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Anaerobic co-digestion of poultry droppings and briquetted wheat straw at mesophilic and thermophilic conditions: Influence of alkali pretreatment

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ABSTRACT

Anaerobic co-digestion of poultry droppings (PD) and briquetted wheat straw (BWS) with alkali additive in the form of KOH (BWS_{add}) or without any additive (BWS_{raw}) was conducted using continuously stirred tank reactors (CSTRs) under both mesophilic (35 °C) and thermophilic (53 °C) conditions. The aims of the study were to compare 1) co-digestion of PD and BWS versus mono-digestion of PD; 2) co-digestion of PD and BWS with or without additives; and 3) mesophilic and thermophilic anaerobic digestion (AD).

Co-digestion of PD and BWS was superior to mono-digestion of PD in terms of gas production. Co-digestion of PD with BWS_{add} at thermophilic temperatures resulted in a higher methane volumetric yield per kg substrate compared to mesophilic conditions. With and without additive, co-digestion with BWS produced 8% and 11% higher yields at thermophilic conditions than at mesophilic conditions. Co-digestion of PD with BWS_{add} resulted in, respectively, 14% and 27% more methane produced at mesophilic and thermophilic conditions over mono-digestion of PD. When mono-digesting PD, the mesophilic temperature was superior to the thermophilic since methane yield was higher in the mesophilic temperature regime.

1. Introduction

Poultry farming is an up-and-coming industry in Bangladesh with more than 0.1 million households and commercial farms [1] tending 3122 million birds [2], generating 114 million metric ton of raw poultry droppings (PD) annually. Of these droppings, 20% is discarded, 40% is sold at markets after sun-drying for a set time, 30% is used as fertilizer for crops and 10% is used for fish culture [3]. The current application of PD is not sustainable in the long run because of associated environmental problems such as deterioration of soil quality, buildup of phosphorus in the soil [4] and air, soil and water contamination resulting from both chemical (such as ammonia emission to the air) and biological (such as pathogens proliferating in soils and water bodies) pollutants, which can lead to adverse effects on aquatic and human health.

AD of PD is a key technology for producing high-value bioenergy in the form of biogas. However, due to the low C:N ratio of PD (less than 10) [5], it is often necessary to add carbon-rich lignocellulosic co-substrates such as crop residues to raise the C:N ratio and improve methane yield [6]. Wheat is the second-largest grain crop and staple food in Bangladesh. The cropping year 2015–16, produced 2.36 million tons of wheat straw which has the energy potential of 715 million m^3 biogas, equivalent to 16,500 TJ [7]. Lignocellulosic material like wheat straw (WS) is an abundant byproduct in farming and may be interesting as a co-substrate for poultry droppings in order to increase productivity in anaerobic digestion plants. The challenge in co-digestion lies in balancing the C:N ratio of the co-substrate to the feedstock as well as balancing macro and micronutrients, pH, inhibitors/toxic compounds and dry matter content [8]. Anaerobic co-digestion of PD and WS

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potentially provides renewable energy, environmental protection as well as better management of waste disposal [9]. However, the main components of WS is cellulose (between 40 and 50%), followed by hemicelluloses (31–43%) and lignin (6–16%) [10]. This not only means a slow microbial degradation, but its bulk density significantly increases its cost of handling, transportation [11], and storage [12]. Briquetting of WS is a pre-treatment technology where the straw is densely compressed. The reduction in storage, handling and transport costs can justify the associated cost of this process [11]. Briquetting compresses the straw to a density of 1000 kg m^{-3}, preventing a floating layer and easing mixing in the digester to achieve a high biogas yield from straw [13]. Taking into account the energy consumption for briquetting the straw and the energy output from briquetted straw, Xavier et al. [13] found that the briquetting technology could be more advantageous than using fresh wheat straw if the straw has to be transported over longer distances, due to the lower transportation costs.

Similar to briquetting, chemical pre-treatments may be used to promote the hydrolysis of lignocellulosic compounds. Chemical compounds are basically used to modify the structure of specific compounds, mainly by changing the pH (alkali or acids) or by promoting enzymatic hydrolysis [13]. The addition of strong sulfuric acid (H_2SO_4) to lignocellulosic materials has been widely explored and has been shown to effectively solubilize hemicellulose and lignin and to expose the cellulose component to hydrolysis [15]. However, its practical implementation is limited due to technical problems, such as specific enzymatic inhibition caused by the sulfur concentration [16], or other environmental aspects related to wastewater purification and product distillation [17]. Lignin in plant cell walls combines with holocelluloses to form lignin carbohydrate complexes (LCC). These LCCs make the plant cell wall resistant to microbial attack. Therefore, prior to anaerobic digestion, an alkaline pretreatment process that alters the structure and composition of the substrate may be useful to break up the lignocellulosic feedstock [18] and is in fact more effective at solubilizing lignin than acid or hydrothermal processes [19]. Alkaline conditions promote changes in the structure of the lignin, saponification of the ionic bonds between hemicelluloses and lignin, swelling of the fibers and increases in pore size [20].

The gas production and decomposition rates of organic waste are influenced by environmental factors such as temperature, pH, hydraulic retention time (HRT) and substrate concentration. Temperature is an important factor for microbial activity, and previous studies report a relationship between temperature and methanogenesis during anaerobic digestion [21–23]and thus the volume of gas produced [24–27]. In the bibliography, thermophilic conditions (>45 °C) have been reported as being superior to mesophilic conditions (25–40 °C), not only because of a reduction in the pathogen load and odor emission [28,29], but also because of a higher organic matter degradation rate [30,31]. However, Hutnan and Hornak [32] found that an increase in the temperature resulted in a reduction of the biogas yield due to the stronger inhibition of free ammonia (NH_3) with rising temperatures.

To our knowledge, few studies have looked at anaerobic co-digestion of PD with briquetted WS either with a chemical additive [2% (w/w) KOH] or without an additive, at thermophilic and mesophilic conditions. Therefore, the aim of the study was to investigate the influence of pre-treatment (briquetting with or without alkali addition) of WS on methane production when co-digested with PD. In addition, the study compared biogas and methane production and process performance of lab-scale CSTRs operated at a temperature from mesophilic (35 °C) and thermophilic (53 °C) temperature regimes.

2. Materials and methods

2.1. Substrates and inocula

The PDs used both in the batch and continuous experiments were collected from the poultry farm “Spring Source Bio Aps” (8800 Horsens, Denmark). After collecting from the farm, the PDs were kept at −18 °C. Wheat straw was collected from a farm near Viborg (Central Jutland, Denmark) and briquetted using a BP 6500 briquetting machine (CF Nielsen, Denmark). Briquetted wheat straw without additives (BWS_{raw}) and briquetted wheat straw with additives (BWS_{add}) [2% (w/w) KOH] were used as co-substrates and collected from the biogas plant at Research Centre Foulum (Aarhus University, Denmark). The briquetting process used no external binding agent for biomass densification. Pressures applied during the process (compression–decompression cycles) ranged from 150 to 200 MPa above atmospheric pressure, as described by Xavier et al. [14].

Two temperatures, one was from thermophilic temperature regime (53 °C) and another was from mesophilic temperature regime (35 °C) were used in the lab-scale CSTR and batch assay, respectively. Both inocula were obtained from mesophilic and thermophilic reactors of the biogas plant at Research Centre Foulum, mainly co-digested cattle manure with wheat straw and grass which had been running stable for more than a year under the same conditions. The average total solids (TS) and volatile solids (VS) contents of the inoculum were 4.8% and 3.3% (wet basis), respectively. The average pH of the inoculum was 7.7, ammonium nitrogen was 4.55 gL^{-1} and volatile fatty acid (VFA) content was 47.0 mg L^{-1}.

2.2. Ultimate methane yield

Ultimate methane yields of PD, BWS_{raw} and BWS_{add} were determined in batch assays at both mesophilic and thermophilic temperatures. Prior to starting the batch assay, thermophilic and mesophilic inocula were pre-incubated for 21 days in order to deplete the residual biodegradable organic material (degasification) [48]. Three 0.5 L (0.2 L working volume) bottles per substrate were filled at an inocula:substrate ratio of approx. 1:1, determined on a VS basis. The total mass of raw samples of the mixture was calculated on the basis of VS by using equation (1):

$$P_i = \frac{m_i \times C_i}{m_s \times C_s} \tag{1}$$

where, P_i is the VS mass ratio (and the calculations aimed to achieve a fixed P_i equal to 1); m_i is the amount of inoculum (g); C_i is the concentration of VS(%) in the inoculum; m_s is the amount of substrate (g) and C_s is the concentration of VS(%) in the substrate.

In addition, three bottles were filled with inoculum only and used as blanks (control). After filling, each bottle was sealed with a butyl rubber stopper and aluminum crimps, and the headspace was flushed with pure N_2 for 2 min. The bottles were then incubated for 90 days at 35 °C and 53 °C.Periodically, the total volume of biogas produced per bottle was measured. The measurement of biogas volume was done by inserting a needle connected to a tube with inlet to a column filled with acidified water (pH < 2) through the butyl rubber. The produced biogas was measured by water displacement until two pressures (column and headspace in bottles) were equal [33].

The average cumulative biogas production (endogenous biogas production of the inoculum) was subtracted from the biogas production of the experimental bottles at each sampling time. Volume of biomethane was obtained from the corrected methane percent composition of produced biogas. The corrected methane percent