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Optimization of biological hydrogen production for anaerobic co-digestion of food waste and wastewater biosolids

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HIGHLIGHTS

- Anaerobic co-digestion of 21 mixtures of FW, PS, and WAS were evaluated.
- The maximum hydrogen yields of FW + PS and FW + WAS were achieved at ratios of 75:25.
- The maximum hydrogen yield FW + PS + WAS was achieved at ratio of 80:15:5.
- Optimum COD/N of FW + PS, FW + WAS, and FW + PS + WAS were 26, 31 and 30, respectively.
- A synergistic effect of co-digestion was observed and quantified.

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ABSTRACT

Batch anaerobic co-digestion studies were conducted using 21 mixtures (M1–M21) of food waste (FW), primary sludge (PS), and waste activated sludge (WAS) at 37 °C and an initial pH of 5.5 ± 0.2. The results showed that co-digestion of FW and sludges had a positive impact on the hydrogen production. The maximum hydrogen yields by co-digestion of FW + PS, FW + WAS, and FW + PS + WAS were achieved at volumetric ratios of 75:25, 75:25, and 80:15:5, respectively, with corresponding optimal COD/N mass ratios of 26, 31 and 30, respectively. Furthermore, the synergistic effect of co-digestion was proven and quantified: the measured hydrogen productions were higher than the sums of the hydrogen productions calculated from each fraction, and the highest percentage increase above the calculated value of 101%, was achieved in the FW + PS + WAS mixture (80:15:5).

1. Introduction

Minimal or zero use of hydrocarbons, with only water as a combustion production and a high energy yield of 122 kJ/g (2.75 times greater than that of hydrocarbon fuel) render hydrogen as one of the promising sustainable energy resources (Han and Shin, 2004). Hydrogen production addresses three of today's major energy problems: soaring energy demand, environmental pollution, and fossil fuel dependence (Momirlan and Veziroğlu, 1999). Due to high electricity requirement by conventional physico-chemical hydrogen production methods (such as water electrolysis, chemical cracking of hydrocarbons, etc.) biological hydrogen production has recently attracted more attention (Hawkes et al., 2002). Photo-fermentation and dark fermentation are the two main types of biological hydrogen production (Antonopoulou et al., 2010). Lower operational cost, greater hydrogen production rate, wider range of organic substances and simplicity rationalize the superiority of dark fermentation over photo-fermentation (Xie et al., 2012; Hallenbeck and Benemann, 2002).

Since carbohydrates are the preferred substrates for dark fermentative hydrogen-producing bacteria such as *Clostridium* species, food waste (FW) with its high content of organic matter and carbohydrates, and its easily hydrolysable nature has a high hydrogen production potential (Kim et al., 2004). Moreover, FW, as an important municipal and agricultural waste, can be an economical source for fermentative hydrogen production (Zhu et al., 2008). FW

Abbreviations: C/N, carbon to nitrogen ratio; DOPF, dufferin organics processing facility; FA, free ammonia; FW, food waste; PS, primary sludge; SCOD, soluble chemical oxygen demand; SSO, source separated organics; S^0/X^0, initial substrate-to-biomass ratio; TA, total ammonia; TCOD, total chemical oxygen demand; TN, total nitrogen; TP, total phosphorous; TSS, total suspended solids; TVFAs, total volatile fatty acids; VSS, volatile suspended solids; VS/TS, volatile solids to total solids ratio; WAS, waste activated sludge.

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includes uneaten food and food preparation leftovers from residences, commercial establishments such as restaurants, institutions like school cafeterias, and industrial sources like factory lunch-rooms (Zhang et al., 2007). Generally, they consist mainly of starch, protein, and fat, with a small amount of cellulose and hemi-cellulose which are possible sources for bioenergy production (Yuan et al., 2006). However, FWs can be highly variable depending on their resources. Some studies on characteristics of FWs indicated their variability and reported: moisture contents of 74–90%, volatile solids to total solids ratios (VS/TS) of 80–97%, and carbon to nitrogen ratios (C/N) of 14.7–36.4 (Zhang et al., 2007).

However, FW may be lacking in nitrogen which is an essential nutrient for hydrogen producers (Kim et al., 2004). Therefore, the concept of co-digestion of FW and sewage sludges (primary sludge and waste activated sludge) has been investigated to improve biohydrogen production, since the addition of sludges to FW supplied a more balanced carbon to nitrogen (C/N) ratio (Kim et al., 2004). The C/N ratio is one of the most significant parameters for co-digestion of FW and sludges process, which not only balances the nutrients, but also enhances the bacterial productivity of hydrogen and preclude ammonia inhibition (Lin and Lay, 2004). The main products of the biodegradation of proteins in anaerobic conditions are ammonia and various amino acid compounds, but digestion can be inhibited by high free ammonia concentrations in the range of above 200 mg/L (Liu and Sung, 2002). Salerno et al. (2006) reported the ammonia inhibition of hydrogen production from glucose in batch tests at 30 °C. Even though only biohydrogen production rate was highly influenced by ammonia (defined as the sum of NH_3 and NH_4^+ species) concentrations above 2 g N/L in batch tests, in continuous flow tests, both hydrogen production rates and yields were inhibited by high ammonia concentrations. When the ammonia concentration was 2 g N/L, the maximum biohydrogen production were 56 mL/h (at pH of 6.2) and 49 mL/h (at pH of 5.2), but when the ammonia concentration was 10 g N/L the maximum biohydrogen production decreased to 16 mL/h (at pH of 6.2) and 7 mL/h (at pH of 5.2). Furthermore, a continuous flow reactor operated at ammonia concentrations of 0.8–7.8 g N/L, achieved an overall yield of 1.1–1.9 mol H_2/mol glucose, with hydrogen production failing at ammonia liquid phase concentrations higher than 1.6 g N/L. Furthermore, free ammonia (FA) has been suggested as the main cause of inhibition since it is freely membrane-permeable (De Baere et al., 1984). Thus, the C/N ratio should be strictly controlled effective hydrogen production. Previously, Elbesgbishy and Nakhla (2012) demonstrated that the proper C/N ratio for anaerobic methanogenic co-digestion of bovine serum albumin and starch was 12.8:1, and Chen et al., 2008 who reviewed the literature reported that the general optimum value for the stable performance of anaerobic digestion of solids waste was 20:1. However, the desired C/N ratio for efficient hydrogen formation by co-digestion of rice straw and sewage sludge was 25:1 [Kim et al., 2012]. Sreela-or et al. (2011) observed that the optimum hydrogen production from the co-digestion of food waste and sludge in batch fermentation by anaerobic mixed cultures, occurred at a C/N ratio of 33:1. According to Kim et al. (2004) the optimal C/N ratio in batch fermentation at 35 °C was 1.66 g carbohydrate-COD/g protein-COD achieved by the mixture of 87:13 (food waste: primary and secondary sludges).

As apparent from the literature surveyed above, only a handful studies explored co-digestion of FW and wastewater sludges for biohydrogen production, i.e. Kim et al. (2004), Zhu et al. (2008), Sreela-or et al. (2011), Tawfik and El-Qulish (2012), etc. The aforementioned studies not only did not define explicitly the optimum C/N ratio, but also used local food waste from cafeterias (Zhu et al., 2008; Sreela-or et al. (2011)), restaurants (Tawfik and El-Qulish, 2012), dining halls (Kim et al., 2004; Li et al., 2008), that are not representative of overall food waste received at source separated organics (SSO) processing facilities. As alluded to above, FW is a very heterogeneous waste with widely different characteristics, and thus from a practical perspective in order to design centralized co-digestion processes, the organic fraction of municipal solid wastes collected from the various sources is definitely more representative than individual food waste sources. Furthermore, the literature studies on biohydrogen from co-digestion have not focussed on delineating the synergistic effects of co-digestion due to scope limitations and merely focussed on hydrogen production per unit organic matter (COD or VS) irrespective of the source of the organic matter in the mixture. Thus, the primary objectives of this study were to investigate biohydrogen production from FW, primary sludge (PS) and/or waste activated sludge (WAS) in a wide range of mixtures, delineate the optimum COD/N ratios, and quantify the synergistic effect of co-digestion using representative food waste samples.

2. Methods

2.1. Substrates and seed

Three substrates were used in this study: food waste (FW) i.e. organic fraction of municipal solid wastes, primary sludge (PS) and waste activated sludge (WAS). The food waste was obtained from the Dufferin Organics Processing Facility (DOPF) in Toronto, Ontario, Canada. The city of Toronto's DOPF receives approximately 25,000 metric tons/year of source separated organics (SSO) material from Toronto's Green Bin and the commercial Yellow Bag collection programs. After separation of plastic and inert, the DOPF is to separate the film plastic bin finer and organic material is process by anaerobic digestion (Van Opstal, 2006). The PS and WAS samples for this study were collected from the Adelaide Pollution Control Plant located in London, Ontario, Canada.

Anaerobic digested sludge was collected from the primary anaerobic digester at St. Mary's wastewater treatment plant (St. Mary's, Ontario) and used as seed sludge for all batches used in this study. The characteristics of the three substrates and seed are presented in Table 1.

2.2. Batch anaerobic digestion

Batch anaerobic studies were conducted using FW, PS and/or WAS as substrates. Twenty-one different substrate mixtures of FW, PS and/or WAS, M1–M21, were used. Table 2 shows the substrate compositions of the 21 mixtures by volume. The specific volumes were derived from the following procedures. Based on previous experience (Nasr et al., 2011), an initial substrate-to-biomass (S^0/X^0) ratio of 2 g COD/g VSS was selected for all batches used in this biohydrogen experiment, with a total liquid of substrate and seed of 200 mL,

$$S^0/X^0 = \frac{\text{g TCOD}_{\text{substrate}}}{\text{g VSS}_{\text{seed}}} = \frac{V_{\text{sub}} \times \text{TCOD}_{\text{substrate}}}{V_{\text{seed}} \times \text{VSS}_{\text{seed}}} = 2 \quad (1)$$

Subsequently, the volumes of FW, PS and WAS were calculated based on the ratios of substrates, noting that the TCOD of the mixture used in Eq. (1) was calculated based on the TCOD of FW, PS and WAS and the mixing ratios. In addition, seed sludge required pre-treatment to inhibit hydrogen-consuming bacteria under anaerobic condition. The purpose of seed pre-treatment was to suppress hydrogen-consuming bacterial activity as much as possible, while preserving the activity of the hydrogen-producing bacteria at the same time to harness hydrogen production (Cai et al., 2004). Baghchehsaraee et al. indicated that the amount of hydrogen produced by heat-pretreated inocula was 7 times more than