeding. 1: heating coil in the reactor, 2: pump for feeding and circulation, 3: pump for feeding, 4: cutting mixer for preparation of the substrate, 5: weighing cell for control of the amount of slurry fed to the reactor.

In the present study the effects of temperature on the methane production rate and methane yield in the digestion of straw and sugar beet tops were investigated. The energy output was compared with the energy input to determine the temperature at which the best energy balance could be achieved. The experimental results were obtained in pilot-scale reactors, whereas the energy balances were calculated both for the pilot scale reactors and for theoretical examples of farm-scale systems.

2. Materials and methods

2.1. Pilot-scale reactors

The study was performed in two identical reactor tanks, each with an active volume of 1.8 m³ and a total volume of 2.2 m³, that were stirred continuously. The tanks were constructed of stainless steel (6 mm) and were insulated by a 100 mm layer of mineral wool. They were equipped with eccentric screw pumps (AB TELFA, Göteborg) used for feeding and recirculation, and with stirrers (Mamic OY, Finland), pH probes (MiniCHEM, TPS, Australia), temperature regulation, slurry-level indicators and gas volume meters (Gallus, G1.6 IR, Euromekanik AB, Sweden). The temperature of the one reactor (reactor 1) was regulated by a heat exchanger, whereas the temperature of the other (reactor 2) was regulated by a heating coil placed in the bottom and the lower part of the walls of the reactor. Fig. 1 shows a schematic view of reactor 2.

2.2. Substrate

The substrate consisted of sugar beet tops that were ensiled on a bedding of wheat straw and were stored in bunker silos. For the substrate from harvest year 1, sugar beet tops together with the straw, which was used as bedding, was used. For the substrate from the harvest year 2 only sugar beet tops were used, since the straw had decomposed during storage, so that the methane potential of the straw was considered to be too low. The substrate was prepared once a week by mixing beet tops and straw (if added) with water to obtain a slurry with a volatile solids (VS) content of 4.2–5.6%. The average content of total solids (TS), VS,

lactic acid and volatile fatty acids (VFAs), respectively, for the substrate that was prepared during months 17–24 is shown in Table 1.

2.3. Operation of the pilot-scale reactors

The reactors were initially inoculated with digestate from an unheated anaerobic digester fed with cow manure (Önnestad, Sweden). The reactors were fed semicontinuously, either twice a week or once a day. During the startup period (months 1–4) the operational temperature of both reactors was 20 ± 2 °C. During months 5–14 the temperature in reactor 1 was slowly decreased to 11 °C, whereas in reactor 2 it was gradually increased to 37 °C. During this period the reactors were fed 70 l of substrate twice a week, resulting in an average organic loading rate (OLR) of 0.5–0.6 kg VS m⁻³ day⁻¹ (where m³ refers to the active reactor volume) and a hydraulic retention time (HRT) of 90 days (Table 2). The substrate from harvest year 1 was used until month 11, and the substrate from harvest year 2 was used during the rest of the experiment.

Until month 15, the amount of substrate fed was controlled by the level indicator, and the amount of effluent was measured by timing the pump. During month 15 an extra tank equipped with a weighing cell (shown in Fig. 1) was installed, allowing the amount of substrate fed to be controlled by weight, although the amount of effluent emptied from the reactor was still measured by timing.

During months 16–24 the operational temperatures were set to 15 °C and 30 °C for reactor 1 and 2, respectively. During month 16 the reactors were fed 70 l of substrate twice a week. During month 17–24 the reactors were fed once a day and OLRs from 1 to 4 kg VS m⁻³ day⁻¹ was applied to determine the maximum OLRs at 15 °C and 30 °C, respectively (Table 2). The initial OLR for this period was 1 kg VS m⁻³ day⁻¹ for both reactors. This was increased to 2.1, but since reactor 1 was overloaded at this OLR, the amount was decreased to 1.6 for this reactor, which was then run at this OLR for the rest of the experiment. The OLR for reactor 2 was first increased to 3.3 kg VS m⁻³ day⁻¹ and then to 4.1 kg VS m⁻³ day⁻¹ (Table 2).

2.4. Monitoring the process

The data on temperature, pH, volume of gas produced and energy input for heating (only for reactor 2) was monitored on-line using the PLC system SLC 5/05 with RSLogix 500 as software (Rockwell Automation) for data collection and Citect 5 (Autic System AB, Landskrona, Sweden) as the Human Machine Interface software. The control system was also used to control the feeding and temperature. The methane content of the biogas produced was measured on-line (but not continuously) using a methane detector based on infrared light absorption (Simrad GD10 IR Gas Detector, Safetech HB, Västra Frölunda, Sweden).

The alkalinity and the concentration of lactic acid and of VFAs (acetic acid, propionic acid, butyric acid and valeric acid) were measured off-line. Sampling and analysis were carried out as described by Björnsson et al. [15], except that the alkalinity was measured using a Scott Titroline titrator (Tillquist, Sundbyberg, Sweden). VS and TS were analyzed as described in APHA [16]. From the alkalinity that was measured, α was calculated as the difference between total alkalinity and partial alkalinity divided by the partial alkalinity [17]. A value of α of less than 1 indicates a stable process, whereas a value above 1 is a sign of instability [18].

2.5. Energy consumption

2.5.1. Energy for heating

During operation of the pilot scale reactors, the energy consumed by the heating of reactor 2 was monitored. The energy consumption at each loading rate was plotted against the difference in temperature between the reactor and

Table 1

Average values and standard deviations (shown in brackets) for the TS, VS, lactic acid and VFA content of the feed slurry prepared for month 17–24

TS (%)	VS (%)	Lactic acid (g l ⁻¹)	Acetic acid (g l ⁻¹)	Propionic acid (g l ⁻¹)	Butyric acid (g l ⁻¹)	Valeric acid (g l ⁻¹)
6.4 (0.54)	4.7 (0.38)	2.9 (1.20)	4.0 (0.86)	2.3 (0.54)	1.7 (0.61)	1.4 (0.72)

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