Optimization of anaerobic hydrogen and methane production from dairy processing waste using a two-stage digestion in induced bed reactors (IBR)

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Abstract

This study investigated the effects of pH, temperature and hydraulic retention time (HRT) and organic loading rate (OLR) on hydrogen production from dairy processing waste (DPW) in semi-continuous 60 L pilot induced bed reactors (IBR). Results show pH played a key role on hydrogen production and the optimal pH range was in 4.8-5.5. Digestion under thermophilic temperatures (60 °C) had advantages of gaining higher hydrogen yield and suppressing the growth of methanogens. The optimal OLR was 32.9 g-COD/l-d at HRT of 3 days. Under optimal conditions highest hydrogen yield was 160.7 ml/g-COD_{removed} with 44.6% COD removal. Two-stage digestions demonstrated more energy gain from methane production and further COD removal. The overall gas production in two-stage digestion was 71.7 ml hydrogen and 61.0 ml methane per gram DPW COD. The overall COD removal under optimal conditions was 88.2%.

Keywords:

Hydrogen production, Dairy processing waste (DPW), Induced bed reactor, Two-stage digestion

1. Introduction

Hydrogen is considered an alternative fuel of great potential. It is environmentally friendly because only water is produced when it is combusted, and was identified as a clean energy carrier for the future at the first World Hydrogen Conference [1]. Hydrogen has an energy density of 143 MJ/kg,

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which is 2.6 times higher than methane and 3.3 times higher than gasoline. Hydrogen has great potential to reduce the use of fossil fuels. However, in industry, the majority of hydrogen is produced from fossil-fuel sources such as: natural gas, oil, and coal [2].

Dairy processing waste (DPW) is the waste produced from manufacturing dairy products: cheese, yogurt, ice cream, milk, butter, etc. DPW is high in chemical oxygen demand (COD) due to its lactose, fat and protein content, and therefore needs to be appropriately treated. The discharge of excess amounts of DPW, such as cheese whey, onto land can damage the chemical and physical structure of soil, pollute groundwater and may also affect air quality [3, 4]. Now there are more and more whey protein concentrate and isolate products [5], which has reduced DPW quantities. However, finding a novel, cost-effective disposal or utilization technology for waste has been an important issue for the dairy industry because of:

- 1) still high lactose content in DPW;
- 2) high investment cost in whey protein processing equipment;
- 3) increased volume of dairy processing byproducts;
- 4) increasingly strict legislative requirements.

Anaerobic digestion is a potential technology for both hydrogen production and food waste management. Anaerobic digesters can produce energy from inexpensive and renewable energy sources such as food processing waste. Recent research proved that certain strains of bacteria (e.g., bacteria from the genus *Clostridium*) are particularly effective at producing hydrogen as a by-product during anaerobic digestion of organic waste material [6]. Although various studies have been done on producing hydrogen with anaerobic digestion, there are still several obstacles that must be overcome before applying this technology economically at an industrial level. Induced bed reactors (IBR) are designed specifically for anaerobic digestion[7], and IBR has the ability of handling short HRT digestion of many organic wastes that may contain high un-dissolved solids [8, 9]. This may make it a very good digester for hydrogen production because studies show low HRT is typically required for hydrogen production[10, 11] .

Recent studies have shown production of hydrogen and methane anaerobically from wastes organics in two-stage systems; for example, [12, 13] show hydrogen and methane can be produced using cheese whey. Other materials such as cassava wastewater[14] and sweet sorghum[15] can also be used to produce hydrogen and methane. In those studies UASB or CSTR digesters were used. However, no research has been reported using the substrate DPW. In the dairy industry large amounts of DPW, which has high content of fat, protein and lactose and may contain cleaning chemicals, is produced. And no published anaerobic hydrogen production study is based on IBR digester. In this research, single-stage digestions were performed first in 60 L pilot IBRs to explore the optimal conditions of pH, temperature and HRT/OLR for hydrogen production from DPW. Later under optimal hydrogen production conditions, a second unit IBR was added for testing the performance of methane production from the effluent of the hydrogen reactor.

2. Material and Methods

2.1. Substrate and seed

DPW was provided by Aggie Creamery (Utah State University, Logan). DPW is a mix of dairy production wastes. About 40-50% (by volume) of DPW is cheddar cheese whey; 50-55% of DPW is the waste from the production of ice cream, yogurt and milk; and about 5% is rinsing wastewater. DPW was stored at 4 °C before use. Its characteristics are presented in Table 1. The inoculum was from the sludge of an anaerobic digester that was used for biogas production from algae in Logan Wastewater Treatment Facility (Logan, UT).

2.2. Experiment set-up

Two 60 L IBRs were constructed and installed. To enrich hydrogen-producing bacteria and inactivate methanogens, a 25 L inoculum was mixed with 20-25 L DPW in a 60 L IBR to reach the pH of 5.0-5.5. Then the mixture (inoculum sludge and DPW) was heat-treated (65 °C) overnight.

Single-stage digestion: two duplicate IBRs were used for optimization of hydrogen production from DPW (Figure 1). Three different parameters: temperature, pH, and HRT were examined. One IBR was set at temperature of 40 °C and another was set at 60 °C (due to the heat loss during transfer, liquid temperatures in the central digester areas were 37-38 °C and 55-58 °C, respectively). Three pH ranges (4.0-4.5, 4.8-5.3 and 5.5-6.0) and three HRT values (1, 3 and 5 days) were tested in a 3 factor full factorial design. Each digestion run lasted at least two weeks to obtain steady-state at ≥ 4 times the HRT.

The two-stage digestion setup is illustrated in Figure 1. The two-stage system had a 60 L hydrogen IBR and a 60 L methane IBR. The effluent of the hydrogen IBR was used as influent for the methane IBR. The hydrogen IBR was operated under the optimal pH/HRT/temperature conditions found in the single-stage digestion preliminary trials. The second stage methane digester was operated at pH of 6.8-7.5 and temperature of 40 °C. The inoculum for the methane IBR was from the same sludge source (Logan wastewater treatment facility), but without heat treatment.

2.3. IBR operation

Temperature was monitored and controlled with Cole-Parmer 16B-33 controllers (Vernon Hills, IL) and heating cable (Mor Electric Heating Assoc., Comstock Park, MI). pH could be controlled with controllers (Model 350, Cole-Parmer, Vernon Hills, IL) and associated peristaltic pumps (Cole-Parmer 7553-80) to keep pH within ± 0.1 of the set point in the digesters by adding sodium hydroxide solution (1 mole/L) in the hydrogen IBR. No chemical was needed for pH adjustment in the methane IBR. Feed rate was automated with timers (Model R-94400-62, Cole Parmer, Vernon Hills, IL) and electrically-controlled valves (Model P251SS-120-A, Ingersoll Rand, Dublin, Ireland) that regulated air supply to a diaphragm pump (ARO 1", Ingersoll Rand, Dublin Ireland). The IBRs were fed every four hours.

2.4. Analytical methods

Total solids (TS) and volatile solids (VS) were measured by standard methods (APHA, 1998). Total chemical oxygen demand (COD), total organic carbon (TOC), total nitrogen (TN) and total ammonia ($\text{NH}_4\text{-N}$) were analyzed using Hach test kits (Hach DR/870). Biohydrogen and biogas production were measured by mass flow meters (Model 822-L, Sierra, Monterey, CA). Data for gas flow rate were saved every five minutes using a datalogger (CR 1000, Campbell Scientific, Logan, UT). Biogas and biohydrogen composition were analyzed in an Agilent 6890 GC using an RT-M sieve 5A Plot capillary column (Restek) (Agilent, Santa Clara, CA). The statistics analyses were performed in R software (version 3.0.3) [16].

3. Results and discussion

3.1. Single-stage digestion

Three parameters temperature, pH, and HRT were examined for optimization of hydrogen production from DPW. Values of temperature, pH, HRT and OLR in each experimental run are listed in Table 2. The results of COD removal, hydrogen yield, hydrogen content, and methane content in nine experimental runs are shown in Figure 2. The statistical significance of these three parameters on COD removal, hydrogen yields, hydrogen content, and methane content was analyzed by analysis of variance (ANOVA).

3.1.1. Effects of pH on hydrogen production

Keeping pH in certain range is crucial during semi-continuous or continuous digestion operation. pH should be in the range 6.8-7.5 for single stage methane anaerobic digestion [17]. Three pH ranges (4.0-4.5, 4.8-5.5 and 5.6-6.0) were tested to examine effect on hydrogen production from DPW. As listed in Table 2, experiments I, II and III were run in the pH range of 4.0-4.5; experiments IV, V and VI were run in the pH range of 4.8-5.5; and experiment VII, VIII and IX were run in the pH range 5.6-6.0. As shown in Figure 2, digestions in the pH range 4.8-5.5 had higher COD removal/hydrogen yield/hydrogen content and lower methane content than the digestions in the other two pH ranges. The highest hydrogen yield-160.7 ml H₂/g-COD_{removed}, highest COD removal-44.6%, and highest hydrogen content-50.2% and lowest methane content-2.8% were all obtained in the 4.8-5.5 pH range. Statistical significance results show pH had significant impacts on COD removal, hydrogen yield, hydrogen content and methane content (ANOVA, $p < 0.05$). Such results were expected because the H⁺ in the extracellular environment selects the bacteria that can survive at this pH range, and at the same time suppresses or kills other organisms that cannot grow [18, 19]. Different pH ranges may result in different pathways during the complex digestion process. Although methanogens were killed or inactivated during seed preparation (see Material and Methods), in the pH range 5.6-6.0 some methanogens eventually grew in the later period of our semi-continuous digestions. That might be why the methane content was higher than for pH ranges 4.0-4.5 and 4.8-5.5 (Figure 2). Growing methanogens may have rapidly consumed the produced hydrogen, which led to a low hydrogen yield. At pH 4.0-4.5 methane content was relatively low, which suggests a good suppression of methanogens. However, low COD removal and hydrogen yield may suggest that this pH range also suppresses the growth of hydrogen-producing bacteria. 4.8-5.5 was the optimal pH range for not only the growth of hydrogen producing bacteria but also the suppression of methanogens. Similar results were obtained by other studies using different substrates [20-23]. In order to increase the pH sodium hydroxide was used, which is expensive for applying to full-scale digestion. Cheap pH buffer addition should be considered and investigated in future research.

3.1.2. Effects of HRT/OLR on hydrogen production

Organic concentration of DPW was 98.7 g-COD/l. When HRTs were kept at 1, 3 and 5 days, the OLR rates were 98.7 g-COD/l-d, 32.9 g-COD/l-d and 19.74 g-COD/l-d, respectively. As listed in Table 2, experiments I, IV and VII were run with 1 day HRT (98.7 g-COD/l-d); experiments II, V and VIII were run with 3 days HRT (32.9 g-COD/l-d), and experiments III, VI and IX were run with 5 days HRT (19.74 g-COD/l-d). Statistical analyses showed HRT/OLR had significant impacts on COD removal and hydrogen yield (ANOVA, $p < 0.05$), but not on hydrogen content and methane content

(ANOVA, $p > 0.05$). As shown in Figure 2, under the optimal pH range 4.8-5.5, when HRT increased from 1 to 3 days (OLR decreased from 98.7 to 32.9 g-COD/l-d) the hydrogen yield increased from 111.4 to 160.7 ml H₂/g-COD_{removed} at 60 °C; when HRT increased from 3 to 5 days (OLR decreased from 32.9 to 19.74 g-COD/l-d) the hydrogen yield decreased from 160.7 to 131.5 ml H₂/g-COD_{removed} at 60 °C. Accordingly, the highest COD removal – 44.6% was obtained in 3 days HRT compared to 40.2 % in 1 day HRT and 42.6% in 5 days HRT. These results suggest that too high or too low HRT/OLR is not optimal for hydrogen production.

Different substrates may affect the optimal HRT/OLR because of their characteristics. Here, DPW has high organic content (mainly lactose) and very low non-biodegradable solids. When using another substrate that has relatively low organic content, the optimal HRT/OLR may be different [18, 24-26]. Other factors that might be considered are feeding type: batch, continuous or semi-continuous operation. In our study, DPW was pumped every 4 hours. The optimal HRT/OLR might be different due to less impact to sludge bed when fed continuously.

3.1.3. Effects of temperature on hydrogen production

Each experimental run was performed under both mesophilic 40 °C and thermophilic temperatures 60 °C. Statistics analyses show temperature had significant impact in hydrogen yield, COD removal and methane content ($p < 0.05$), but not in hydrogen content. As shown in Figure 2, hydrogen yields were higher at 60 °C than at 40 °C except experiment I (no significant difference in I). The largest difference was obtained in experiment VI, where 131.5 ml H₂/g-COD_{removed} at 60 °C versus 116.5 ml H₂/g-COD_{removed} at 40 °C. Also in experiment VI, COD removal was 8% higher at 60 °C than at 40 °C. These results were expected because increasing the temperature typically can enhance the activity of the enzymes until the optimal temperature is reached [27]. Another advantage of thermophilic digestion is increased solubility of some polymeric substrates. Thermophilic temperature digestion is suitable for some biomass containing substances that are difficult to hydrolyze, e.g., lignocelluloses [28]. Moreover, the methane content was lower at 60 °C than at 40 °C (Figure 2), especially in the pH range 5.6-6.0. This result indicates that 60 °C had a better suppression of methanogens than 40 °C. Combined with the previous pH results, it is concluded that pH and temperature are two important factors that keep methane content low during hydrogen production. In the pH range 4.8-5.5 and 3 days HRT, our results showed 40 °C digestion had low methane content and relatively high hydrogen yield and COD removal as well. Thus, 40 °C is also feasible for hydrogen production from DPW when the digestions are operated under the optimal pH range and HRT/OLR.

3.2 Two-stage digestion

3.2.1. Methane production performance

In single-stage hydrogen production the highest COD removal was 44.6 %. There is still high COD in the effluent of hydrogen production. Further treatment is necessary before being discharged. Two-stage digestion was performed to produce both hydrogen and methane. The hydrogen IBR was operated under optimal conditions (3 days HRT/32.9 g/l-d OLR/pH of 4.8-5.5/60 °C) that were found in previous single-stage digestion. The effluent of the hydrogen production was used as influent for methane production (Figure 1). Table 3 lists the results of methane production in the second stage. Four different HRTs (8, 12, 15 and 20 days) were tested. COD removals in the four different HRTs were all above 50%. With the increase in HRT the COD removal increased. Over 70% COD removal was achieved when HRT reached 15 days or higher. pH inside the IBR were all 6.8-7.5, which was the optimal range for methane production. No chemical was needed for controlling pH in the methane IBR. Two-stage digestion had an advantage because chemical or buffer is usually

required to increase pH when digesting DPW in single-stage digestion[29]. The methane yields were 168.8-178.1 ml CH₄ ml/g-COD_{removed}. The highest methane yield was found with HRT 15 of days. The methane content was in the range of 60-65%.

3.2.2. Overall performance

The overall performance of two-stage digestion was evaluated. Table 4 summaries the two-stage digestion under the optimal condition for hydrogen production and 15 days HRT for methane production. COD removal of 88.2% was reached in overall two-stage digestion. The effluent COD was as low as 11.7 g/l compared to the original DPW- 98.7g/l. Furthermore, after thermophilic treatment in the hydrogen IBR the effluent will have less pathogens [30]. It is safer to reuse or dispose the effluent. It should be noted that the methane IBR's operation is very flexible. Many HRTs/OLRs can be set without affecting pH inside the digester (Table 3). Higher HRT in the methane IBR means more complete digestion. For getting maximal energy and COD removal a larger volume methane IBR size compared to the hydrogen IBR is recommended in order to make a correspondingly higher HRT. As listed in Table 4 one gram COD of DPW can produce 71.7 ml H₂ and 61.0 ml CH₄. Compared to hydrogen single-stage digestion, 238.9 kJ more energy in heating value was produced in two-stage digestion of one gram DPW COD. Thus, it can be concluded for hydrogen production that using two-stage anaerobic process provides higher energy than using a single-stage anaerobic digestion.

Table 5 compares this study with some other previous research. It should be noticed that among all the results listed in Table 5 [13, 14, 31], our 60 L pilot-scale research had much larger digester size. Thus, our studies could be closer to large-scale digestion. Compared to other cheese whey two-stage digestions, this research had significantly higher hydrogen yield than that of two-phase mesophilic UASB process at an organic loading rate of 47.4 g COD/l-d (160.7 ml-H₂/g-COD_{removed} versus 41 ml-H₂/g-COD_{removed}) [31]. The hydrogen production rate from this study was lower than that of mesophilic CSTR process at an organic loading rate of 182 g COD/l-d; because the CSTR hydrogen process had much higher OLR (182 g COD/l-d versus 32.8 g COD/l-d) and much lower HRT (0.25 d versus 3 d) [13]. Within the same thermophilic hydrogen two-stage digestion, our results were very similar to the two-stage cassava wastewater digestion in terms of hydrogen yield, methane yield and overall COD removal [14].

4. Conclusions

In this study, optimization of anaerobic hydrogen production from DPW was explored in semi-continuous pilot-scale (60 L) IBRs. We found the optimal conditions for hydrogen production from DPW were: HRT 3 days / OLR 32.9 g-COD/l-d, pH range of 4.8-5.5, and 60 °C. Under these conditions, the highest hydrogen yield was 160.7 ml/g-COD_{removed}, highest COD removal was 44.6% and highest hydrogen content 50.2% was achieved. Two-stage digestions were tested later for further energy extraction and COD removal. Results show two-stage production of hydrogen and methane can greatly increase the amount of energy harvested and will increase COD removal. With an HRT of 15 days in the methane IBR, methane yield was 178.1 ml methane per gram COD_{removed} and COD removal was 73.1%. The overall gas production in two-stage digestion was 71.7 ml H₂ and 61.0 ml CH₄ per gram COD_{loaded}. And the overall COD removal was as high as 88.2%. This study demonstrated that the production of both hydrogen and methane can be efficiently coupled in a two-stage IBR digestion system. The pilot-scale research here provides the data and design requirements for full-scale application.

Acknowledgements

The authors would like to acknowledge the financial support of the Utah Agricultural Experiment Station (Logan, Utah) and the USDA. The authors would also like to thank Aggie Creamery at Utah State University for providing dairy processing waste, Logan Wastewater Treatment Facility for providing the seed sludge and Carl Hansen's help in installing and operating the IBRs.

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List of tables

Table 1- Characteristics of dairy processing waste (DPW)

Dairy Processing Waste (DPW)		
pH		4.5±0.6
Total COD (g/L)		98.7±4.0
Soluble COD (g/L)		75.6±2.6
Total Solids (TS, g/L)		61.1±4.8
Volatile Solids (VS, g/L)		55.3±3.7
Total Organic Carbon (TOC, g/L)		24.8 ± 3.3
Total nitrogen (g/L)		4.06±1.21
NH ₃ -N(g/L)		2.30±0.81

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Table 2-Values of temperature, pH, HRT and OLR in each experiment run

Experiment run number	Temperature (°C)	pH	HRT (days)	OLR (g-COD/l-d)
I	40 or 60	4.0-4.5	1	98.7
II	40 or 60	4.0-4.5	3	32.9
III	40 or 60	4.0-4.5	5	19.74
IV	40 or 60	4.8-5.3	1	98.7
V	40 or 60	4.8-5.3	3	32.9
VI	40 or 60	4.8-5.3	5	19.74
VII	40 or 60	5.5-6.0	1	98.7
VIII	40 or 60	5.5-6.0	3	32.9
IX	40 or 60	5.5-6.0	5	19.74

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Table 3-Methane production performance in two-stage digestion

HRT (days)	OLR (g/l-d)	Influent pH	COD Removal (%)	pH inside digester	Methane Yield (ml/g-COD _{removed})	Methane content (%)
8	7.0	5.7±0.2	53.4±0.3	7.0±0.2	168.8±3.2	61.3±0.4
12	5.6	5.7±0.2	61.2±0.8	7.2±0.3	170.4±1.8	62.5±0.3
15	3.7	5.7±0.2	73.1±1.2	7.2±0.2	178.1±2.9	62.7±0.5
20	2.8	5.7±0.2	75.7±0.6	7.3±0.2	145.2±3.2	64.7±1.1

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Table 4-Overall performance of two-stage digestion

	Overall two-stage IBR digestion
Hydrogen production unit	
optimal HRT(days)	3
OLR(g-COD/l-d)	32.9
optimal pH	4.8-5.5
Temperature (°C)	60
hydrogen yield (ml-H ₂ /g-COD _{removed})	160.7
hydrogen production rate(ml-H ₂ /l-d)	2358.3
COD removal (%)	44.6
Methane production unit	
methane yield (ml-CH ₄ /g-COD _{removed})*	178.1
methane production rate(ml-CH ₄ /l-d)	483.3
COD removal (%)*	73.1
Overall gas production (ml-H ₂ :ml-CH ₄ /COD _{loaded})*	71.7:61.0
Overall COD removal (%)*	88.2

351 *: Calculation based on 15 days HRT in the methane IBR.

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Table 5-Comparison of two-stage digestion to some other studies

	Two-stage IBRs (present study)	Two-stage CSTR+UASB[13]	Two-stage UASBs[31]	Two-stage UASBs[14]
Substrate	DPW	Cheese whey powder	Cheese Whey	Cassava wastewater
Temperature (°C)	60	37	35	55
HRT(days)	3	0.25	1	-
OLR(g-COD/l-d)	32.9	182	47.4	12
Hydrogen production unit				
Digester size (L)	60	2(CSTR)	3	4
hydrogen yield (ml-H ₂ /g-COD _{removed})	160.7	-	41	169
hydrogen production rate(ml-H ₂ /l-d)	2358.3	25000	2510	-
COD removal (%)	44.6	-		35
Methane production unit				
Digester size (L)	60	0.79(UASB)	15	24
methane yield (ml-CH ₄ /g-COD _{removed}) *	178.1	210	-	164.8
methane production rate(ml-CH ₄ /l-d)	483.3	-	-	-
COD removal (%) *	73.1			72
Overall gas production (ml-H ₂ :ml-CH ₄ /COD loaded)*	71.7:61.0	-	-	-
Overall COD removal (%) *	88.2	82	94	86.4

355 *: Calculation based on 15 days HRT in the methane IBR.

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List of figures

Figure 1–Schematic of single-stage and two-stage induced bed reactor (IBR) digestion. (A) single-stage IBR digestion. (B) two-stage IBR digestion.

Figure 2—Results of (A) COD removals, (B) hydrogen yields, (C) hydrogen content and (D) methane content in nine experiment runs. Error bar represents standard deviation.