Renewable Energy 128 (2018) 1–8

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Semi-continuous anaerobic co-digestion of dairy manure, meat and bone meal and crude glycerol: Process performance and digestate valorization

Fetra J. Andriamanohiarisoamanana [a], Aya Saikawa [a], Takumi Kan [a], Guangdou Qi [a], Zhifei Pan [a], Takaki Yamashiro [a], Masahiro Iwasaki [a], Ikko Ihara [b], Takehiro Nishida [a], Kazutaka Umetsu [a, *]

[a] *Graduate School of Animal and Food Hygiene, Obihiro University of Agriculture and Veterinary Medicine, Obihiro, Hokkaido, 080-8555, Japan*
[b] *Graduate School of Agriculture Science, Kobe University, Kobe, 657-8501, Japan*

ARTICLE INFO

Article history:
Received 22 April 2017
Received in revised form
29 March 2018
Accepted 16 May 2018
Available online 17 May 2018

Keywords:
Meat and bone meal
Crude glycerol
Anaerobic co-digestion
Struvite
Water recycling
Digestate

ABSTRACT

The objective of this study was to investigate the effects of the addition of meat and bone meal (MBM) and crude glycerol (CG) on the anaerobic digestion of dairy manure (DM) with respect to digestion performance and digestate fertilizer value. The anaerobic co-digestion of DM, MBM and CG was conducted in semi-continuous stirred tank reactors at 37 °C with organic loadings between 2.63 and 2.86 g volatile solids (gVS)/L·d. Run 1 was a control reactor, while in Runs 2 and 3, DM was co-digested with MBM at ratios of 3.0:1.0 and 1.0:1.0 (gVS_{DM}:gVS_{MBM}), respectively. In Run 4, DM and MBM were co-digested with CG at a ratio of 1.0:0.7:0.3 (gVS_{DM}:gVS_{MBM}:gVS_{CG}). The results showed that methane yields were increased by 9.1% and 30.2% in Runs 2 and 3, respectively, compared to Run 1, while the highest methane yield (0.39 $L/gVS_{added}\cdot d$) was obtained in Run 4. The co-digestion of DM with MBM increased the ammoniacal nitrogen in the digestate by 2.1- to 2.3-fold, while no significant difference was observed for phosphorus. Due to the overabundance of nutrients in soil, the recovery of phosphorus and nitrogen and the recycling of water are the best strategies to sustain anaerobic digestion via an environmentally friendly approach.

1. Introduction

The transition from conventional to renewable energy generating systems is a global challenge that is needed to mitigate greenhouse gas emissions and alleviate the reliance on fossil fuels, which are projected to be depleted near the middle of this century [1]. Among renewable energy technologies, anaerobic digestion has an essential role in the next generation of energy matrices, as it is robust, weather-independent and stable. Anaerobic digestion has been used to treat different types of organic wastes in an environmentally friendly manner to produce end-products such as biogas and digestate. Biogas is a versatile energy carrier that can be used directly in combined heat and power or be upgraded into biomethane by processes such as water scrubbing, pressure swing adsorption or the Sabatier reaction, which can then be fed into the natural gas grid [2]. On the other hand, digestate is a well-known biofertilizer that can be applied directly to soil in a liquid or solid form. In addition, nutrients can be recovered to replace chemical fertilizers, and the valorization of digestate has an important role in the economics of a successful biogas plant [3].

Dairy manure (DM) is ubiquitous organic matter that is rich in nutrients and is a good biofertilizer. However, when poorly managed, DM can often be as a potential threat to the environment [4] as it emits greenhouse gases, such as carbon dioxide, methane and nitrous oxide; causes air pollution [5]; and contains large amounts of pathogenic microorganisms. Nevertheless, it is the most suitable material for anaerobic digestion in terms of physico-chemical characteristics and microbial community diversity. Although DM has a high buffer capacity and contains macro- and micro-nutrients necessary for anaerobic digestion, the challenges of anaerobic mono-digestion of DM include moderate methane yields and low reactor efficiency [6]. Thus, DM is often co-digested

---

* Corresponding author.
E-mail address: umetsu@obihiro.ac.jp (K. Umetsu).

https://doi.org/10.1016/j.renene.2018.05.056

with other organic substrates such as crude glycerol [7] and food waste [8].

Animal by-products that are not edible are generated during the processing of meat products in the slaughterhouse industry. These by-products include heads, feet, offal, excess fat, blood, feathers, and bones, representing approximately almost 30% of the live weight of an animal [9]. Classified as category II animal by-products, these wastes have to be processed in rending plants at 133 °C for 20 min at 3 bars into particle sizes of less than 50 mm [10] to produce meat and bone meal (MBM), a low moisture content, nitrogen-rich and powder-like product. In Japan, MBM was used as animal feed before the outbreak of Bovine Spongiform Encephalopathy in 2001 [11]. Thereafter, the use of MBM in the livestock industry and crop farming was banned and has subsequently been incinerated or used in the cement manufacturing company. However, after Japan was declared to be a BSE-free country by the OIE in May of 2013, the Japanese government has subsequently allowed the use of MBM as an organic fertilizer since June of 2014. As phosphorus (P) is an essential constituent of bones and teeth, and more than 75% of the total mineral in an animal's body is P [12], MBM is a potential organic fertilizer with an average P content of 5.3% in dry matter [9]. Moreover, MBM is a potential candidate substrate for anaerobic digestion since it has a calorific value of 17.1 MJ/kg in dry matter [13], which can be converted into biogas [14].

Anaerobic digestion of MBM has been investigated by Wu et al. using different total solid contents (TS) [14] and thermochemical pretreatments [15]. They reported that improved methane yields were obtained at a TS of less than 5%, while free ammoniacal nitrogen and volatile fatty acids accumulations were observed at a TS of more than 5% [14]. Moreover, pretreatment of MBM with 5 g/L NaOH at 131 °C increased MBM solubilization and methane yield [15]. However, from a practical standpoint, these results are challenging due to a high demand on diluent water (to bring TS to less than 5%) and moderate reactor efficiency, while the thermo-alkaline pretreatment of MBM may not be a cost-effective process. Therefore, anaerobic co-digestion of MBM with a high moisture content substrate (e.g., dairy manure, which has a high buffer capacity and contains the essential nutrients for the success of anaerobic digestion) may reduce the usage of water in the co-digestion process, while the use of a carbon-rich substrate (e.g., crude glycerol (CG), a biodiesel by-product [7]) may improve the solubilization and carbon to nitrogen (C/N) ratio of the substrate [16]. To the best of our knowledge, no study has investigated the anaerobic co-digestion of MBM with other organic wastes in a continuous experiment.

The agronomic value of organic wastes has been reported to increase after an anaerobic digestion treatment. For example, the availability of nutrients for plants (nitrogen, phosphorus and potassium) and humic substances were increased in digestate compared to undigested substrate [17,18,19]. In addition to the specific characteristics of digestate, such as it being odorless, the reduction of pathogenic bacteria and good fluidity [20], the application of digestate not only improved the soil fertility and quality by the efficient use of soil minerals but also improved biological properties of the soil including microbial biomass carbon and enzyme activities [21,22]. However, the nutrients in digestate obtained from the anaerobic digestion of DM are often imbalanced, and require the supplementation of other elements to meet the nutrient requirements of plants [23]. Therefore, the anaerobic co-digestion of DM with MBM and CG is expected to improve the nutrient balance in digestate since the nutrient contents in digestate is proportionately dependent on the composition of the injected substrate [17].

Phosphorus is an essential nutrient in plants and animals and has different roles in cell structure and biochemical reactions. Unlike nitrogen, which is a relatively unlimited resource, P is a finite resource that is solely obtained from phosphate rock. However, the world consumption of phosphate rock is growing annually, 44.5 million tons in 2016 [24], while the world phosphate rock reserves decreased remarkably from 71 billion tons in 2012 to 68 billion tons in 2016 and are expected to be exhausted in 50–100 years [25]. Therefore, the recovery of P lost in waste streams, which accounts for 80–85% of the P used to grow crops and animals [12], is the only alternative to sustain the P supply and to reduce the fast depletion of phosphate rock reserves. Since anaerobic digestion is acknowledged as the best alternative to treat organic wastes in an environmentally friendly manner, the recovery of nutrients from digestate can have a significant impact on the future of biofertilizer. Moreover, it is more advantageous in terms of ammonium and orthophosphate availability and pH and temperature increases [26] compared to raw materials. Furthermore, little treatment is required for digestate since a large number of pathogens are killed during anaerobic digestion [4].

The objective of this study was to investigate the change in reactor performance and fertilizer values during the anaerobic co-digestion of DM, MBM and CG in a semi-continuous fed experiment. Because the application of digestate to agricultural land is an important process to help fight greenhouse gases emissions by replacing mineral fertilizers [27], the direct application of liquid digestate was investigated. However, due to the overabundance of phosphorus in on-farm agricultural land and the important role of nutrient recovery in waste management, food security and environmental quality [28], a strategy to recover nutrients (nitrogen and phosphorus) and recycle water from digestate was proposed.

2. Materials and methods

2.1. Materials

DM was obtained from the free stall dairy farm located at Obihiro University of Agriculture and Veterinary Medicine, Hokkaido, Japan. The average total solids content (TS), the volatile solids content (VS) and the VS to TS ratio of the DM was 12.50%, 11.00% and 0.88, respectively. MBM was obtained from a rending plant located in Hokkaido, with TS, VS and a VS to TS ratio of 98.46%, 68.47% and 0.70, respectively. Crude glycerol (CG) was obtained from a local biodiesel-company that transforms used cooking oils into biodiesel with TS, VS and a VS to TS ratio of 80.98%, 75.23% and 0.93, respectively.

The inoculum was obtained from an active mesophilic biogas plant treating DM as the sole substrate, with TS and VS of 6.74% and 4.56%, respectively.

2.2. Experimental setup

A laboratory-scale bench experiment was conducted using semi-continuous stirred tank reactors with working volumes of 12 L as schematically described previously [29]. The reactors were automatically and intermittently stirred for 15 min every 2 h at 60 rpm with a mixing paddle. The reactors were fed with 12 L of fresh inoculum, which was acclimatized to the new environment for 5 days at 38 °C prior to the addition of dairy manure. To adjust the hydraulic retention time (HRT) to 30 days, which is the average HRT of the mesophilic biogas plant in Hokkaido, the DM was diluted with water and fed into the reactors with an average organic loading rate (OLR) of 2.76 gVS/L·d. The reactors were fed with DM until there were signs of process stability, which included the stable production of biogas, a methane concentration of more than 50% and a digestate pH of between 7.5 and 8.5, which were