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Abstract

Anaerobic digestion is booming in the nations of Europe. In fact, Italy alone has approximately 500 plants in operation or in some phase of start-up. Previous studies have made evident the potential that lies in digested manure residual biogas. Nevertheless, much of the potential goes unrealized when enormous amounts of digestate are produced, but are then stored in uncovered tanks. This research work designed, constructed, and tested a low-cost digestate storage tank cover system capable of abating CO_2eq atmospheric emissions and then recovering the biogas. The experiment, carried out at a 1MW electric anaerobic digestion plant, demonstrated that collecting the residual biogas from the digested liquid fraction storage tank made it possible to avoid atmospheric emissions of up to 1260t CO_2eq annually and to increase the methane yield of the installation by 3%.

Keywords: residual biogas; anaerobic digestion; coverage system; storage tank; digestate liquid fraction

1 Introduction

In recent years, as a consequence of high renewable energy subsidies, anaerobic digestion (AD) of feedstocks and animal manures has spread throughout Europe and many installations have recently been constructed (EurObserv'ER, 2010). In the Piemonte region of northwest Italy alone, 37 AD plants have been constructed in the last five years and 58 more are awaiting approval or are in start-up. The average installed power of these plants is 0.5MWel with an average daily digestate production of 100m^3 per installed MWel (DEIAFA, 2012, unpublished data). Given these figures (installations and production capability), an estimated 1.8 million tons of digested slurry per year will require management during the coming years in the region.

Anaerobic digestion plants require that digestate be stored in tanks prior to field application; the storage capacity must be sufficient to meet the minimum requirement of 120-180 days of storage (Regione Piemonte, 2007) and to meet the application timing requirements of crop growth. Prior to storage, the anaerobically-digested slurry is generally separated mechanically to produce a solid fraction that is rich in nutrients and can be conveniently transported over long distances. The liquid fraction, that contains lower total solid (TS) concentrations than the original digested slurry, is more suitable for liquid manure handling equipment. In addition, a crust or sediment is less likely to form during storage, which reduces the need to mix the slurry prior to its collection for agronomic utilization. As reported by others (e.g., Sommer, 1997; Lindorfer et al., 2007), biogas and ammonia (NH_3) losses are expected from the stored digested slurry due to its large amount of undigested volatile solids (VS) and high ammonium nitrogen (NH_4-N) concentration. Menardo et al. (2011), in work carried out at the national level through batch trials, found that stored digested slurry contains significant residual biogas potential. In particular, Gioelli et al. (2011) have conducted pilot scale studies at two 1MWel AD plants and reported average biogas emissions of 468 L_N m^{-2} surface day^{-1} and 190 L_N m^{-2} surface day^{-1} from uncovered, non-separated digestate and digested liquid fraction storage tanks, respectively. Moreover, Gioelli et al. (2009) found average daily NH_3 emission rates from stored non-separated digestate ranged between 2.06 and 4.44 $gNH_3\ m^{-2}$ surface and between 7.89 and 14.6 $gNH_3\ m^{-2}$ surface from digested liquid fraction. Biogas consists mainly of methane (CH_4) and carbon dioxide (CO_2), two of the main greenhouse gases (GHG) that affect the global environment and climate (IPCC, 2007). Atmospheric NH_3 also impacts the environment through particulate matter formation, aquatic eutrophication, and soil acidification (Goebes, 2003), which indicates that biogas and NH_3 losses from plant storage structures can represent an environmental hazard.

In terms of actual practice, our monitoring of regional AD plants has shown that digestate and digested liquid fraction are generally stored in uncovered tanks (Gioelli et al., 2012). Furthermore, although several natural (straw, peat, and light expanded clay aggregates) and synthetic (geotextile, plastic, and rubber) materials (VanderZaag et al., 2008, Balsari et al., 2006) are available to abate diffuse emissions, many have limitations. Nicholson et al. (2002) demonstrated that while simple storage covering results in reduced ammonia emissions, only a small reduction is attainable with methane due to its release during mixing at the end of the storage period. Rigid covers are another option, but as underlined by Horning et al. (1999), they are costly and impractical. Specifically, after such a cover is installed, parts of it may require removal for agitation and pumping when the manure is removed for application, which necessitates that a permanent opening be installed that can be sealed between pumping intervals (Nicolai et al., 2004). Inflated dome covers address this issue by an opening when the dome is deflated during manure agitation and removal (Stenglein et al., 2011). At biogas plants, CH_4 emission to the atmosphere from digestate can be avoided by connecting the storage tank to the gas bearing system (Moitzi et al., 2007), which offers the added potential to increase the AD plant biogas yield (Menardo et al., 2011). None of the above impermeable covers recover the complete residual biogas produced by the digestate because pumping and mixing operations allow air to enter the tank and dilute the biogas. The most common solution in Italy for digestate storage tank coverage is to use a pressurised double membrane cover system; however, this method also falls short. Specifically, it fails to meet the spring and autumn seasons demands when digestate is applied frequently and quickly and the digestate in the tank is never fully collected. Additionally, during these repeated pumpings, air must be collected from outside the cover to compensate for the depression created under the cover. To address the flaws of available technology, we designed, installed, and tested the efficacy of an innovative floating coverage system to store and collect the emitted residual biogas on a 6000m^3 storage tank of a 1MWel AD plant. The research was carried out within the "EU-Agro-Biogas Project" funded under the Sixth Framework Programme.

2 Materials and Methods

2.1 Description of the AD plant

The plant selected for installation of the floating cover is located in the Piemonte Region of northwest Italy. It is a completely stirred tank reactor (CSRT) with 1MWel of installed power. Two 6000 m^3 double-chambered, air-tight fermenters are operated in series under mesophilic conditions (41°C). The fermenters are fed with a mixture of cattle slurry (23%), farmyard manure (30%), energy crops (27%), and agricultural by-products (20%). Solid feedstocks are loaded to fermenters by means of a mixing wagon running 20 h per day, whereas the liquid one is fed by a pumping station. The organic load rate (OLR) of the plant is 1.55 kg volatile solids m^{-3} day^{-1}, and hydraulic retention time (HRT) is approximately 105 days.

Approximately 100 m^3 of fresh digestate is loaded daily into a 5m^3 mixing pit by overflow from the second fermenter, and mechanically separated by a screw press (Sepcom, model 065). The digested solid fraction (approximately 20 t day^{-1}) is stored in a static heap for at least 90 days and used as applied fertilizer on the farm or transported to other farmlands. The digested liquid fraction (approximately 80 m^3 day^{-1}) is stored in a 6100m^3 (Ø 36m, 6m wall height) aboveground uncovered tank and applied to grasslands and arable crops during three seasons of the year: spring (about 40%), summer (30%), and autumn (30%). The storage capacity of digestate and the length of the storage period depend on factors such as biogas plant type, crop rotation and regional regulations. However, in most 1MWhel agricultural biogas plants operating in northwest Italy the digestate is stored in tanks of about 6000m^3 (Gioelli et al., 2011).

2.2 Design and concept of the floating cover

To enable collection of residual biogas from the digestate liquid fraction during frequent tank unloading (spring, autumn), a floating cover system was designed by DEIAFA in collaboration with Ecomembrane® Company (Cremona, Italy). The cover is floated over the slurry surface so that it can move up and down with the slurry level during loading and unloading operations. In this way, the volume occupied by the biogas beneath the structure remains constant, even during digestate collection events. Typically, during storage a natural crust forms on the surface of digested slurry, which can lift the structure and compromise the seal. A crust also requires that the slurry be mixed prior to collection and/or agronomic utilisation, however, a floating cover makes stirring impossible because the cover needs rotation on its vertical axis during slurry mixing. To reduce the probability of crust formation beneath the cover, the newly designed floating cover was placed directly over the surface of digested liquid fraction in which the total solids content is lower compared to that of the unseparated digestate.

2.2.3 Coverage description

The following are components of the coverage system:

- peripheric floating frame (diameter 35.7 m) (Fig. 1) composed of 48 polypropylene and stainless steel modules linked by U stainless steel profiles. Each module is 2.3 m long, 0.56 m high, and 0.1 m thick. To provide structure buoyancy, four polypropylene panels are mounted on each module;
- central floating post (Fig. 2) fabricated from nine polypropylene blocks (1.1 m long x 1.1 m wide x 0.6 m high) that supports a 2.4 m high stainless steel frame. The post has a buoyancy capacity of approximately 4 t;
- polyvinyl chloride (PVC) coated on two sides with a polyester fibre membrane covering the entire tank surface (~1000m^2). The membrane is resistant to atmospheric agents and impermeable to gas. The membrane (weight: 1.2 t) leans on the central floating unit and is folded again under the peripheric structure to avoid biogas leaking;
- two pumps placed on opposite sides of the coverage that are activated by buoyancy level switches. When rainwater accumulates, the pumps act to remove it from the cover.

The total structure (central post, peripheric floating frame, and PVC membrane) weighs 3.5 t. When the structure is placed on the slurry surface it partially sinks into the slurry and creates an airtight gas volume of about 1800 m^3. A gas line connects the cover system to the plant gasometer with these elements:

- centrifugal pump (maximum flow rate: 80m^3 h^{-1}) positioned on the concrete roof of one of the two fermenters;
- flexible pipe connected to the top of the post by a flange. The line is free to move up and down with the coverage according to the digested liquid fraction level in the tank;
- water trap mounted midway between the biogas collection point of the coverage and the centrifugal pump. The water trap is positioned on the ground between storage tank and fermenters, so that coverage water can flow through the gas line and be discharged;

- control panel equipped with a pressure probe that detects the biogas pressure within the gas line. It includes a switch that turns the pump on, a timer that turns the pump off after one minute of operation, and a temperature probe.

The biogas recovery system operates optimally under slightly depressed conditions so that biogas fails to accumulate beneath the coverage because any allowed to do so would inflate the membrane and increase its surface area exposed to the wind. Being that the structure floats freely on the slurry surface and is not secured to the tank, when the slurry level within the tank is close to the maximum, the inflated coverage would be subjected to a sail effect and risk being blown away. To this end, when the biogas pressure below the coverage is higher than -4 mbar, the centrifugal pump is triggered to run minute and is then turned off. This functioning ensures the structure does not collapse should the biogas stored by the coverage fall below the volume collected by the pump. The recovered biogas is then pumped to the AD plant gasometer (~500m^3 volume).

2.3 Storage tank floating cover placement

The cover system was readied for placement on top of the digested liquid fraction storage tank of the 1 MWel AD plant after all cover components were assembled. The coverage was coupled with a lifting frame, which was a circular iron structure made up of 24 elements with the same diameter (35.7 m) as the cover. The frame was suspended by a crane and aligned with the coverage for proper fit. It was then connected to the peripheric floating frame by 24 (Ø 5 mm) steel cables (Fig. 3a) that reduce the potentially crushing vertical stresses on it when the coverage is lifted. The coverage was then lifted by a truck-crane and placed atop the tank (Fig. 3b). Three workers and a total of 80 hours were required to pre-assemble and install the covering system.

2.4 Recovered biogas measurement by the floating cover

After the coverage was installed, the amount of collected biogas was recorded daily for 12 months. The amount of recovered biogas from the tank was determined indirectly as a function of pump working hours and flow rate. The pump flow rate was also determined indirectly through measurement of the air speed at the pump outlet according to:

$$Q = V * S * 3600 \qquad (1)$$

where:

Q = flow rate (m^3 h^{-1})

V = air velocity (m s^{-1})

S = area of the pump outlet (m^2)

The amount of biogas collected by the pump was calculated according to:

$$V = Q * h \qquad (2)$$

where:

V = amount of biogas recovered (m^3)

Q = pump flow rate (m^3 h^{-1})

h = hours of functioning of the pump

Pump work hours were recorded by an hour-counter installed on the gas line control panel. Biogas characteristics were determined by weekly samples taken directly from the gas line that connects the floating cover to the plant gasometer. Samples were stored in gasbags and analysed for their CH_4 and CO_2 content by means of a portable gas analyser (Draeger X-AM 7000). Recorded data were normalized to normal m^3 (Nm^3) (dry gas, T=0°C, P=1013hPa) according to VDI 4630 (2006). Recorded data were converted into CO_2 equivalents (CO_2eq), assuming a global warming potential of 25 and 1 for CH_4 and CO_2, respectively (IPCC, 2007).

2.5 Measurement of digested liquid fraction temperature

The temperature of the digested liquid fraction was measured with four sets of thermocouple sensors (Type K) connected to data loggers (Onset Hobo). Each set was made up of two thermocouples; one placed on the bottom of the tank and the other one 0.2 m from the surface of the digested liquid fraction. The four sets of thermocouples were placed to form an ideal cross on the surface of the digested slurry.

2.6 Chemical analysis of digested liquid fraction

On the first working day of each month, three samples of digested liquid fraction were collected at the outlet of the mechanical separator in front of the storage tank entrance. Samples were collected during the 6 hours (3-hour interval between samplings) that the separator functioned. Thereafter, the samples were mixed and a third representative sample was created from the sub-samples. All digested liquid fraction sub-samples were tested for pH, TS and VS content. Total solid and VS were determined in accordance with standard methods (AOAC, 1990); pH was measured by pH-meter (Hanna Instruments, Italy).

3. Results and discussion

During the nine-month experimental period, the biogas produced by the plant was, on average, 11,726 m^3 day^{-1}. The degree of organic matter degraded during the anaerobic digestion process was between 47.3% and 62.4%.

The chemical characteristics of the digested liquid fraction are listed in Table 1. Despite the long retention time (105 days), the percentage of VS measured in the digested slurry samples showed a residual availability of undigested organic matter in the digested substrate. The pH values suggested a regular course within the fermenters.

In early spring, a mechanical separator failure occurred, which made it impossible to load the tank with digestate due to the risk of crust formation. Therefore, the monitoring of biogas production had to be suspended until the separator was repaired and put into operation again. Following the failure, the coverage was removed from the tank and slurry was mixed and pumped into another storage tank. Once the mechanical separator was repaired, the digestate was again separated, the coverage was repositioned, and the monitoring activity was restarted on the first work day of July. On average, the digested liquid fraction temperature ranged between 15.7°C and 30.7°C; a wide variability was detected in daily methane yields as shown in Fig. 4. The average methane concentration of the biogas was 56.5% (range 51.5%-67.2%). The amount of recovered methane peaked in February and March, just prior to the digested liquid fraction collection for agronomic utilisation; in the same months, the highest VS contents of digested liquid fraction were measured (Table 1).

On average, over nine months of monitoring, 191.6 Nm^3 (range 141-232 Nm^3) of residual CH_4 was recovered daily from the storage tank (Fig. 5), which corresponds to a daily production of 0.191 Nm^3 CH_4 m^{-2} of storage surface and 1.91Nm^3 CH_4 m^{-3} of fresh digested liquid fraction loaded into the tank. A previous pilot scale study by Gioelli et al. (2011) estimated 1.33Nm^3 CH_4 emitted day^{-1} from digested liquid fraction over a five-month timeframe. The data from Gioelli et al. (2011), however, referenced a digested liquid fraction characterized by a lower VS content.

The biogas plant yields averaged 6200Nm^3 CH_4 day^{-1}. According to experimental results, the residual CH_4 (191.6 Nm^3 day^{-1}) collected from the storage of the digested liquid fraction accounts for approximately 3% of the total daily methane yield of the AD. Considering the average hourly methane consumption (approximately 260Nm^3 h^{-1}) of the combined heat and power (CHP) system of the plant, the latter value (191.6 Nm^3 day^{-1}) allows the production of approximately 0.74 additional MWhel per day (approximately 270 MWhel per year). The investment cost for the purchase and installation of the storage tank cover system is in the range of 60€ m^{-2} of covered surface. Payback for the cover system is less than one year given the electric energy surplus possible with the biogas recovered from the storage tank at the current national market price (280€ MWh^{-1}). This value could however, in time be improved as the tested cover system was a prototype; new and cheaper versions, already under study by our research group, will reduce this calculation.

Aside from economic benefits, there are environmental benefits to the coverage system design. Covering the digested liquid fraction storage tank of a 1MWel AD plant makes it possible to avoid atmospheric emissions of as much as 160 kgCO_2eq produced per MWhel, which increases the environmental sustainability of the process.

4. Conclusions

The experiments confirmed the results of earlier studies, which underlined the residual biogas potential of digested liquid fraction. Therefore, the digestate storage tank coverage must be strongly encouraged to increase AD plant environmental sustainability. The developed floating coverage system was shown to be a reliable low cost solution for collecting the residual biogas emitted from digestate liquid fraction storage. Its practicality comes from its relatively simple modular construction and ability to fit tanks of different shapes (squared, rectangular, circular) and sizes.

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Figure captions

Fig. 1. Peripheric floating frame;

Fig. 2. Central floating post

Fig. 3. a) Floating cover installation; b) Covered storage tank

Fig. 4. Methane emission and digested liquid fraction temperature patterns.

Fig. 5. Average daily methane yield recorded from the digested liquid fraction storage tank.

Table captions

Table 1. Chemical characteristics of the digested liquid fraction during the monitoring period.

Fig. 1

Fig 2

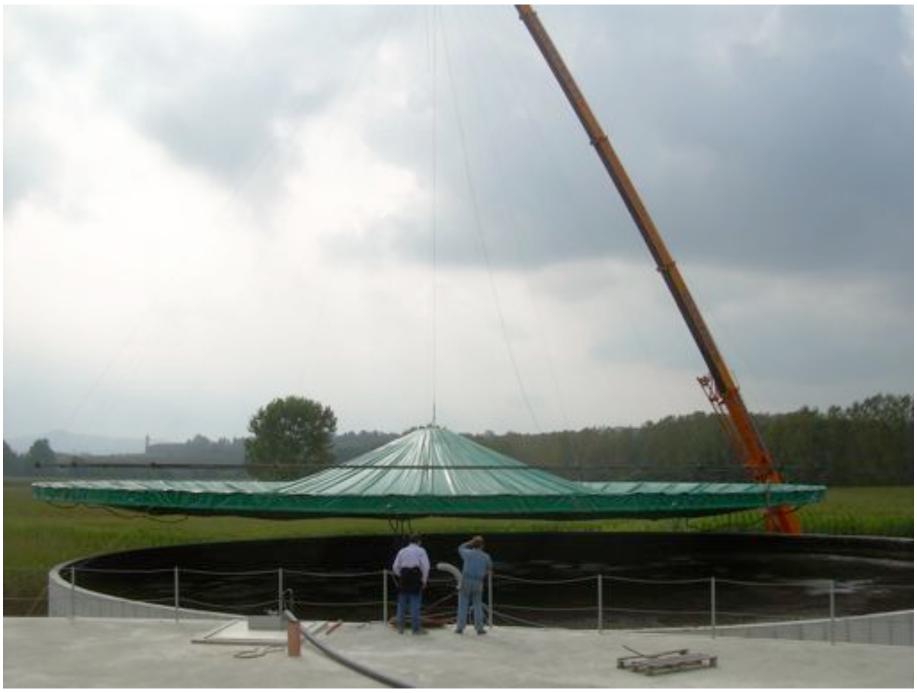


Fig. 3 a

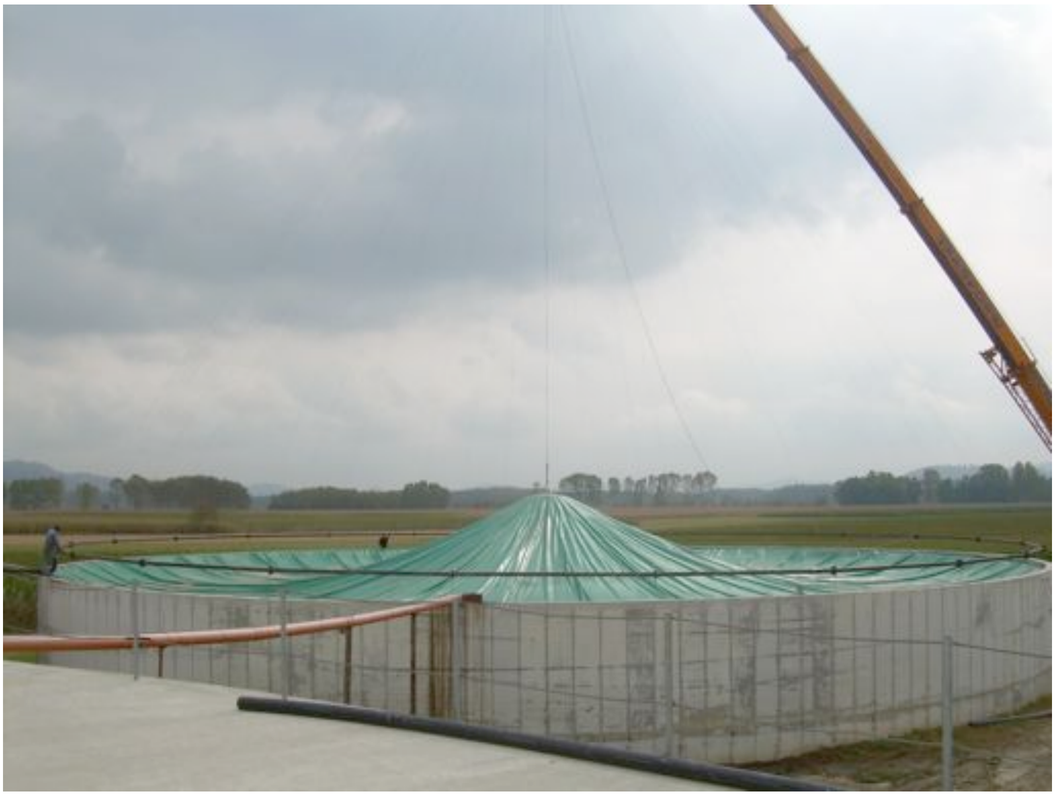
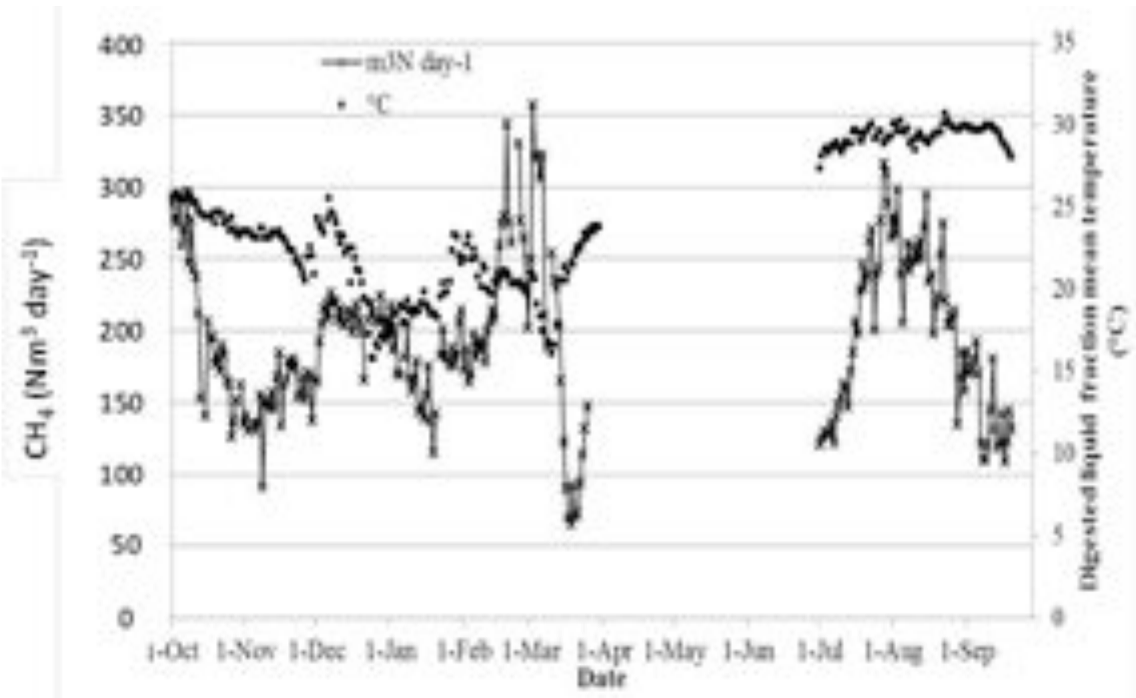
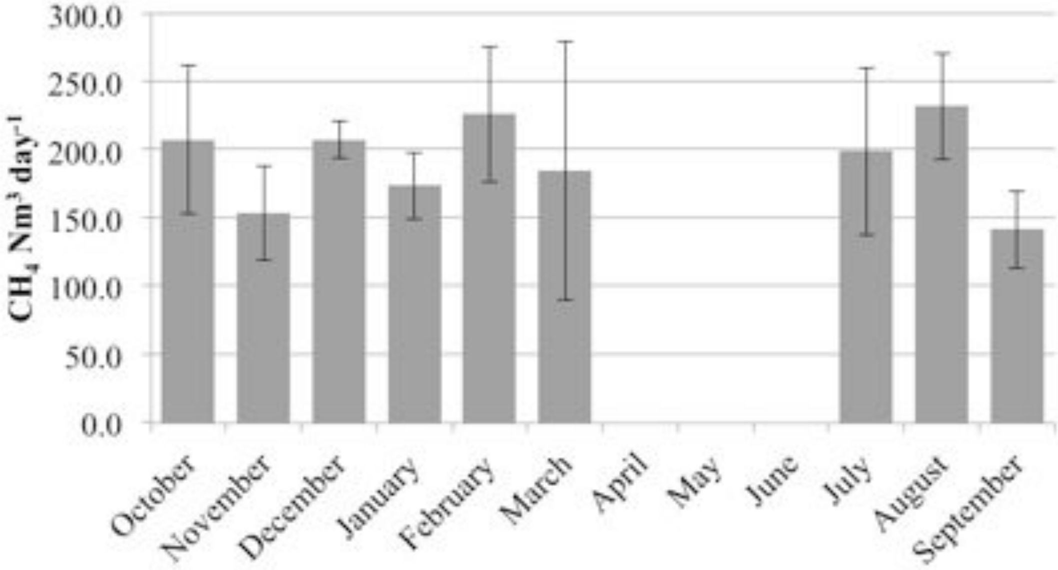


Fig. 3b



m3N day-1
°C
CH_4 (Nm^3 day^{-1})
Digested liquid fraction mean temperature (°C)
Date
1-Oct
1-Nov
1-Dec
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun
1-Jul
1-Aug
1-Sep

Fig. 4



300.0
250.0
200.0
150.0
100.0
50.0
0.0
CH4 Nm3 day-1
October
November
December
January
February
March
April
May
June
July
August
September

Fig. 5

	pH	Total Solids (%)	Volatile Solids (%)	VS/TS
Oct	8.1	6.31	4.23	0.67
Nov	8.3	5.91	3.90	0.66
December	8.2	6.43	4.31	0.67
January	8.0	6.25	4.19	0.67
February	8.2	6.57	4.73	0.72
March	8.3	6.74	4.18	0.62
July	8.3	6.51	4.10	0.63
August	8.8	6.15	3.75	0.61
September	8.2	6.34	4.06	0.64

Table 1.