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Recovery of energy and nutrient resources from cattle paunch waste using temperature phased anaerobic digestion

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ABSTRACT

Cattle paunch is comprised of partially digested cattle feed, containing mainly grass and grain and is a major waste produced at cattle slaughterhouses contributing 20–30% of organic matter and 40–50% of P waste produced on-site. In this work, Temperature Phased Anaerobic Digestion (TPAD) and struvite crystallization processes were developed at pilot-scale to recover methane energy and nutrients from paunch solid waste. The TPAD plant achieved a maximum sustainable organic loading rate of 1–1.5 kgCOD m^{-3} day^{-1} using a feed solids concentration of approximately 3%; this loading rate was limited by plant engineering and not the biology of the process. Organic solids destruction (60%) and methane production (230 L CH_4 kg^{-1} VS_{fed}) achieved in the plant were similar to levels predicted from laboratory biochemical methane potential (BMP) testing. Model based analysis identified no significant difference in batch laboratory parameters vs pilot-scale continuous parameters, and no change in speed or extent of degradation. However the TPAD process did result in a degree of process intensification with a high level of solids destruction at an average treatment time of 21 days. Results from the pilot plant show that an integrated process enabled resource recovery at 7.8 GJ/dry tonne paunch, 1.8 kg P/dry tonne paunch and 1.0 kg N/dry tonne paunch.

1. Introduction

Cattle slaughterhouses generate large volumes of solid waste and wastewater rich in organic contaminants and nutrients (Johns, 1995; Liu and Haynes, 2011; Marcos et al., 2010; Martinez et al., 2012), and are therefore strong candidates for treatment processes aimed at recovery of both energy and nutrient resources.

Waste and wastewater originates from several major process operations at a slaughterhouse including cattle preparation, cattle slaughter, recovery of by-products and reprocessing of by-products (Liu and Haynes, 2011). Generally, waste streams from different processing areas are transported separately within the site then combined for bulk treatment (e.g. in an anaerobic lagoon). Combined slaughterhouse waste is composed of a mixture of grease, fat, protein, blood, intestinal content, manure and cleaning products (Johns, 1995). It contains high concentrations of organic matter (represented by chemical oxygen demand, COD); fat, oil and grease (FOG); nitrogen (N); phosphorus (P) and other trace elements. The current default technologies for treating Australian abattoir waste include primary treatment for separation of coarse solids, followed by lagoon based treatment for the effluent wastewater including: covered or uncovered anaerobic lagoons for carbon removal; nitrification/denitrification for nitrogen removal and partial phosphorous removal; and in some cases polymer dosing for enhanced P removal. This is followed by facultative storage and either irrigation, limited reuse or discharge to sewer.

Cattle paunch is a major waste produced at cattle slaughterhouses and is comprised of partially digested cattle feed, mainly containing grass and grain. The volume and composition of paunch waste varies according to individual animals and site handling practices but is reported at approximately 60 kg of wet paunch waste per animal, corresponding to approximately 10% of the total weight of the live animal (Tritt and Kang, 1991). The paunch stream is reported to contain 20–30% of the organic matter and 40–50% of P from the combined waste streams available on site (Jensen et al., 2014). Paunch is separated from the cattle intestine after slaughter and is commonly diluted using process water to form a waste stream with 2–5% solid content to enable pump

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transport within the slaughterhouse (termed wet dump paunch processing). The amount and type of the paunch waste contents is dependent on age, weight of the animal, kind of feed and fasting time before slaughter. In Australia 8–9 million cattle are slaughtered for meat production each year (ABS, 2015) with approximately 300 million cattle slaughtered globally (FAOSTAT, 2012). These activities generate approximately 0.2 million tonnes of paunch waste in Australia and 15 million tonnes globally. Paunch waste may contain pathogens and is considered as a high biological risk solid waste (Hejnfelt and Angelidaki, 2009). Internationally, incineration or non-agriculture land disposal are common handing practices. In Australia, paunch is commonly mixed with green waste and composted prior to disposal or re-use in agriculture. However, paunch composting is a major source of odour and this practice is facing increasing regulation and restriction. There is an existing need to develop on-site treatment technology to stabilize and sustainably dispose or recycle this waste stream; particularly closed vessel technologies that eliminate odours and enable recovery of energy and nutrient resources.

Anaerobic digestion is a suitable technology for stabilisation of many organic wastes and allows energy recovery in the form of methane. The economic feasibility of the process is driven by (i) the methane potential – as the recovered energy could reduce energy costs of the slaughterhouse; (ii) degradable fraction – as the reduction in waste solids will reduce final disposal costs; and (iii) the speed of degradation – which impacts vessel size and capital costs. During anaerobic digestion nutrients are released in soluble form, which allows crystallization and subsequent recovery from the effluent as fertilizers, increasing the production of sustainable resources and improving value recovery from the waste.

Cattle slaughterhouses generate multiple waste streams with highly variable compositions and methane yields ranging from 200 to 1000 L CH_4 kg^{-1} VS (Hejnfelt and Angelidaki, 2009; Zhang and Banks, 2012). For batch mesophilic anaerobic digestion, a methane potential of 237 L CH_4 kg^{-1} VS has been reported for Australian paunch solid waste, corresponding to a degradable fraction of approximately 0.6, the hydrolysis rate was fitted at 0.11 day^{-1} (Astals et al., 2014). The relatively poor methane yields and slow hydrolysis rates reported by Astals et al. suggest paunch is a strong candidate for pre-treatment technologies aimed at improving overall digestion performance. Low intensity thermophilic pretreatment was identified for assessment due to the potential to utilise the abundant supply of low quality waste steam readily available at many Australian slaughterhouses. Previous research has demonstrated success in applying low intensity thermal pretreatment to increase the methane potential of sewage sludge streams by 25% (Ge et al., 2010) with substantial improvements in cellulosic hydrolysis rates also reported (Ge et al., 2011b).

Nutrients such as nitrogen and phosphorus are a major resource stream present in slaughterhouse wastewater. Paunch is relatively high in P, the P concentrations from paunch/offal processing and rendering facilities are above 50 mg L^{-1} (Johns et al., 1995; Kabdaşl et al., 2009) and are therefore in the range for economical struvite crystallization, which would mitigate impacts of phosphorous release during anaerobic digestion on downstream processing. However, struvite crystallization has not been demonstrated in this application previously.

Overall, paunch is a major byproduct stream from red meat processing, with limited existing options for treatment or resource recovery. Anaerobic digestion is potentially effective, particularly to reduce pathogen risks and waste volumes, and retrieve resources. However, there are very few published case studies, particularly for continuous systems, or integrated energy-nutrient recovery systems. This paper addresses these gaps by demonstrating practical application of anaerobic digestion of paunch solids, with subsequent recovery of struvite.

2. Methodology

2.1. Substrate

Paunch solids were used as the substrate for the Temperature Phased Anaerobic Digestion (TPAD) process. The paunch solids were collected as dewatered paunch cake from a rotating drum screen, and were collected prior to treatment using composting. The composition of the dewatered paunch solids is shown in Table 1, composition of centrate from the screen is shown for comparison. The screened paunch had a solids content of approximately 12% and was diluted to approximately 3% solids using process water. The decision to collect dewatered paunch (rather than whole paunch) was based on accessibility constraints at the pilot plant site.

2.2. Process design and operation

The paunch resource recovery process consisted of 2 main treatment steps. First, a TPAD plant was designed to stabilise solids, mobilise nutrients and recover energy from the paunch waste; second, a crystallization plant was designed to recover nutrients from the digestate in the form of struvite. A process flow diagram for the pilot-scale setup is shown in Fig. 1.

2.2.1. Anaerobic digestion

The anaerobic digestion process was based on Temperature Phased Anaerobic Digestion (TPAD) (Ge et al., 2010, 2011a). TPAD is a two-stage thermophilicmesophilic treatment process. The first reactor (20 m^3) was operated at higher temperature (>50 °C), with a 4–6 day retention time while the second reactor (95 m^3) was operated at moderate temperature (~35 °C) with a 16–20 day retention time. The reactors were cylindrical vessels constructed from stainless steel (SS304, Kaima Engineering, Australia). Mixing in the reactors was achieved by re-circulation through external pumps (Compact C, Mono Pumps Pty. Ltd.). Temperature in the thermophilic reactor was maintained by circulation through an external shell and tube heat exchanger as part of the mixing system. The TPAD process was monitored and controlled using a process logic control system (MicroLogix 1400, Rockwell Automation, Inc.).

At start-up each reactor was inoculated using digester sludge from an onsite crusted anaerobic lagoon. The lagoon was treating combined slaughterhouse wastewater and the specific methanogenic activity (SMA) of the sludge was 0.14 gCOD g VS^{-1} d^{-1} at 35 °C (data not shown). The demonstration plant operated in semi-continuous mode. There were 10 feed events per day, feed events occurred as a sequential process where waste material was first pumped from the mesophilic digester (R2) and returned

Table 1
Characteristics of screened wastewater, dewatered paunch solids and diluted paunch feed.

Characteristics	Screened wastewater	Dewatered paunch solids	Diluted paunch feed
Total solids (g L^{-1})	7.5	117	31.4 ± 1.6
Volatile solids (g L^{-1})	5.6	105	28.1 ± 1.6
Chemical oxygen demand (g L^{-1})	9	111	29.6 ± 3.6
Volatile fatty acid (g L^{-1})	0.63	1.8	0.7 ± 0.3
TKN (mg L^{-1} N)	220	2100	414 ± 40
TAN (mg L^{-1} N)	16	N/A	101 ± 20
TP (mg L^{-1} P)	108	700	221 ± 24
PO_4–P (mg L^{-1} P)	60	N/A	42.3 ± 7.2

Note: Screened wastewater and dewatered paunch had few sample events, therefore standard error not calculated.