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A pilot scale study on synergistic effects of co-digestion of pig manure and grass silage

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ABSTRACT

This study aimed to assess the system stability and synergistic effects of co-digesting pig manure (PM) and grass silage (GS) in a pilot-scale study. Anaerobic digestion of PM alone and co-digestion of PM with GS was carried out in a 480-L continuously stirred tank reactor. The experiment consisted of two phases. In Phase I, PM was digested at an organic loading rate (OLR) of 0.87 kg volatile solid (VS) $m^{-3}\cdot d^{-1}$, and in Phase II, PM and GS were co-digested at 1:1 on a VS basis at an OLR of 1.74 kg VS$\cdot m^{-3}\cdot d^{-1}$. The pilot-scale anaerobic digestion system was stable in both phases. At the steady state, average pH and free ammonia concentrations were 7.99 and 233.0 mg l^{-1} in Phase I and were 7.77 and 158.3 mg l^{-1} in Phase II, respectively. The specific methane yields increased from 154 ml CH_4/g VS added in Phase I to 251 ml CH_4/g VS added in Phase II. On average, soluble chemical oxygen demand and VS removal efficiencies increased from 81.4% and 41.4% in Phase I to 87.8% and 53.9% in Phase II, respectively. Further evaluation of synergism suggests that co-digestion of PM and GS can improve system stability and biogas yields despite marginal synergistic effects at pilot-scale.

1. Introduction

Globally, pig production is one of the main animal agricultural enterprises from which large volumes of high nutrient content manure is produced. Pig manure (PM) has the potential to be environmentally harmful if handled in an inappropriate manner. Historically PM has been land-spread as an organic fertilizer for growing grass and other crops. However, application rates of PM have recently been curtailed primarily due to regulations. For example, the EU Nitrates Directive has limited the amount of organic nitrogen applied to grasslands and tillage lands to 170 kg N/hectare/year (S.I. No. 610, 2010). This has resulted in an increase in land area required for PM application in the EU, and a consequent drive to find alternative treatment and disposal methods for PM. In addition, many countries have agreed to reduce GHG emissions from agriculture and increase production of renewable energy. Ireland, for example, has agreed to reduce GHG emissions by 20% of 2005 levels by 2020 (as part of the EU, 2020 growth strategy), and is required to generate 16% of gross final consumed energy through renewable means by 2020 (under the 2009 Renewable Energy Directive (2009/28/EC)). Therefore, there is a need to explore and develop alternative non land-spread options for PM management which can reduce GHG emissions and generate renewable energy.

Anaerobic digestion (AD) is an environmentally friendly technology for the PM management (Dennehy et al., 2017a). AD of PM can help reduce odor, pathogen levels and greenhouse gas emissions in addition to producing a valuable bioenergy source in the form of methane-rich biogas (Chae et al., 2008). The resulting digestate can also be a valuable fertilizer because it typically contains higher concentrations of biologically available nitrogen than raw manure (Kaparaju and Rintala, 2011). In this regard, AD has been recognised worldwide as a valuable technology. A large number of large-scale agricultural or centralized biogas plants for treating animal manures, agricultural crops, wastewater and

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organic wastes have been constructed in Europe and Asia-Pacific Region (Angelidaki and Ellegaard, 2003; Clarke et al., 2016; Nghiem et al., 2017; Pantaleo et al., 2013).

Climatically suited to the production of grass, the agricultural area is predominately grassland with 4.3 million ha compared to only 0.28 million ha of arable land in Ireland (Hamelinck et al., 2004). Grass is normally utilized by grazing animals and is conserved as grass silage (GS) for feeding to ruminants over the winter months (Xie et al., 2011). Therefore, GS could be readily available for anaerobic co-digestion with PM. Studies have shown the beneficial effects of co-digesting manures with a range of agricultural residues. For example, Kaparaju and Rintala (2005) in a study of the co-digestion of PM with potato tubers found that co-digestion improved specific methane yields and increased process stability. Similar results were found when co-digesting a range of different manures (cattle manure and PM) and agricultural/food residues (such as whey, GS, sugar beet tops, energy crops, quinoa residues and herbal extract residues) as substrates (Alvarez and Lidén, 2008; Gelegenis et al., 2007; Lehtomäki et al., 2007; Li et al., 2011). Compared to AD of PM alone, co-digestion with agricultural residues can enhance the process performance by: (i) overcoming ammonia inhibition which is sometimes a feature in digestion of pure manure (Xie et al., 2012a); and (ii) optimising the carbon to nitrogen (C/N) ratio in the feedstock for the AD (Wu et al., 2017).

Laboratory-scale research has shown that it is feasible to co-digest PM and GS, and that the optimum PM to GS ratio in the feedstock for process stability and biogas production when co-digesting GS and PM was 1:1 on a volatile solid (VS) basis (Xie et al., 2011). Similar results have been found by Dechrugsa et al. (2013) in laboratory scale batch experiments on co-digestion of grass and PM. It has been calculated that by employing co-digestion of PM and GS at a 3:2 mix ratio on a VS basis, a 654-sow pig unit could generate 371 MWh/a electricity and 530 MWh/a heat, compared with 268 MWh/a electricity and 383 mWh/a heat at a 4:1 mix ratio; a much lower electricity and heat generation can be expected during mono-digestion of PM alone (Xie et al., 2012a). However, it remains unknown if pilot scale studies can demonstrate that co-digestion of PM and GS at optimal operating conditions derived from lab scale studies can generate the methane yields underlying these energy yield estimates at full scale, taking into account the variations in mass transfer efficiencies and substrate properties and composition at varied scales of studies. In addition, scientific results from pilot-scale studies can further contribute towards the establishment of mathematical tools to guide the operation of on-farm anaerobic co-digestion systems (Xie et al., 2016).

In this study, anaerobic co-digestion of PM with GS was investigated in a pilot-scale anaerobic digester to examine (1) process stability in terms of pH, oxidation reduction potential (ORP) and concentrations of ammonium nitrogen and free ammonia; (2) the effect of anaerobic co-digestion of PM and GS on biogas productivity and removal of soluble chemical oxygen demand (COD) and VS.

2. Materials and methods

2.1. Feedstock

Pig manure was collected from a local pig farm and GS was sourced from a conserved pit on an Irish farm. Pig manure was stored in two 1 m^3 intermediate bulk containers (IBCs) and was fed into the digester with a water submersible pump (FTS 1100A1, Florabest). The precision chopped GS had an average chop length of 5 cm and was mixed to ensure a homogenous feedstock. It was then stored in individual plastic bags sized for each day's feeding in a freezer room (−17 °C) to prevent biological decom position during the study. Prior to the daily feeding, the frozen GS in the individual bag was transferred to a cold room (4 °C) for one day and placed at room temperature for 1 h. The characteristics of fresh PM and GS are given in Table 1.

2.2. Pilot-scale anaerobic digester

The pilot-scale anaerobic digester was designed to allow remote control. The system consisted of four components: (a) the digester, (b) feeding system, (c) control panel and (d) biogas storage system. The schematic of the digester is shown in Fig. 1. The digester was cylindrical and constructed from 316-stainless steel. It had a total volume of 480 l and a working volume of 360 l. Two propellers fabricated from 316 stainless steel were installed for continuously homogenizing the feedstock and rotation (30–60 rpm) was controlled by an electric three-phase motor (380 V) operated by an inverter (Hitachi SJ200, Japan) through the control panel. A Tiger 80 submersible vortex chopper pump (Arven S.R.L. Italy) with a capacity of about 250 l/min was placed inside the digester to circulate the digestate after each feeding and before each discharge so as to avoid the build-up of GS and fibre at the surface of liquid digestate. The external surface of the digester was wrapped with a water jacket, to maintain a constant temperature of 37 °C, and fully enclosed with insulating material to minimize heat loss. Two air operated valves with an inner diameter of 10.16 cm (4 inches) on the bottom of the digester allowed the removal of the digestate and permitted collection of the samples for subsequent chemical analysis.

The feeding system was located at the top of the reactor. The GS feeding system was comprised of a pipe and two chambers controlled using two compressed-air operated valves. These valves allowed the feeding of GS into the reactor tank through the removable cover, while preventing air from entering the digester by opening the top and bottom valves consecutively. Pig manure was fed into the digester via a 1 L chamber where both ends were connected with 3.8 cm (1.5 inches) diameter pipes; one pipe was connected to the inlet of a submersible pump (FTS 1100A1, Florabest) placed in the PM storage IBCs, and the other was submerged in the IBCs. Recirculation of the PM prior to feeding helped ensure a uniform feedstock in the IBCs. The PM feeding chamber was controlled using a compressed-air operated valve, thereby preventing air from entering the digester.

Table 1
Characteristics of raw PM, GS and inoculum.

Characteristics	GS	PM	Inoculum
DM (% of FW)	34.50	3.71	1.56
VS (% of FW)	31.60	2.61	0.79
Ash (% of FW)	2.90	1.1	0.77
NDF (% of DM)	61.51	–	–
ADF (% of DM)	39.62	–	–
pH	4.47	7.90	8.00
Lactic acid (% of DM)	10.49	–	–
VFA (% of DM)	3.36	–	–
CP (% of DM)	14.71	–	–
WSC(% of DM)	2.76	–	–
DMD (% of DM)	68.50	–	–
sCOD ($g \cdot l^{-1}$)	–	24.41	6.70
tCOD ($g \cdot l^{-1}$)	–	128.90	36.64
sCOD (% of DM)	24.64	–	–
NH_4^+-N ($mg \cdot l^{-1}$)	–	1640	2387

Note: FW: fresh weight, DM: dry matter; VS: volatile solids; NDF: neutral detergent fiber; ADF: acid detergent fiber; VFA: volatile fatty acid; CP: crude protein; WSC: water soluble carbohydrate; DMD: dry matter digestibility; sCOD: soluble COD.