Effect of PVA-gel on Performance Improvement of Two Stage Thermophilic Anaerobic Membrane Bioreactor

By

Mr. Supawat Chaikasem
March 31, 2014

Final Comprehensive Exam

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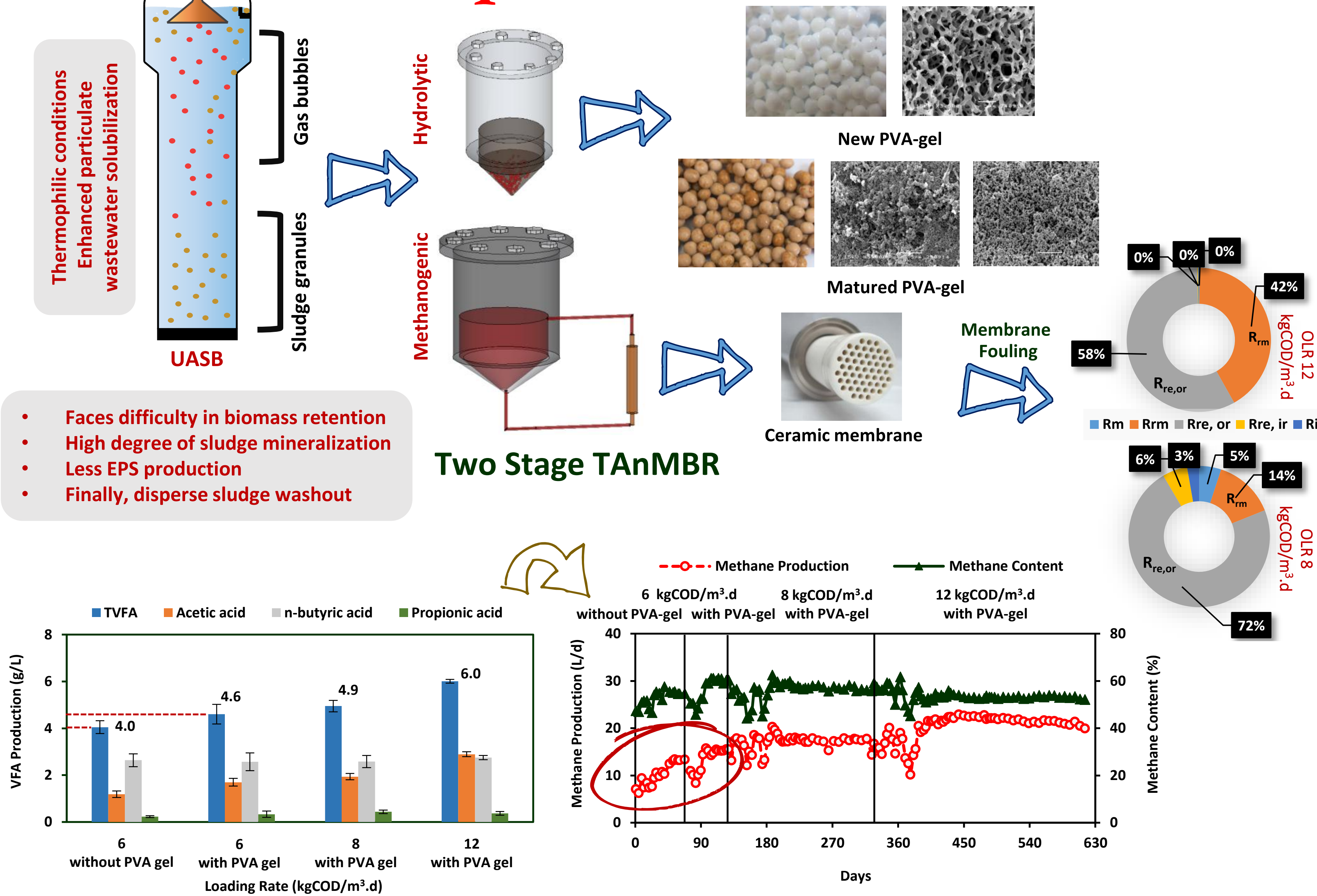
Graphical Abstract



Presentation Outline

Background
Stage 1

Objectives of the Study
Stage 2

Methodology
Stage 3

Results and Discussions
Stage 4

Conclusions and Recommendations
Stage 5

Question from External Examiner
Stage 6

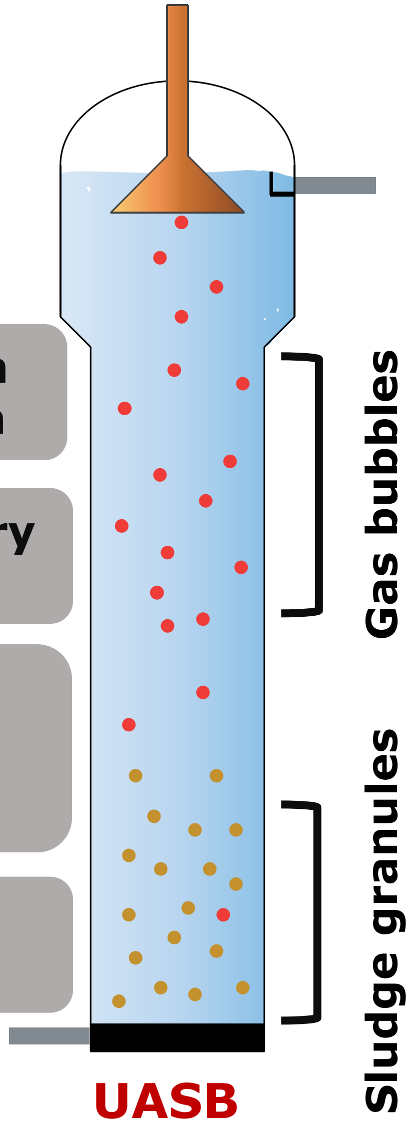
Anaerobic Process

WW with High Concentration

Energy recovery : biogas

Low sludge yield | production

Low energy requirement

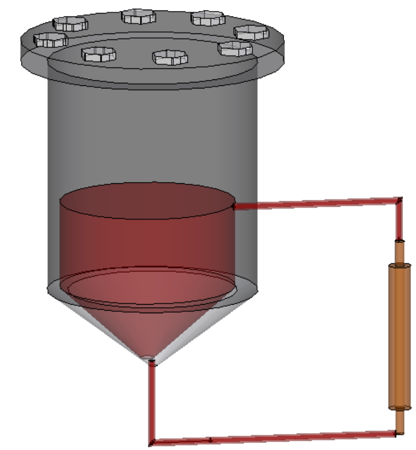


UASB

- High tendency **sludge mineralization**
- **Retard** granule formation
- **Biomass washout** from reactor

Thermophilic conditions

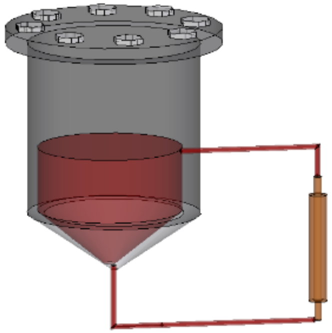
Particulate WW



AnMBR

- **Higher biodegradation rate (25-50%)**
- **More VFA to more methane**
- **Higher methane production (25–50%)**

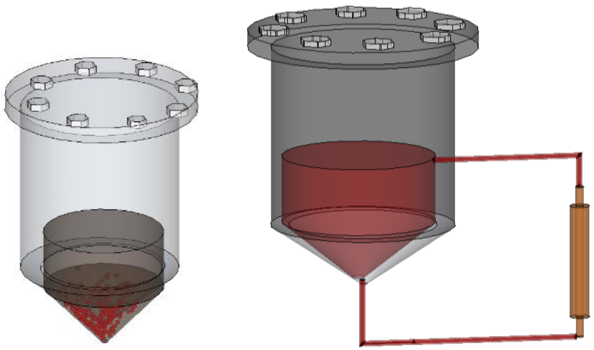
Why and How of a Two Stage TAnMBR ?



Single stage AnMBR

- Acidogens and methanogens have **different growth rates**
- **pH** tolerance
- Process stability, overall reaction rate, solid removal and biogas production **?**

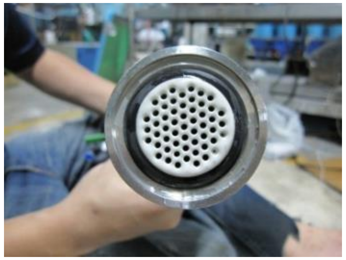
Two Stage AnMBR



Hydrolytic   Methanogenic

- **PVA-gel** for hydrolytic reactor
- **MF Ceramic membrane** for methanogenic reactor

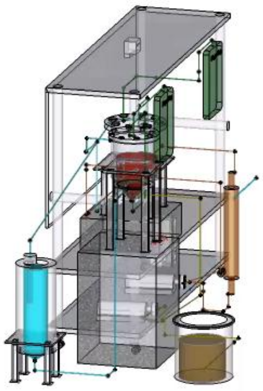
PVA-gel



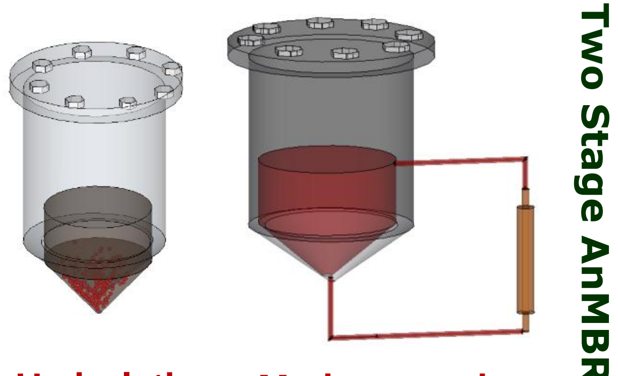
Ceramic Membrane

- Faces **difficulty** in **biomass retention**
- High degree of **sludge mineralization**
- **Less EPS** production
- Finally, disperse **sludge washout**

Objectives



- **To investigate the effect of PVA-gel as biocarrier on total VFA concentration and methane production of two stage TAnMBR**
- **To study the performance at optimized two stage TAnMBR in different loading rates**
- **To investigate the fouling characteristics of two stage TAnMBR**



Research Framework

Anaerobic Seed Sludge

Tapioca Starch Based Wastewater

Hydrolytic Consortia Isolation

Methanogenic Consortia Isolation

Butyric acid

Acclimatization to 55 °C

→

Two-Stage TAnMBR

- 6 COD/m³.d
- 8 COD/m³.d
- 12 kg COD/m³.d

→

Performances Analysis

- Removal Efficiency (COD)
- VFA Profile
- Fouling Investigation (TMP, Flux and EPS)
- Methane Productivity

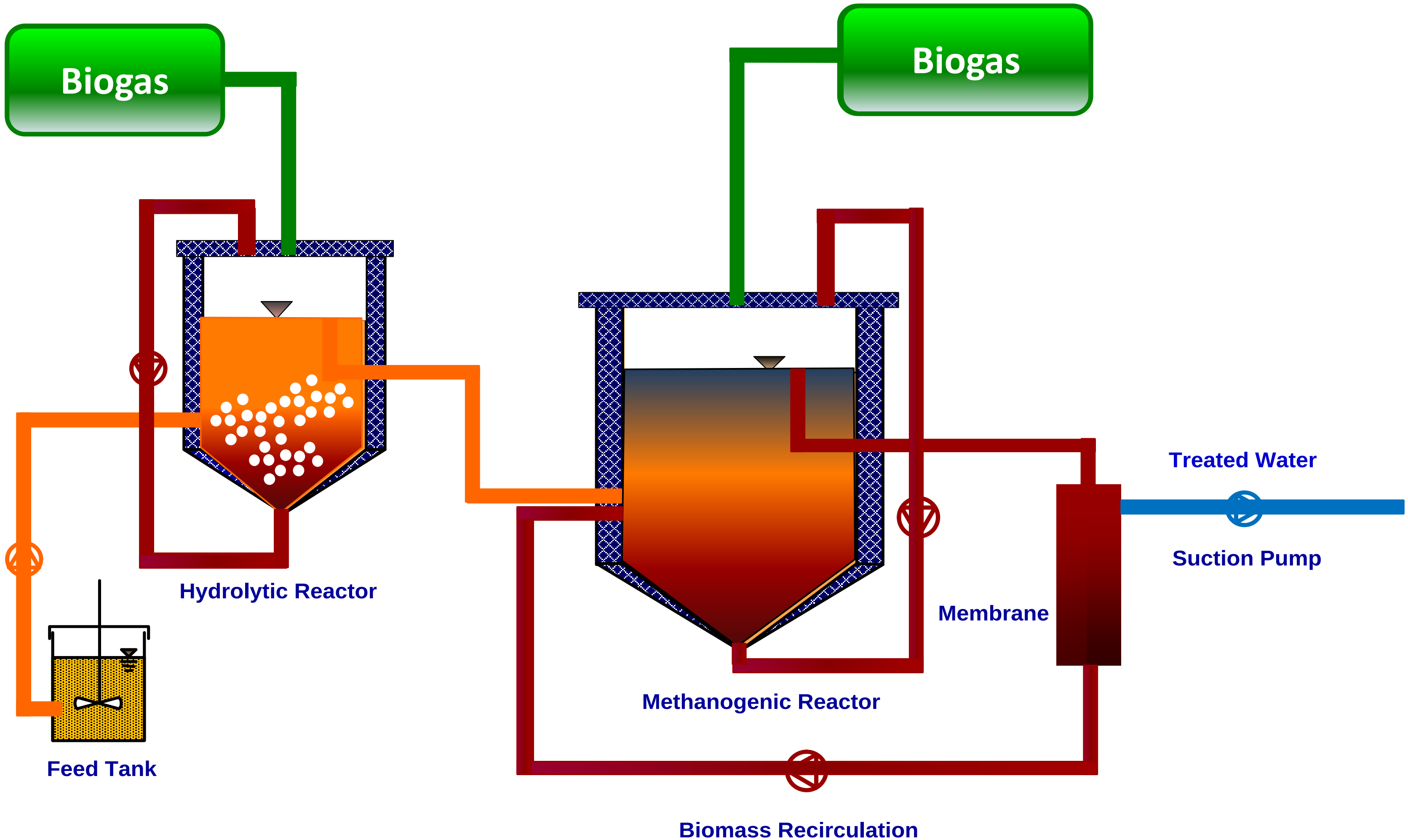
Hydrolytic

Methanogenic

Permeate

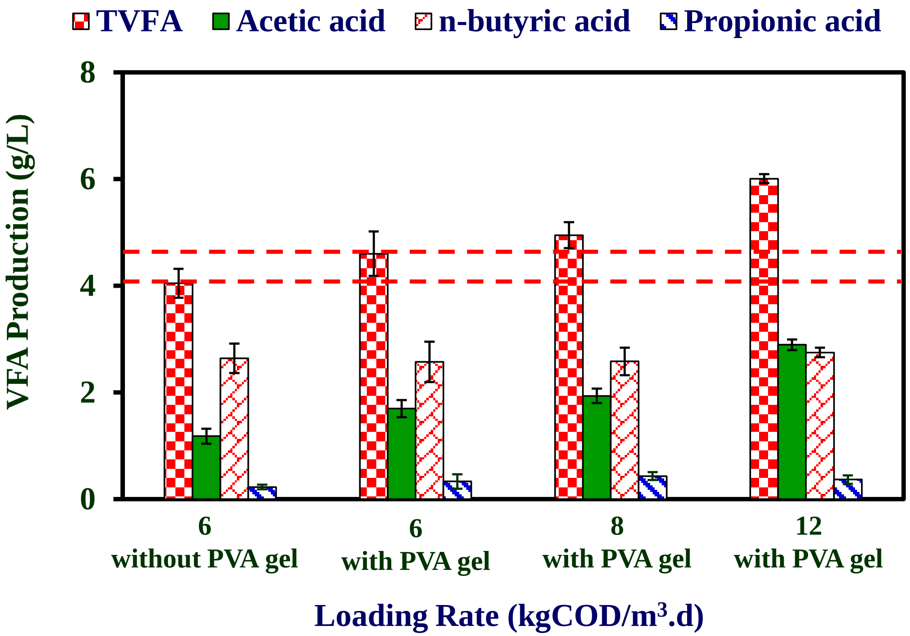
Parameter	Loading rate (kgCOD/m³.d)		
	6	8	12
pH	[illegible].3±0.2	7.5±0.1	7.8±0.3
TCOD (g/L)	**14.5±1.4**	**20.6±1.2**	**23.9±0.8**
TS (g/L)	**11.9±1.8**	**15.6±1.1**	**20.3±1.1**
SS (g/L)	**9.8±1.7**	**13.6±2.0**	**16.8±0.8**
TKN (mg/L)	775±20	950±50	1,100[illegible]0
NH_4^+-N (mg/L)	600±24	680±40	807±53
TP (mg/L)	165±10	210±15	230±22

Experimental Setup : Two Stage Anaerobic Membrane Bioreactor



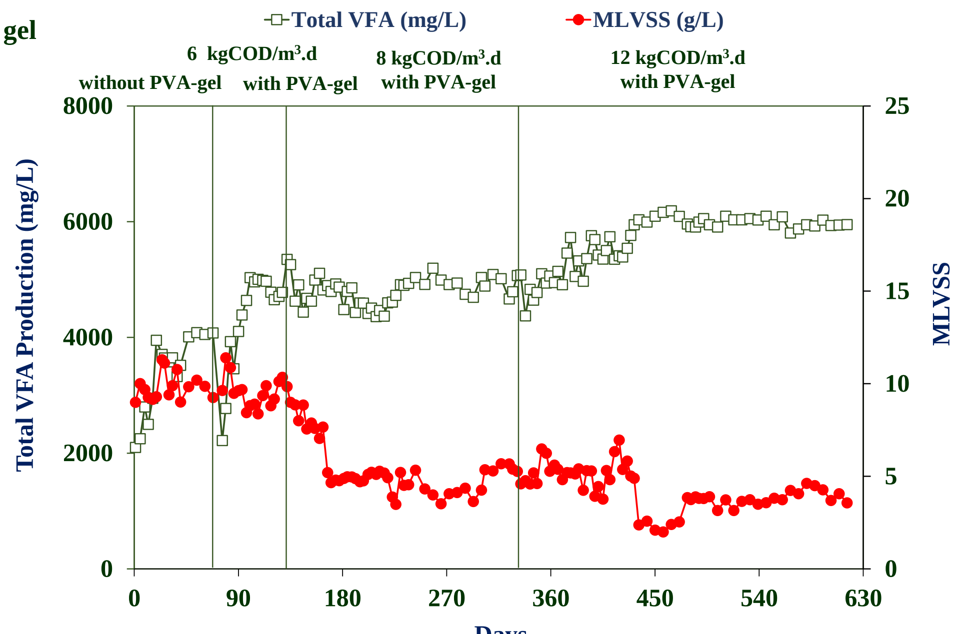
Results and Discussion

Hydrolytic Reactor Performance



✓ **Total VFA : Once PVA-gel was added, VFA significantly increased from 4 to 4.6 g/L. It also significantly increased with OLR to 4.9 and 6.0 g/L at OLR 8 and 12 kgCOD/m³.d**

✓ **VSS: Decreased with increasing OLR. At steady stage, it showed little change, indicating a balance between degradation of old biomass and accumulation of fresh biomass.**



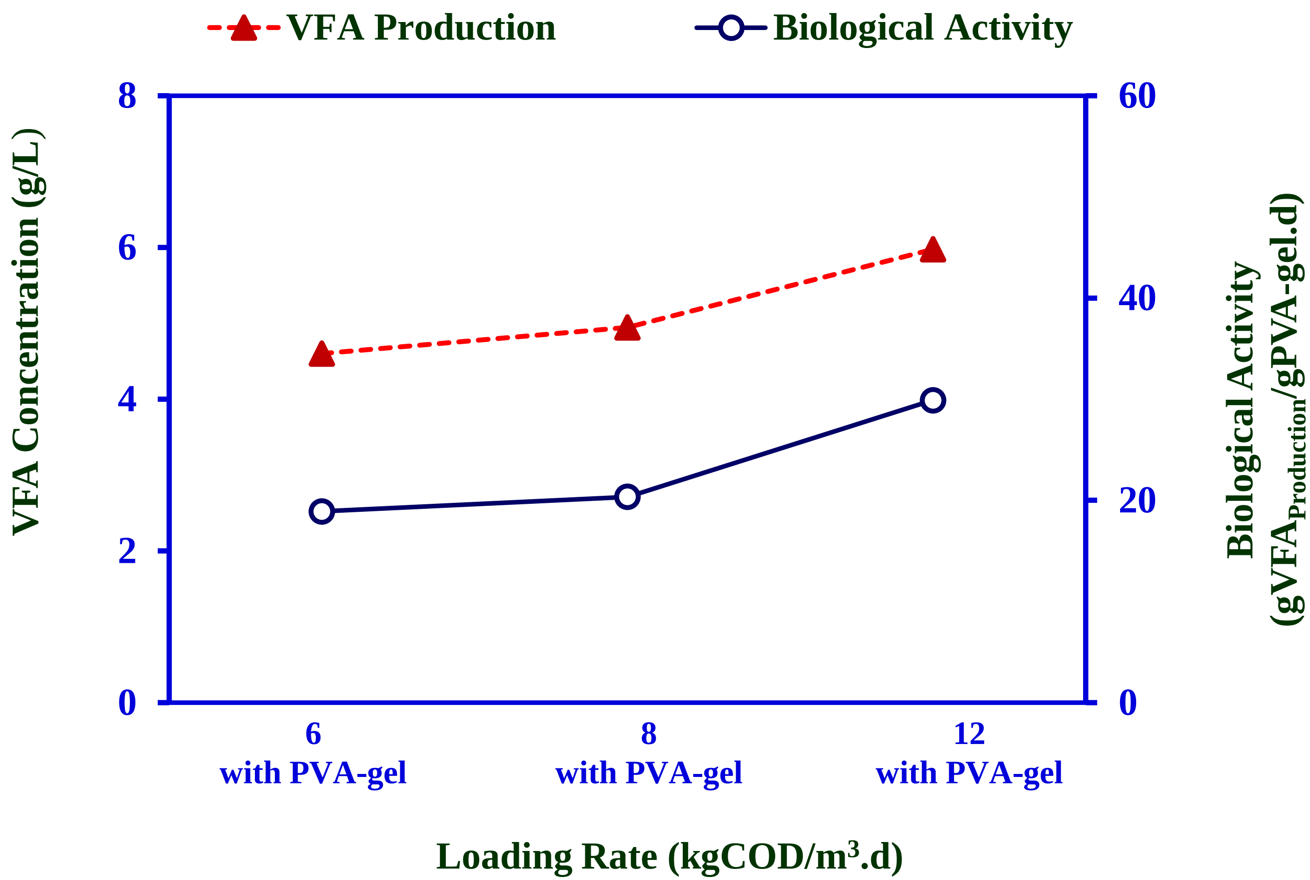
✓ **High H_2 partial pressure: VFA more than two carbon atoms (butyric acid) will be predominant**

✓ **Lim et al. (2008) and Jiang et at. (2013) reported the similar observation about butyric acid tend to decrease while acetic acid increased with increasing OLR because acetogenic activity performed well at higher OLR**

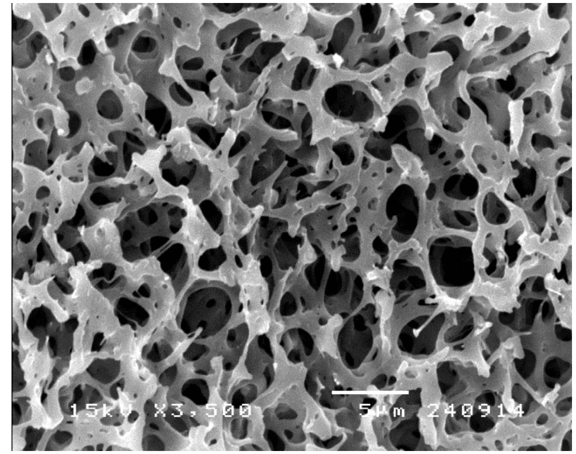
Page 64, Fig 4.11

Results and Discussion

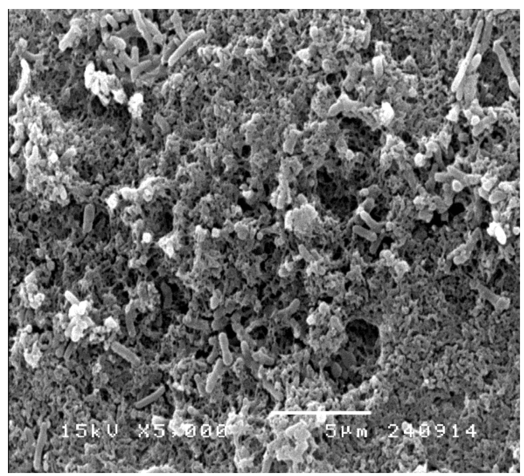
Hydrolytic Reactor Performance

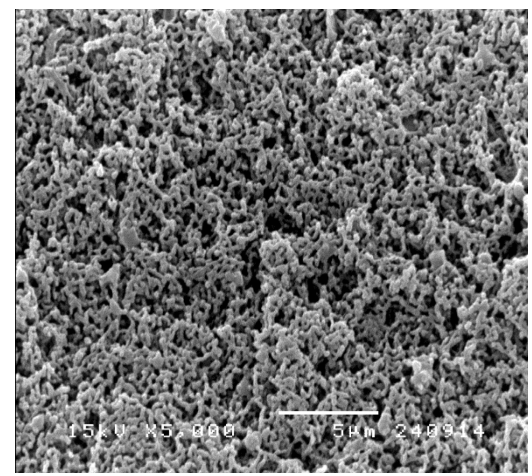


- ✓ **Biological Activity 18.9, 20.3 and 29.9 gVFA/L PVA-gel.d at OLR 6,8,12 kgCOD/m^3.d**
- ✓ **VFA: Increasing with the biological activity of hydrolytic reactor with PVA-gel addition**



New PVA-gel
(Settling velocity 143 m/h)



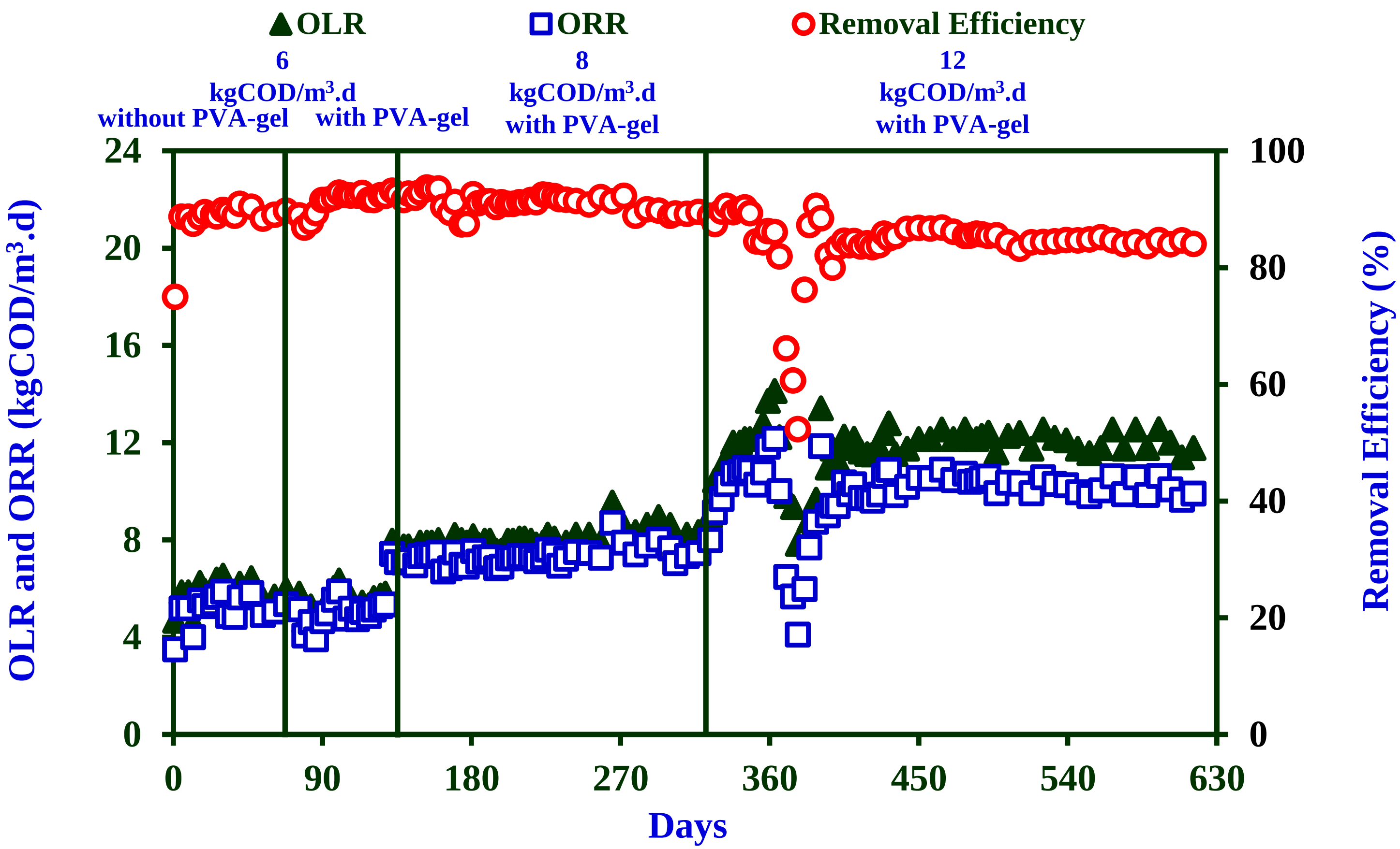


Matured PVA-gel
(Settling velocity 228 m/h with biomass attachment of 0.5gVSS/gPVA-gel)

Obj 2

Results and Discussion

Methanogenic Reactor Performance

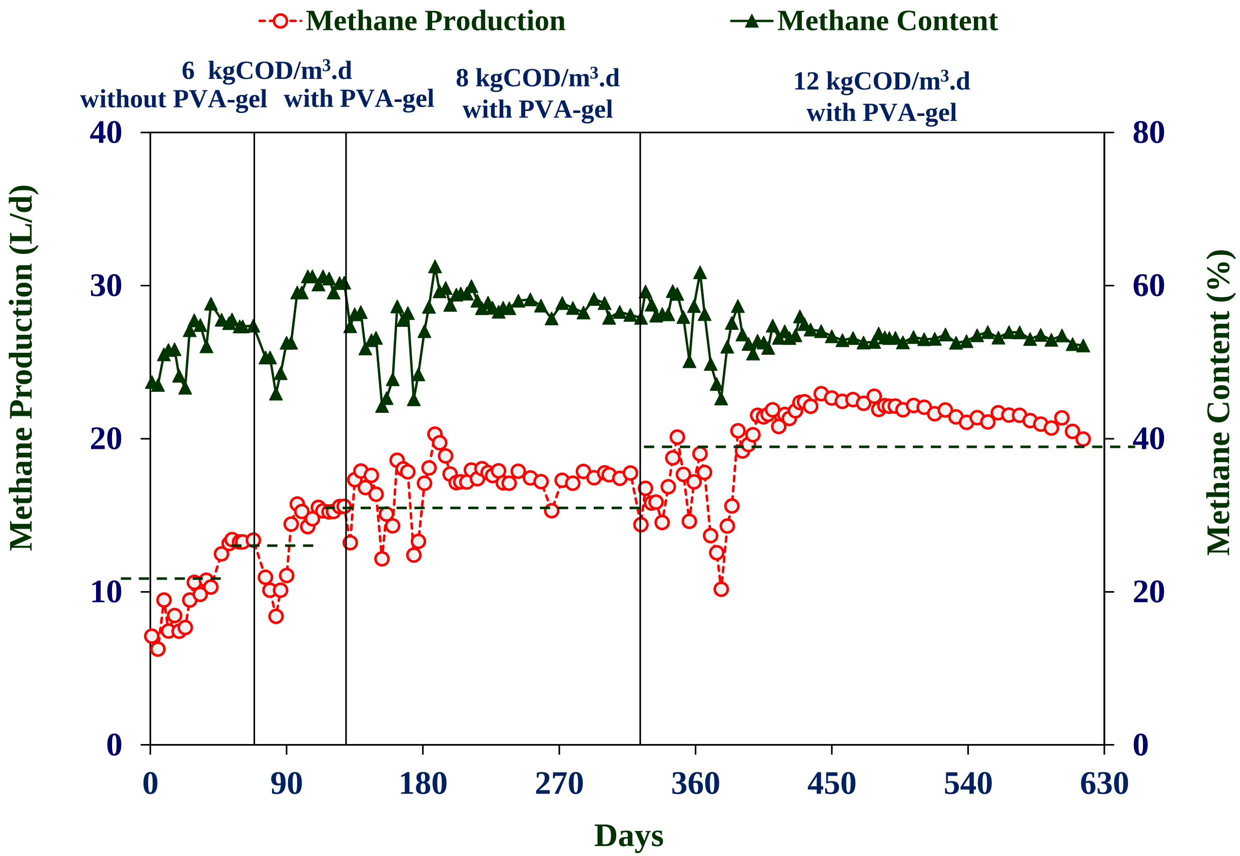


- ✓ OLR and ORR: ORR increase with increasing OLR
- ✓ As a results, methane production increase with increasing OLR
- ✓ COD removal remained fairly high between 84-90%

Obj 2

Results and Discussion

Methanogenic Reactor Performance



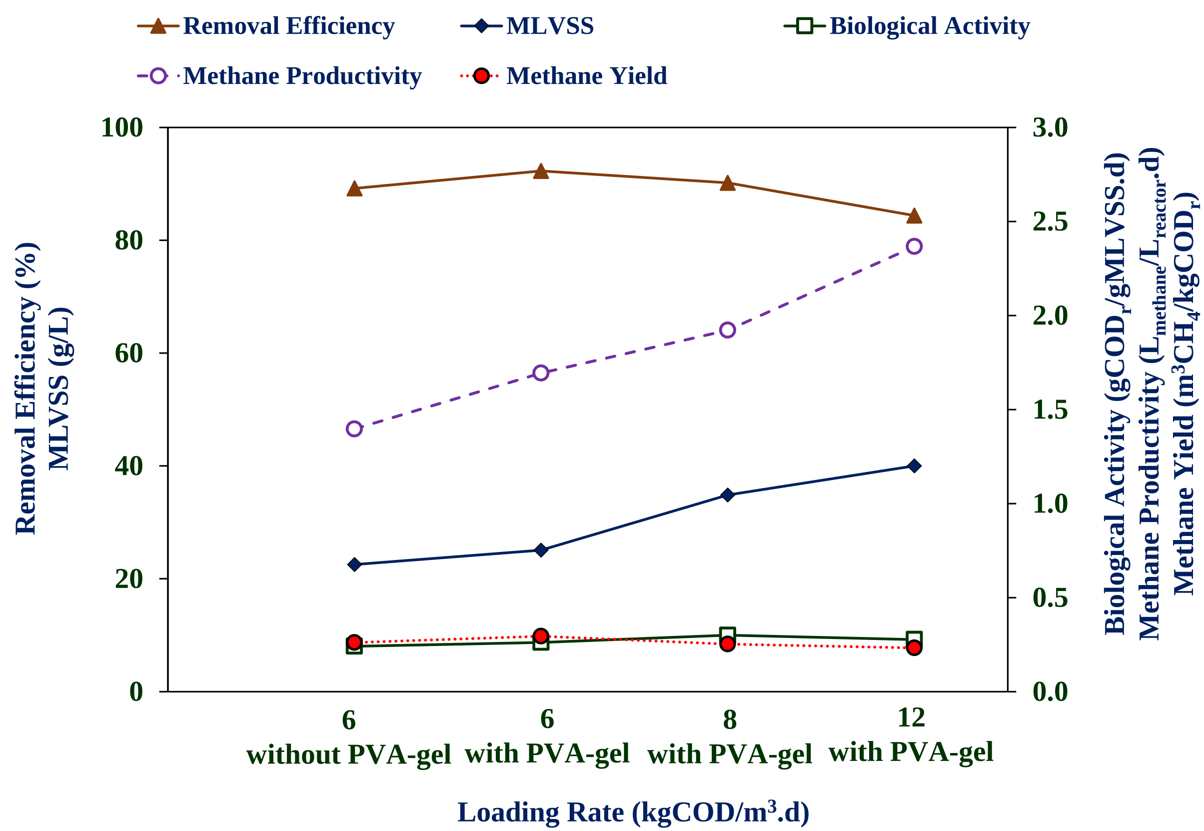
- ✓ **Methane Content: 53-60%**
- ✓ **Methane Generation: increase from 13 to 15 L/d with PVA-gel addition, and increased to 17 and 22 L/d with increasing OLR**
- ✓ **Methane Productivity: increase from 1.4 to 1.7 L/L.d with PVA-gel addition, and increased to 1.9 and 2.4 L/L.d with increasing OLR**

Obj 2

Page 69, Fig 4.15

Results and Discussion

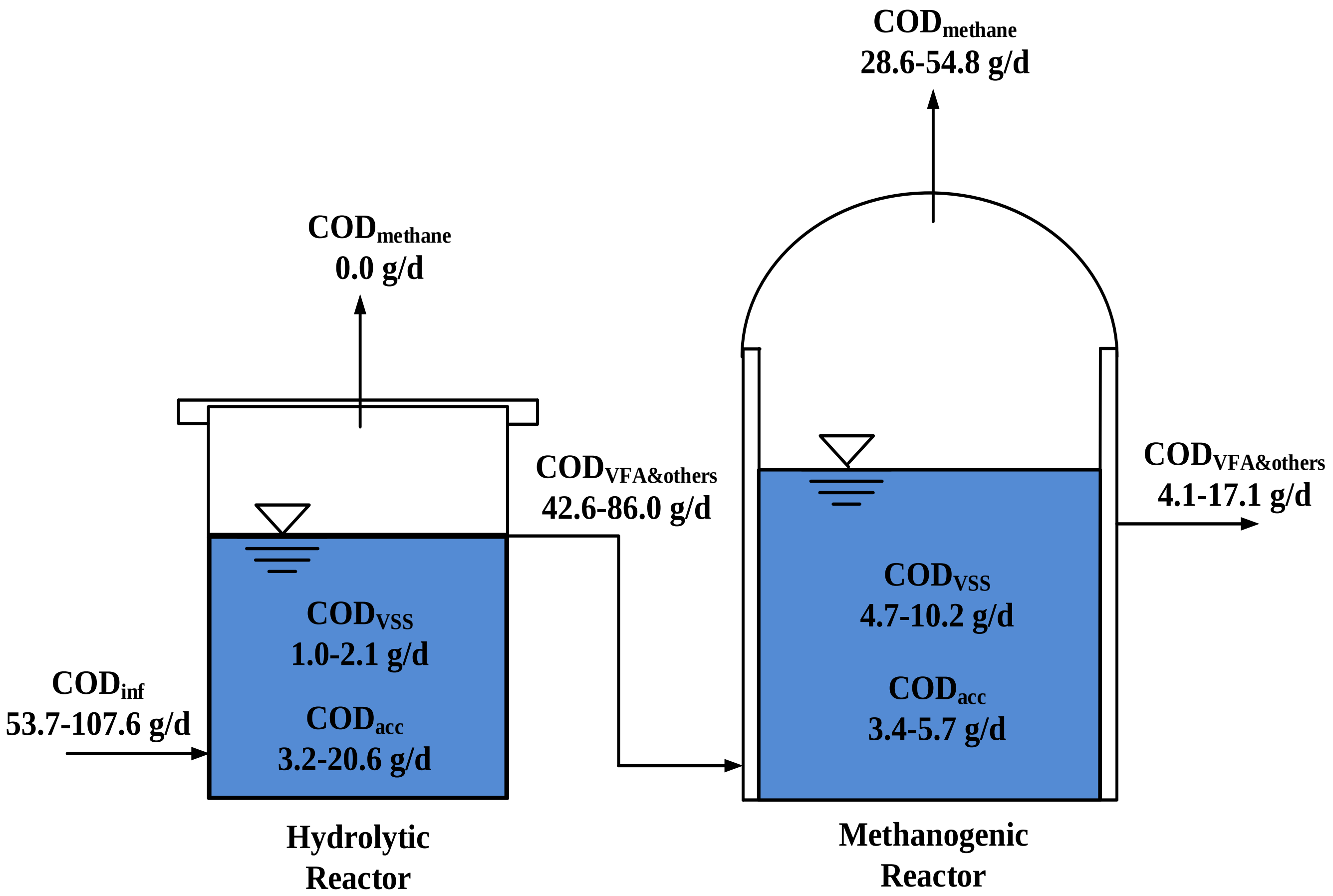
Methanogenic Reactor Performance



- ✓ **MLVSS: gradually increased from 23 to 25 g/L in later stage, and increase to 35 and 40 g/L with increasing loading rate**
- ✓ **Methanogenic Activity: 0.24 and 0.30 $kgCOD_r$/kgMLVSS.d. This indicated the balance between organic removal rate and biomass concentration**
- ✓ **Methane Productivity: increase from 1.4 to 1.7 with PVA-gel addition, and to 1.9 and 2.3 $L_{methane}/L_{reactor}$.d with increasing loading rate**
- ✓ **Methane Yield: 0.23 to 0.29 $m^3CH_4/kgCOD_r$**

Results and Discussion

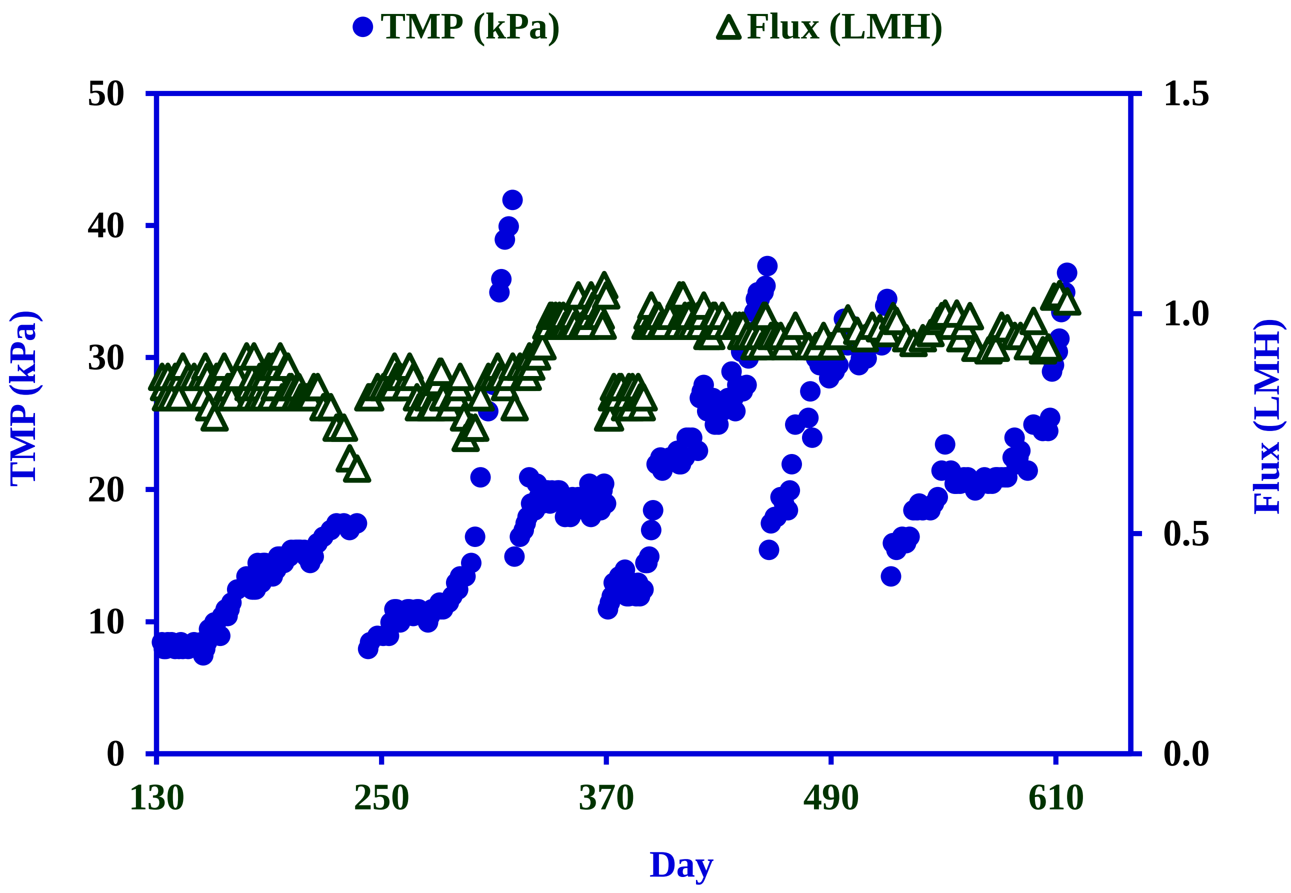
Pathway of Organic Carbon



- ✓ The pathway of COD$_{inf}$ can be summarized as COD$_{VFA\&others}$, COD$_{methane}$, COD$_{VSS}$ and COD$_{acc}$
- ✓ Hydrolytic reactor: 79.3, 90.3, 91.7 and 79.9% of COD$_{inf}$ were transferred to VFA, and about 3.8, 3.6, 1.5 and 1.0% were formed biomass
- ✓ Methanogenic reactor: 11.1, 10.9, 10.5 and 11.9% of COD$_{inf}$ were formed biomass , and about 67.1, 73.7, 70.8 and 63.7% were converted to methane

Results and Discussion

Membrane fouling



- ✓ Flux: 0.86 and 1.04 $L/m^2.h$ to maintain OLR at 8 and 12 $kgCOD/m^3.d$
- ✓ TMP: Once TMP increased, membrane cleaning was done by chemical cleaning
- ✓ Fouling Analysis was conducted according to resistance in series model

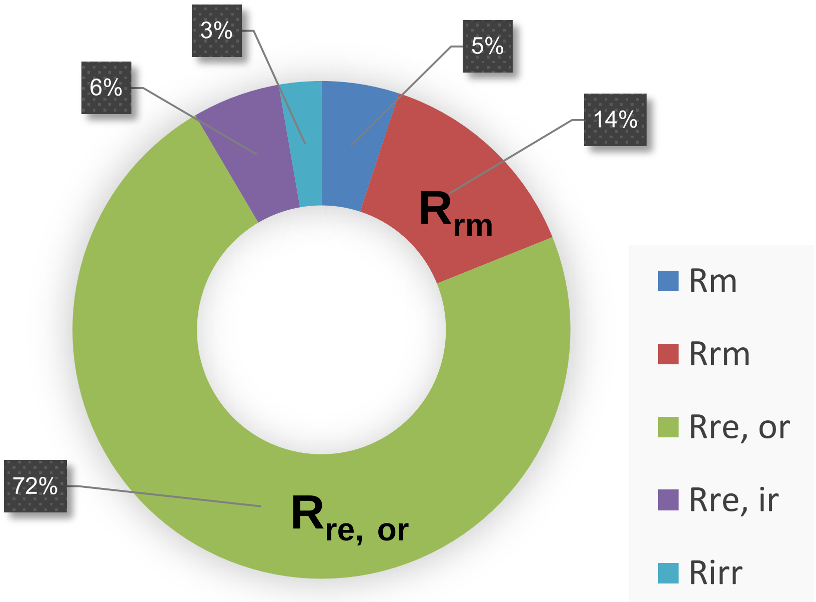
Obj 3

Page 76, Table 4.10

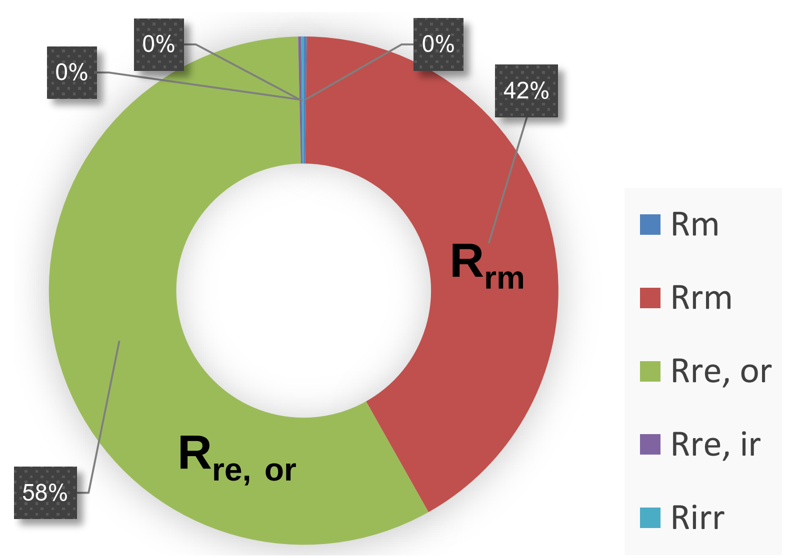
Results and Discussion

Membrane fouling

Item	Membrane Resistance (m^{-1})	
	OLR 8 kgCOD/m³.d	OLR 12 kgCOD/m³.d
Intrinsic membrane resistance (R_m)	3.81×10^8	3.81×10^8
Removable fouling resistance (R_{rm})	1.05×10^9	8.07×10^{10}
Reversible organic fouling resistance ($R_{re, or}$)	5.49×10^9	1.12×10^{11}
Reversible inorganic fouling resistance ($R_{re, ir}$)	4.32×10^8	3.71×10^8
Irreversible fouling resistance (R_{irr})	2.08×10^8	2.94×10^8
Total filtration resistance (R_t)	7.56×10^9	1.94×10^{11}



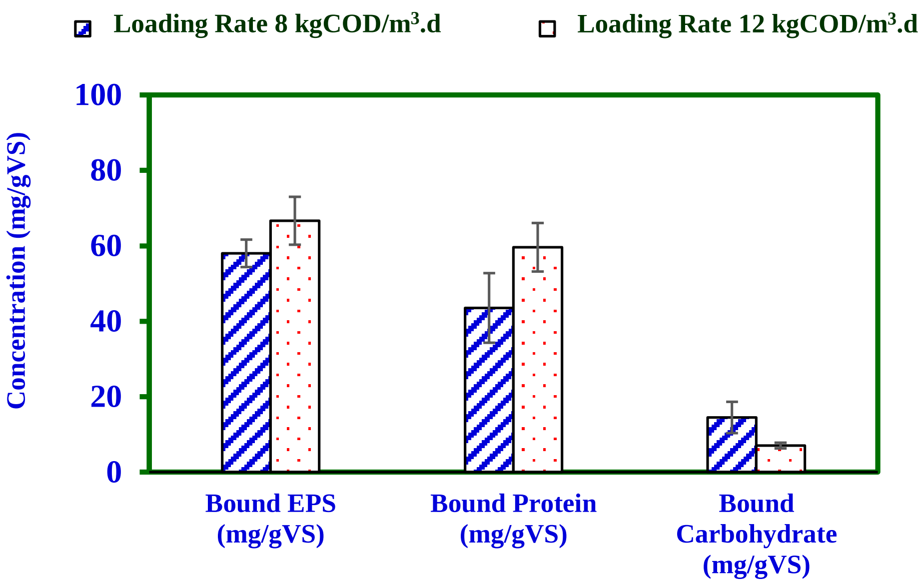
OLR 8



OLR 12

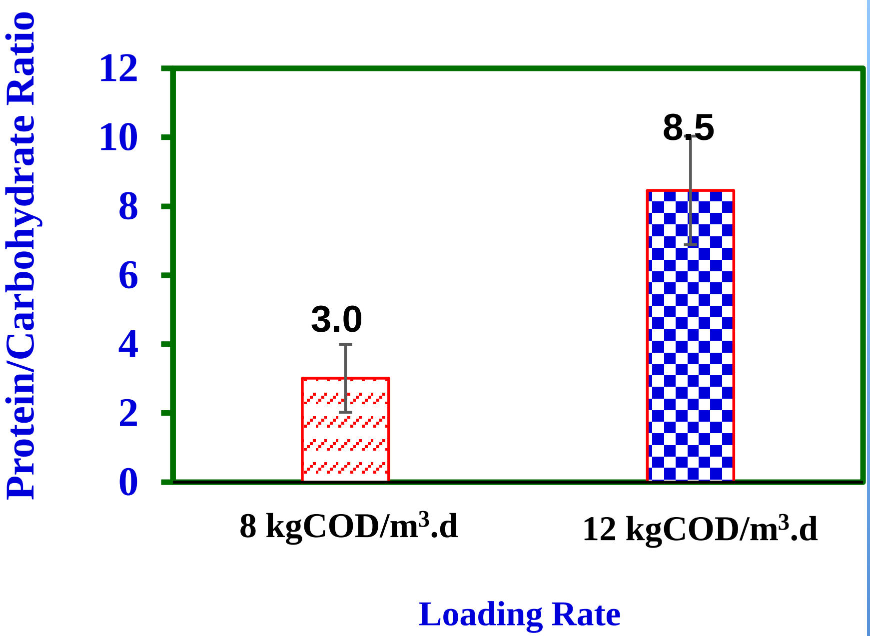
Results and Discussion

Membrane fouling



- ✓ Bound EPS: 58 and 66.7 mg/gVSS
- ✓ Bound Protein: 43.5 and 59.6 mg/gVS
- ✓ Bound Carbohydrate: 14.5 and 7.1 mg/gVSS

- ✓ PN/PS ratio: 3.0 and 8.5 due to high protein and low carbohydrate
- ✓ Filtration resistance: Higher PN/PS ratio more sticky favor to promote cake layer formation
- ✓ Predominant fouling: protein



Energy Balance and Comparison

	AnMBR (Literature)	Two Stage TAnMBR
Energy Generation	5-20* kWh/m³	14.6-24.3 kWh/m³
Energy Requirement	3-7.3* kWh/m³	12-15 kWh/m³

- Heating
- Mixing pump, biomass recirculation pump
- Pumping (suction) to membrane

*Source: Fuch et al. (2003); Liao et al. (2006)

Conclusion

Bioresource Technology 168 (2014) 100–105

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journal homepage: www.elsevier.com/locate/biortech

Effect of polyvinyl alcohol hydrogel as a biocarrier on volatile fatty acids production of a two-stage thermophilic anaerobic membrane bioreactor

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Desalination and Water Treatment

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Performance improvement in a two-stage thermophilic anaerobic membrane bioreactor using PVA-gel as biocarrier

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Published online: 04 Jul 2014.

Conclusion

Chaikasem, S., Abeynayaka, A. and Visvanathan, C. (2014). Effect of polyvinyl alcohol hydrogel as a biocarrier on volatile fatty acids production of a two-stage thermophilic anaerobic membrane bioreactor. *Bioresource Technology*, 108, 100-105.

- VFA concentration was significantly increased from 4.0 to 4.6 g/L at OLR 6 kgCOD/m^3.d with PVA-gel addition.
- Biological activity had increased from 0.50 to 0.61 gVFA/gMLVSS.d when PVA-gel was added in hydrolytic reactor at loading rate 6 kgCOD/m^3.d. The increasing in biological activity at similar OLR with constant biomass concentration could be due to the benefit of PVA-gel.
- The positive effect of PVA-gel on hydrolytic reactor

Objectives

- To investigate the effect of PVA-gel as biocarrier on total VFA concentration and methane production of two stage TAnMBR.

Conclusion

Chaikasem, S., Jacob, P. and Visvanathan, C. (2014).Performance improvement in a two-stage thermophilic anaerobic membrane bioreactor using PVA-gel as biocarrier. *Desalination and Water Treatment*, 1-11.

- **The ORR was observed as 5.3, 5.5, 7.6 and 10.1 kgCOD/m^3.d in loading rate of 6 (without PVA-gel), 6 (with PVA-gel), 8 (with PVA-gel) and 12 (with PVA-gel) kgCOD/m^3.d with COD removal efficiency of 84-92%.**
- **Methane productivity significantly increased from 1.4 to 1.7 $L_{methane}/L_{reactor}$.d at OLR 6 kgCOD/m^3.d. The increasing in methane productivity was due to increase in VFA concentration in hydrolytic effluent to methanogenic reactor.**
- **The total membrane resistance (R_t) at loading rate 12 kgCOD/m^3.d was higher than loading rate 8 kgCOD/m^3.d.**
- **The majority of membrane fouling at higher loading condition was caused by accumulation of organic compounds .**

Objectives

- **To study the performance at optimized two stage TAnMBR in different loading rates.**
- **To investigate the fouling characteristics of two stage TAnMBR.**

Publication of This Study

International Conference

Chaikasem, S., Abeynayaka, A. and Visvanathan. C. (2012). Effect of Biocarrier on the Performance of Two Stage Thermophilic Anaerobic Membrane Bioreactor. Water and Environment Technology Conference, Tokyo, Japan, June 29-30, 2012.

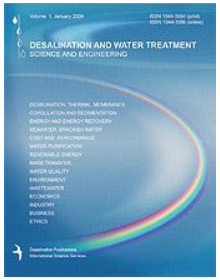
Chaikasem, S., Abeynayaka, A. and Visvanathan. C. (2013).Effect of Biocarrier on the acidogenesis process of Two Stage Thermophilic Anaerobic Membrane Bioreactor. International Conference of Solid Waste 2013, Hong Kong, May 5-8, 2013.

Chaikasem, S., Jacob, P. and Visvanathan. C. (2013). Improvement of Two-Stage Thermophilic Anaerobic Membrane Bioreactor Performance by Biocarrier Addition. 2013 International Environmental Engineering Conference and Annual Meeting of the Korean Society of Environmental Engineers, Seoul, Korea, June 11-13, 2013.

Chaikasem, S., Jacob, P. and Visvanathan. C. (2014). Performance Evaluation of a Two Stage Thermophilic Anaerobic Membrane Bioreactor for Treating High Strength Particulate Wastewater. The 4th IWA Regional Conference on Membrane Technology 2014, Ho Chi Minh City, Viet Nam, December 3-6, 2014.

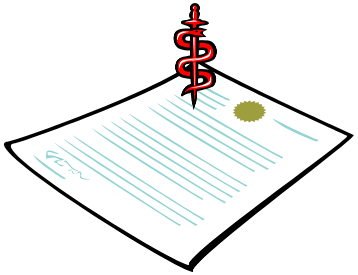
Publication of This Study

Publications



Chaikasem, S., Jacob, P. and Visvanathan. C. (2014). Improvement of Two-Stage Thermophilic Anaerobic Membrane Bioreactor Performance by Biocarrier Addition. *Desalination and Water Treatment*, 1-11.

Chaikasem, S., Abeynayaka, A. and Visvanathan. C. (2014). Effect of PVA-gel as biocarrier on volatile fatty acids (VFA) production of two-stage thermophilic anaerobic membrane bioreactor. *Bioresource Technology*, 168, 100-105.



Recommendations for Future Research

- The cultivated PVA-gel from the hydrolytic reactor should be use as seed sludge to start up the hydrolytic reactor. Furthermore, the effect of cultivated PVA-gel on degradation of organic matters to organic acids should be studied.

- The identifying microbial species and quantifications through microbial techniques such as fluorescence in situ hybridization (FISH), polymerase chain reaction (PCR) and denaturing gradient gel electrophoresis (DGGE) in different OLR should be studied.

- The parameter governing flux and fouling should be varied and studied. The effect of HRT and F/M ratio on fouling behavior in TAnMBR should be studied. Furthermore, anaerobic degradation model (Monod model, Contois model, Chen and Hashimoto model, Grau second order model, Stover-Kincannon model etc) should be developed in parallel with HRT variation at particular OLR.

- There is growing concern of recovering methane dissolved in the effluent. In this research much focus was not given to this issue by measurement but it was found by using carbon balance. Thus to ensure and increase the methane productivity of the system, striping of methane from the effluent needs to be addressed and effective primary data needs to be generated to address this issue.

Response to Comments of External Examiner

Effect of PVA-gel on Performance Improvement of Two Stage Thermophilic Anaerobic Membrane Bioreactor

Final Comprehensive Exam

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March 31, 2015

Question from External Examiner

Detail in the attached document

Conclusion Letters

1. It would be great if rationale/hypothesis section is also included in the objective.

Answer : I have added the hypothesis of the study in Section 1.3 on Page 3. The detail of hypothesis was shown as follows; the hypothesis of this study is that the total VFA concentration and methane production efficiency could be increased by the addition of PVA-gel as biocarrier into hydrolytic reactor, under thermophilic condition. Moreover, membrane fouling should be minimized by operating membrane in an external semi dead-end configuration by combining cross-flow and dead end configuration to single unit as two stage TAnMBR.

2. One part is mission in this section in statistical analysis. Since the student collected enough data for this research, it should be pretty easy to conduct statistical analysis to examine whether the findings are statistically different under different conditions.

Answer : I have added the statistic analysis in Section 3.7.10 on Page 52. The data analysis was carried out using SPSS 21.0. The statistical significance of values to compare the mean obtained during each experiment condition was carried out using analysis of variance (one-way ANOVA) to test the significance of the results, and $p < 0.05$ was considered to be statistically significant.

Question from External Examiner

Detail in the attached document

3. The student plotted all the data in the graphs, which is fine and adequate. It would be great in summary table for each condition is provided to quickly look the results. Also, why the VOLR selected was 6 and then increase to 8 and finally to 12 kgCOD/m^3.d. It seems the increase in loading rate a bit random. Some justification on this will be great.

Answer : I have added the summary table. The summary table was incorporated in each section to quickly look the results. The summary tables were added in Table 4.1 to 4.4 on Page 57, 59, 62 and 63. Moreover, overall OLR was increased by 2 kgCOD/m^3.d. However, once OLR was increased from 8 to 10 kgCOD/m^3.d, the two stage TAnMBR was not faced the problem about VFA accumulated. Therefore, OLR was finally increased to 12 kgCOD/m^3.d and operated until the system was stable. This sentence was justified in section 3.7.5 on Page 45.

Question from External Examiner

Detail in the attached document

Table 4.1 on Page 57

Day (d)	OLR ($kgCOD/m^3.d$)	pH	VFA (g/L)	MLVSS (g/L)	Methane Content (%)	Temp (°C)
1-6	2.0	5.5±0.2	-	13.7±0.6	-	35
7-13	3.0	5.6±0.1	-	13.0±0.5	-	37
14-40	4.0	4.7±0.1	1.8±0.4	11.0±1.1	7.9	39
41-48	6.0	5.4±0.2	2.6±0.2	8.5±1.0	5.2	41
49-58	10.0	5.5±0.3	2.5±0.1	5.0±0.8	2.8	43
59-77					1.9	45
78-92	14.67	5.3±0.1	2.2±0.1	4.8±0.6	1.0	47
93-99	16.0	5.3±0.2	2.7±0.1	8.3±0.9	0.6	49
100-105					0.6	51
106-124					0.3	53
125-139					nd	55
140-145	18.67	5.2±0.3	2.2±0.1	8.9±0.1	nd	55

Question from External Examiner

Detail in the attached document

Table 4.2 on Page 59

<table>
<tr><th>Day (d)</th><th>OLR (kgCOD/m³.d)</th><th>pH</th><th>Removal Efficiency (%)</th><th>MLVSS (g/L)</th><th>Methane Content (%)</th><th>Temp (°C)</th></tr>
<tr><td>1-6</td><td>2.0</td><td>7.1±0.1</td><td>-</td><td>20.3±0.2</td><td>-</td><td>35</td></tr>
<tr><td>7-13</td><td rowspan="2">2.5</td><td rowspan="2">7.0±0.2</td><td>-</td><td rowspan="2">19.9±0.6</td><td>-</td><td>37</td></tr>
<tr><td>14-37</td><td>-</td><td>26.3</td><td>39</td></tr>
<tr><td>38-40</td><td rowspan="2">3.0</td><td rowspan="2">7.3±0.1</td><td>64.7</td><td rowspan="2">10.3±0.4</td><td>28.3</td><td>39</td></tr>
<tr><td>41-48</td><td>56.1</td><td>40.2</td><td>41</td></tr>
<tr><td>49-58</td><td>3.5</td><td>7.6±0.2</td><td>76.0</td><td>12.5±0.9</td><td>46.3</td><td>43</td></tr>
<tr><td>59-77</td><td>3.5</td><td>7.1±0.1</td><td>71.1</td><td>9.2±0.4</td><td>42.0</td><td>45</td></tr>
<tr><td>78-92</td><td rowspan="5">5.3</td><td>7.3±0.1</td><td>68.1</td><td>11.7±0.8</td><td>53.9</td><td>47</td></tr>
<tr><td>93-99</td><td>7.2±0.2</td><td>61.1</td><td>12.5±0.5</td><td>54.4</td><td>49</td></tr>
<tr><td>100-105</td><td>7.4±0.3</td><td>58.9</td><td>12.0±0.9</td><td>55.8</td><td>51</td></tr>
<tr><td>106-117</td><td>7.0±0.5</td><td>56.0</td><td>10.4±1.2</td><td>53.7</td><td>53</td></tr>
<tr><td>118-124</td><td rowspan="2">7.2±0.4</td><td rowspan="2">54.0</td><td rowspan="2">5.9±0.5</td><td rowspan="2">49.0</td><td>53</td></tr>
<tr><td>125-129</td><td rowspan="2">7.0</td><td>55</td></tr>
<tr><td>130-139</td><td>7.7±0.1</td><td>72.5</td><td>15.2±1.1</td><td>46.5</td><td>55</td></tr>
<tr><td>140-145</td><td>8.0</td><td>7.3±0.1</td><td>71.8</td><td>16.6±0.9</td><td>47.7</td><td>55</td></tr>
</table>

Question from External Examiner

Detail in the attached document

Table 4.3 on Page 62

Wastewater	Reactor	T (°C)	OLR ($kgCOD/m^3.d$)	VFA (g/L)	Reference
Synthetic (Molasses)	Multistage biofilm	35	5-9	1.5-3.7	Ghaniyari-Benis et al. (2009)
Synthetic (Molasses)	Two stage TAnMBR	55	5-12	2.5-6.9	Wijekoon et al. (2011)
Cassava wastewater	Two stage UASB	55	5-15	5.0-13.0	Intanoo et al. (2014)
Synthetic (Tapioca starch)	Two stage TAnMBR	55	6-12	4.0-6.0	This study

Question from External Examiner

Detail in the attached document

Table 4.4 on Page 63

Wastewater	Reactor	T (°C)	$TCOD_{inf}$ (g/L)	$TCOD_{eff}$ (g/L)	TCOD Removal Efficiency (%)	Reference
Cheese whey	Two stage AnMBR	37	68.6	65.6-56.6	18	Saddoud et al. (2007)
Cassava Wastewater	Two stage UASB	55	15	9.75-12	20-35	Intanoo et al. (2014)
Synthetic (Tapioca starch)	Two stage TAnMBR	55	15-24	13.0-19.1	8-20	This study

Question from External Examiner

Detail in the attached document

2. How about homoacetogens? This should be clarified.

Ans: I had clarified the explanation of homoacetogens in Section 2.2 on Page 5-6. Methanogenic archaea and homoacetogens are the main hydrogen consumers. At low hydrogen partial pressures, hydrogen forming reactions become thermodynamically favorable and there is a shift in fermentation toward the production of acetate and away from butyrate and ethanol. However, homoacetogems become increasingly important for removing hydrogen especially when methanogenic archaea is inhibited. An increased in acetic acid in the first stage reactors enhance acetoclastic methanogenesis in second stage reactors. Moreover, low and high hydrogen partial pressure maintained by hydrogenotrophic methanongens (<2 Pa) and homoacetogens (<200 Pa) are a key requirement for thermodynamic feasibility of reaction products (Kotsyurbenko et al., 2001; Paulo et al., 2003). Hence, high H_2 partial pressure will be favored with the formation of VFA having more than two carbon atoms (butyric acid and propionic acid) while low H_2 , acetic acid will predominate.

Question from External Examiner

Detail in the attached document

5. Section 4.1.1 Any contribution of particulate organic matters to MLVSS? and How MLVSS was differentiate with tapioca starch particulate?

Ans: Tapioca starch based synthetic wastewater was heated at 55 ± 3 °C to dissolve the particulate matter before feeding to the system. This was done to simulate high strength particulate wastewater discharge at high temperature. However, there was the contribution of particulate matters to VSS in small quantity. It was difficult to differentiate VSS from particulate matters. This was due to the paticulate matters was heated at high temperature to make it dissolve in soluble form. Also, particulate matter is solubilized by enzymes excreted by hydrolytic microorganisms to generated soluble organic components including the products of hydrolysis are converted in to VFA. This explanation was incorporated in Section 3.3 on page 37 about the reason for heated the tapioca starch before feeding to the system.

Question from External Examiner

Detail in the attached document

6. Section 4.1.2 Why not use acetic acid as substrate?

Ans: At high H_2 partial pressure in hydrolytic reactor will be favoured with the formation of VFA having more than two carbon stoms (e.g. butyric acid and propionic acid) and ethanol. These products are converted further to methanogenic substrate such as acetic acid, H_2 and CO_2 by the acetogeic bacteria through the acetogenic dehydrogenation reaction. Therefore, butyric acid was used as sole carbon source during enrichment and acclimatization phase of the study. This explanation was incorporated in Section 3.7.3.2 on Page 43-44.

9. Section 4.2.1 Did you also quantity biomass attached in PVA-gel. How about the biomass attached in the PVA-gel?

Ans: Yes. The methodology for measuring the quantity biomass attached in PVA-gel was incorporated in Section 3.10.5 on Page 52. Also, the biomass attaced in the PVA-gel was 0.5 gVSS/gPVA-gel. Please see the detail in the Section 4.2.3 on Page 63-64.

10. Section 4.2.1 At higher loading rate what would have happen without PVA-gel?

Ans: The MLVSS (representing the microbial concentration) in hydrolytic reactor would be decreased with increasing loading rates. This is the reason why PVA-gel was used as biocarrier in hydrolytic reactor

Question from External Examiner

Detail in the attached document

16. Section 4.2.2 It would be good if incorporated mass balance in terms of COD to see the organic distribution.

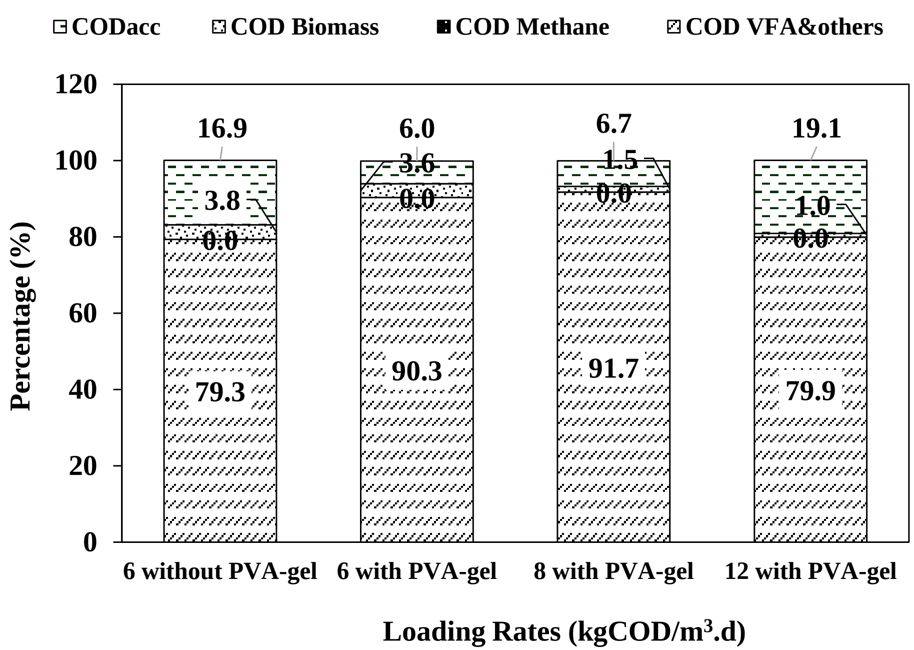
Ans: The mass balance in tems of COD distribution (pathway of organic carbon) was incorporated in Section 4.4.3 and Appendix H.

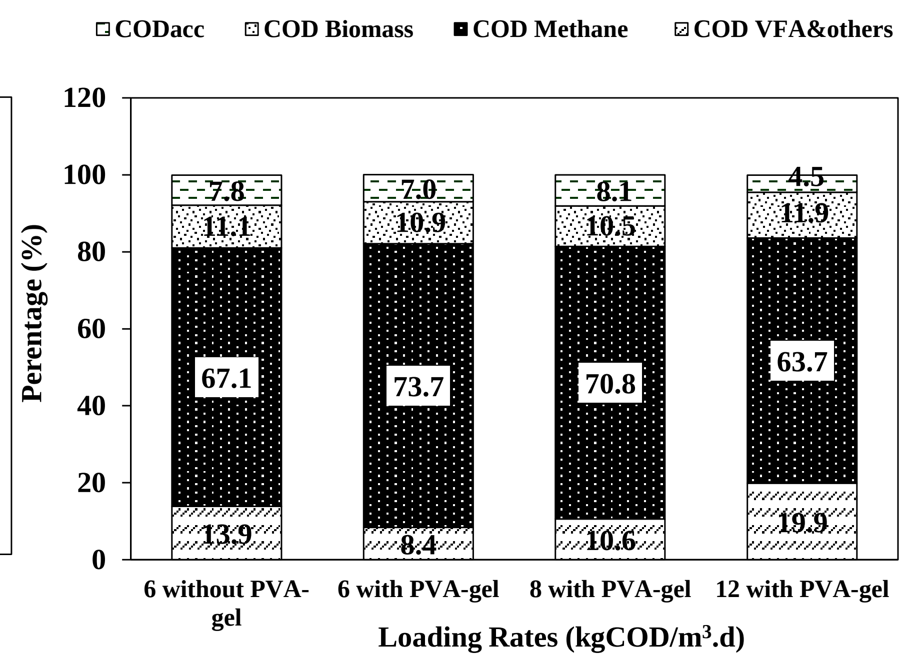
$COD_{influent} = COD_{VFA\&others} + COD_{methane} + COD_{vss} + COD_{accumulate}$	
$COD_{influent}$	COD concentration of tapioca starch based synthetic wastewater
$COD_{VFA\&others}$	COD concentrations of effluents VFA, including acetate, butyrate, propionate, other types of VFA, and the other patterns of COD which converted to trace amount of CO_2, H_2, methane dissolved in the effluent
$COD_{methane}$	$COD_{methane}$ was a part of organic matter that was measured in gaseous methane
COD_{vss}	COD_{vss} represents the organic matter contributing to biomass formation
$COD_{accumulate}$	COD concentration of complex organic matter that is non-biodegradable organic matter but can be measured as a part of COD

Question from External Examiner

Detail in the attached document

Continue question 16.





- ✓ The pathway of COD_{inf} can be summarized as $COD_{VFA\&others}$, $COD_{methane}$, COD_{VSS} and COD_{acc}
- ✓ Hydrolytic reactor: 79.3, 90.3, 91.7 and 79.9% of COD_{inf} were transferred to VFA, and about 3.8, 3.6, 1.5 and 1.0% were formed biomass
- ✓ Methanogenic reactor: 11.1, 10.9, 10.5 and 11.9% of COD_{inf} were formed biomass, and about 67.1, 73.7, 70.8 and 63.7% were converted to methane

Microorganism

Working to make

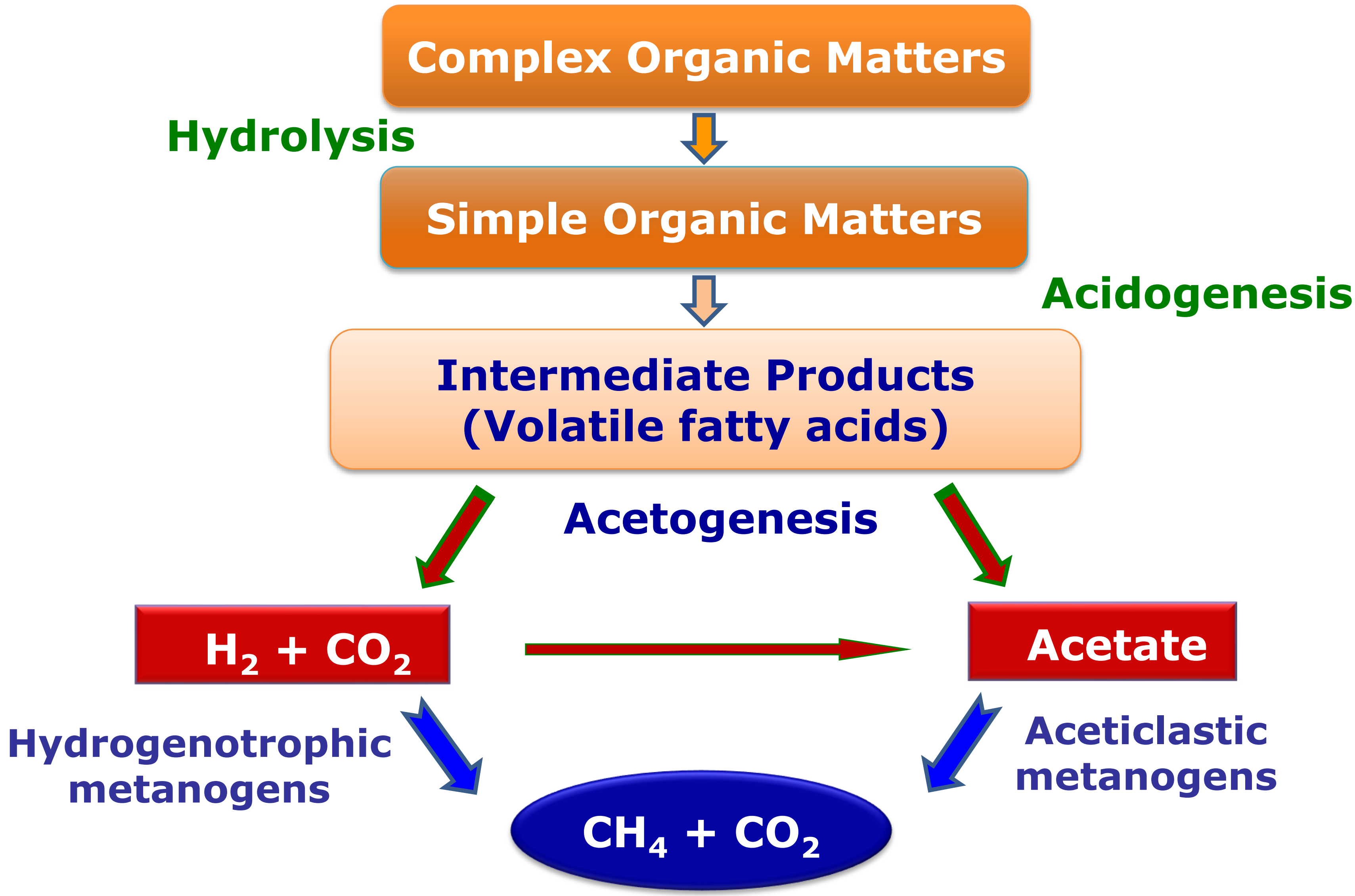
WASTE to

CH_4

Thank You for Your Attention

Clean Environment
Clean Energy
Clean Future

Anaerobic: Metabolic Pathway



Characteristic of Anaerobic Bacteria

Acid formers	Methane formers
➢ Facultative bacteria	➢ Strictly anaerobe
➢ Substrate is higher organic acid	➢ Substrate is VFA
➢ 5.5<pH<7.2	➢ 6.8<pH<7.8
➢ Non-specific to substrate	➢ Specific to substrate
➢ Robust (can adapt to new condition)	➢ Sensitive to new environmental condition ie. pH, Temperature
➢ Yield coefficient (0.2-0.5)	➢ Yield coefficient (0.02-0.1)
➢ Generation time 8-12 hours	➢ Generation time 10-20 days

Source: Metcalf&Eddy, 2003

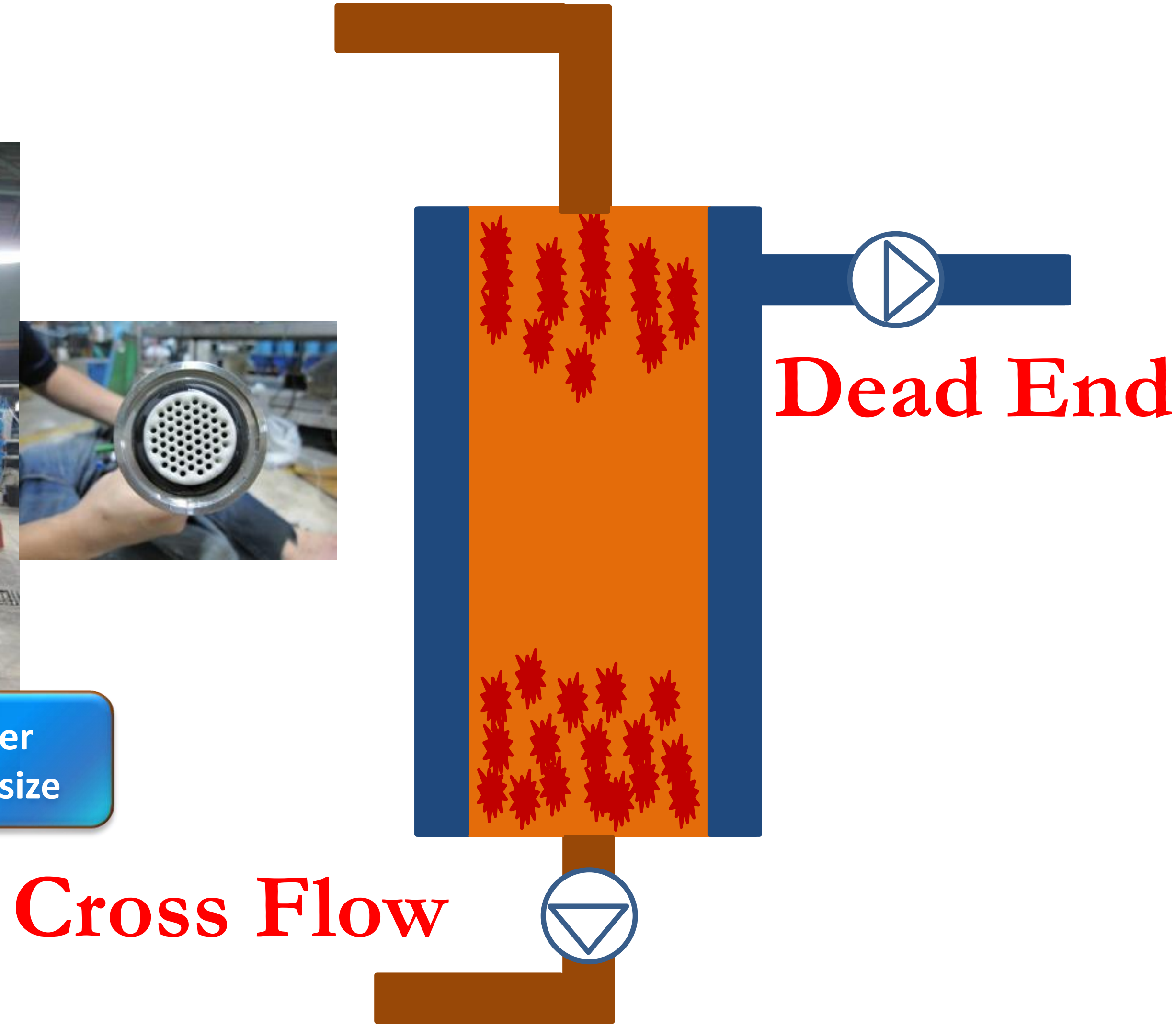
Symbiotic relationship between two groups of bacteria is important

Conversion reaction

Reaction	ΔG°' (kJ/mol)	
	25°C	55°C
Butyrate to Acetate		
$CH_3CH_2CH_2COO^- + 2H_2O \longrightarrow 2CH_3COO^- + H^+ + 2H_2$	+48.1	+37.9
$CH_3CH_2CH_2COO^- + 2HCO_3^- \longrightarrow 2CH_3COO^- + H^+ + 2HCOO^-$	+45.5	+36.1
Propionate to Acetate		
$CH_3CH_2COO^- + 3H_2O \longrightarrow CH_3COO^- + HCO_3^- + H^+ + 3H_2$	+76.1	+62.3
$CH_3CH_2COO^- + 2HCO_3^- \longrightarrow CH_3COO^- + H^+ + 3HCOO^-$	+72.2	+59.7
Acetate to Methane		
$CH_3COO^- + H_2O \longrightarrow HCO_3^- + CH_4$	-31.0	-34.7
Hydrogen to Methane		
$HCO_3^- + H^+ + 4H_2 \longrightarrow CH_4 + 3H_2O$	-135.6	-122.5
Formate to Methane		
$4HCOO^- + H^+ + H_2O \longrightarrow CH_4 + 3HCO^-$	-130.4	-118.9

Mode of Operation: Partial Sedimentation

Monolith Ceramic Micro filter membrane with 0.1 µm pore size



Membrane Operation in external semi dead-end Mode (Combination between Dead End and Cross Flow

Ceramic Membrane Specification

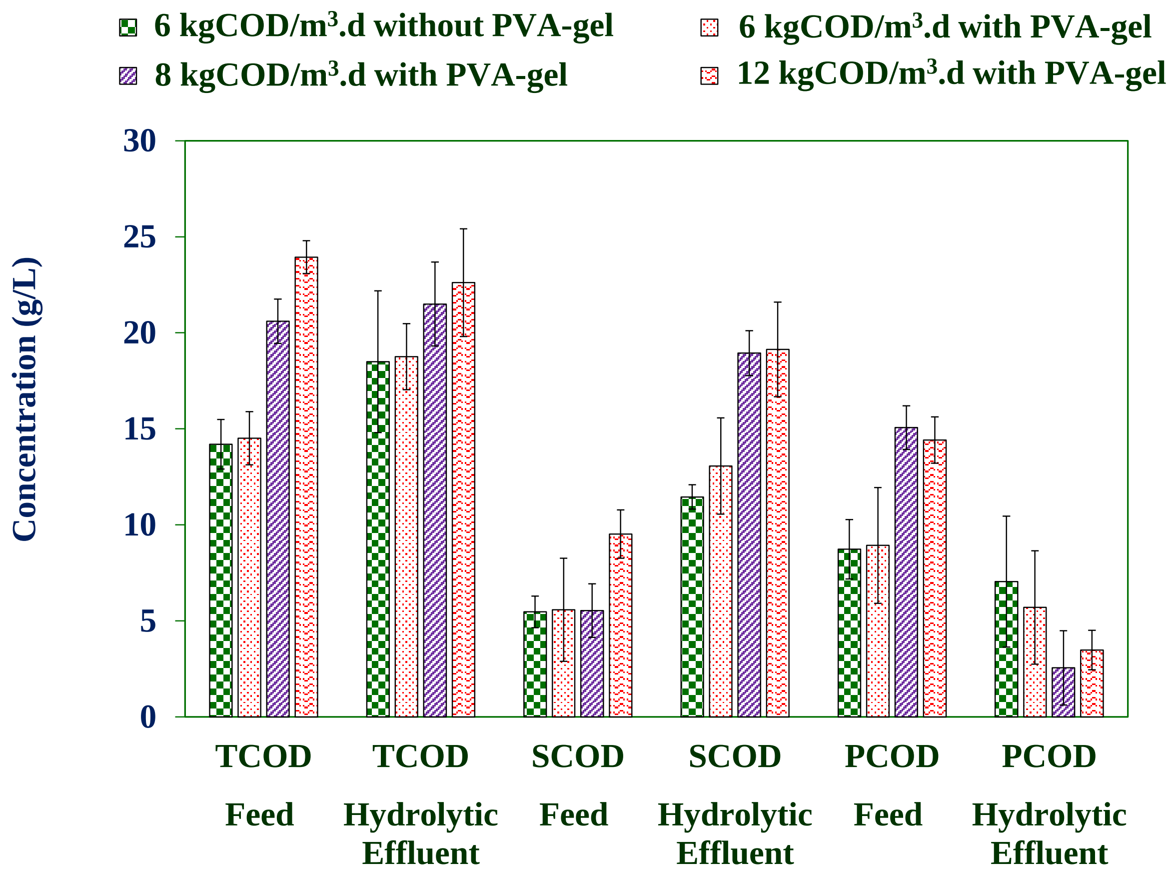
Parameter	Value/Specification
Membrane manufacturer	NGK Insulator, Japan
Membrane material	Ceramic
Membrane type	Microfiltration
Module configuration	Tubular (multi-channel)
Channel number	55
Effective surface area	0.18 m^2
Pore size	0.1 μm
Maximum flux	87.5 $L/m^2.h$
Dimensions	Diameter-30 mm, Length-450 mm
Configuration	Inside-Out
Operating pressure range	20-90 kPa
Maximum operating temperature	300°C

Operating Conditions of Two Stage TAnMBR

Parameter	Unit	Hydrolytic Reactor	Methanogenic Reactor	Overall
pH	-	5.4±0.5	7.2±0.3	-
Temperature	°C	55	55	55
Influent COD	g/L	15 20 24	12 16 19.2 (Calculated)	15 20 24
Loading rates	kgCOD/m^3.d	18.67 23.33 36	7.46 9.33 14.4	6 8 12
HRT	h	19.45 16	38.92 32	58.37 (6, 8 kgCOD/m^3.d) 48 (12 kgCOD/m^3.d)
SRT	d	0.81 0.67	∞	-
Flow rate	L/d	3.7 4.5	3.7 4.5	3.7 (6, 8 kgCOD/m^3.d) 4.5 (12 kgCOD/m^3.d)
Working volume	L	3	6	9
Biomass retention	-	PVA-gel (30% v/v)	Ceramic Membrane	-
Permeate flux	L/m^2.h	0.86 (6, 8 kgCOD/m^3.d) 1.04 (12 kgCOD/m^3.d)		

Results and Discussion

Hydrolytic Reactor Performance

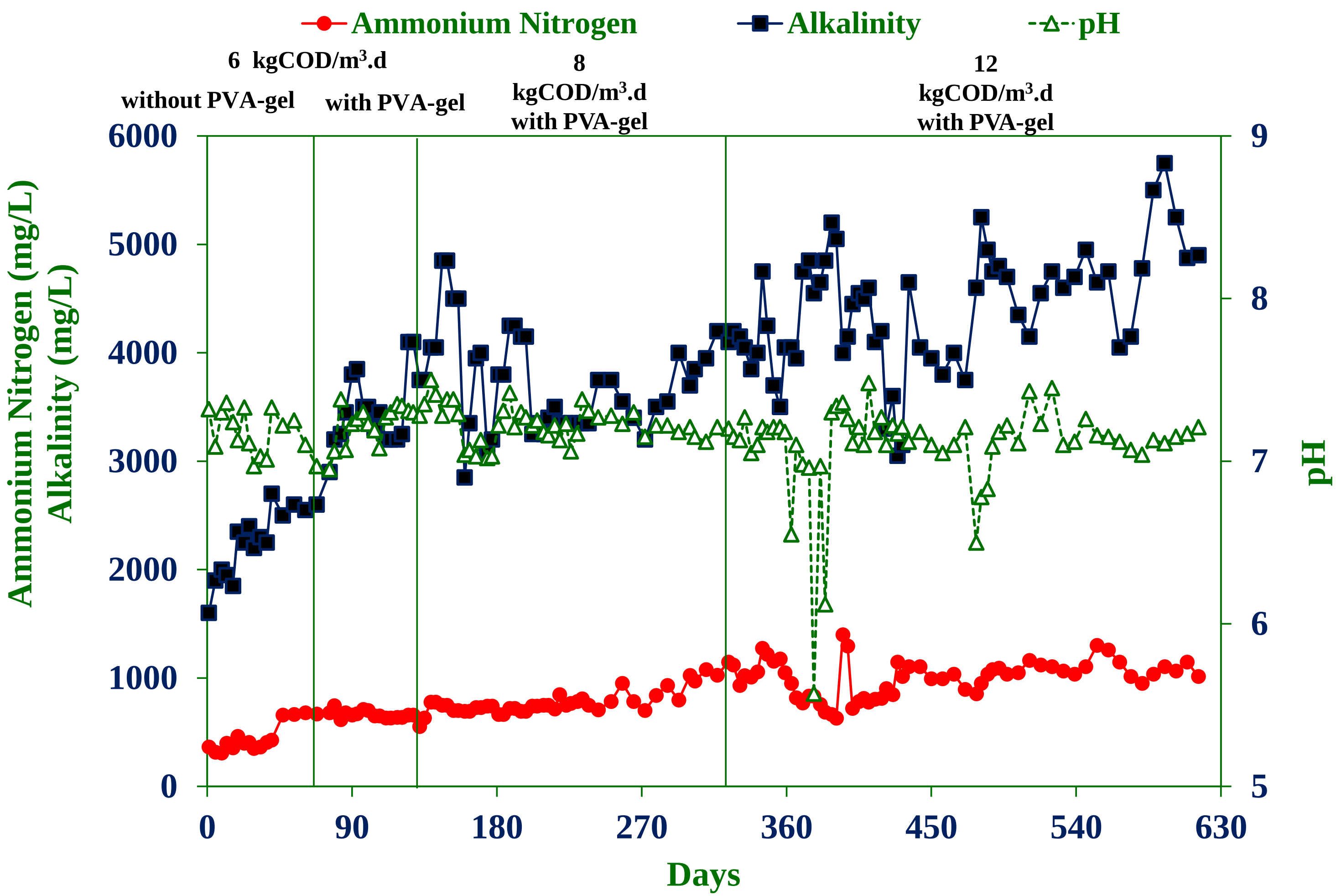


✓ **SCOD : increasing from 11.5 to 13.1 g/L with PVA-gel addition. Also, increase with increasing loading rate from 13.1 g/L, and increase to 18.9 and 19.1 g/L at 8 and 12 kg COD/m^3.d**

✓ **PCOD: An increasing in SCOD while decreasing in PCOD could be due to the particulate matter was being utilized by acidogens to produce SCOD and VFA**

Results and Discussion

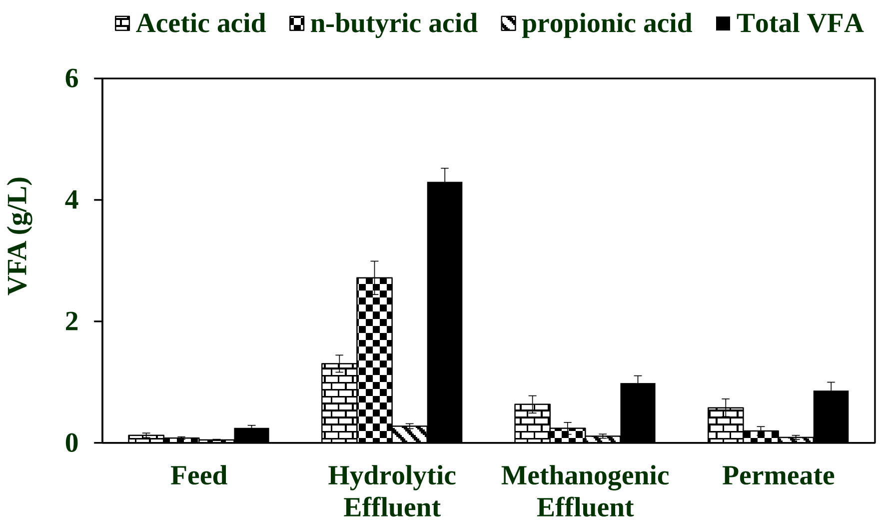
Methanogenic Reactor Peformance



- ✓ **Ammonia: 664, 900 and 1,100 mg/L**
- ✓ **Alkalinity: 2,590, 3,480, 3,695 and 4,717 mg/L**
- ✓ **pH: 7.2**

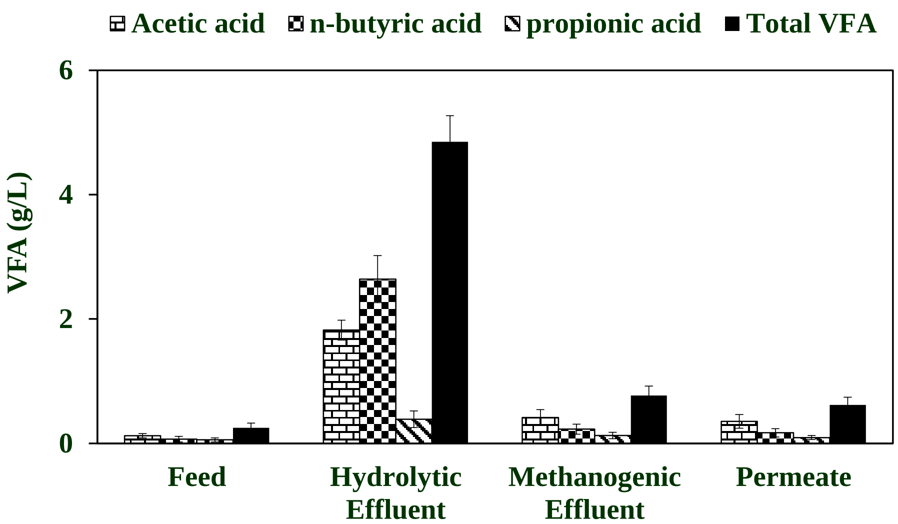
Results and Discussion

VFA Profile of System



6 kgCOD/m^3.d without PVA-gel

- ✓ VFA generation: 4.0 g/L
- ✓ VFA removal efficiency : 77%
- ✓ Predominant type of VFA : acetic acid and butyric acid

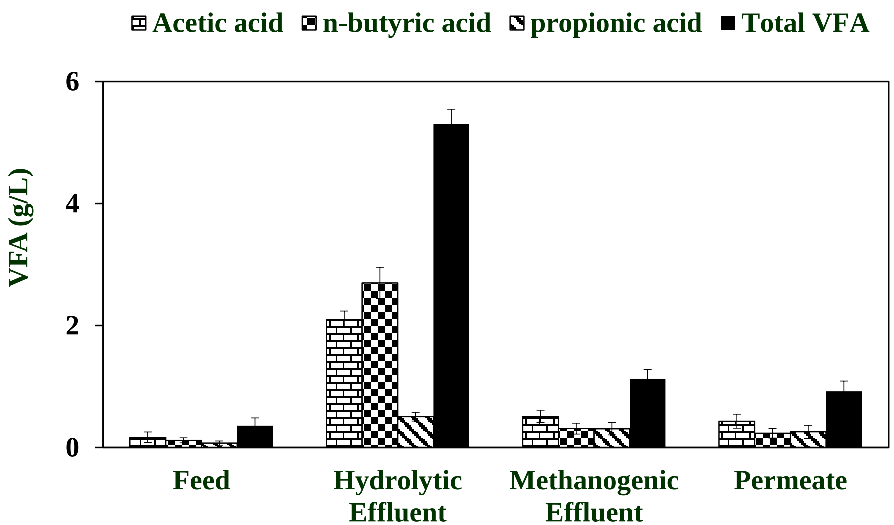


6 kgCOD/m^3.d with PVA-gel

- ✓ VFA generation: 4.6 g/L (increase 15%)
- ✓ VFA removal efficiency : 84%
- ✓ Predominant type of VFA : acetic acid and butyric acid
- ✓ Propionic acid : less than inhibition level (500mg/L)

Results and Discussion

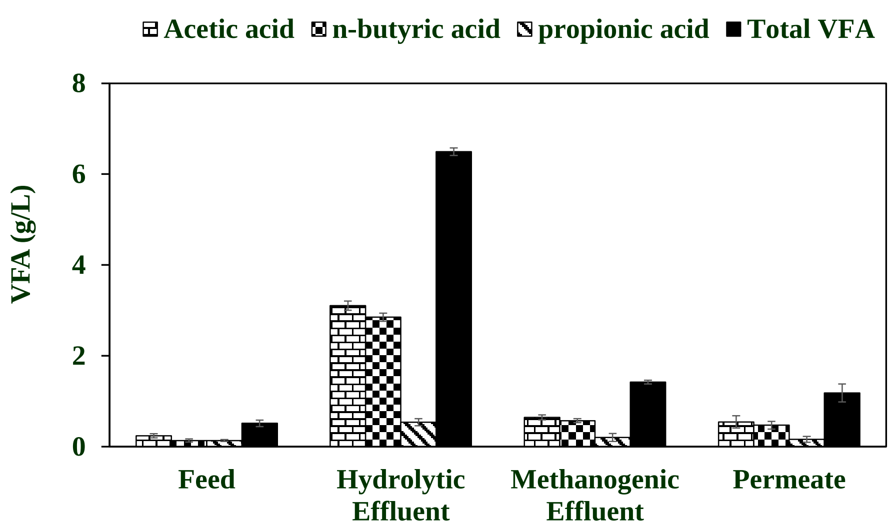
VFA Profile of System



8 kgCOD/m^3.d with PVA-gel

- ✓ VFA generation: 4.9 g/L
- ✓ VFA removal efficiency : 79%
- ✓ Predominant type of VFA : acetic acid and butyric acid

- ✓ VFA generation: 6.0 g/L
- ✓ VFA removal efficiency : 70%
- ✓ Predominant type of VFA : acetic acid and butyric acid



12 kgCOD/m^3.d with PVA-gel