



Fredericton, Canada

June 13 – June 16, 2018/ *Juin 13 – Juin 16, 2018*

## **VOLATILE FATTY ACID PRODUCTION FROM POTATO WASTE USING THERMAL HYDROLYSIS PROCESS DURING MESOPHILIC ANAEROBIC DIGESTION**

Bhargav, Mohit<sup>1,2</sup>, and Singh, Kripa<sup>1</sup>

1 University of New Brunswick, Canada

2 mohit.bhargav@unb.ca

**Abstract:** Approximately 20,000 hectares of potatoes are cultivated every year in New Brunswick of which 25% is diverted towards the fresh market, 19% towards seeding and the remaining 56% is destined for industrial processes to manufacture several potato products which in turn generates an abundant waste stream rich in starch. Considering the applicability of potato waste as a substrate for anaerobic digestion, this study investigates the effectiveness of degree of solubilization due to thermal pre-treatment on volatile fatty acids (VFAs) production under mesophilic anaerobic digestion (35°C). This study is carried out with heat shocked mixed culture and quantitatively establishing operating conditions (Organic Loading Rate [OLR] and Hydraulic Retention Time [HRT]) which helps in predicting the product spectrum for VFAs production. The experimental runs were dedicated to produce maximum VFA concentrations (dependent variable) considering potato waste as a feedstock at multiple OLRs (6 and 9 kg/m<sup>3</sup>.day) and multiple HRTs (0.5, 1, 2 days), keeping pH constant at 7. Experimental runs are dedicated to quantifying the independent variables influencing VFA production rates by changing one variable at a time and evaluating their effects on acetic acid yield. This study will assist in determining the feasibility of pretreatment technology to produce volatile fatty acids using mesophilic anaerobic digester. Potato starch from a local potato processing industry was thermally hydrolyzed in a stirred and externally heated Parr reactor. Experimental results for thermal pre-treatment indicate that raising the pre-treatment temperature from 100°C to 140°C led to an increase in the ratio of ((SolubleCOD, SCOD)/(TotalCOD, TCOD)) from 63-67% to 87-92% along with volatile suspended solids reduction of 59-65% and 85-89% respectively due to solubilization. At an OLR of 9 kg/m<sup>3</sup>.day and HRT of 2 days, maximum VFA yield and maximum acetic acid yield of 0.66 mgCOD<sub>volatilefattyacids</sub>/mgCOD<sub>influent</sub> and 0.29 mgCOD<sub>aceticacid</sub>/mgCOD<sub>influent</sub> were reported from potato waste that was thermally hydrolyzed at 100°C, making these operating conditions ideal for maximum concentrations of VFAs.

### **1 INTRODUCTION**

Resource recovery is an attractive and sustainable waste management approach aimed at extracting valuable resources from waste. Because of increasing oil prices, this process has gained tremendous appreciation over the years, and research is focused on maximizing selective extraction of value-added products using anaerobic digestion (AD). AD has the potential to provide a valuable carbon sources from low-value organic waste streams, which in turn makes harvesting bio-products from the wastewater treatment process more economical.

Approximately 20,000 hectares of potatoes are cultivated every year in New Brunswick of which 25% is diverted towards the fresh market, 19% towards seeding and the remaining 56% is destined for industrial

processes [New Brunswick Potatoes 2017] to manufacture several potato products which in turn generates an abundant waste stream rich in starch. This potato waste poses significant disposal challenges for the industries such as bulk volume, logistics and disposal costs. The typical disposal method for potato waste is moving it to landfills, where it will degrade with due time, but it will create several problems like leachate production [Shu et al. 2006], and emission of greenhouse gases like methane and carbon dioxide [Abichou et al. 2006] which contributes towards global warming. These problems are primarily because of high organic matter (predominantly carbohydrates) and moisture content present in the waste. This organic matter makes potato waste an ideal substrate for anaerobic digestion leading to a well-established process of biogas production [Lin et al. 1982]. Biogas containing methane has a significant positive impact on the environment by utilizing this low-value organic waste to produce either heat or electricity and minimizing our dependency on non-renewable natural resources.

Generation of value-added products from AD follows four sequential steps: i.e., hydrolysis, acidogenesis, acetogenesis, and methanogenesis [McCarty 1964]. The first step, i.e., hydrolysis of organic matter, can often be a rate-limiting step considering the complex physical and chemical structure of the substrate [Izumi et al. 2010, Ma et al. 2011, Rafique et al. 2010]. Pre-treatment methods are employed before the anaerobic digestion for enhanced resource recovery from organic waste [Mossier et al. 2005, Hendricks et al. 2009, Ariunbaatar et al. 2014]. Pre-treatments results in disintegration of cell membranes which lead to partial or full solubilization of organic compounds [Haug et al. 1978], making the organic matter readily fermentable, and this results in increased hydrolysis rate. As the microbial culture present in the fermenter has less concentration of complex molecules to hydrolyze, this is a direct measure of enhanced anaerobic biodegradability. Methane production rate and substrate utilization rate were found inversely proportional to particle size [Esposito et al. 2011, Kim et al. 2000]. Thermal, chemical, and thermo-chemical pre-treatment methods have been studied widely for enhanced AD for several substrates [Kim et al. 2002, Valo et al. 2004, Tanaka et al. 2002, Carrère et al. 2009]. To further enhance resource recovery, two-phase systems are preferred for acidogenic and methanogenic activity which improve process control and enhance process stability [McCarty 1964].

Despite the attractiveness of methane production using AD, the economics of utilizing biogas is often questioned based on the market value. In addition to that, detailed knowledge of the acid phase of the two-phase AD is still required as it has the potential to provide several other bioproducts like hydrogen [Oh et al. 2003, Ginkel et al. 2005, Zhang et al. 2003], which produces volatile fatty acids as a byproduct. This has initiated the development of processes that yield products like volatile fatty acids (VFAs) consisting of carboxylic acids like acetic acid, which is an intermediate product formed during AD. Production of acetic acid remains a lucrative option considering its application as a chemical reagent in the field of chemistry.

To obtain maximum acetate production from polysaccharide breakdown during methanogenesis, low hydrogen partial pressure must be maintained which is accomplished by scavenging homoacetogens and hydrogenotropic methanogens [McCarty 1964]. Inhibition of these homoacetogens and hydrogenotropic methanogens by heat shocking the mixed culture should provide volatile fatty acids and hydrogen as the product, instead of methane. Obtaining VFAs as the final product has always been challenging as it is difficult to answer which VFAs and in what proportions are obtained. Although several studies have indicated acetic acid production during dark fermentation for hydrogen production [Oh et al. 2003, Su et al. 2009], where conversion of long chain fatty acids can be a rate limiting step for production of acetate, as interspecies hydrogen transfer is affected by heat shocking as it inhibits homoacetogens/hydrogenotropic methanogens which increases the partial pressure of hydrogen (Speece 1996), and eventually limiting the conversion of propionic acid to acetic acid. In such a case, it needs to be understood that there are some inherent biological limitations when producing other bioproducts other than methane as some of the influent chemical oxygen demand (COD) goes towards hydrogen generation and only certain amount of volatile fatty acids can be produced.

A significant knowledge gap exists to determine the effect of solubilization due to thermal pretreatment on the production of VFAs from heat-shocked mixed cultures. This alternate process requires further research and development to provide a substitute for the conventional process of commercial VFAs production, which follows chemical routes. Hence, this study aims to investigate the effect of solubilization due to thermal pre-treatment at different temperatures on VFAs production to obtain maximum concentration of

VFAs. In addition to that, the effect of different operating conditions like hydraulic retention time (HRT) and organic loading rate (OLR) was also analyzed for VFAs production.

## 2 MATERIALS

### 2.1 Substrate and Inoculum

Potato waste from a local potato processing industry was used in this study for anaerobic digestion. Anaerobic seed sludge was obtained from ADI® Systems pilot reactor used for the treatment of sugar and starch-based wastewater and was used as inoculum. Wastewater composition and seed sludge characteristics are provided in Table 1 and Table 2 respectively. All samples were stored at 2°C-4°C.

Table 1: Characteristics of wastewater

Parameters (g/L)	Wastewater
Total Solids	15.008 ± 0.32
Total Suspended Solids	14.258 ± 0.28
Volatile Suspended Solids	13.255 ± 0.14
Total COD (TCOD)	14.983 ± 0.29
Soluble COD (SCOD)	0.1228 ± 0.03
pH	7.87 ± 0.31
Alkalinity (g-CaCO <sub>3</sub> /L)*	5.885 ± 0.35

Average ± standard deviation

\*After addition of sodium bicarbonate

Table 2: Sludge characteristics

Parameters (g/L)	Values
Mixed Liquor Suspended Solids (MLSS)	27.154 ± 0.42
Mixed Liquor Volatile Suspended Solids (MLVSS)	25.905 ± 0.35

Average ± standard deviation

## **2.2 Experimental set-up**

### **2.2.1 Reactor Operation**

#### **2.2.1.1 Parr Reactor (4560 Series, Parr Instrument Company, Illinois, USA) (for thermal pre-treatment)**

A Parr Reactor (total volume 600 mL and working volume 400 mL) was employed in the study and operated in batch mode. It was used to treat starch solution at two different pre-treatment temperatures (100°C and 140°C) to enhance solubilization. The temperature was controlled using an external heater. All the experiments were conducted at the same agitator rpm and time, i.e., 150 rpm and 30 minutes, respectively.

#### **2.2.1.2 Anaerobic Respirometer System (Challenge AER-208, Arkansas, USA)**

Reactors (total volume 310mL and working volume 250mL) were employed in the study and operated in batch mode. Two identical reactors each for starch (no thermal pre-treatment, NO\_THP), starch (after thermal pre-treatment at 100°C, THP\_100) and starch (after thermal pre-treatment at 140°C, THP\_140) were used. Each reactor was stirred at the constant speed of about 250 rpm. The temperature was controlled at 35°C using a water bath connected to a water recirculator. Nutrients were supplied along with substrate and to minimize pH variation, sodium bicarbonate (NaHCO<sub>3</sub>) was used as pH buffering reagent to maintain the pH between 6.8-7.2. Reactors were flushed with nitrogen gas to create anaerobic conditions.

The effect of acidogenesis of potato starch was investigated by operating the reactor at OLRs of 6, 9, 12 kg/m<sup>3</sup>.day, while the effect of HRT was investigated by operating the reactor at HRTs of 0.5, 1, 2 days.

## **2.3 Analytical Method**

All analysis was carried out in accordance with Standard Methods [APHA, AWWA, WEF 2005]. All COD and solids analysis were triplicated unless stated otherwise and conducted before and after every experimental run. All COD analysis was measured using the titrimetric method. COD analysis after thermal pre-treatment was carried out after centrifugation at 4750 rpm for 30 minutes and then, filtering the solution through 1.2µm glass fiber filter and 0.45µm membrane filter for filtered COD and soluble COD measurements respectively. VFA samples, before being analyzed using gas chromatography, were centrifuged at 4750 RPM for 30 minutes followed by filtering the sample solution through a 0.45µm membrane filter and then adding 5% v/v phosphoric acid. VFAs were analyzed with Varian CP-3800 Gas Chromatograph. It is equipped with a wall coated open tubular fused silica column (0.32 mm inner diameter) with a wall thickness of 1.2µm and a flame ionization detector (FID). The temperature of the injection port is initially set to 80°C, which rises to a maximum of 180°C, while the FID temperature of the oven is set to 300°C. Helium (He) is used as a carrier gas as a flow rate of 5 mL/min.

## **3 RESULTS AND DISCUSSION**

### **3.1 Selection of thermal pre-treatment temperature**

The degree of COD solubilization can be studied at several different temperatures. However, it has been reported that pre-treatment temperature is directly proportional to the degree of solubilization [Haug et al. 1978]. 24% increase of methane production was reported if kitchen waste was thermally treated at 120°C [Ma et al. 2011], whereas thermal pretreatment of fruit and vegetable waste at 175°C provided 11.7% decrease in methane production [Liu et al. 2012]. Treatments at a higher temperature (above 150°C) showed increased solubilization but no increase in methane production because of the Maillard reaction (Jiang et al. 2012). Therefore, it can be said that enhanced biogas production was mostly due to solubilization of particulates and any temperature higher than 145°C-150°C might lower the performance of anaerobic digester due to the formation of melanoidins [Dwyer et al. 2008]. This was the reason why pre-treatment temperatures of 100°C and 140°C were chosen.

### 3.2 Effect of thermal pre-treatment at 100°C and 140°C

Wastewater sample was thermally hydrolyzed in Parr reactor. Table 3 compares the result for thermally hydrolyzed starch at different pre-treatment temperatures. Thermal pre-treatments results in partial or full solubilization of organic compounds [Haug et al. 1978], making the organic matter readily fermentable, and this results in increased hydrolysis rate. In case of starch, thermal pre-treatment leads to granular swelling and particulate solubilization which resulted in total suspended solids reduction of 59-65% and 85-89% at 100°C and 140°C respectively, in comparison to starch (NO\_THP). Since a non-buffered solution was used, pH dropped down to approximately 6.25 and 5.38 from 7.91 for thermally hydrolyzed starch at 100°C and 140°C respectively. Drop in pH was also reported during gelatinization [Marchal et al. 1999]. The degree of solubilization was measured as the ratio of ((SolubleCOD, SCOD)/(TotalCOD, TCOD)). There is loss of some water as the solution is allowed to cool down at room temperature after thermal pre-treatment, hence TCOD values after thermal pre-treatment are higher for starch(THP\_100) and starch(THP\_140).

Table 3: Characteristics of wastewater after thermal pre-treatment at different temperature

Characteristics	TCOD (g/L)	FCOD (g/L)	SCOD (g/L)	TS (g/L)	TSS (g/L)	VSS (g/L)	pH -
NO_THP	14.96 ± 0.61	0.123 ± 0.53	0.090 ± 0.04	15.74 ± 0.59	14.59 ± 0.98	13.68 ± 0.26	7.91 ± 0.17
THP_100	15.01 ± 0.69	12.09 ± 0.14	8.02 ± 0.19	15.45 ± 0.84	5.82 ± 0.12	5.15 ± 0.16	6.25 ± 0.25
THP_140	15.07 ± 0.16	13.98 ± 0.85	13.12 ± 0.07	15.19 ± 0.43	2.51 ± 0.29	2.09 ± 0.94	5.38 ± 0.62

Average ± standard deviation

### 3.3 Effect of Organic Loading Rate and Hydraulic Retention Time

The effect of OLR on VFAs production was conducted at mesophilic conditions, i.e., 35°C, pH of 7.0 was maintained using NaHCO<sub>3</sub> and HRT of 0.5, 1, 2 days. Individual reactors were assumed to be at a steady state when VFA concentration in the product stream, i.e., effluent reached a constant value. Gas composition, i.e., the ratio of methane to carbon dioxide remained almost constant with values ranging from 0.05 to 0.1 during fermentation process for starch with NO\_THP, THP\_100, THP\_140.

#### 3.3.1 Starch with no thermal pre-treatment (NO\_THP)

Figure 1 shows the variation in concentration of VFAs at OLRs of 6, 9 and 12 kg-COD/m<sup>3</sup>.day with HRTs of 0.5, 1, 2 days. For above mentioned operating conditions, the concentration of individual organic acids increased significantly reaching a steady state value after 10-14 days. GC analysis for VFA classification revealed the presence of several organic acids like acetic acid (AA), propionic acid (PA), and butyric acid (BA). Table 4 shows the concentration of individual VFAs at the end of digestion process under different operating conditions. Maximum VFA yield of 0.651 was obtained at an OLR of 9 kg/m<sup>3</sup>.day and an HRT of 2 days. Since it is always difficult to predict the product spectrum, analysis of individual VFAs was necessary as the distribution of fermentation products may reveal relevant information regarding the operational conditions and signify which set of conditions promote the production of a particular organic acid.

Irrespective of operating conditions, acetic acid was the dominant product followed by butyric acid and then propionic acid. At an OLR of 6 kg/m<sup>3</sup>.day and HRT of 2 days, acetic acid and butyric acid together combined to cover approximately 65-72% of the product spectrum. Application of higher HRT proved beneficial as the concentration of VFAs increased with increasing HRT. Alkalinity i.e. buffering capacity for the anaerobic sludge was maintained by dosing sodium bicarbonate.

The concentration of VFAs produced was significantly affected at high OLR, especially at 12 kg/m<sup>3</sup>.day (data not shown). Acetic acid remained the dominant product, followed by butyric acid, and together they combined only approximately 38% of the product spectrum. Propionic acid concentration was significantly higher in comparison to OLR of 9 kg/m<sup>3</sup>.day. Often, production of isobutyric acid, isovaleric acid, and valeric acid was also noted; but often their concentrations were low, and hence were not quantified by GC for every injection. Reactor operation at this OLR was highly unstable as substrate loading rate was high, and so was the viscosity of fermentation broth.

Table 4: Effect of different OLRs and HRTs on VFAs production with starch (NO\_THP)

	Organic Loading Rate (kg/m <sup>3</sup> .day)					
	6			9		
HRT (d)	0.5	1	2	0.5	1	2
<b>VFAs (g/L)</b>	1.48 ± 0.62	3.00 ± 0.32	4.87 ± 0.48	2.28 ± 1.12	4.83 ± 0.71	7.13 ± 0.67
<b>AA (g/L)</b>	0.68 ± 0.25	1.28 ± 0.13	2.45 ± 0.26	1.06 ± 0.53	2.55 ± 0.41	3.85 ± 0.30
<b>PA (g/L)</b>	0.20 ± 0.08	0.65 ± 0.15	0.99 ± 0.13	0.54 ± 0.22	0.93 ± 0.13	1.47 ± 0.16
<b>BA (g/L)</b>	0.60 ± 0.28	1.07 ± 0.09	1.42 ± 0.13	0.69 ± 0.40	1.36 ± 0.20	1.81 ± 0.25
<b>AA yield</b>	0.048	0.092	0.174	0.075	0.181	0.274
<b>VFA yield</b>	0.14	0.286	0.447	0.207	0.442	0.651

Average ± standard deviation

AA yield = Acetic Acid yield = (COD<sub>aceticacid</sub>/COD<sub>influent</sub>); VFA yield = (COD<sub>volatilefattyacids</sub>/COD<sub>influent</sub>)

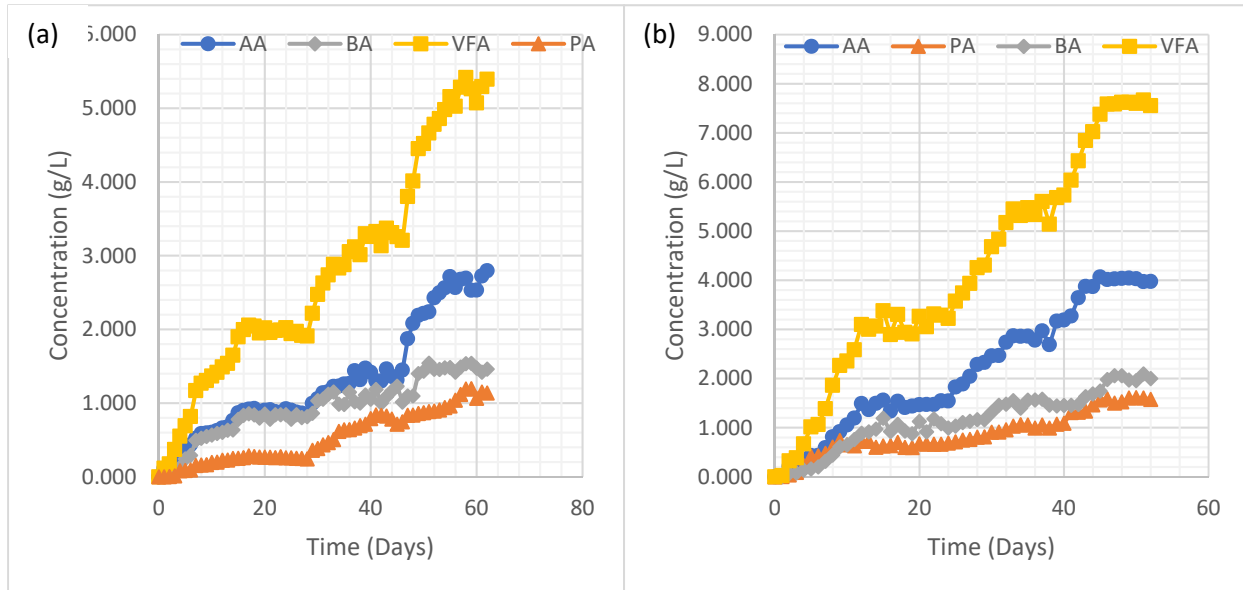


Figure 1: Concentration profiles for VFAs at OLR of a) 6 kg/m<sup>3</sup>.day and b) 9 kg/m<sup>3</sup>.day

### 3.3.2 Starch with thermal pre-treatment at 100°C (THP\_100)

To analyze the effect of COD solubilization on VFA production, starch was thermally hydrolyzed at 100°C, and Table 2 provides characteristics of starch after pre-treatment. COD solubilization helped in achieving steady state conditions faster than starch that was not thermally pre-treated, which is evident from Figs 2 showing the variation on the concentration of individual VFAs at OLRs of 6 kg/m<sup>3</sup>.day and 9 kg/m<sup>3</sup>.day with HRTs of 0.5, 1, 2 days. Table 3 shows the concentration of individual VFAs at the end of the anaerobic digestion process.

Irrespective of operating conditions, acetic acid remains the dominant product as was reported before with starch (NO\_THP) followed by either propionic acid or butyric acid. At an OLR of 9 kg/m<sup>3</sup>.day and HRT of 2 days, maximum VFA yield, and acetic acid yield was found to be 0.66 and 0.29. To maintain the reactor operating pH near neutral, NaHCO<sub>3</sub> was used to maintain alkalinity.

OLR of 12 kg/m<sup>3</sup>.day (data not shown) significantly reduced reactor performance which may be attributed to the combination of high soluble COD and high substrate loading rate at the beginning of the study. Similar observations were reported by Kim et al. 2003. Concentrations of propionic acid and butyric acid decreased to as low as 0.01 g/L and 0.06 g/L respectively. Because of reactor foaming, the study was stopped after ten days.

Table 5: Effect of different OLRs and HRTs on VFAs production with starch (THP\_100)

HRT (d)	Organic Loading Rate (kg/m <sup>3</sup> .day)					
	6			9		
	0.5	1	2	0.5	1	2
<b>VFAs (g/L)</b>	1.86 ± 0.82	3.78 ± 0.35	5.13 ± 0.91	3.25 ± 1.21	5.43 ± 0.87	7.40 ± 0.8
<b>AA (g/L)</b>	0.93 ± 0.41	1.64 ± 0.80	2.4 ± 0.6	1.73 ± 0.59	2.96 ± 0.57	4.07 ± 0.52
<b>PA (g/L)</b>	0.38 ± 0.29	1.02 ± 0.07	1.3 ± 0.16	0.83 ± 0.35	1.1 ± 0.24	1.64 ± 0.18
<b>BA (g/L)</b>	0.55 ± 0.18	1.11 ± 0.20	1.45 ± 0.11	0.69 ± 0.26	1.36 ± 0.13	1.70 ± 0.16
<b>AA yield</b>	0.106	0.11	0.17	0.12	0.22	0.29
<b>VFA yield</b>	0.17	0.35	0.475	0.29	0.48	0.66

Average ± standard deviation

AA yield = Acetic Acid yield = (COD<sub>aceticacid</sub>/COD<sub>influent</sub>); VFA yield = (COD<sub>volatilefattyacids</sub>/COD<sub>influent</sub>)

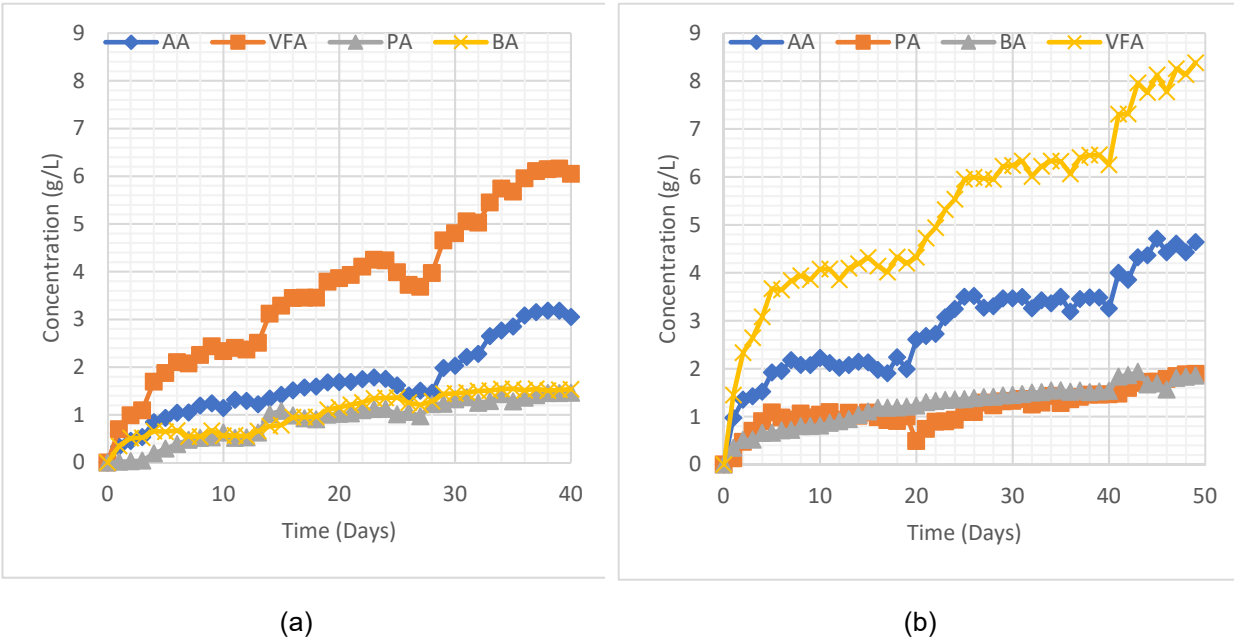


Figure 2: Concentration profiles for VFAs at OLR of a) 6 kg/m<sup>3</sup>.day and b) 9 kg/m<sup>3</sup>.day

### 3.3.3 Starch with thermal pre-treatment at 140°C (THP\_140)

Table 2 provides characteristics of starch after pre-treatment at 140°C. Maximum solubilization was achievable as the ratio of SCOD/TCOD was approximately 85-89%. Figure 3 shows the variation in concentration of VFAs at OLRs of 6 kg/m<sup>3</sup>.day and 9 kg/m<sup>3</sup>.day with HRTs of 0.5, 1, 2 days. Operational instability persisted for 12 kg/m<sup>3</sup>.day irrespective of HRT. For other OLRs, i.e., 6 and 9 kg/m<sup>3</sup>.day, the concentration of individual organic acids increased significantly at the beginning of each experimental run but was always less than the concentration achieved with for experimental runs with starch (NO\_THP) and starch (THP\_100°C). This may be attributed to the formation of complex particles which are not readily degraded by the microbial culture. GC analysis for VFA speciation revealed the presence of acetic acid, propionic acid, and butyric acid. Table 5 shows the concentration of individual VFAs at the end of the anaerobic digestion process. Acetic acid and propionic acid were the dominant products, while minimal quantities of butyric acid were formed during the entire run.



Table 5: Effect of different OLRs and HRTs on VFAs production with starch (THP\_140)

HRT (d)	Organic Loading Rate (kg/m <sup>3</sup> .day)					
	6			9		
	0.5	1	2	0.5	1	2
<b>VFAs (g/L)</b>	0.66 ± 0.50	1.71 ± 0.16	2.8 ± 0.44	1.14 ± 0.42	2.71 ± 0.41	4.40 ± 0.42
<b>AA (g/L)</b>	0.38 ± 0.28	1.03 ± 0.07	1.28 ± 0.16	0.68 ± 0.25	1.3 ± 0.14	1.9 ± 0.19
<b>PA (g/L)</b>	0.28 ± 0.21	0.69 ± 0.1	1.06 ± 0.11	0.45 ± 0.18	1.16 ± 0.17	1.52 ± 0.04
<b>BA (g/L)</b>	0	0	0.45 ± 0.19	0.0	0.25 ± 0.1	0.93 ± 0.22
<b>AA yield</b>	0.027	0.073	0.09	0.05	0.09	0.129
<b>VFA yield</b>	0.055	0.142	0.254	0.09	0.23	0.395

Average ± standard deviation

AA yield = Acetic Acid yield = (COD<sub>aceticacid</sub>/COD<sub>influent</sub>); VFA yield = (COD<sub>volatilefattyacids</sub>/COD<sub>influent</sub>)

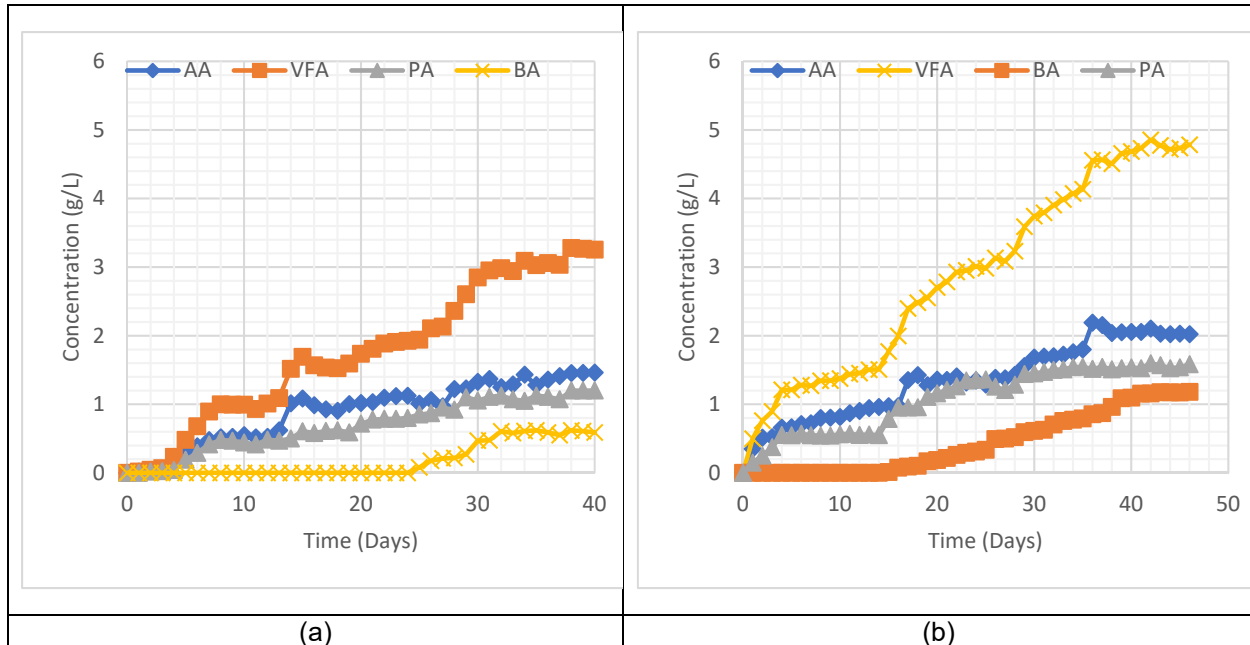


Figure 3: Concentration profiles for VFAs at OLR of a) 6 kg/m<sup>3</sup>.day and b) 9 kg/m<sup>3</sup>.day

For all the above experimental runs, the concentration of VFAs increased with increasing OLR and increasing HRT, but the VFAs yield and acetic acid yield remained the approximately the same for starch (NO\_THP) and starch (THP\_100). Yields for individual VFAs decreased significantly for starch (THP\_140), which as suggested before can be attributed to overcooking of the starch sample.

## 4 CONCLUSIONS

The maximum VFAs yield of 0.66 and acetic acid yield 0.29 was observed for starch (THP\_100), at operating conditions of 9 kg/m<sup>3</sup>.day and HRT of 2 days. In addition to that, reactors reached the steady-state conditions faster which are a result of solubilized starch, that is readily fermentable by the microbial culture. Above this pre-treatment temperature, the concentration of VFAs decreased resulting in a simultaneous decrease in VFAs yield. This implies that thermal pre-treatment at a temperature above 100°C led to increased solubilization but had no positive effects on VFAs production. This is a result of decreased biodegradability of the substrate due to the possible formation of complex and toxic compounds. Since the yields for VFAs and acetic for starch (NO\_THP) and starch (THP\_100) are approximately the same, this implies that this is the maximum concentration of VFAs that can be obtained from this potato waste.

## Acknowledgement

The authors would like to acknowledge the funding agencies including Natural Science and Engineering Research Council (NSERC) and New Brunswick Innovation Foundation (NBIF). Dr. Dennis Connor is acknowledged for his technical support.

## References

- Abichou, T., J. Chanton, D. Powelson, J. Fleiger, S. Escoriza, Y. Lei, and J. Stern. 2006. "Methane Flux and Oxidation at Two Types of Intermediate Landfill Covers." *Waste Management* 26 (11): 1305-1312. doi:10.1016/j.wasman.2005.11.016
- Ariunbaatar, J., A. Panico, G. Esposito, F. Pirozzi, P.N.L. Lens. (2014) "Pretreatment methods to enhance anaerobic digestion of organic solid waste." *Applied Energy* 123: 143-156.
- Carrère, H., B. Sialve, and N. Bernet. 2009. "Improving Pig Manure Conversion into Biogas by Thermal and Thermo-Chemical Pretreatments." *Bioresource Technology* 100 (15): 3690-3694. doi:10.1016/j.biortech.2009.01.015
- Dwyer, J., D. Starrenburg, S. Tait, K. Barr, D. J. Batstone, and P. Lant. 2008. "Decreasing Activated Sludge Thermal Hydrolysis Temperature Reduces Product Colour, without Decreasing Degradability." *Water Research* 42 (18): 4699-4709. doi:10.1016/j.watres.2008.08.019.
- Esposito, G., L. Frunzo, A. Panico, and F. Pirozzi. 2011. "Modelling the Effect of the OLR and OFMSW Particle Size on the Performances of an Anaerobic Co-Digestion Reactor." *Process Biochemistry* 46 (2): 557-565. doi:10.1016/j.procbio.2010.10.010
- Haug, R. T., D. C. Stuckey, J. M. Gossett, and P. L. McCarty. 1978. "Effect of Thermal Pretreatment on Digestibility and Dewaterability of Organic Sludges." *Journal of the Water Pollution Control Federation* 50 (1): 73-85.
- Hendriks, A. T. W. M. and G. Zeeman. 2009. "Pretreatments to Enhance the Digestibility of Lignocellulosic Biomass." *Bioresource Technology* 100 (1): 10-18. doi:10.1016/j.biortech.2008.05.027.
- Izumi, K., Y. -K Okishio, N. Nagao, C. Niwa, S. Yamamoto, and T. Toda. 2010. "Effects of Particle Size on Anaerobic Digestion of Food Waste." *International Biodeterioration and Biodegradation* 64 (7): 601-608. doi:10.1016/j.ibiod.2010.06.013
- Jiang, Y., L. Marang, J. Tamis, M. C. M. van Loosdrecht, H. Dijkman, and R. Kleerebezem. 2012. "Waste to Resource: Converting Paper Mill Wastewater to Bioplastic." *Water Research* 46 (17): 5517-5530. doi:10.1016/j.watres.2012.07.028.
- Kim, I. S., D. H. Kim, and S. -H Hyun. 2000. Effect of Particle Size and Sodium Ion Concentration on Anaerobic Thermophilic Food Waste Digestion. *Water Science and Technology*. Vol. 41.
- Kim, J. C. Park, T. Kim, M. Lee, S. Kim, SW Kim, J. Lee. 2002. "Effects of various pretreatment for enhance anaerobic digestion with waste activated sludge." *Journal of Bioscience and Bioengineering* 95(3): 271-275.
- Kim, M., C. Y. Gomec, Y. Ahn, and R. E. Speece. 2003. "Hydrolysis and Acidogenesis of Particulate Organic Material in Mesophilic and Thermophilic Anaerobic Digestion." *Environmental Technology (United Kingdom)* 24 (9): 1183-1190. doi:10.1080/09593330309385659.
- Lin, K. C., R. C. Landine, and S. Bliss. 1982. "Temperature Effect on the Anaerobic Treatment of Potato-Processing Wastewater." *Canadian Journal of Civil Engineering* 9 (3): 549-557. doi:10.1139/l82-064.

- Liu, X., W. Wang, X. Gao, Y. Zhou, and R. Shen. 2012. "Effect of Thermal Pretreatment on the Physical and Chemical Properties of Municipal Biomass Waste." *Waste Management* 32 (2): 249-255. doi:10.1016/j.wasman.2011.09.027.
- Ma, J., T. H. Duong, M. Smits, W. Verstraete, and M. Carballa. 2011. "Enhanced Biomethanation of Kitchen Waste by Different Pre-Treatments." *Bioresource Technology* 102 (2): 592-599. doi:10.1016/j.biortech.2010.07.122.
- Marchal, L. M., J. Jonkers, G. Th Franke, C. D. De Gooijer, and J. Tramper. 1999. "The Effect of Process Conditions on the  $\alpha$ -Amylolytic Hydrolysis of Amylopectin Potato Starch: An Experimental Design Approach." *Biotechnology and Bioengineering* 62 (3): 348-357. doi:10.1002/(SICI)1097-0290(19990205)62:3<348::AID-BIT11>3.0.CO;2-F.
- McCarty, P.L., 1964. Anaerobic waste treatment fundamentals. *Public Works* 95 (9), 107-112.
- Mosier, N., C. Wyman, B. Dale, R. Elander, Y. Y. Lee, M. Holtzapple, and M. Ladisch. 2005. "Features of Promising Technologies for Pretreatment of Lignocellulosic Biomass." *Bioresource Technology* 96 (6): 673-686. doi:10.1016/j.biortech.2004.06.025.
- New Brunswick Potatoes. c2017. Agriculture, Aquaculture and Fisheries; [accessed 2017 June 25]. <http://www2.gnb.ca/content/gnb/en/departments/10/agriculture/content/crops/potatoes.html>
- Oh, S. -E, S. Van Ginkel, and B. E. Logan. 2003. "The Relative Effectiveness of pH Control and Heat Treatment for Enhancing Biohydrogen Gas Production." *Environmental Science and Technology* 37 (22): 5186-5190. doi:10.1021/es034291y.
- Rafique, R., T. G. Poulsen, A. -S Nizami, Z. -U -Z Asam, J. D. Murphy, and G. Kiely. 2010. "Effect of Thermal, Chemical and Thermo-Chemical Pre-Treatments to Enhance Methane Production." *Energy* 35 (12): 4556-4561. doi:10.1016/j.energy.2010.07.011.
- Shu, H. -Y, H. -J Fan, M. -C Chang, and W. -P Hsieh. 2006. "Treatment of MSW Landfill Leachate by a Thin Gap Annular UV/H<sub>2</sub>O<sub>2</sub> Photoreactor with Multi-UV Lamps." *Journal of Hazardous Materials* 129 (1-3): 73-79. doi:10.1016/j.jhazmat.2005.08.009.
- Speece. R.E. 1996. *Anaerobic biotechnology for Industrial Wastewaters*. Nashville, TN: Archae Press.
- Standard Methods for the examination of water and wastewater. APHA, AWWA, WEF 2005.
- Su, H., J. Cheng, J. Zhou, W. Song, and K. Cen. 2009. "Improving Hydrogen Production from Cassava Starch by Combination of Dark and Photo Fermentation." *International Journal of Hydrogen Energy* 34 (4): 1780-1786. doi:10.1016/j.ijhydene.2008.12.045.
- Tanaka, S., K. Kamiyanm. 2002. "Thermochemical pretreatment in the anaerobic digestion of waste activated sludge." *Journal of Water Science and Technology* 46(10): 173-179
- Valo, A., H. Carrère, and J. P. Delgenès. 2004. "Thermal, Chemical and Thermo-Chemical Pre-Treatment of Waste Activated Sludge for Anaerobic Digestion." *Journal of Chemical Technology and Biotechnology* 79 (11): 1197-1203. doi:10.1002/jctb.1106.
- Van Ginkel, S. W., S. -E Oh, and B. E. Logan. 2005. "Biohydrogen Gas Production from Food Processing and Domestic Wastewaters." *International Journal of Hydrogen Energy* 30 (15): 1535-1542. doi:10.1016/j.ijhydene.2004.09.017
- Zhang, T., H. Liu, and H. H. P. Fang. 2003. "Biohydrogen Production from Starch in Wastewater Under Thermophilic Condition." *Journal of Environmental Management* 69 (2): 149-156. doi:10.1016/S0301-4797(03)00141-5.