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Synergistic effect from anaerobic co-digestion of sewage sludge and organic wastes

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A B S T R A C T

Anaerobic mono-digestion and co-digestion of primary sludge and two organic wastes (namely food waste or paper pulp reject) were evaluated by biomethane potential assessment and kinetics modelling to elucidate the synergistic effect. The specific methane yields were 159, 652 and 157 mL/g VS added during mono-digestion of primary sludge, food waste and paper pulp reject, respectively. Co-digestion of primary sludge with either food waste or paper pulp reject resulted in much higher specific methane yields of 799 and 368 mL/g VS, respectively. pH and intermediate inhibitions (e.g. volatile fatty acids and ammonium-*N*) were not observed. The synergistic effect was also confirmed by examining the VS and COD removals. COD balance also identified and validated the enhanced specific methane yields from both primary sludge and organic waste (i.e. additional 32 and 19% of COD was converted to biogas during co-digestion of primary sludge with food waste or paper pulp reject, respectively). The apparent first order rate constant derived from kinetics modelling increased from 0.18 to 0.63 d^{-1} during mono-digestion of paper pulp reject and co-digestion of primary sludge with paper pulp reject, which can be attributed to the initial high soluble biodegradable fraction in primary sludge.

1. Introduction

Concern over the disposal of large quantities of organic wastes from domestic, industrial, and agricultural sources together with the need to reduce green-house gas emissions have been a major driver for further development of anaerobic digestion technology (Edwards et al., 2015). Anaerobic digestion has been widely used by wastewater treatment plants (WWTPs) to stabilize sewage sludge prior to land application or disposal and at the same time produce biogas (which is a renewable fuel) to offset some of the energy input to the treatment process (Tyagi and Lo, 2013). During anaerobic treatment, nitrogen and phosphorus are liberated into the liquid phase in the form of ammonia and phosphate (Yilmazel and Demirer, 2013), thus, anaerobic digestion can also be an excellent platform for nutrient recovery (Xie et al., 2013).

A recent and notable trend in the development of anaerobic digestion technology is to co-digest two or more substrates together (Xie et al., 2016). Co-digestion can overcome several inherent problems associated with single substrate digestion such as the lack of micronutrients, imbalanced C/N ratio, and unfavorable (i.e. too high or too low) organic loading rates (Mata-Alvarez et al., 2011). In the context of the water industry, the existing spare capacity of anaerobic digestion infrastructure at wastewater treatment plants allows for anaerobic co-digestion of sewage sludge with organic waste to generate supplementary revenue via gate fees or service charges, whilst producing electricity and heat (Edwards et al., 2015). In addition, co-digestion can also help to defer capital investment for additional waste management facilities (Nghiem et al., 2014). Indeed, rapidly increasing landfill levies worldwide along with the possibility for nutrient recovery present considerable potential driving forces for further adoption of co-digestion (Yong et al., 2015). Although successful co-digestion of sewage sludge and various organic wastes such as food waste (Koch et al., 2016; Ratanatamskul et al., 2015; Tuyet et al., 2016), fat oil and grease (Martínez et al., 2012), crude glycerol (Nghiem et al., 2014; Silvestre et al., 2015), have been reported in many recent studies, several key aspects of the anaerobic co-digestion process remain poorly understood. In particular, little is known about the synergistic effect of co-digestion on anaerobic performance and the associated mechanisms responsible for such effect (Mata-Alvarez et al., 2014).

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Co-digestion can enhance the degradation of each individual substrate (Mata-Alvarez et al., 2011). In other words, co-substrate addition can result in synergistic effects, which result in either a boost in specific methane yield of the individual substrate in the mixture or an increase in biogas production kinetics, differing from the additive effect where an increase in methane production is simply due to a higher mass of available biodegradable organic matter per unit volume from co-substrate addition. There have been some evidence that co-digestion can also result in some antagonistic effects (Silvestre et al., 2014). In some cases, no obvious effects of co-digestion compared to mono-digestion have also been reported (Silvestre et al., 2015). It is widely hypothesized that co-digestion can improve the process performance mainly because of (i) a more balanced C:N ratio and sufficient macro and micro-nutrients (Wang et al., 2012), (ii) a high buffering capacity (Xie et al., 2011), and (iii) and a higher readily biodegradable organic fraction (Astals et al., 2014). These factors attributed to the synergistic effects are associated inherently with co-substrate properties and composition. For example, sludge with a low C/N ratio can be co-digested with waste paper with a high carbon content to achieve an optimum C/N ratio of 20–25 (Yen and Brune, 2007).

The reported synergistic effects vary in the literature (Aichinger et al., 2015; Astals et al., 2014; Pagés-Díaz et al., 2014). In other words, such effects can be reflected as increased methane yields, accelerated biodegradation processes or a combination of both. Pagés-Díaz et al. (2014) investigated optimal mixture composition between cattle slaughterhouse wastes, municipal solid waste, manure and various crops, and assessed the synergistic effect solely by specific methane production rate. Aichinger et al. (2015) interpreted the synergistic effect as an increased hydrolysis rate constant rather than an increased specific biogas yield for a mixture of raw sludge and co-substrates over the specific biogas yield for individual substrates. Similarly, Astals et al. (2014) identified the synergetic effect during anaerobic co-digestion of pure and slaughterhouse carbohydrate, protein, and lipid substrates as an improvement of process kinetics, rather than an increase in ultimate biodegradability. As the rate limiting step in anaerobic co-digestion is the hydrolysis of complex polymeric substances such as extracellular polymeric substances in sewage sludge, it is important to evaluate the impact of synergistic effects during anaerobic co-digestion on both the specific methane yields and the process kinetics.

Diversified approaches have been implemented to analyze the synergistic effects in the previous studies. Yun et al. (2015) defined the synergistic effects as an increased methane yield from waste activated sludge, and analyzed the synergistic effects during anaerobic co-digestion with food waste assuming a full conversion of food waste (1 g COD = 350 mL methane). Ebner et al. (2016) used a co-digestion performance index calculated as the ratio of the bio-methane potential of the co-digestion blend to the weighted average based upon VS content of the individual substrate bio-methane potentials. However, both studies have not quantified the extent of such effect. Aichinger et al. (2015) employed a COD balance approach to quantify the extent of synergistic effects. It is noteworthy that whey was chosen to be the model co-substrate corresponding to a full conversion rate, thus enabling a simplified quantitative analysis of the extent of synergistic effects from raw sludge (Aichinger et al., 2015). Nevertheless, in most of these studies, kinetics modelling has not been applied to further elucidate the impact of co-substrates addition on improving the anaerobic co-digestion process kinetics.

This study aims to systematically elucidate synergistic effects during anaerobic co-digestion of primary sludge with organic wastes by applying a BMP assay based kinetics modelling approach together with COD balance calculations. The specific objectives of this study are: (i) to assess the process stability, (ii) to quantify synergistic or antagonistic effects of co-digesting primary sludge and organic waste on specific methane yields and VS removals based on COD balance, and (iii) to examine whether the reaction kinetics can be associated with the synergistic effect.

2. Materials and methods

2.1. Primary sludge and co-substrates

Digested sludge from the Wollongong wastewater treatment plant was used as the inoculum. Raw primary sludge was also from the same plant. Primary sludge was stored at 4 °C for less than three days prior to BMP evaluation. The organic co-substrates include food waste and paper pulp reject (denoted as FW and PPR respectively). Dog food from Optimum (Lamb and Rice) composing mainly of carbohydrate, protein, and lipids was used to represent food waste. Paper pulp reject was primarily cellulose in powder form from a paper mill in New South Wales, Australia. Key properties of inoculum, sludge and co-substrates was shown in Table 1.

2.2. Biochemical methane potential assay

2.2.1. Experimental equipment

BMP assay was performed according to the protocol described by Angelidaki et al. (2009). The BMP system previously used by Nghiem et al. (2014) was modified for this study. The BMP system included an array of 12 fermentation glass reactors (Wiltronics Research Pty Ltd) and a gas collection gallery. The glass reactor consisted of a rubber stopper, a water-filled S-shaped airlock with a valve, and a syringe for collecting liquid samples. The fermentation glass reactor (1 L in volume) was submerged in a water bath (Model SWB20D, Ratek Instrument Pty Ltd) to maintain a constant temperature of 35.0 ± 0.1 °C. The gas collector was an inverted plastic measuring cylinder (1 L), which was initially filled with and partially submerged in a NaOH solution (1 M).

2.2.2. Experimental protocol

Prior to the BMP experiment, all fermentation reactors were flushed with pure N_2 and subsequently filled with 750 mL of organic substrates and inoculum (Table 2). Co-substrate and primary sludge were added to the reactor on a 1:1 VS basis. Inoculum and tap water were then added to obtain 750 mL of substrate volume in total. Reactor 1 and 2 served as controls with the addition of inoculum and tap water to obtain the residual biogas production from the inoculum alone. After loading with the substrate, the reactors were flushed with N_2 for 5 min and immediately sealed with the rubber stopper. The reactors were then placed into the water bath, and the valve was opened to allow biogas to enter the gas collection gallery. All reactors were manually mixed once a day. Since the inoculum can provide all necessary micronutrients, no supplemental nutrients were added to the mixture. All BMP experiments were conducted in duplicate.

2.3. Analytical methods

Liquid sample was taken from each reactor once every 3–4 days using a 5-mL syringe. After immediate pH measurement, the sample was then centrifuged at 3900 rpm for 10 min and then at 18,000 rpm for 20 min at 4 °C. The supernatant was obtained for soluble COD measurement using a Hach DBR200 COD Reactor and a Hach DR/2000 spectrophotometer (program number 430 COD LR) according to the US-EPA Standard Method 5220. For analysis of volatile fatty acids (VFAs) and ammonia-*N*, the supernatants were further filtered through 0.45 μm cellulose filter paper. TS, VS, alkalinity and VFAs were measured according to the guidelines