Transforming the Infectious Septage into Biogas by Co-digestion Process

Miss Nanja Hummelink

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การเปลี่ยนรูปสลัดจ์บ่อเกรอะติดเชื้อเป็นก๊าซชีวภาพโดยกระบวนการย่อยสลายร่วม

นางสาวนันยา ฮูมเมลิงค์

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรมหาบัณฑิต
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นันยา ฮูมเมลิงค์ : การเปลี่ยนรูปสลัดจ์บ่อเกรอะติดเชื้อเป็นก๊าซชีวภาพโดยกระบวนการย่อยสลายร่วม (Transforming the Infectious Septage into Biogas by Co-digestion Process) อ.ที่ปรึกษาวิทยานิพนธ์หลัก: ผศ. ดร. ปฏิรูป ผลจันทร์, 147 หน้า.

ความต้องการใช้พลังงานนั้นมีเพิ่มขึ้นทุกวันตามจำนวนประชากรที่เพิ่มขึ้นในขณะที่ทรัพยากรธรรมชาติมีอยู่อย่างจำกัด ในขณะเดียวกันจำนวนประชากรที่เพิ่มขึ้นเหล่านี้ก่อให้เกิดของเสียเป็นจำนวนมาก ตัวอย่างเช่นสลัดจ์บ่อเกรอะ(ตะกอนที่สะสมอยู่ในบ่อเกรอะและมีธาตุอาหารสะสมอยู่)ซึ่งมักจะมีการจัดการอย่างไม่เหมาะสม เพื่อเป็นแนวทางหนึ่งในการแก้ไขปัญหาเหล่านี้ผู้วิจัยจึงได้เล็งเห็นถึงความสำคัญของการหาอัตราส่วนผสม (v/v) ที่เหมาะสมระหว่างน้ำเสียจากการแปรรูปลำไยเนื้อสีทอง (LW) ซึ่งเป็นของเสียที่เกิดขึ้นมากในภาคเหนือของประเทศไทยและสลัดจ์บ่อเกรอะ (septage) ที่มีศักยภาพการผลิตก๊าซมีเทนสูงสุดโดยใช้กระบวนการ Modified Biochemical Methane Potential (BMP) โดยทำการศึกษา 3 อัตราส่วนผสม (septage+LW) คือ ที่อัตราส่วน ซีโอดีต่อทีเคเอ็นเท่ากับ 100:1.1 100:2.5 และ 100:5 ซึ่งอัตราส่วน ซีโอดีต่อทีเคเอ็นเท่ากับ 100:5 มีศักยภาพการผลิตก๊าซมีเทนสูงสุด (143 มิลลิกรัมมีเทน/กรัมของแข็งระเหย) จากนั้นนำเอาระบบถังหมักแบบทีแพด (Temperature-phased Anaerobic Digestion: TPAD) มาประยุกต์ใช้โดยใช้กระบวนการหมักร่วมระหว่างของเสียที่กล่าวมาข้างต้นเพื่อเป็นการบำบัดของเสียโดยได้ผลผลิตเป็นก๊าซชีวภาพและปุ๋ยอินทรีย์ชนิดเหลวที่ปราศจากเชื้อโรคโดยในขั้นตอนนี้ประกอบด้วยถังปฏิกรณ์ขนาด 30 ลิตรควบคุมที่สภาวะเทอร์โมฟิลิก (55 องศาเซลเซียส) ต่อด้วยถังปฏิกรณ์ขนาด 10 ลิตรควบคุมที่สภาวะ เมโซฟิลิก (35 องศาเซลเซียส) เดินระบบที่อัตราภาระบรรทุกสารอินทรีย์เท่ากับ 0.5/1.0, 1.7/2.0, 1.5/3.0 และ 4.5/5.0 กก.ของแข็งระเหย/ลบ.ม.-วัน (ค่าอัตราภาระบรรทุกของถังเทอร์โมฟิลิก/ถังเมโซฟิลิก) โดยค่าเฉลี่ยปริมาณก๊าซชีวภาพและ ศักยภาพการผลิตมีเทน ที่ภาระบรรทุกสารอินทรีย์ 1.5/3.0 มีค่าเท่ากับ 1,659 มล./วัน, 22.2 มล./ก.ของแข็งระเหยที่เติมและที่ภาระบรรทุกสารอินทรีย์ 4.5/5.0 มีค่าเท่ากับ 3,628 มล./วัน, 14.5 มล./ก.ของแข็งระเหยที่เติม ตามลำดับ ประสิทธิภาพในการกำจัดของแข็งระเหยของระบบที่อัตราภาระบรรทุกสารอินทรีย์เท่ากับ 1.4/3.0 มีค่าเท่ากับ 27.4 เปอร์เซ็นต์ ส่วนที่อัตราภาระบรรทุกสารอินทรีย์เท่ากับ4.5/5.0 มีค่า 47.8 เปอร์เซ็นต์ตามลำดับ ส่วนประสิทธิภาพการกำจัดแบคทีเรียที่เป็นอันตรายที่อัตราภาระบรรทุกสารอินทรีย์เท่ากับ 1.5/3.0 และ 4.5/5.0 มีค่ามากกว่า 90 เปอร์เซ็นต์

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5887520520 : MAJOR HAZARDOUS SUBSTANCE AND ENVIRONMENTAL MANAGEMENT
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As population growth rapidly increases, energy consumption becomes higher while natural resources have been continuously reduced. As a result of the population increasing, also the waste is increased. For example, infectious septage (the sludge accumulated in the septic tank and contained of essential nutrients) that is usually mismanaged. To address these problems, the researcher aimed to determine the ratio (v/v) between septage and wastewater generated from Golden Dried Longan production (LW) that provided the maximum methane yield by using of the Modified Biochemical Methane Potential (BMP) test. Three different waste mixtures (septage+LW) with the COD:TKN ratios of 100:1.1, 100:2.5, and 100:5 are tested. The experimental results presented that the ultimate specific methane yield of the COD:TKN ratio of 100:5 rendered the highest value (143 $mlCH_4/gVS_{added}$). The Temperature-phased Anaerobic Digestion (TPAD) system was then tested for co-digesting waste mixture to produce biogas and organic fertilizer. The TPAD system was consisted of a 30 L-thermophilic (55°C) and a 10 L-mesophilic (35°C) reactors. The Organic Loading Rate (OLR) was started from 0.5/1.0 kg VS/m^3-d (OLR of thermophilic/mesophilic reactor) and sequentially increased to 1.7/2.0, 1.5/3.0, and 4.5/5.0 kg VS/m^3-d, respectively. Biogas volume and specific methane yield at OLR of 1.5/3.0 kg VS/m^3-d were 1,659 ml/day and 22.2 $mlCH_4/gVS_{added}$, while 3,628 ml/day and 13.4 $mlCH_4/gVS_{added}$ were obtained at OLR of 4.5/5.0 kg VS/m^3-d. The volatile solids removal at OLR1.4/3.0 was 27.4% while 47.8% was detected at OLR4.5/5.0. The pathogen removal efficiency of TPAD system was over 90% throughout the experimental period.

Field of Study: Hazardous Substance and Environmental Management Student's Signature .....
Advisor's Signature .....

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LIST OF ABBREVIATIONS

BMP Biochemical Methane Production

C Concentration at a Time, mg/l

C_0 Influent Concentration, mg/l

cm Centimeter

COD Chemical Oxygen Demand

d Day

E. coli Escherichea coli

FC Faecal Coliform

F/M Food per Microorganism

g Gram

h Hour

HRT Hydraulic Retention Time

l Liter

mg Milligram

MPN Most Probable Number

MS Mesophilic of septage

MSL Mesophilic of septage and longan wastewater

OLR Organic Loading Rate

TC Total coliform

TKN Total Kjeldahl Nitrogen

TN Total Nitrogen

TP Total Phosphorus

TPAD Temperature-Phased Anaerobic Digestion

TPAD1 Temperature-Phased Anaerobic Digestion of septage

TPAD2 Temperature-Phased Anaerobic Digestion of septage and longan wastewater

TS Thermophilic of septage

TS Total Solid

TSL Thermophilic of septage and longan wastewater

TSS Total Suspended Solid

VS Volatile Solid

VSS Volatile Suspended Solid

yr Year

CHAPTER I

INTRODUCTION

1.1 Background

Nowadays, energy consistence is the main driving force in most developed countries. As population growth rapidly increases, energy consumption becomes higher while limited fuel sources like coal, natural gas and crude oil have been continuously reduced. To address this problem, the Ministry of Energy (2015) (MoE) has the Alternative Energy Development Plan (AEDP 2015) for increasing energy usage in forms of electric, heat and biomass up to 30% of total energy consumption in 2036.

Wastewater management systems in Thailand generally use a septic tank to treat residential wastewater as it is convenient to set up, easy for maintenance, and can remove considerable amounts of organic substances. Septage, the sludge accumulated in the septic tank, has characteristics similar to animal waste that contains low organic contents but high essential nutrients such as nitrogen and phosphorus (Metcalf & Eddy, 2014). Moreover, to greater concern, septage also contains pathogens that can transmit to the contacted people (Yen-Phi, 2010). Septage is usually removed from households by commercial vehicles (septic trucks) from private companies; however, it is usually mismanaged. This, partly, is contributed by the lack of strict Public Health Law. Consequently, illegal dumping in the river, waste lands, and agricultural areas has usually been done to reduce waste transportation and disposal cost, which becomes a major environmental problem in Thailand.

Considering its vast amount and nutrient-rich characteristic, using septage as a substrate to produce biogas becomes an interesting approach. In addition to promoting renewable energy, it also helps to solve the problems of illegal dumping. Septage has the potential to be used as a single substrate to produce biogas (Lin, 1998); it can be more efficiently co-digested with other substrates containing high

organic carbon and low nutrients such as leachate (Lin, 2000) and food waste (Prabhu, 2014). According to the potential of waste or biomass in Thailand and the MoE's energy development plan, co-digestion between septage and industrial waste under appropriate conditions could be the solution for environmental problems and supporting the use of renewable energy.

In the Northern part of Thailand, longan is, economically, one of the most important crops. There are more than 93 factories located in Chiang Mai and Lumphun provinces of the northern part of Thailand using longan as the raw material (Department of Agriculture, 2014). Since the management of wastewater from these factories is quite complicated it results in illegal dumping as well as the problem of odor and insect in the production areas. As wastewater generated form the longan processing factory contains high concentration of organic carbon, it has high potential for bio transformation. In this work, wastewater produced from a factory at the Rim Rong village, Makruejae Sub-district, Muang District, Lamphun, where golden dried longan is largely produced, is chosen in the study. The main goal is to find the suitable conditions for biogas production by co-digestion between septage and golden dried longan production wastewater (LW). The temperature-phased anaerobic digestion (TPAD) systems, consisting of a Thermophilic (55°C) and a Mesophilic (35°C) reactors, is utilized. This system has been reported to be relatively effective and capable of removing pathogens.

1.2 Objective

1 To determine the ratio (v/v) between septage and wastewater generated from Golden Dried Longan production that provides the maximum methane yield.

2 To assess the performance of the TPAD system in producing biogas from the codigesting between septage and LW and removing pathogens.

1.3 Hypothesis

1 Co-digestion of septage and LW can enhance wastewater treatment efficiency and biogas production.

2 TPAD systems can effectively remove pathogens in septage to the levels that the effluent can be used for agricultural irrigation.

1.4 Scope of Study

1. Septage sample would be taken from a septic truck. The source of septage was from the residential area. Samples collected were stored in a 2 m^3-water tank at ambient temperature before using.

2. LW would be collected from a longan processing factory at the Rim Rong village, Makruejae Sub-district, Muang District, Lamphun. Samples were kept in the -20°C cold room prior to using.

3. Three Chemical Oxygen Demand (COD):Total Kjeldahl Nitrogen (TKN) ratios, i.e. 100:1.1, 100:2.5, and 100:5, between septage and LW were investigated. The experiment conducted was conformed with the Biochemical Methane Production (BMP) test.

4. The studied TPAD system comprised of two reactors: the first 30 l-reactor was operated under the Thermophilic condition (at 55°C) while the other 10 l-reactor was operated under the Mesophilic condition (at 35°C). The system would be operated at the organic loading rate of 3.0 kg Volatile Solid/ m^3-d.

5. All experiments would be conducted at the Department of Environmental Engineering, Faculty of Engineering, Chiang Mai University.

CHAPTER II

THEORETICAL BACKGROUND AND LITERATURE REVIEW

Theoretical Background

2.1 Biogas Theory

2.1.1 Anaerobic process

2.1.1.1 Anaerobic treatment

Anaerobic treatment is the biological treatment without the use of air or elemental oxygen. In anaerobic treatment organic pollutants are converted by anaerobic microorganisms to biogas which are methane (CH_4), carbon dioxide (CO_2) and other products as showed in Equation 1 by Metcalf & Eddy (2004).

$$\text{CHONS} \longrightarrow CH_4 + CO_2 + H_2 + NH_3 + H_2S + \text{Other products} \quad (1)$$

(Organic substances)

The overall anaerobic conversion of biodegradable organic materials to final end products, methane and carbon dioxide, is occurred from the co-operation of two types of bacteria; acid forming or non–methanogenic bacteria and methanogens. Anaerobic treatment comprises four steps (Figure 2.1) which occurred in order as followed;

Step 1 Hydrolysis

Large organic matter molecules, i.e. carbohydrate, protein and fat, are hydrolised into their simple monomer compounds such as glucose, amino acid and some fatty acids. This process is mediated by extracellular enzymes produced by microorganisms.

Step 2 Acidogenesis

The simple monomer compounds from the hydrolysis step are degraded further to volatile fatty acid such as propionic, butyric, valeric and acetic acid.

Step 3 Acetogenesis

The volatile fatty acids from the acidogenesis step are transformed by acid forming bacteria and hydrogen forming bacteria to acetic acid, hydrogen gas (H_2) and carbon dioxide (Equation 2 and 3).

$$CH_3CH_2COOH + H_2O \longrightarrow CH_3COOH + CO_2 + H_2 \quad (2)$$

(Propionic acid)

$$CH_3CH_2CH_2COOH + 2H_2O \longrightarrow 2CH_3COOH + 2H_2O \quad (3)$$

(Butyric acid)

These reactions are brought about by the facultative bacteria and the obligate bacteria both of which known as acid formers or non – methanogenic bacteria. During this step the pH of the system decreases because the production of acid by these bacteria.

Step 4 Methanogenesis

Finally, methane producing bacteria, known as methanogens, convert acetic acid and hydrogen gas produced in the acetogenesis step to final products which are mainly CH_4 and CO_2. This step is called the methanogenic phase or methanogenesis. These reactions (Equation 4 and 5) are also known as methane formation.

$$4H_2 + CO_2 \longrightarrow CH_4 + 2H_2O \quad (4)$$

$$CH_3COOH \longrightarrow CH_4 + 2H_2O \quad (5)$$

The accumulation of acetic acid and hydrogen gas from the previous step can affect methane formation, as the methanogenesis bacteria cannot survive in acidic conditions (Raja Priya, 2009).

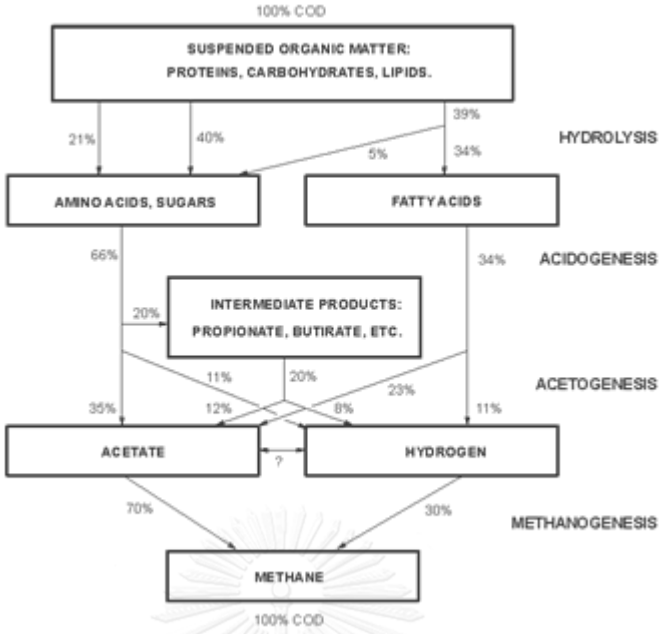


Figure 2.1 Anaerobic treatment process (Lubbe., 2007)

2.1.1.2 The rationale for anaerobic treatment process

The rationale for anaerobic treatment process can be explained by considering the advantage and disadvantages of this process.

1 Advantages of anaerobic treatment process

- Less energy required

Anaerobic process is the net energy producer instead of energy user, as in the case of aerobic process. The anaerobic treatments need no air supply, in contrast with the aerobic process which requires energy in aeration step. On the other hand, the anaerobic process produces methane which is the source of energy. Aerobic treatment is energy-intensive process for the removal of organic matter, requiring 0.5-0.75 kWh of aeration energy for 1 kg of COD removal (Lettinga, 1994).

- Low production of biomass

Anaerobic treatment processes utilize more than 90% of the biological degradable organic matter (COD) for methane production, with only 10% or less converted to

biomass. Because of the relatively lower growth rate of anaerobic microorganisms, a small amount of sludge was produced small amount. Aerobic treatment process, generates considerable amounts of sludge. Biological oxidation of every kilogram of soluble BOD produces 0.5 kg of sludge. The costs of treatment and disposal of sludge account for 30-60% of the total operational costs in a conventional activated sludge process.

- Smaller reactor volume required

The volumetric organic loading rates normally used for that anaerobic process are 5-10 times higher than for aerobic process (Speece, 1996), so smaller reactor volumes and less space may be required for treatment. The large volumetric organic loading rate can be applied. Moreover, the land requirements for the anaerobic treatment unit are reduced.

- Low nutrient requirement

Owing to the lower biomass synthesis rate during the anaerobic process, the nutrient requirements are considerably lower, with the anaerobic process requiring just 20% of the nutrients required for the aerobic process. The cost for nutrient addition is much lesser in anaerobic process for anaerobic process because less biomass is produced.

- Ability to reduce concentrations of refractory organics

With proper acclimation, many of the previously identified refractory organics such as carbon tetrachloride, chloroform, trichloroethylene, formaldehyde, and phenol have been successfully transformed to a lower toxic by anaerobic microorganisms (LaGrega, 2006).

2 Disadvantages of anaerobic treatment process

- Operation consideration

Anaerobic processes require long start-up time, their sensitivity to possible toxic compounds, operational stability, the potential for odor production, and corrosiveness of the digester gas are considered to be problematic. However, with proper wastewater characterization and process design these problems can be avoided and/or managed.

- Need for alkalinity addition

Alkalinity in wastewater results from the presence of hydroxide (OH^-), carbonates (CO_3^{2-}) and bicarbonates (HCO_3^{2-}). The alkalinity in wastewater helps to resist changes in pH caused by the presence of acid. Alkalinity concentration of 2,000 to 3,000 mg/l as $CaCO_3$ may be needed in anaerobic process to maintain an acceptable pH with the high gas phase CO_2 concentration (Metcalf & Eddy, 2004).

2.1.1.3 Associated Anaerobic Microorganisms

1 Hydrolytic Bacteria

Hydrolysis of macromolecules such as lipids, proteins and carbohydrates under anaerobic reactor conditions is primarily an extracellular enzymic reaction, and many microorganisms produce extracellular enzymes, chiefly hydrolases. The function of the hydrolytic enzymes, such as lipases, proteases and cellulases, is the degradation of complex molecules into units which can be assimilated by the microbial cell. In an anaerobic digestion process where organic polymers form a substantial portion of the waste stream to be treated, the hydrolysing bacteria and their enzymes are of paramount importance because their activity produces the simpler substrates for the succeeding steps in the degradation sequence.

2 Fermentative Acidogenic Bacteria

This stage of the digestion process is the fermentation of amino acids and sugars, giving rise to the intermediary products and acetate or H_2. Acetate is the most important compound quantitatively produced in the fermentation of organic substrates by bacterial populations, with propionate production of secondary consequence.

3 Acetogenic Bacteria or Acetate-H_2 Producing Bacteria

Acetate-forming (acetogenic) bacteria grow in a symbiotic relationship with methane-forming bacteria. Acetate serves as a substrate for methane-forming bacteria. For example, when ethanol (CH_3CH_2OH) is converted to acetate, carbon dioxide is used and acetate and hydrogen are produced (Equation 6).

$$CH_3CH_2OH + CO_2 \longrightarrow CH_3COOH + 2H_2 \quad (6)$$

When acetate-forming bacteria produce acetate, hydrogen also is produced. If the hydrogen accumulates and significant hydrogen pressure occurs, the pressure results in termination of activity of acetate-forming bacteria and loss of acetate production. However, methane-forming bacteria utilize hydrogen in the production of methane (Equation 7) and significant hydrogen pressure does not occur.

$$CO_2 + 4H_2 \longrightarrow CH_4 + 2H_2O \quad (7)$$

Acetate-forming bacteria are obligate hydrogen producers and survive only at very low concentrations of hydrogen in the environment. They can only survive if their metabolic waste hydrogen is continuously removed. This is achieved in their symbiotic relationship with hydrogen-utilizing bacteria or methane-forming bacteria. Acetogenic bacteria reproduce very slowly. Generation time for these organisms is usually greater than 3 days.

4 Methanogenic Bacteria

Methane-forming bacteria are predominantly terrestrial and aquatic organisms and are found naturally in decaying organic matter, deep-sea volcanic vents, deep sediment, geothermal springs, and the black mud of lakes and swamps. These bacteria also are found in the digestive tract of humans and animals, particularly the rumen of herbivores and cecum of non-ruminant animals.

There are Gram-negative and Gram-positive methane-forming bacteria that reproduce slowly. Gram stain results (negative, positive, and variable) are different within the same order of methane-forming bacteria because of their different types of cell walls.

The reproductive times or generation times for methane-forming bacteria range from 3 days at 35°C to 50 days at 10°C. Because of the long generation time of methane-forming bacteria, high retention times are required in an anaerobic digester to ensure the growth of a large population of methane-forming bacteria for the degradation of organic compounds. At least 12 days are required to obtain a large population of methane-forming bacteria.

Methanogenic Bacteria can divide into two groups.

1) Hydrogenotrophic Methanogens or Hydrogen Utilizing Chemolithotrophs

The hydrogenotrophic methanogens use hydrogen to convert carbon dioxide to methane (Equation 8). By converting carbon dioxide to methane, these organisms help to maintain a low partial hydrogen pressure in an anaerobic digester that is required for acetogenic bacteria.

$$CO_2 + 4H_2 \longrightarrow CH_4 + 2H_2O \qquad (8)$$

2) Acetotrophic Methanogens or Acetate Splitting Bacteria

The acetotrophic methanogens “split” acetate into methane and carbon dioxide (Equation 9). The carbon dioxide produced from acetate may be converted by hydrogenotrophic methanogens to methane (Equation 8). Some hydrogenotrophic methanogens use carbon monoxide to produce methane (Equation 10).

$$4CH_3COOH \longrightarrow 4CO_2 + 2H_2 \quad (9)$$

$$4CO + 2H_2O \longrightarrow CH_4 + 3CO_2 \quad (10)$$

The acetotrophic methanogens reproduce more slowly than the hydrogenotrophic methanogens and are adversely affected by the accumulation of hydrogen. Therefore, the maintenance of a low partial hydrogen pressure in an anaerobic digester is favorable for the activity of not only acetate-forming bacteria but also acetotrophic methanogens. Under a relatively high hydrogen partial pressure, acetate and methane production are reduced.

2.1.2 Operational Conditions of Anaerobic Digestion

Some environment factors can disturb anaerobic digestion, either by enhancing or inhibiting parameters for example, specific growth rate, decay rate, gas production, substrate utilization, start-up and response to changes in input.

1 Alkalinity and pH

Sufficient alkalinity is necessary for proper pH control. Alkalinity serves as a buffer that prevents rapid change in pH. Enzymatic activity or digester performance is influenced by pH. Acceptable enzymatic activity of acid-forming bacteria occurs above pH 5.0, but acceptable enzymatic activity of methane-forming bacteria does not occur below pH 6.2. Most anaerobic bacteria, including methane-forming bacteria, perform within a pH range of 6.8 to 7.2 well.

The pH in an anaerobic digester initially will reduce with the production of volatile acids. However, as methane-forming bacteria consume the volatile acids and alkalinity is produced, the pH of the digester rises and then stabilizes. At hydraulic retention times over 5 days, the methane-forming bacteria begin to rapidly consume the volatile acids.

In a properly operating anaerobic digester a pH of between 6.8 and 7.2 occurs as volatile acids are transformed to methane and carbon dioxide (CO_2). The pH of an anaerobic system is significantly affected by the CO_2 content of the biogas.

Digester stability is improved by a high alkalinity concentration. A reduce in alkalinity below the normal operating level has been used as an indicator of pending failure. A reduce in alkalinity can be caused by 1) an accumulation of organic acids due to the failure of methane-forming bacteria to convert the organic acids to methane, 2) a slug discharge of organic acids to the anaerobic digester, or 3) the presence of wastes that inhibit the activity of methane-forming bacteria. A reduce in alkalinity frequently precedes a rapid change in pH.

The composition and concentration of the feed directly influence the alkalinity of the anaerobic digester. For example, large quantities of proteinaceous wastes transferred to the anaerobic digester are associated with relatively high concentrations of alkalinity. The alkalinity is the result of the release of amino groups ($-NH_2$) and production of ammonia (NH_3) as the proteinaceous wastes are degraded. Also, thickened sludge has relatively high alkalinity. This alkalinity is due to the increased feed rate of proteins within the thickened sludge.

Alkalinity is present primarily in the form of bicarbonates that are in equilibrium with carbon dioxide in the biogas at a given pH. When organic compounds are degraded, carbon dioxide is released. When amino acids and proteins are degraded, carbon dioxide and ammonia are released.

The release of carbon dioxide results in the production of carbonic acid, bicarbonate alkalinity, and carbonate alkalinity (Equation 11).The release of ammonia results in the production of ammonium ions (Equation 12).

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^- \leftrightarrow 2H^+ + CO_3^{2-} \quad (11)$$

$$NH_3 + H^+ \leftrightarrow NH_4^+ \quad (12)$$

The equilibrium between carbonic acid, bicarbonate alkalinity, and carbonate alkalinity as well as ammonia and ammonium ions is a function of digester pH. Bicarbonate alkalinity is the primary source of carbon for methane forming bacteria.

Significant changes in alkalinity or pH are introduced in an anaerobic digester by substrate feed or the production of acidic and alkali compounds, for example

organic acids and ammonium ions, respectively, during the degradation of organic compounds in the digester.

Alkalinity in an anaerobic digester also is derived from the degradation of organic-nitrogen compounds, such as amino acids and proteins, and the production of carbon dioxide from the degradation of organic compounds. When amino acids and proteins are degraded, amino groups ($-NH_2$) are released and alkalinity is produced. When amino groups are released, ammonia is produced. The ammonia dissolves in water along with carbon dioxide to form ammonium bicarbonate (NH_4HCO_3) (Equation 13).

$$NH_3 + H_2O + CO_2 \leftrightarrows NH_4HCO_3 \quad (13)$$

However, the degradation of organic compounds produces organic acids that destroy alkalinity. For example, as a result of the degradation of glucose, acetate is formed (Equation 14). This acid destroys alkalinity, for example, ammonium bicarbonate (Equation 15), and the alkalinity is not returned until methane fermentation occurs (Equation 16).

$$C_6H_{12}O_6 \longrightarrow 3CH_3COOH \quad (14)$$

$$3CH_3COOH + 3NH_4HCO_3 \longrightarrow 3CH_4COONH_4 + 3H_2O + 3CO_2 \quad (15)$$

$$3CH_3COONH_4^+ + 3H_2O \longrightarrow 3CH_4 + 3NH_4HCO_3 \quad (16)$$

Although anaerobic digester efficiency is satisfactory within the pH range of 6.8 to 7.2, it is best when the pH is within the range of 7.0 to 7.2. Values of pH below 6 or above 8 are restrictive and somewhat toxic to methane-forming bacteria. To maintain a stable pH, a high level of alkalinity is required.

2 Temperature

Temperature phases for anaerobic bacteria growth can be divided to 3 phases;

- The thermophilic range is 50-56 °C; bacterial in this phase calls “Thermophilic bacteria”.

- The mesophilic range is 20-45 °C; bacterial in this phase calls “Mesophilic bacteria”.

- The psychorophilic range is 5-15 °C; bacterial in this phase calls “Psychorophilic bacteria”.

Although 25-50% more activity occurs in thermophilic digesters than in mesophilic digesters, there are several significant microbiological characteristics associated with thermophilic anaerobes and thermophilic digestion that may adversely affect digester performance. These characteristics include 1) the low bacterial growth or yield (increase in population size) of these anaerobes, 2) the high endogenous death rates of these bacteria, and 3) the lack of diversity of these anaerobes. These characteristics are responsible for 1) relatively high residual values of volatile acids, for example, >1,000mg/l, and 2) inconsistent treatment of sludge during continuously shifting operational conditions. Also, thermophilic anaerobes are very sensitive to rapid changes in temperature. Therefore, fluctuations in digester temperature should be as small as possible, that is, <1°C per day for thermophiles and 2–3°C per day for mesophiles.

3 Nutrients in the wastewater

Nutrients, carbon and energy required for microorganism may derive from the component of the wastewater. Wastewater suitable for being treated in anaerobic filter should have COD:N:P ratio at least 100:1.1:0.2 and low level of suspended solid to prevent media clogging. Phosphorus (P) is directly involved in biosynthesis, whereas nitrogen (N) is involved in the energy transfer system of microorganisms. Moreover, the wastewater should have adequate amount of micro – nutrient, e.g. Fe, Co, Ni, SO_4^{2}-, for bacteria to maintain their activities (Tuntoolavest, 1995).

4 Toxic substance and reaction inhibitors

A variety of inorganic and organic wastes can cause toxicity in anaerobic digesters. Many toxic wastes are removed in primary clarifiers and transferred directly to the anaerobic digester. Heavy metals may be precipitated as hydroxides in primary sludge, and organic compounds such as oils and chloroform are removed in primary scum and sludge, respectively. Industrial wastewaters often contain wastes that are toxic to anaerobic digesters.

- Cations toxic

Four cations are associated with alkali compounds. These cations or metals are calcium (Ca), magnesium (Mg), potassium (K), and sodium (Na) (Table 2.1). The salts of these metals, for example, sodium hydroxide (NaOH), often are added to anaerobic digesters to increase alkalinity and pH. The cations also may be transferred to anaerobic digesters from industrial wastes.

Table 2.1 Activating and inhibiting concentration of cations (Smith, 1964)

Cations	Concentration (mg/l)		
	Activate	Middle inhibit	Very inhibit
Na^{+}	100 – 200	3,500 – 5,500	>8,000
K^{+}	200 – 400	2,500 – 4,500	>12,000
Ca^{2+}	100 – 200	2,500 – 4,500	>8,000
Mg^{2+}	75 – 150	1,000 – 1,500	>3,000

The cations have stimulatory and inhibitory effects on anaerobic digesters. At relatively low concentrations (100–400 mg/l) the cations are desirable and enhance anaerobic bacterial activity. At concentrations >1,500 mg/l the cations begin to exhibit significant toxicity. Diluting the cation concentration can prevent cation toxicity. Combining of some ions can increase toxicity (Table 2.2).

Table 2.2 Relative ions (Smith, 1964)

Toxic ion	Toxic enhancement ion
Ammonium (NH_4^+)	Calcium, Magnesium, Potassium
Calcium (Ca^{2+})	Ammonium, Magnesium
Magnesium (Mg^{2+})	Ammonium, Calcium
Potassium (K^+)	None
Sodium (Na^+)	Ammonium, Calcium, Magnesium
Ammonium (NH_4^+)	Sodium
Calcium (Ca^{2+})	Sodium, Potassium
Magnesium (Mg^{2+})	Sodium, Potassium
Potassium (K^+)	Ammonium, Calcium, Magnesium
Sodium (Na^+)	Sodium
	Potassium

- Toxicity of heavy metal

Numerous heavy metals such as cobalt (Co), copper (Cu), iron (Fe), nickel (Ni), and zinc (Zn) are found in wastewaters and sludges and are transferred to anaerobic digesters. These metals are referred to as “heavy” because of their undesired impact on wastewater treatment processes and operational costs including their accumulation in sludges. High concentrations of metals in sludges affect sludge disposal options and costs (Table 2.3 and 2.4).

Table 2.3 Heavy metal concentration that can inhibit anaerobic fermentation system(Smith, 1964)

Heavy metal	Concentration, (mg/l)
Arsenic (As)	0.5 – 1.0
Cadmium (Cd)	0.01 – 0.02
Chromium (Cr^{6+})	1.0 – 1.5
Copper (Cu^{2+})	0.5 – 1.0
Nickel (Ni^{2+})	1.0 – 2.0
Zinc (Zn^{2+})	0.5 – 1.0

Table 2.4 Heavy metal that need to be considered its toxicity in anaerobic treatment process (Smith, 1964)

Generally found	Often found	Seldom found
Cadmium (Cd^{2+}) Chromium (Cr^{6+}) Copper (Cu^{2+}) Lead (Pb^{2+}) Nickel (Ni^{2+}) Zinc (Zn^{2+})	Arsenic (As) Iron (Fe) Manganese (Mn) Mercury (Hg) Silver (Ag)	Aluminium (Al) Cobalt (Co) Molybdenum (Mo) Selenium (Se) Tin (Sn)

- Volatile Fatty Acid toxicity

Anaerobic reactor instability is generally manifested by a marked and rapid increase in VFA concentrations; this is frequently indicative of the failure of the methanogenic population due to other environmental disruptions such as shock loadings, nutrient depletion or infiltration of inhibitory substances. Acetate has been described as the least toxic of the volatile acids, whilst propionate has often been implicated as a major effector of digester failure. Microbial growth was observed to be significantly inhibited at 35 g/l acetate in one investigation although sudden concentration increases in either acetic or n-butyric acid reportedly caused stimulation rather than inhibition of methanogens in others. Propionate was found to be more inhibitory than butyrate for Bacteroides, but the reverse applied in the case of *Peptostreptococcus*. Methanogenic populations were demonstrated to be inhibited at propionate concentrations in excess of 3,000 mg/l, although this effect could be overcome by acclimation. The methanogen *Methanobacterium formicicum* was reported to tolerate both acetate and butyrate at concentrations of up to 10,000 mg/l although variable inhibitory levels for propionate of 1,000 mg/l and 5,000 mg/l have been recorded (Sandra M. Stronach, 1986).

5 Mixing

Anaerobic digester content should be mixed. Mixing enhances the digestion process by distributing bacteria, substrate, and nutrients throughout the digester as well as equalizing temperature. The metabolic activities of acetate-forming bacteria and methane-forming bacteria require that they be in close spatial contact. Slow, gentle mixing ensures that contact. Also, mixing provides for efficient hydrolysis of wastes and production of organic acids and alcohols by acid-forming bacteria. For example, insoluble starches are kept from clumping by mixing action. This allows the hydrolytic bacteria to attack a much larger surface area of the starches and provides for their rapid hydrolysis.

Mixing can be accomplished through mechanical methods or gas recirculation. These methods include external pumps, gas injection or recirculation from the floor or roof of the digester, propellers or turbines, and draft tubes. Mechanical mixers are more effective than gas recirculation, but they often become clogged or fouled with digester solids.

6 Retention Time

There are two significant retention times in an anaerobic digester. These are solids retention time (SRT) and hydraulic retention time (HRT). The SRT is the average time that bacteria (solids) are in the anaerobic digester. The HRT is the time that the wastewater or sludge is in the anaerobic digester. The SRT and the HRT are the same for a suspended-growth anaerobic digester that has no recycle. If recycle of solids is incorporated in the operation of the digester, then the SRT and HRT may vary significantly.

HRT values affect the rate and extent of methane production. Of all the operational conditions within an anaerobic digester, for example, temperature, solids concentration, and volatile solids content of the feed sludge, HRT is perhaps the most important operational condition affecting the conversion of volatile solids to gaseous products.

2.1.3 Anaerobic digestion technology

1 Anaerobic Digestion

Anaerobic digesters are capable of treating insoluble wastes and soluble wastewaters. It is well known as a treatment process for sludge that contains large amounts of solids (particulate and colloidal wastes). These solids require relatively long digestion periods (10–20 days) to allow for the slow bacterial processes of hydrolysis and solubilization of the solids. Once solubilized, the resulting complex organic compounds are degraded to simplistic organic compounds, mostly volatile acids and alcohols, methane, new bacterial cells ($C_5H_7O_2N$), and a variety of simplistic inorganic compounds such as carbon dioxide and hydrogen gas (H_2).

Anaerobic digestion process can be divided to 2 type; Dry Digestion Process and Wet Digestion Process shows in Figure 2.2.

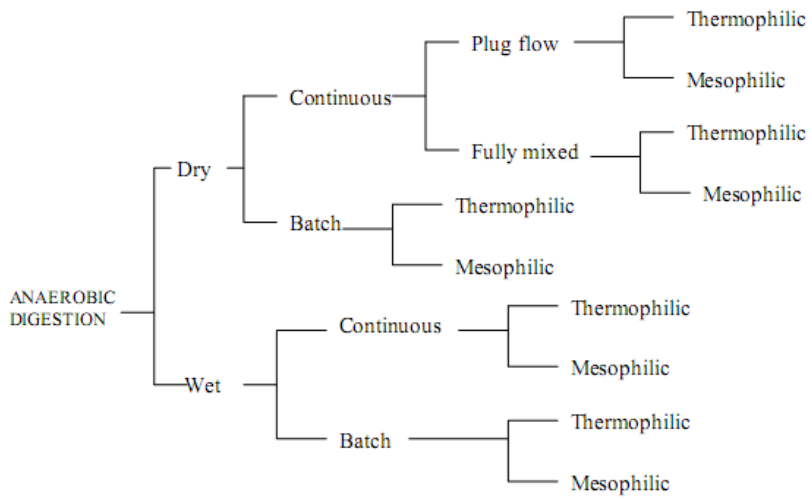


Figure 2.2 Anaerobic digestion process, divides by operating criteria. (Evans, 2001)

2 Continuously Stirred Tank Reactor (CSTR)

A CSTR, continuous flow stirred tank reactor (CFSTR) or completely mixed reactor, is used very commonly in many industrial fields. It is frequently equipped with baffles and a mixer which is operated at a sufficiently high speed so that the

mixing is assumed to be perfect. It is assumed to be homogeneous and instantaneous so that any reactant carried into the reactor by the feed is dispersed regularly throughout the reactor without any time delay. In addition, the reaction is assumed to take place only in the reactor so that the effluent composition is similar to the reactor composition.

The most often used method to get mathematical expression of biokinetics is steady state operation, where feed is supplied continuously until a steady state is achieved. Then, effluent concentration is recorded, and another steady state run should begin by changing the feed concentration and/or the feeding rate. Thus a number of steady state runs are required to obtain data relating reaction rate to concentration whereas a single unsteady-state run may be used to gain the similar information from a batch reactor. By varying independent variables, for example flow rate and/or influent substrate concentration, it is possible to solve mathematical expressions experimentally. The CSTR model is shown in Figure 2.3.

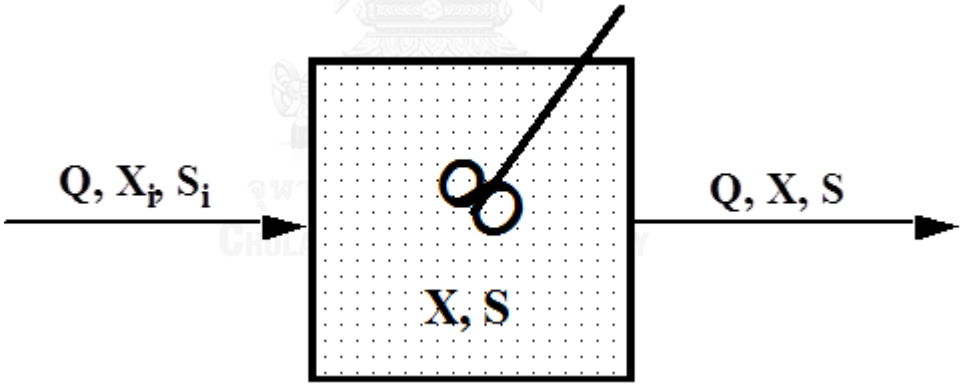


Figure 2.3 The CSTR (Q: flow, Xi: influet biomass, Si: influent substrate, X: biomass, S: substrate)

3 Single Stage anaerobic digester

A typical single-stage digester consists of a tank or reactor. Digester operations consist of sludge addition and withdraw, mixing, heating, gas collecting, and supernating. These operations are possible because of stratification of the digester content. Stratification results in the following layers from top to bottom of the digester: gas, scum, supernatant, active digester sludge, and digested sludge and

grit (Figure 2.4). Single-stage digesters are more easily upset than two-stage digesters. This is because of the presence of the simultaneous activities of two groups of bacteria, the acid-forming bacteria and the methane-forming bacteria. Because acid-forming bacteria grow more rapidly than methane-forming bacteria and are more tolerant of fluctuations in operational conditions, an imbalance between acid production rate and methane production rate often occurs. This imbalance may cause a decrease in alkalinity and pH that result in digester failure.

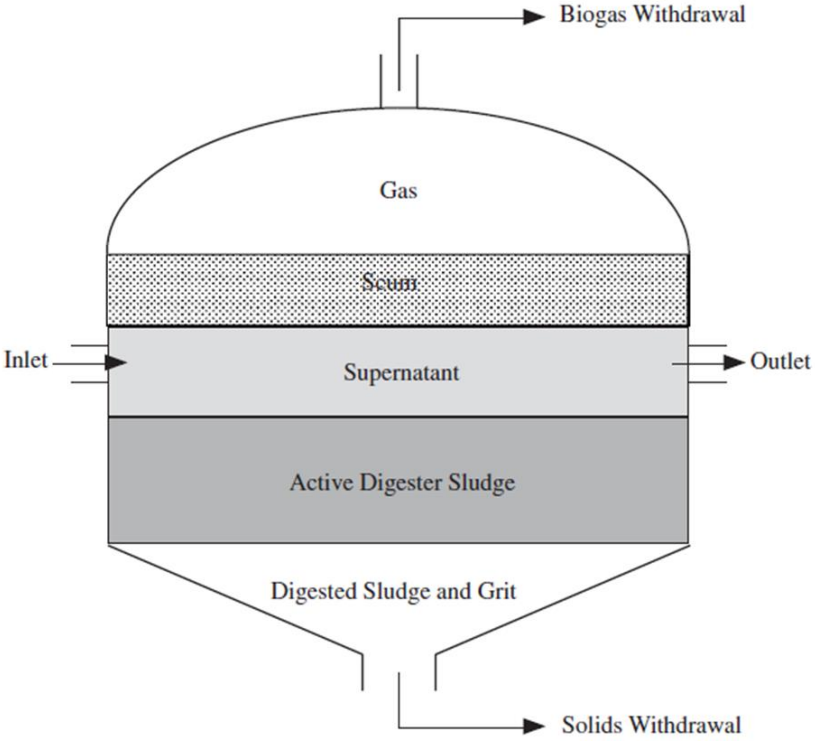


Figure 2.4 Single state sludge digester

4 Two stage sludge digester

Two-stage digester systems consist of at least two separate tanks or reactors. A limited variety of two-stage systems are available. A two-stage system yields increased efficiency and stability over a single-stage system. A two-stage system is capable of obtaining methane production and solids reduction similar to those of a single-stage system at a lesser HRT. Also, toxicants are removed in the first stage.

In some two-stage systems acid production occurs in the first stage or tank and methane production occurs in the second stage (Figure 2.5). In some two-stage

systems, sludge digestion and methane productions occur simultaneously and continuously in one tank and sludge thickening and storage occur in the other tank (Figure 2.6). In this configuration the first stage is continuously mixed and heated for sludge digestion, whereas stratification is permitted in the second stage, where sludge thickening and storage occur.

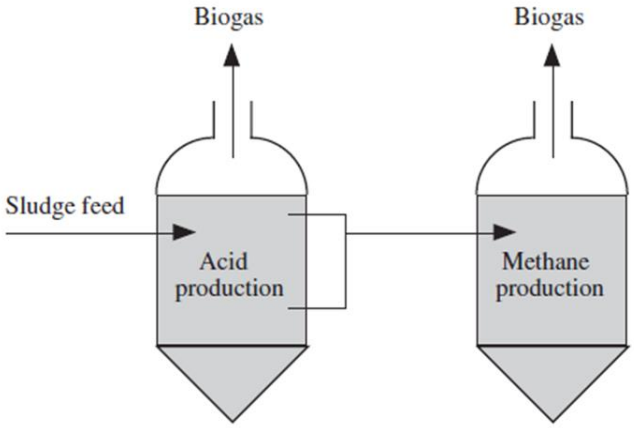


Figure 2.5 Two state anaerobic digester (acid production; methane production)

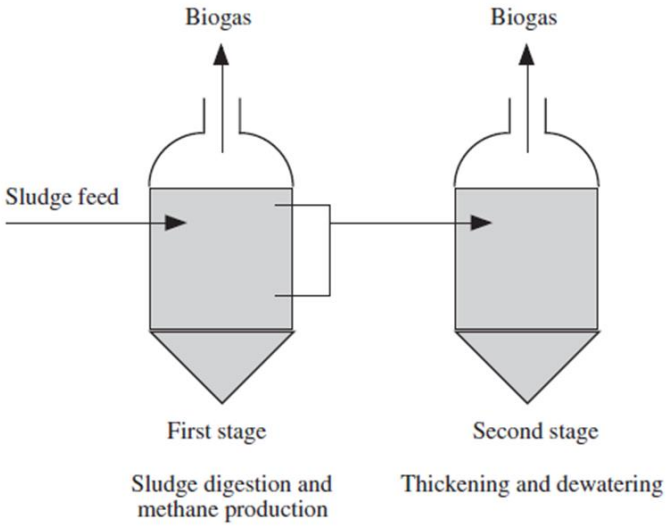


Figure 2.6 Two state anaerobic digester (sludge digestion and methane productions; sludge thickening and storage)

Other two-stage systems consist of temperature-phased anaerobic digestion (TPAD) of sludges or wastewaters. These systems are consisted of thermophilic and mesophilic anaerobic digestion (Figure 2.7). These systems provide for developed dewater ability of sludges and reduction in numbers of pathogens.

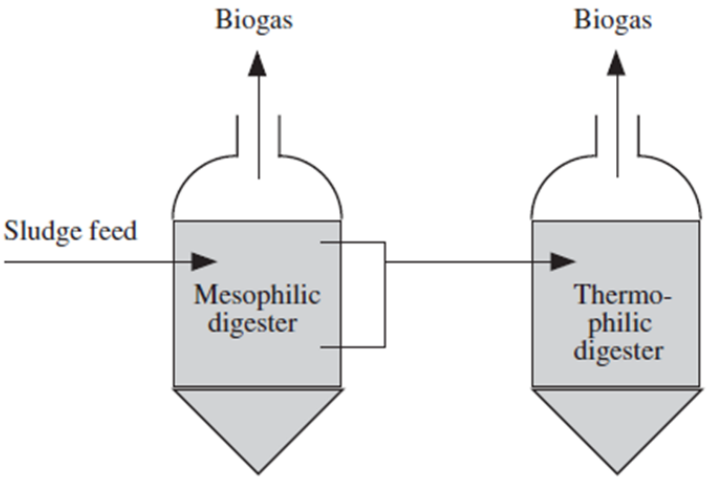


Figure 2.7 Temperature-phase anaerobic digestion (TPAD)

Comparing TPAD with single-stage anaerobic digestion, TPAD presents greater in methane yield, volatile solid removal, and pathogens removal. Moreover, this system can be operated using a higher organic loading rate with higher stability over single-stage anaerobic digestion. Pathogens are efficiently removed by TPAD because the temperature and retention time of the thermophilic reactor. Table 2.5 shows temperature and retention time required for some pathogens removal.

Table 2.5 Temperature and retention time required for pathogens removal

Organism	Observations
Salmonella typhosa	No growth beyond 46°C; death within 30 minutes at 55-60°C and within 20 minutes at 60°C; destroyed in a short time in compost environment.
Salmonella sp.	Death within 1 hour at 55°C and within 15-

	20 minutes at 60°C.
Shigella sp.	Death within 1 hour at 55°C.
Escherichia coli	Most die within 1 hour at 55°C and within 15-20 minutes at 60°C.
Entamoebahistolytica cysts	Death within a few minutes at 45°C and within a few seconds at 55°C.
Taeniasaginata	Death within a few minutes at 55°C.
Trichinellaspiralis larvae	Quickly killed at 55°C; instantly killed at 60°C.
Brucellaabortus or Br. suis	Death within 3 minutes at 62-63°C and within 1 hour at 55°C.
Micrococcus pyogenes var. aureus	Death within 10 minutes at 50°C.
Streptococcus pyogenes	Death within 10 minutes at 54°C.
Mycobacterium tubercuiosis var. hominis	Death within 15-20 minutes at 66°C or after momentary heating at 67°C.
Corynebacterium diphtheria	Death within 45 minutes at 55°C.
Necatoramericanus	Death within 50 minutes at 45°C.
Ascarislumbricoides eggs	Death in less than 1 hour at temperatures over 50°C.

2.2 Septic Tank

Septic tank (Figure 2.8) is a closed tank without oxygen addition, so it is operated under anaerobic condition. Generally, septic tank is used to treat wastewater from toilet, kitchen or other wastewater. The biological process occurred in the septic tank results in the biodegradable organic matters being digested and, parts of it, being used for new cells production. Remaining solids and produced new cells are accumulated inside a septic tank in form of septage. Septage production rate of the septic tank in Thailand is reported to be 1 l/person-d by Pollution Control Department (1994). To maintain the sufficient working volume of a septic tank, septage needs to be removed regularly (around once per year). If the non-

biodegradable matters such as plastic, sanitary napkin, and toilet paper, are flushed down a septic tank, they will be accumulated inside and made the tank full before reasonable time.

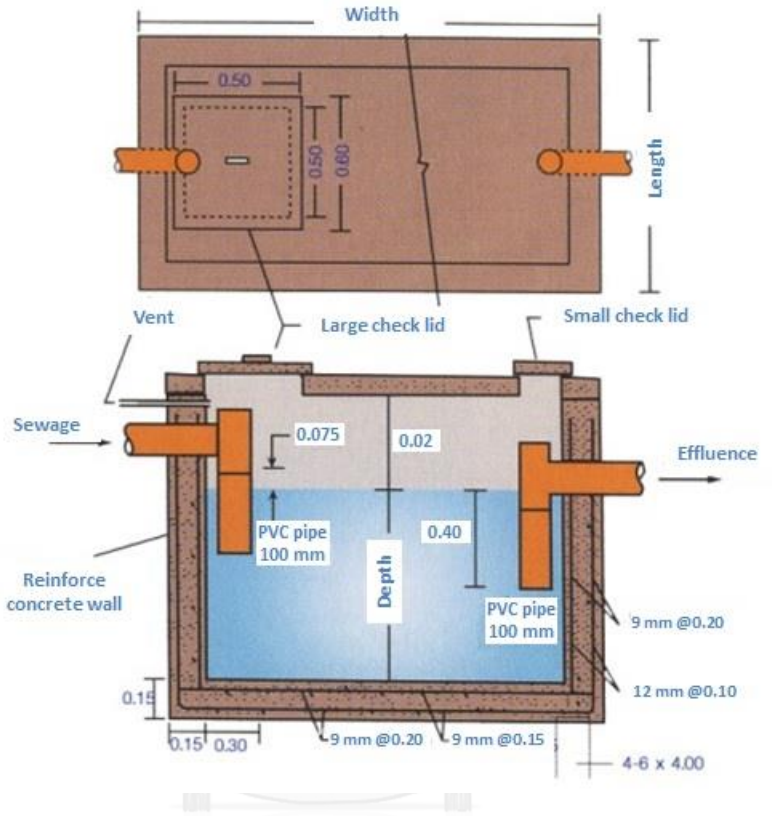


Figure 2.8 Standard of small septic tank

Source: http://www.pcd.go.th/info_serv/en_water_wt.html#

Because the efficiency of a septic is not very high (around 40-60 percent) septage still has COD higher than the effluent standard. Table 2.5 shows septage characteristic in the septic tank.

Table 2.6 Septage characteristic in the septic tank

Parameter	Concentration (mg/l)	
	General value[(1)]	General value[(2)]
1. Biochemical Oxygen Demand: BOD	6,000	5,000
2. Total Solids: TS	40,000	40,000
3. Supended Solids: SS	15,000	20,000
4. Total Kjeldahl Nitrogen: TKN	700	1,200
5. Ammonia Nitrogen: NH_3	400	350
6. Total Phosphorus: TP	250	250
7. Grease	8,000	-

Source: (1) Wastewater Engineering Treatment and Reuse, (Metcalf & Eddy, 2003)

(2) Domestic wastewater management plant 3, (Tuntoolavest, 1995)

Pathogens in septic tank

Several types of enteric microorganism are existed in human excreta; some of these are pathogenic and some are not. They can be classified into such major groups as bacteria, viruses, protozoa, and helminthes. Some of the important enteric bacteria commonly found in human excreta and wastewater (human wastes), are listed in Table 2.6. (Feachem, 1983) estimated the possible outputs of some pathogens in the feces and wastewater of a tropical municipal as shown in Table 2.7. These tables can conclude that human wastes are a potential public health hazard, being the beginning of the transmission route of many diseases. The engineering profession responsible for the collection, transport, treatment and disposal or reuse of these wastes must be aware of the potential infectivity and transmission of these diseases, so as to be able to ensure that these pathogens do not pose an actual threat to human health. (Feachem, 1983)

Table 2.7 Enteric pathogen in human excreta and wastewater ((Gaudy, 1980); (Feachem, 1983))

Pathogenic bacteria	Disease	Transmission[a]	Geographical distribution
Vibrio cholera	Cholera	Person→person	Asia, Africa, some parts of Europe
Salmonella typhi	Typhoid fever	Person (or animal)→person	Worldwide
Other Salmonellae	Various enteric fevers (often called paratyphoid), gastroenteritis, septicemia (generalized infections in which organisms multiply in the bloodstream)		
Shigella dysenteriae and other species	Bacterial dysentery	Person→person	Worldwide
Pathogenic Escherichia coli	Diarrhea	Person→person	Worldwide

[a] Transmission mode is generally through the fecal-oral route, i.e. the excreted disease may be ingested by other persons or the excreted diseases go through some development (water, soil, or animals) and infect other persons.

Table 2.8 Possible output of selected pathogens in the feces and sewage of a tropical community of 50,000 in a developing country (Feachem, 1983)

Pathogenic bacteria	Prevalence of infection in country (percentage)	Average number of organisms per gram of feces	Total excreted daily per infected person	Total excreted daily by town	Concentration per liter in town sewage
Pathogenic *E.coli*[d]	?	10^8	10^{10}	?	?
Salmonella spp.	7	10^6	10^8	$3.5x10^{11}$	7,000
Shigella spp.	7	10^6	10^8	$3.5x10^{11}$	7,000
Vibrio cholerae	1	10^6	10^8	$5x10^{10}$	1,000

? Uncertain

Note: This table is hypothertical, and the data are not taken from any actual, single town. For each pathogen, however, the figures are reasonable and congruous with those found in the literature. The concentrations derived for each pathogen in sewage are in line with higher figures in the literature, but it is unlikely that all these inflections at such relatively high prevalences would occur in any one community

2.3 Fruit processing industry

Thailand is the agricultural country having cultivated area around 27.25 percent. More than half of this area is rice fields and others are for vegetables and fruits planting. Because of its appropriate soil and climate, longan (Dimocarpus longan lour) has ubiquitously been planted in the northen provinces of Thailand. Longan production can be exported in form of fresh, dried, freezed, and canned. Longan production creates yearly income more than billion baths and the tendency of exporting is still increased. Office of Agricultural Extension and Development 6,

Chiang Mai reported that longan was planted widely in Chiang Mai, Lamphun, and Chiang Rai. In the north of Thailand, longan has been planted over than 1,120 km^2 (Table 2.8), more than 343 tons/km^2 of longan is produced. Chiang Mai and Lumphun had longan production more than 250,000 tons in year 2010 (Table 2.9).

Data from a Longan processing factory (Sawasdee Golden Dried Longan, 2001) reported that longan peelings and longan seed weighed 50 percent of total weight and longan peelings weighed 40 persent of the combined weight of peelings and seed. Thus, in 1 kg of total weight the peelings weight is 0.2 kg. Considering amount of longan production in one year (Table 2.8 and 2.9), longan peelings can be estimated to be 105,046 tons/yr. Practically, longan peelings and seed are disposed with municipal waste or just dumped in the processing factory. These practices cause many environmental problems such as odor of decomposition, contamination in the river by leachate and insects that affect human health. Moreover, particulate and/or toxic gases are produced if longan peelings are disposed of by open burning.

Table 2.9 Important longan farming provinces in Thailand, 2009

Province	Area (km^2)
Kamphaeng Phet	18
Chanthaburi	100
Chiang Rai	212
Chiang Mai	510
Tak	32
Nan	59
Phayao	103
Lunpang	44
Lumphun	439
Loei	43

Source: http://www.arda.or.th/kasetinfo/logan/index.php?option=com_content&view=article&id=292:-2551&catid=16:016&Itemid=11 (Project, 2011)

Table 2.10 Amount of Longan produced in Thailand, 2010

Region/Province	Longan productions brought to market in 2010 (ton)
Total in Thailand	525,230
North	394,252
North East	19,098
Central	111,880
Lumphun	136,341
Chiang Mai	152,346

Source: http://www.oae.go.th/ewt_news.php?nid=9448&filename=index (2010)

1 Characterization of fruit peelings

Various works have stated that fruit scraps have different organic matter contents and C/N ratios (Table 2.10). It can be seen that mango has the highest C/N ratio (76.5) tomato has the lowest C/N of 13.0. Fruit wastes can be used to produce biogas but their C/N ratios need to be adjusted to around 20-30 . Fruits scraps (e.g. mango, pineapple, orange, banana, jackfruit, and tomato) can generate biogas around 0.5-0.6 m^3/kg with methane composition in the range 51-53% (Nand, 1991), while jackfruit peelings can generate 0.72 lbiogas/VS_{added} (Vijayaraghavan, 2006).

Table 2.11 Fruits peelings characteristic

Type	Total solid (TS), %	Total volatile solid (VS), %	COD, g/kg	TKN, %	C/N ratio	Reference
Jackfruit peelings	6	83	78,836 (mg/l)	1.5	-	(Vijayaraghavan , 2006)
Orange peelings	20.17	19.31	1,085 (mg/l)	11.67 (mg N/g)	-	(Martín, 2010)
Potato peelings	119.2 (g/kg)	105.5 (g/kg)	126	-	-	(Raynal, 1998)

Green bean And carrot	179.4 (g/kg)	171 (g/kg)	185	-	-	
lettuce scraps	79.4 (g/kg)	72.1 (g/kg)	97.8	-	-	
Mix fruit and vegetable scraps	84.4 (g/kg)	77.5 (g/kg)	-	2.7 (g/kg)	-	(Viturtia, 1989)
Mix fruit and vegetable scraps	90.4 (g/kg)	82.9 (g/kg)	104.5	2 (g/kg)	-	(Verrier, 1987)
Banana peelings	10.68	86.65	-	1.06	39.1	(Bardiya, 1996)
Pineapple scraps	7.80	89.40	-	0.95	55.1	
Tomato scraps	29.5	95.73	-	4.2	13.0	(Viswanath, 1992)
Mango scraps	26.4	96.4	-	0.5	76.5	
Orange scraps	26.6	94.2	-	1.0	40.5	
Pineapple scraps	12.31	93.79	-	0.9	42.3	
Banana scraps	11.86	95.07	-	1.9	21.3	
Jackfruit scraps	19.85	92.27	-	1.4	33.1	

2 Golden Dried Longan Productions

Golden Dried Longan Production process diagram is presented in Figure 2.9. Considerable amount of wastewater is generated during the process. Data from a factory in Lumphun (Chitlertlam., 2011) reported that of the fresh longan used 1,724 kg/day 281 l/d of wastewater was generated. Considering 5,252 tons Office of Agricultural Economics (2010), fresh longan in 2010, approximately 856 m^3 of wastewater could be generated.

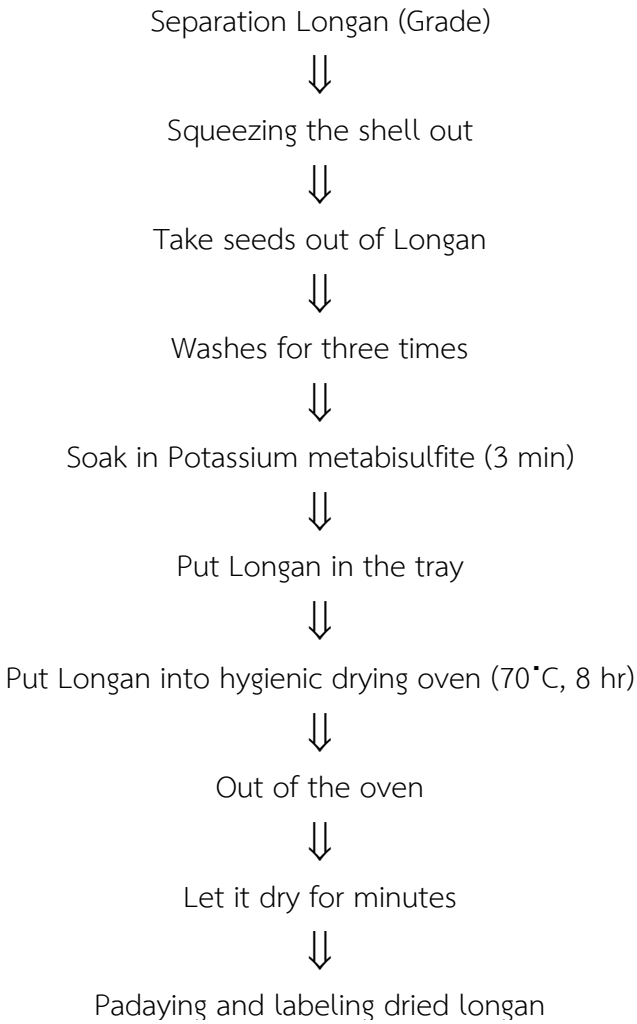


Figure 2.9 Golden dried longan production process

Source: http://www.sawasdeelongan.com/en/production.html (Sawasdee Golden Dried Longan, 2001)

Literature Review

Chiu-Yue Lin (1999) examined CSTR digestion performance of septage and landfill leachate. They were operated as mesophilic condition. The mixture substrate (septage and leachate) was mixed of 1:0, 1:1, 2:1 and 3:1 ratio (base on COD). Each mixture substrate ratio were operated of the solids retention times (SRT) for 20, 10, and 5.3 days. The organic loadings and volatile solids loadings were in ranged of 0.3~1.4 kg COD/m^3/day and 0.79~3.7 kg/m^3/day, respectively. For the same SRT, a higher ratio of septage increased the removal efficiencies of total COD, ammonia nitrogen and total phosphorus (T-P). 0.315 kg COD/m^3/day (ratio of 3:1) of organic loading rate at SRT of 20 days, the total COD, NH_3-N, T-P, volatile solids, carbohydrate and protein removed were 86, 69, 86, 28, 82 and 80%, respectively. Due to an increasing of septage fraction the methane was improved.

Christopher Ziemba (2011) studied single-mesophilic, single-thermophilic, temperature-phased, and single-high temperature (60 or 70°C) batch pre-treatment digester. There were evaluations for pathogen inactivation potential. First-order inactivation rate coefficients for Escherichia coli, Enterococcus faecalis and bacteriophage MS-2 were measured at each digester temperature and full-scale pathogenic bacteria inactivation performance was estimated for each indicator organism and each digester configuration. Inactivation rates were found to rise rapidly over 55°C. Modeling full-scale efficiency, inactivation of single-mesophilic, single-thermophilic and temperature-phase, 60°C, and 70°C batch pre-treatment results were 1-2 log, 2-5 log, 14 log and 16 log, respectively. Complete inactivation (over 100 log reductions) of E. coli and E. faecalis was found in 60 or 70°C batch pre-treatment while less than 70°C was found to be significantly decreased (standard culture enumeration).

Fernández-Rodríguez (2016) investigated the maximum energy production by anaerobic digestion of organic waste. In this study, semicontinuous Temperature Phased Anaerobic Digestion (TPAD) process was used to treat the Organic Fraction of

Municipal Solid Waste (OFMSW) from a mechanical-biological-treatment (MBT) plant. Ratio of 4:10 and 3:6 were operated for thermophilic and measophilic phase, respectively. The performance of TPAD processes was compared with those from single-stage digesters operating at the same SRT. The results presented that the 4:10 TPAD was higher methane production (35-45%) and higher organic matter removed (6-19%) than the 3:6 TPAD. Moreover, the results indicated that TPAD processes reach higher efficiencies for organic matter removed (16%, 10% and 30% for DOC, COD soluble and VS, respectively) and higher methane yields (26-60%) than single-stage operation.

Lin (2000) examined the co-digesting of landfill leachate and septage by a UASB reactor. It was operated at mesophilic condition (35˚C). The mixture substrate (septage and leachate) were 3:1, 2:1 and 1:1 ratios (base on COD) and the ratios of the feeds were changed during the operation period. At 1.5 hydraulic retention time (HRT) and organic loading rate (1:1) of 6.73 kg COD/m^3-day, the total COD, soluble COD, total solids, volatile solids, total volatile fatty acid, total phosphorus, ammonia nitrogen, carbohydrate and protein removed were 42.2%, 58.1%, 45.3%, 68.2%, 73.4%, 44.3%, 47.8%, 53.7% and 44.4%, respectively.

Pussayanavin (2015) investigated two laboratory-scale septic tanks fed with diluted septage and operating at 40 and 30°C performance. They were higher methanogenic activities occurring in the sludge layer of the septic tank operating at steady state of 40°C, the result showed that it was less volatile solids (VS) or sludge accumulation and higher methane (CH_4) production compared with 30°C operation. Molecular analysis found more abundance and diversity of methanogenic microorganisms at 40°C than at 30°C operation. The TVS reduction at 40°C would lengthen the period of septage removal.

Ratanatamskul (2015) studied co-digestion of food waste and sewage sludge from high-rise building for biogas production by an on-site prototype two-stage anaerobic digester (the acidific and methanogenic reactors). The maximum ratio of

mixture substrate (food waste and sewage sludge) was 7:1. Then, the prototype two-stage anaerobic digester was designed and operated. The results of COD and total volatile solid (TVS) removal efficiency were 89 and 74%, respectively with 24 days of HRT, and the methane composition of biogas was 64%.

Song (2004) studied the co-phase anaerobic digestions (mesophilic and thermophilic condition) (TPAD) performance of sewage sludge, and compared to single-stage mesophilic and thermophilic anaerobic digestions. The reduction of volatile solids (50.7-58.8%) from the TPAD system was dependent on the sludge exchange rate, which was up to 46.8% for thermophilic digestion, as well as 43.5% for mesophilic digestion. The specific methane yield was 424–468 $mlCH_4/gVS_{removed}$, which was as similar to the single-stage mesophilic anaerobic digestion. The process stability and the effluent quality in terms of volatile fatty acids and soluble COD of the TPAD system were considerably better than the single-stage mesophilic digestion. The total coliform inactivation of the TPAD system was up to 99.6%, which was same as the single-stage thermophilic digestion. The performance on volatile solid and pathogen inactivation, and stable operation of the TPAD system was greater than thermophilic digester.

Valencia (2009) reported that co-disposal of septage had a positive effect on the municipal solid waste (MSW) stabilization process in Bioreactor Landfill simulators. The simulator receiving septic tank sludge exhibited a 200 days shorter lag-phase as compared to the 350 days required by the control simulator to start the exponential biogas production. The simulator with septage enhanced the increasing of biogas production (0.60 m^3 biogas/kg $VS_{converted}$) and the VS removal efficiency was 60%. Total coliform and fecal coliform were inactivated up to 100% at the end of the research.

Viswanath (1992) investigated the effect of different fruit and vegetable wastes (mango, pineapple, tomato, jackfruit, banana and orange) on biogas production. This study was conducted in a 60 l digester by changing each waste

every fifth day. The anaerobically digested fluid performance and biogas production were determined at different loading rates (LR) and different hydraulic retention times (HRT). The biogas yield was achieved up to 0.6 m^3/kg VS_{added} at HRT of 20 days and LR of 40 kgTS/m^3-d. The hourly gas production was detected HRT of 16 and 24 days. The biogas yield (74.5%) was produced within 12 h of feeding at HRT of 16 day while at a 24 day only 59.03% of the total gas could be achieved.

CHAPTER III

METHODOLOGY

The work of this research is divided into 2 parts. The first part comprises batch experiments in order to determine the suitable septage to LW ratio for biogas production. In the second part, TPAD systems are continuously operated using the obtained suitable waste ratio to access the system performance. Details of the experiment can be described as following;

3.1 Material

Inoculum was collected from an anaerobic digester of Chiang Mai University's wastewater treatment plant (Figure 3.1). Longan wastewater (LW) was collected from a longan processing factory at the Rim Rong village, Makruejae Sub-district, Muang District, Lamphun province (Figure 3.2). Samples were kept in the -20°C cold room prior to using. Septage was obtained from Cherng Doi village, Doi Saket district, Chiang Mai province that was pumped by a septic truck (Figure 3.3). Prior to using, septage was kept in a 2 m^3 tank at ambient temperature. The tank content was thoroughly mixed with a centrifugal pump before septage sample was taken. Characteristics of inoculum and wastes are shown in Table 3.1.

Figure 3.1 Domestic wastewater treatment plant at Chiang Mai University

Figure 3.2 Longan wastewater from a longan processing factory

Figure 3.3 Septage drying bed and septic truck

Table 3.1 Characteristics of inoculum and wastes

Parameter	Inoculum	Septage*	LW
pH	7.15	8.05	3.59
MLSS (mg/l)	20,290	54,120	1,292
MLVSS (mg/l)	8,454	39,260	1,093
Density (kg/l)	0.9939	0.9752	-
TS (mg/l)	19,200	36,590	7,760
VS (mg/l)	10,933	25,755	6,595
COD (mg/l)	-	35,200	14,994
TKN (mg/l)	-	2,052	74

*septage characteristics are of the sample measured right after septage collection

3.2 Determination of the suitable septage to LW ratio

To determine the suitable septage to LW ratio, the modified biochemical methane potential (BMP) assays was performed in 1,000 ml glass bottles with working volume of 400 ml at mesophilic condition (35±2°C) (Figure 3.4). Inoculum (120 ml) was firstly added, following by substrate or mixture of substrates. The volatile solid ratio of inoculum and substrate was fixed at 1:1. Three different waste mixtures (septage+LW) with the COD:TKN ratios of 100:1.1, 100:2.5, and 100:5 were tested along with septage and LW as the sole substrate. The experiment using only inoculum was used as the controlled experiment. The bottle was purged with N_2 gas for 3 minutes and then sealed with a septum. Each experiment was done in triplicate as shown in Table 3.2.

Table 3.2 Substrates used in each experiment

Experiment No. (set)*	Substrate
1	Inoculum
2	Septage
3	LW
4	Septage+LW at 100:1.1
5	Septage+LW at 100:2.5
6	Septage+LW at 100:5

* Replicate set; ratio of septage and LW was presented as COD:TKN

To calculate the amount of biogas produced, pressure measurement of biogas was done every day. Biogas composition was measured when the pressure got to 250 mbar by the portable biogas check (minimum pressure that the portable biogas check could measure).

Results obtained from the modified BMP test were analyzed by fitting the experimental results with the modified Gompertz model (Nielfa (2015); Guangyin Zhen (2016) (Equation 17).

$$M = P \times \exp\left\{-\exp\left[\frac{R_m \times e}{P}(\lambda - t) + 1\right]\right\} \quad (17)$$

Where M = Accumulative methane production (ml CH_4/g VS)

P = Total methane production (ml CH_4/g VS)

R_m = Maximum methane production rate (ml CH_4/g VS)

λ = Lag Phase (d)

t = Digestion time since the startup of BMP test (d)

Effects of co-digestion were evaluated by calculated the synergistic effects (A. Nielfa, 2015) (Equation 18).

$$\alpha = \frac{\text{Experimental value}}{\text{Theory value}} \quad (18)$$

Results meaning:

α > 1*:* the mixture has a synergistic effect in the final production

α = 1: the substrates work independently from the mixture

α < 1*:* the mixture has a competitive effect in the final production.

The suitable septage to LW ratio was chosen based on its superiority of the methane production and synergistic effect. The obtained kinetic coefficients were also considered during the selection of the suitable ratio step.

Figure 3.4 Modified BMP test

3.3 Reactor operation and experimental setup

3.3.1 TPAD Reactor

All experiments were conducted using two lab-scale temperature phase anaerobic digester: TPAD (Figure 3.5 and 3.6). The reactor was constructed from aluminium with a working volume of 30 L for thermophilic (Figure 3.7) and 10 L for mesophilic (Figure 3.8). Biogas was measured by bubble counter machine and was analyzed by Multichannel Portable Gas Analyzer. To make sure that all produced biogas was measured, pH of water in the bubble counter machine was adjusted to 3.5 using sulfuric acid solution to prevent CO_2 from being dissolved into the water. Reactor temperature was controlled using the heater installed in the water jacket between the inner and outer reactors.

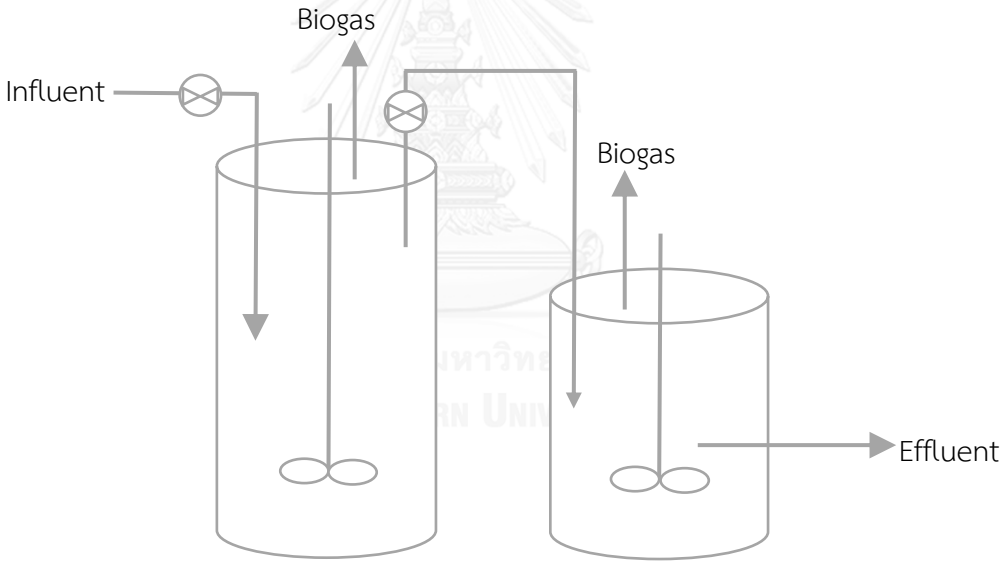


Figure 3.5 Temperature-Phase Anaerobic Digester (TPAD) systems

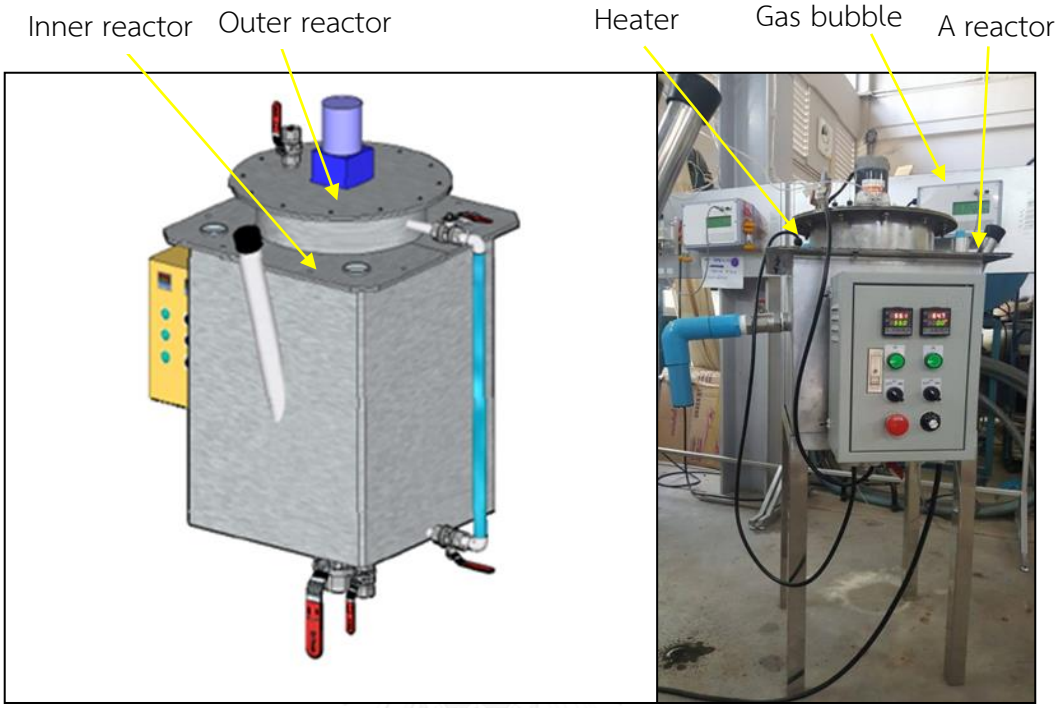
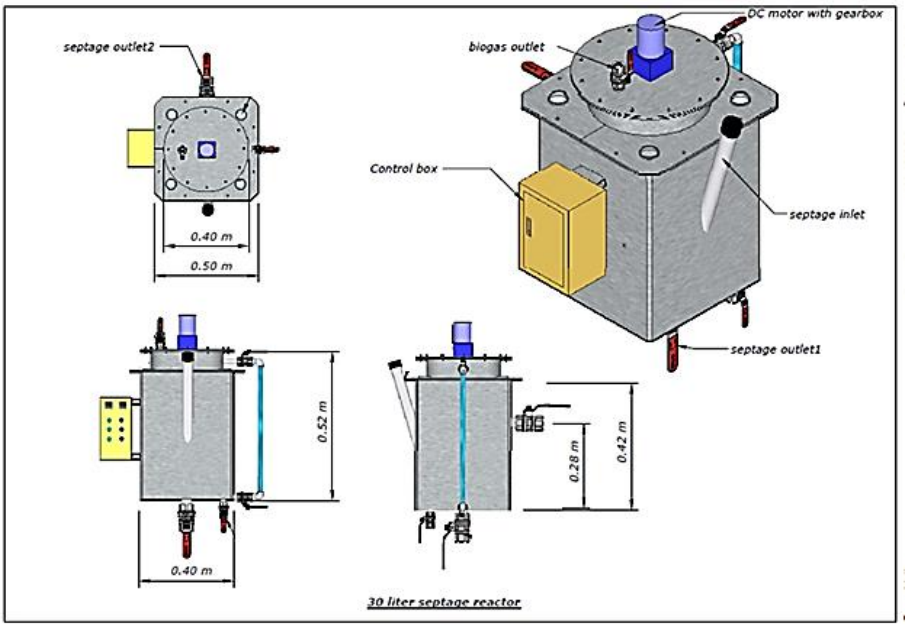


Figure 3.6 Model and real reactors



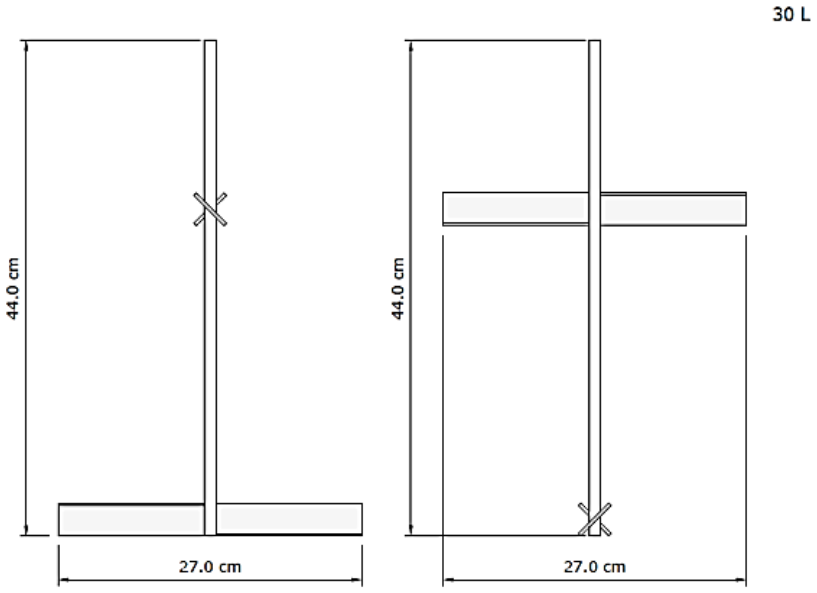
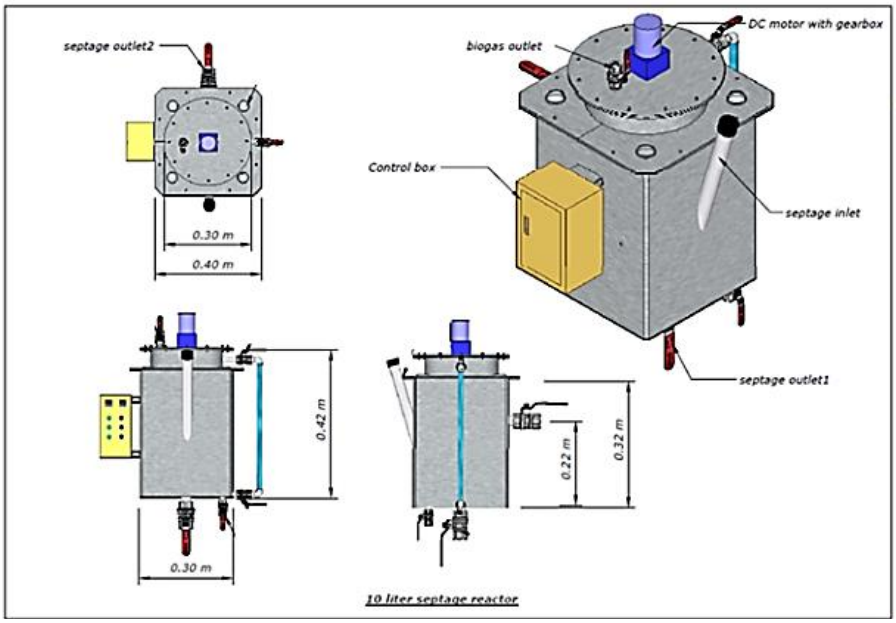


Figure 3.7 Thermophilic reactor dimension



10 L

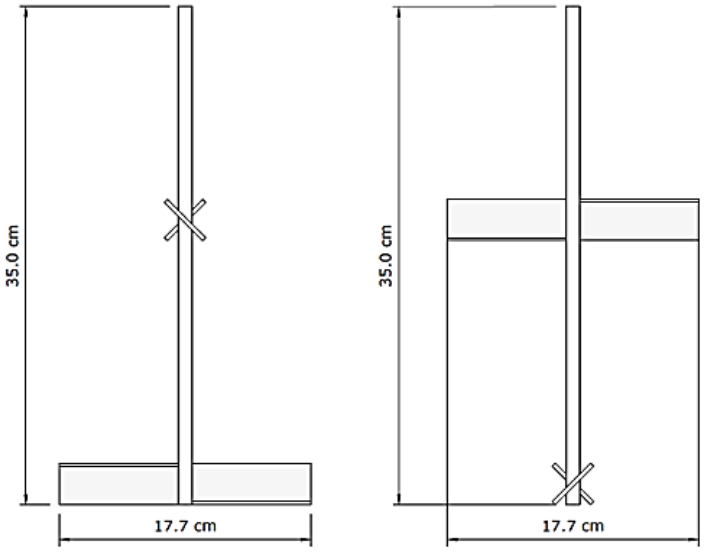


Figure 3.8 Mesophilic reactor dimension

3.3.2 TPAD reactor start up and operation

TPAD reactors were started up using acclimatized seed. To prepare the acclimatized seed, two sets of inoculum were prepared by feeding the original inoculum with septage and the mixture of septage and LW once a day at the OLR of 1 kgCOD/m^3-d. Each set of inoculum was kept at both the 35°C and 55°C. The

acclimatization process was done for 1 month. The acclimatized seeds were used for starting up all studied reactors.

To start up the reactors, 9 l and 3 l of the acclimatized inoculum are added in the thermophilic and mesophilic reactors, respectively. Mixture of septage and LW is fed into each reactor of the TPAD system with Organic Loading Rate (OLR) start from 1 kgVS/m^3-d. OLR of each reactor is then sequentially increased to 2, 3 and 5 kgVS/m^3-d, respectively (Table 3.3). At the OLR of 3 and 5 kgVS/m^3-d, each reactor will be operated for at least 1.5 times of the HRT to evaluate the performance of each OLR. As septage characteristics were changed along the storage time, only the pseudo steady state was presumed to achieved and the performance of reactors after 1.5 times of HRT was used to represent this condition. Reactors are operated continuously under the condition shown in Table 3.4. Effluent sample from each reactor is regularly collected to determine the reactor performance. The details of the measured parameters are presented in the Table 3.5.

Table 3.3 Wastes feeding of all OLR

OLR (kg/m^3*d)	Q (l/d)	LW (l/d)	Septage (l/d)	HRT (d)	1.5HRT (d)
1	0.87	0.20	0.66	34.7	52.0
2	1.73	0.40	1.33	17.3	26.0
3	2.60	0.60	1.99	11.6	17.0
5	8.00	1.85	6.15	3.75	6.00

Table 3.4 Operating condition of TPAD system

Reactor	Temperature (°C)	Speed of the mixer (rpm)	Mixing duration (min)
Thermophilic	55	50	stir 5 stop 15
Mesophilic	35	50	stir 5 stop 15

Table 3.5 Details of parameters and analysis methods

Parameter	Unit	Method	Frequency
pH	-	pH meter	Everyday
Room Temperature	°C	Thermometer	Everyday
Ferment Temperature	°C	Thermometer	Everyday
Total Solid	mg/l	Gravimetric Method	2 times/week
Volatile Solid	mg/l	Gravimetric Method	2 times/week
COD	mg/l	Closed reflux Method	2 times/week
Volatile fatty acids	mg/l	Titration Method	2 times/week
Alkalinity	mg/l	Titration Method	2 times/week
Biogas Production	l	Biogas Collection	everyday
Composition of Biogas Production	%	Biogas Checks (the portable biogas check)	once/week
Total Coliform Bacteria	(MPN/100 ml)	Most Probable Number Method	3 times during steady state
Fecal coliform (Escherichia coli)	(MPN/100 ml)	Most Probable Number Method	3 times during steady state
Salmonella sp.	(MPN/100 ml)	Most Probable Number Method	3 times during steady state

CHAPTER IV

RESULTS AND DISCUSSION

As presented in Chapter 1, the objective of this thesis are 1) to determine the ratio (v/v) between septage and wastewater generated from Golden Dried Longan production (LW) that provides the maximum methane yield, and 2) to assess the performance of the TPAD system in producing biogas from the co-digestion between septage and LW and its performance in removing pathogens. Results and discussion of each part conducted to achieve the objectives are showed in this chapter.

4.1 The suitable septage to LW ratio analysis

Accumulative methane volume obtained from the modified BMP test is shown in Figure 4.1. The highest methane accumulation (227 ml) was found when LW was used as the sole substrate, while septage gave the lowest value at 86.7 ml. When septage was co-digested with LW, the highest methane accumulation (196 ml) was achieved at COD:TKN ratio of 100:1.1, following by 127 ml and 89.2 ml at the ratios of 100:2.5 and 100:5, respectively.

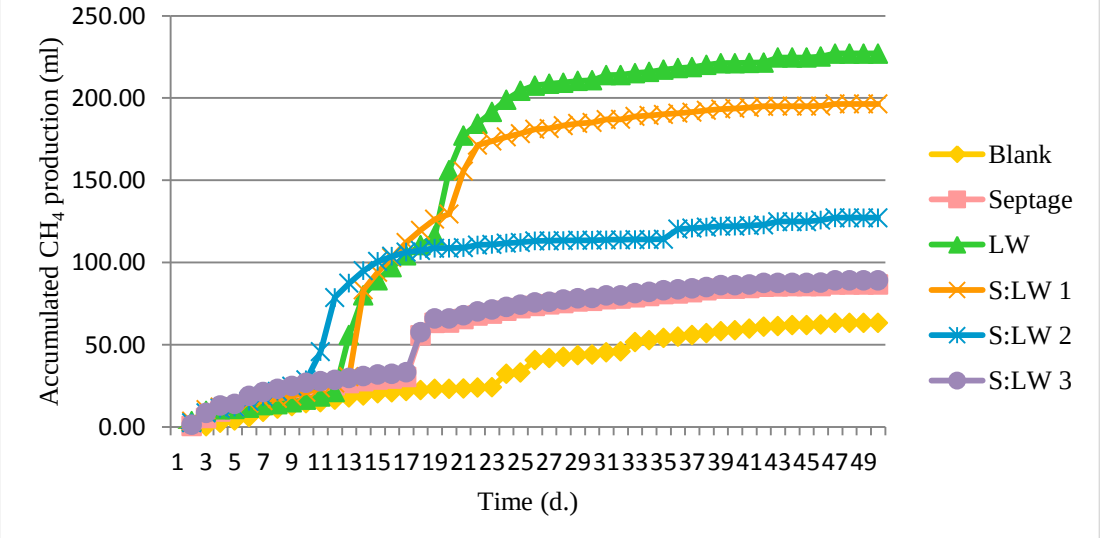


Figure 4.1 Methane accumulations during the BMP test

Analysis of microbial kinetic activities and the synergistic effects was done for choosing the suitable ratio of substrates (septage:LW) during the co-digestion process. Results obtained from the simulation using the MG and the FO models indicated that both models could positively predict the experimental values (Table 4.1) with the coefficient of determination (R^2) in the range of 0.87-0.99 (Figure 4.2) and 0.85-0.91 (Figure 4.3) for MG and FO models, respectively. However, considering the R^2 values, it was obvious that experimental results obtained from all experiments were fitted better by the MG model. This could be explained by the model's assumptions, in which FO model attributes biogas production efficiency to the hydrolysis step, while MG model considers the overall microbial activities. As wastes used in the experiment (septage and LW) did not contain very high suspended solid concentrations (especially for LW which was the high strength wastewater having sugar and simple carbohydrates as the main organic substances), the overall microbial activities were supposed to govern biogas production efficiency and not only the hydrolysis reaction. Consequently, the MG model was selected and the microbial kinetic values obtained from this model were used to explain the differences of co-digesting septage and LW at different ratios.

Results from the MG model showed that the highest ultimate methane production yield (P; 145 $mlCH_4/gVS$) was predicted when LW was used as the sole substrate. Surprisingly, the value obtained from septage (139 $mlCH_4/gVS$) was relatively high. High organic content (VS/TS = 70%) and high methane production rate during degradation process (between day 17-20 in Figure 4.2 (a)) could tentatively explain this high P value for septage.

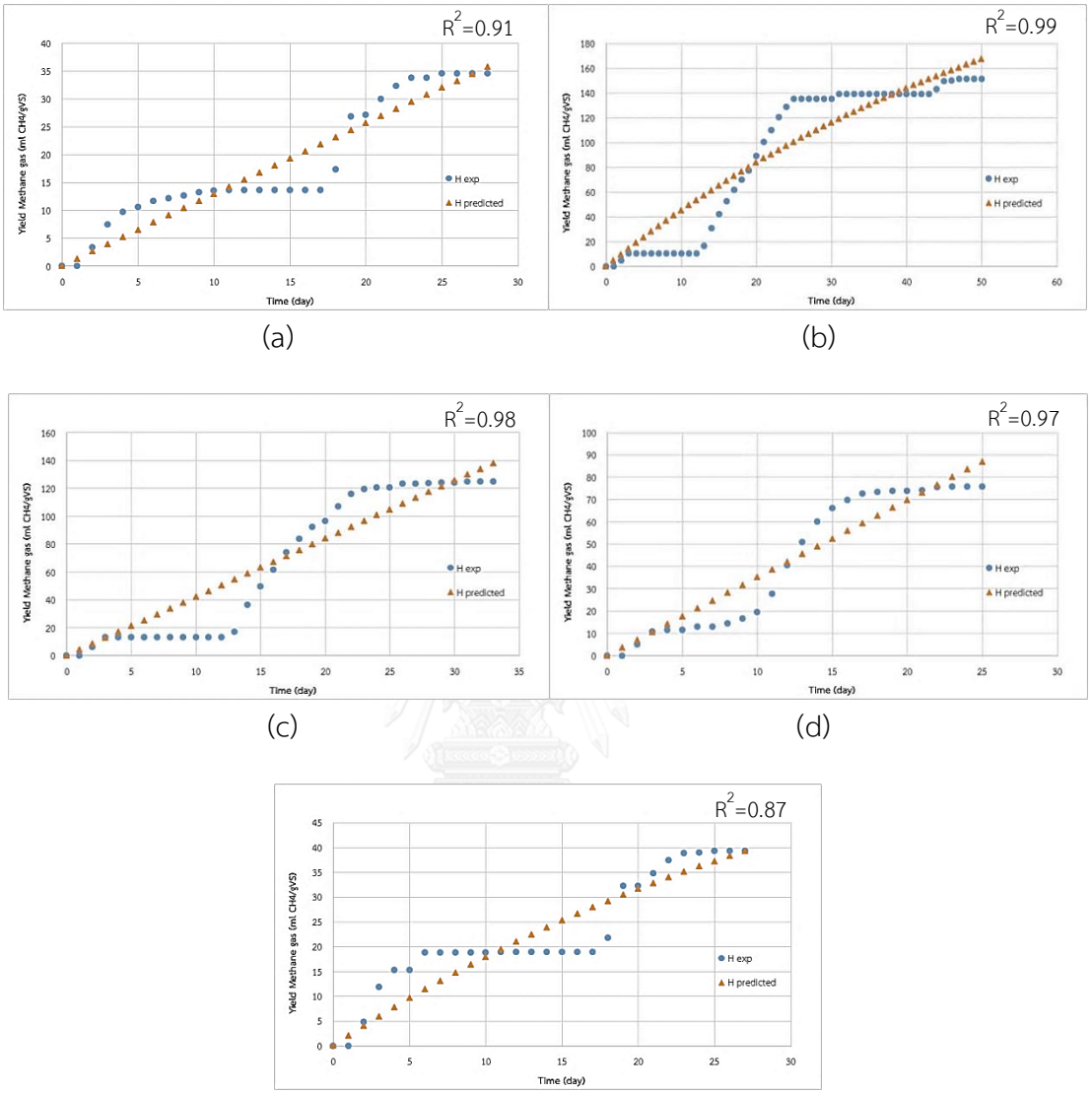


Figure 4.2 The MG model comparison of the predicted and experimental values (a) S (b) LW (c) S:LW 1 (d) S:LW 2 (e) S:LW 3

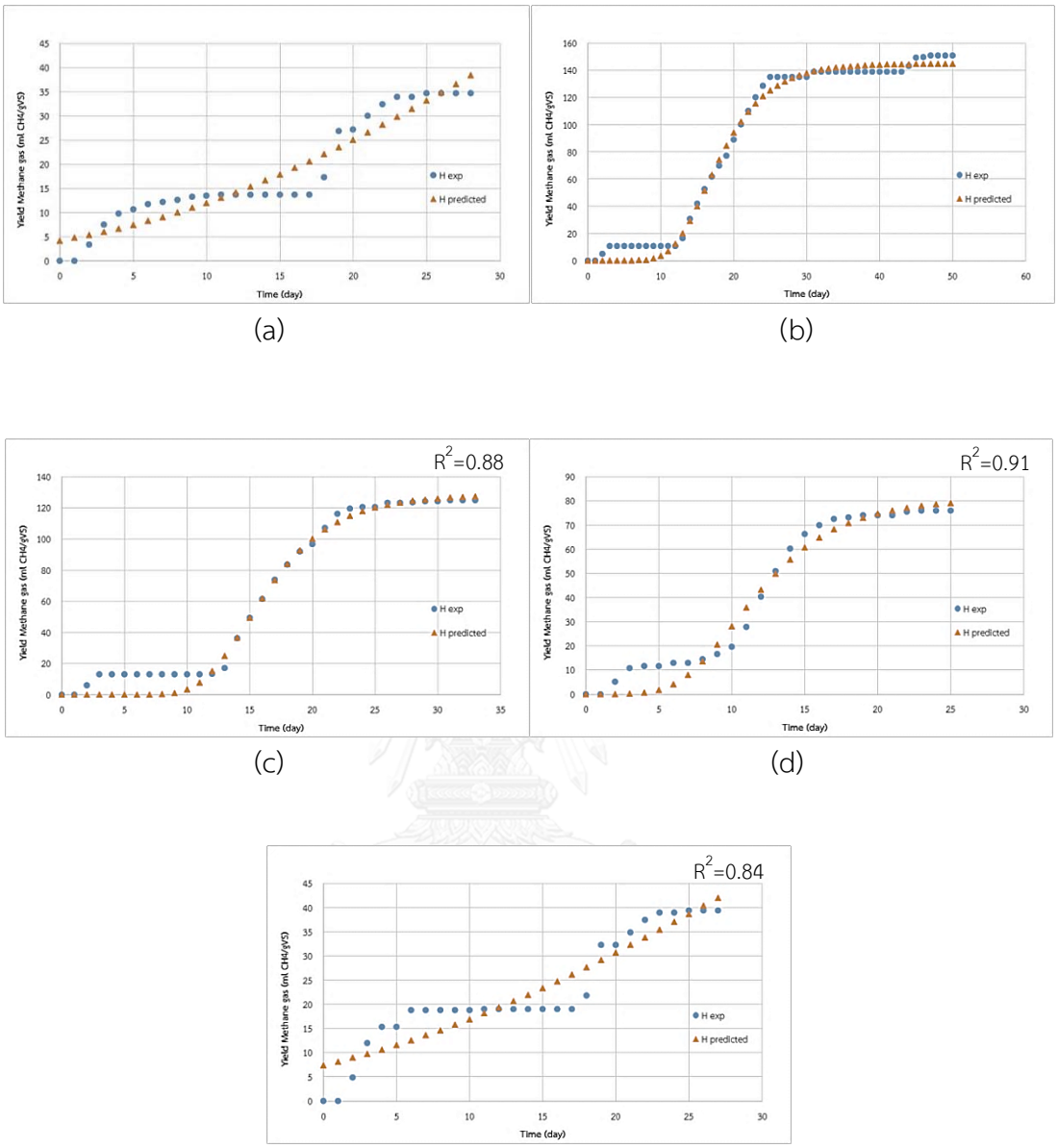


Figure 4.3 The FO model comparison of predicted and experimental values (a) S (b) LW (c) S:LW 1 (d) S:LW 2 (e) S:LW 3

Table 4.1 Microbial kinetic and Synergistic effect values

Substrate	P ($mlCH_4/gVS$)		Kinetic parameter			R^2		Synergistic effect*	
	MG	FO	MG		FO	MG	FO		
			Rm	λ	k_{hyd}				
S	139	811	1.83	7.19	0.00	0.91	0.89		
LW	145	297	11.6	11.6	0.02	0.99	0.88		
S:LW 1	128	9,888	12.8	11.1	0.00	0.98	0.88	0.97 (±0.020)	A
S:LW 2	80.6	2,735	7.78	6.41	0.00	0.97	0.91	0.81 (±0.071)	B
S: LW 3	143	76.2	1.72	2.65	0.03	0.87	0.85	0.89 (±0.009)	A B

*synergistic effects that do not share the same letter show that they are significantly different

For the co-digestion process, of all three tested ratios, the ultimate specific methane yield of the COD:TKN ratio of 100:5 rendered the highest value of 143 ml CH_4/g VS, which was apparently higher than 128 and 80.6 ml CH_4/g VS found at the ratios of 100:1.1 and 100:2.5, respectively. Moreover, the lag phase (2.65 d) was found to be the shortest at the COD:TKN=100:5 compared to 11.1 d and 6.41 d required at the 100:1.1 and 100:2.5 ratios, respectively. This result suggested that microorganisms not only functioned at the higher rate at the COD:TKN=100:5 ratio but they also needed lesser time to acclimatize for substrate biodegradation.

Analysis of synergistic effects revealed that effect of co-digestion at COD:TKN ratio of 100:1.1 was significantly higher than that at 100:2.5 ($P<0.05$) while no difference was found between COD:TKN ratios of 100:1.1 and 100:5. Synergistic effects obtained at 100:1.1 and 100:5 ratios in the range close to 1.00 implied that co-digestion between septage and LW at these ratios tended to have a clearer positive effect (synergistic effect > 1.00) when the system was operated under continuous condition. This was due to the fact that under continuous condition

(when substrate was fed regularly), nutrients of inoculums would not be reliable and the process would completely rely on nutrients provided by the co-digested substrate. From the results gained, it could be concluded that the suitable septage:LW ratio was that at the COD:TKN=100:5. At this ratio, highest ultimate methane production yield was obtained while the lag phase was the shortest. In addition, at this ratio, highest amount of septage was required, which was very advantageous as septage is generated throughout the year while LW is available only during the longan processing season (around 1-2 months a year).

There have been works of using septage as a substrate for biogas production (Table 4.2). When septage was used as a sole substrate, methane yields reported were in the range of (56-83.5 mlCH_4/gVS) ((Lin (1998); (Prabhu, 2014)). Higher methane yield found in this current work when septage was used as a sole substrate (139 mlCH_4/gVS) could be contributed by different characteristics of septage from different sources. Nevertheless, co-digestion of septage with the nutrient and/or alkalinity deficient wastes could apparently improve methane yield. More than two times of methane yield increase was found when co-digesting septage with leachate (Lin (2000); Chiu-Yue Lin (1999)), while methane yield was increased more than three times for septage and food waste co-digestion (Prabhu, 2014). Synergistic effects of co-digesting septage with LW were not clearly shown in this current work. This could be partly explained by the fact that inoculum used in the BMP test could provide some amounts of nutrients to the digested content. Moreover, organic strength of LW used in this current study was apparently lower than those of leachate and food waste reported in the previous works (Lin (2000); (Prabhu, 2014); Chiu-Yue Lin (1999)).Clearer positive effects of co-digestion were expected when operating the system continuously as nutrients and alkalinity would be provided mainly by the mixture of wastes used as the reactor influent.

Table 4.2 Anaerobic digestions using septage as the sole substrate and co-digested substrate

Wastes	Reactor Types	Conditions		Methane Yield ($mlCH_4/gVS$)	References
		Temp. (°C)	OLR		
Septage (S) and leachate (L)	UASB	35±1	6.73 kg COD/m^3-day	S:L;1:1=131	(Lin, 2000)
Septage and food waste (FW)	The BMP test	32	-	S=56±17.6, FW=503±10.8, FW:S;1:2=1,737	(Prabhu, 2014)
Septage and leachate	CSTR	35±1	S=309, S:L;3:1= 315 g COD/m^3-day	S=83.5, S:L;3:1=115	(Chiu-Yue Lin, 1999)
Septage and Longan wastewater	The BMP test	30±2	-	S=139,LW=145, COD:TKN; 100:5=143	This work.

It was estimated using the information gathered from a factory at the Rim Rong village, Lamphun that from 35 longan production factories in Chiang Mai province, 442 m^3 of wastewater could be generated annually. Considering that septage in Chiang Mai municipality (Department of Agriculture, 2014) was estimated to be 142 m^3/d or 51,830 m^3/year (unpublished report), up to 8,354 m^3 of biogas could be produced per year by co-digesting septage and LW (calculated using 1,017 m^3/yr. of septage and 442 m^3/yr. of LW using 143 ml CH_4/g VS obtained at the COD:TKN ratio of 100:5 and 50% CH_4 in the produced biogas). This amount of biogas is equivalent to 16,708 units of electricity (kWh) or 3,843 kg of LPG or 5,012 l of diesel. Additionally, remaining amounts of septage (50,813 m^3/yr) could still be used in the co-digestion process with other wastes to produce more biogas.

4.2 Physical chemical and biological analysis during start-up and operational periods.

The experiments were conducted using two lab-scale TPADs system (Table 4.3). Septage (control system) and mixture of septage and LW were used as the feedstock for studied TPAD systems. The OLR was started from 0.9/1.0 kgVS/m^3-d (presented as OLRs of Thermophilic reactor/Mesophilic reactor) and was sequentially increased to 1.6/2.0, 1.5/3.0 and 4.5/5.0 kgVS/m^3-d for TPAD1, while OLR of TPAD2 was started from 0.5/1.0 kgVS/m^3-d following by 1.7/2.0, 1.4/3.0 and 4.5/5.0 kgVS/m^3-d, respectively. At OLRs of 1.5/3 and 4.5/5 kg VS/m^3-d for TPAD1 and OLRs of 1.4/3.0 and 4.5/5.0 kgVS/m^3-d for TPAD2, the systems were operated for at least 1.5 times of the HRT. As characteristics of septage, the main ingredient of the feedstock, were changed by the storage time, only the pseudo-steady state was assumed to attain. Performance of reactors after they were operated for 1.5 times of HRT at a specific condition was used to represent the pseudo-steady state performance.

Influent and effluent samples from each reactor were regularly collected to determine the reactor performance. The measured parameters were temperature, pH, alkalinity (Alk) and volatile fatty acid (VFA), total solid (TS) and volatile solid VS), total suspended solid (TSS) and volatile suspended solid (VSS), COD, biogas volume and composition, and pathogens (Total coliform, Fecal coliform, E. coli, Salmonella ssp. and Shigella spp.). Results of all experiments are tabulated in Table 4.4-4.6.

Table 4.3 Details of TPAD systems used in the study

System set	Substrate	Reactor	Reactor name
TPAD1	Septage	Thermophilic	TS
		Mesophilic	MS
TPAD2	Septage+LW	Thermophilic	TSL
		Mesophilic	MSL

Table 4.4 (a) Influent (Inf.) and Effluent (Eff.) measured parameters of each TPAD system during start-up period (day 1-25)

Systems		TPAD1		TPAD2	
Reactors		TS	MS	TSL	MSL
pH	Inf.[a]	8.05	7.46-8.25	6.33	7.43-7.76
	Eff.[b]	7.46-8.25	7.41-8.31	7.43-7.76	7.40-7.74
Temp(°C)	Eff.	49.0-55.0	32.5-37.0	49.0-56.5	32.0-37.5
Alkalinity ($mgCaCO_3/l$)	Inf.	2,781-4,352	2,599-5,746	0-3,143	1,511-3,851
	Eff.	2,599-5,746	2,237-4,707	1,511-3,851	2,055-3,484
VFA ($mgCH_3COOH/l$)	Inf.	1,424-2,989	925-3,510	1,922-10,249	890-2,313
	Eff.	925-3,510	1,037-4,413	890-2,313	925-2,074
VFA/Alk.	Eff.	0.26-0.88	0.23-0.79	0.39-0.99	0.45-0.83

[a]Influent

[b]Effluent

Table 4.4 (b) Influent (Inf.) and Effluent (Eff.) measured parameters of each TPAD system during start-up period

Systems		TPAD1		TPAD2	
Reactors		TS	MS	TSL	MSL
TS (mg/l)	Inf.	44,750-55,840	36,980-43,790	6,155-48,340	10,530-30,300
	Eff.	36,980-43,790	33,170-39,870	6,155-48,340	11,520-26,820
VS (mg/l)	Inf.	31,040-38,260	25,090-30,380	5,485-33,640	7,610-20,670
	Eff.	25,090-30,380	22,660-26,440	7,610-20,670	8,050-18,950
COD (mg/l)	Inf.	44,701-69,911	30,829-68,004	4,449-49,200	11,400-33,472
	Eff.	30,829-68,004	28,516-64,614	11,400-33,472	16,101-61,013
Gas volume (ml/d)		0-1,088	0-569	0-8,157	0-121
CH_4 yield ($mlCH_4/gVS_{added}$)		0-25.2	0-29.2	0-682	0-33.7

Table 4.4 (c) Influent and Effluent measured parameters of each TPAD system during start-up period

Systems		TPAD1		TPAD2	
Reactors		TS	MS	TSL	MSL
Total coliform (MPN/100ml)	Inf.	1.6×10^{8}-2.3×10^{9}	490-1.7×10^{3}	3.3×10^{5}-7.9×10^{5}	790-1.8×10^{3}
	Eff.	490-1.7×10^{3}	2.4×10^{4}-9.2×10^{4}	790-1.8×10^{3}	1.3×10^{4}-3.5×10^{4}
Fecal coliform (MPN/100ml)	Inf.	1.7×10^{7}-6.3×10^{7}	490-780	3.3×10^{5}-7.9×10^{5}	18-490
	Eff.	490-780	4.9×10^{3}-9.2×10^{4}	18-490	450-3.5×10^{4}
E. coli (MPN/100ml)	Inf.	1.7×10^{7}	490-780	2.3×10^{4}-7.9×10^{4}	<18
	Eff.	490-780	180-3.3×10^{3}	<18	180-450

Table 4.5 (a) Influent and Effluent measured parameters of TPAD1 and TPAD2 during OLR1.5/3.0 and OLR1.4/3.0 period (day 26-64)

Systems		TPAD1		TPAD2	
Reactors		TS	MS	TSL	MSL
pH	Inf.	8	7.48±0.05	6.89	7.28±0.04
	Eff.	7.48±0.05	7.42±0.04	7.28±0.04	7.34±0.03
Temp(°C)	Eff.	53.7±5.72	36.2±1.09	55.1±0.94	35.5±0.81
Alkalinity ($mgCaCO_3/l$)	Inf.	2,772±377	3,873±367	2,299±89.6	2,921±306
	Eff.	3,873±367	3,835±504	2,921±306	2,972±208
VFA ($mgCH_3COOH/l$)	Inf.	1,543±155	1,948±373	1,830±432	1,654±378
	Eff.	1,948±373	1,916±376	1,654±378	1,649±217
VFA/Alk.	Eff.	0.50±0.0	0.50±0.07	0.57±0.13	0.56±0.07

Table 4.5 (b) Influent and Effluent measured parameters of TPAD1 and TPAD2 during OLR1.5/3.0 and OLR1.4/3.0 period

Systems		TPAD1		TPAD2	
Reactors		TS	MS	TSL	MSL
TS (mg/l)	Inf.	31,400±7,580	41,847±3,351	25,323±5,343	26,717±7,071
	Eff.	41,847±3,351	41,652±1,880	26,717±7,071	29,581±1,969
VS (mg/l)	Inf.	21,463±4,990	30,022±2,607	17,723±3,816	18,584±4,909
	Eff.	30,022±2,607	29,573±1,581	18,584±4,909	21,037±1,440
COD (mg/l)	Inf.	24,543±2,777	37,979±4,048	23,070±1,641	25,315±5,064
	Eff.	37,979±4,048	39,486±5,389	25,315±5,064	27,237±3,566
Gas volume (ml/d)		185±80.5	16.5±19.6	1,637±421	22.0±22.0
CH_4 yield ($mlCH_4/gVS_{added}$)		2.29±1.34	0.54±0.65	20.5±4.56	1.73±1.71

Table 4.5 (c) Influent and Effluent measured parameters of TPAD1 and TPAD2 during OLR1.5/3.0 and OLR1.4/3.0 period

Systems		TPAD1		TPAD2	
Reactors		TS	MS	TSL	MSL
Total coliform (MPN/100ml)	Inf.	230-2.0×10^5	<18-120	2.2×10^3-1.3×10^5	<18-7.5×103
	Eff.	<18-120	130-2.3×10^7	<18-7.5×10^3	2.2×10^4-7.9×10^5
Fecal coliform (MPN/100ml)	Inf.	230-2.0×10^5	<18	330-1.3×10^5	<18
	Eff.	<18	<18-2.4×10^4	<18	165-4.9×10^5
E. coli (MPN/100ml)	Inf.	230-1.7×10^4	<18	170-4.5×10^3	170-4.5×10^3
	Eff.	<18	<18-230	<18	68-2.3×10^4

Table 4.6 (a) Influent and Effluent measured parameters of TPAD1 and TPAD2 during OLR4.5/5.0 period (day 65-95)

Systems		TPAD1		TPAD2	
Reactors		TS	MS	TSL	MSL
pH	Inf.	7.62	7.81±0.09	6.88	7.35±0.05
	Eff.	7.81±0.09	7.74±0.11	7.35±0.05	7.44±0.06
Temp(°C)	Eff.	55.0±1.52	36.0±2.17	55.3±1.57	35.8±1.04
Alkalinity ($mgCaCO_3/l$)	Inf.	2,648±171	2,747±416	1,694±513	1,974±286
	Eff.	2,747±416	2,776±545	1,974±286	2,147±399
VFA ($mgCH_3COOH/l$)	Inf.	1,305±1,167	1,291±294	1,593±918	1,122±462
	Eff.	1,291±294	1,390±222	1,122±462	1,010±233
VFA/Alk.	Eff.	0.47±0.08	0.52±0.12	0.46±0.09	0.48±0.10

Table 4.6 (b) Influent and Effluent measured parameters of TPAD1 and TPAD2 during OLR4.5/5.0 period

Systems		TPAD1		TPAD2	
Reactors		TS	MS	TSL	MSL
TS (mg/l)	Inf.	26,200±1,069	22,742±7,620	18,723±3,001	16,989±10,724
	Eff.	22,742±7,620	24,112±7,292	16,989±10,724	16,878±6,455
VS (mg/l)	Inf.	18,407±950	15,843±4,921	13,677±2,142	12,150±7,436
	Eff.	15,843±4,921	17,188±5,380	12,150±7,436	12,042±4,484
COD (mg/l)	Inf.	20,663±4,719	15,598±4,227	12,814±7,700	11,124±8,232
	Eff.	15,598±4,227	16,810±6,338	11,124±8,232	10,983±8,496
Gas volume (ml/d)		242±229	45.1±43.0	3,452±956	176±71.6
CH_4 yield ($mlCH_4/gVS_{added}$)		0.57±0.49	0.17±0.17	13.8±3.82	0.73±0.54

Table 4.6 (c) Influent and Effluent measured parameters of TPAD1 and TPAD2 during OLR4.5/5.0 period

Systems		TPAD1		TPAD2	
Reactors		TS	MS	TSL	MSL
Total coliform (MPN/100ml)	Inf.	200-2.1×10^{4}	<18-370	1.3×10^{4}-2.3×10^{4}	<18-3.2×10^{3}
	Eff.	<18-370	<18-450	<18-3.2×10^{3}	20-450
Fecal coliform (MPN/100ml)	Inf.	78-400	<18-45	1.3×10^{3}-3.8×10^{3}	<18-170
	Eff.	<18-45	<18-37	<18-170	<18-61
E. coli (MPN/100ml)	Inf.	45-200	<18-20	1.1×10^{3}-2.2×10^{3}	<18-20
	Eff.	<18-20	<18	<18-20	<18-21

4.2.1 Temperature

Temperatures of effluent from TS and MS reactors during start-up period (day 1-25) were in ranges of 49-55°C and 32.5-37°C while those of effluent from TSL and MSL reactors were in ranges of 49-56.5°C and 32-37.5°C, respectively. These temperatures were well within the suitable ranges for thermophilic anaerobes (50-56°C) and mesophilic anaerobes (20-45°C) (Gerardi., 2003)

During the operation period (day 26-95), temperatures of effluent from TS and MS were in ranges of 54-57°C and 34-38°C (Figure 4.4(a)), while those of effluent from TSL and MSL reactors were in ranges of 51-59°C and 34-39°C (Figure 4.4(b)), respectively. The average temperatures of OLR1.5/3.0 (day 26-64) were 53.6±2.20°C and 36.1±1.13°C for TS and MS effluent, and 51.1±0.99°C and 35.5±0.84°C for TSL and MSL effluent. The average temperatures of OLR4.5/5.0 (day 65-95) were 55.0±1.56°C and 36.1±2.22°C for TS and MS effluent, and 55.4±1.60°C and 35.9±0.99°C for TSL and MSL effluent. Drop of effluent temperature of TS reactor during day 60-61 was the result of heater malfunction.

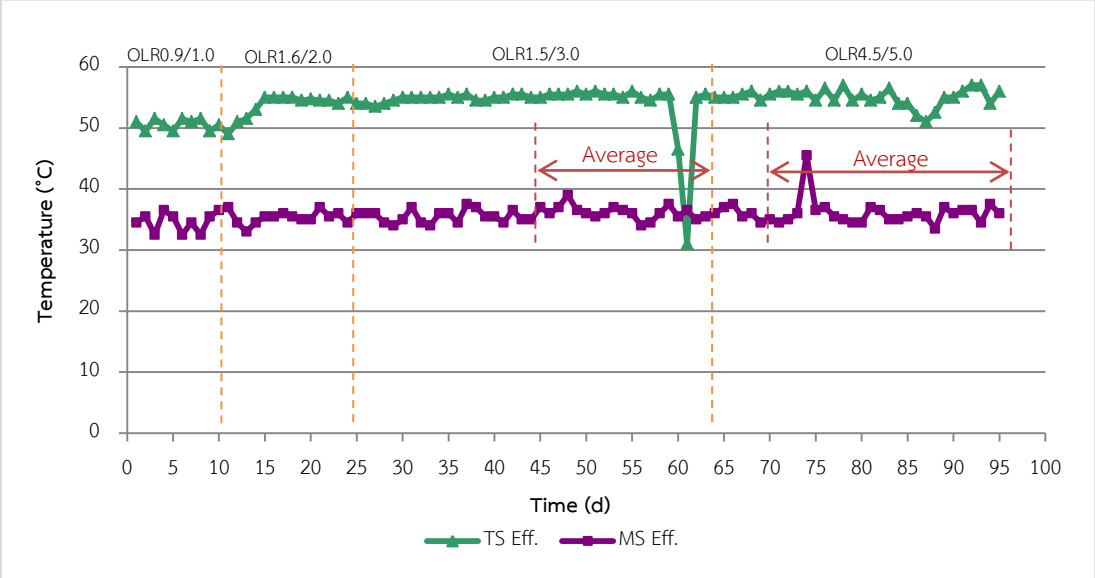


Figure 4.4 (a) Effluent temperatures of TS and MS reactors

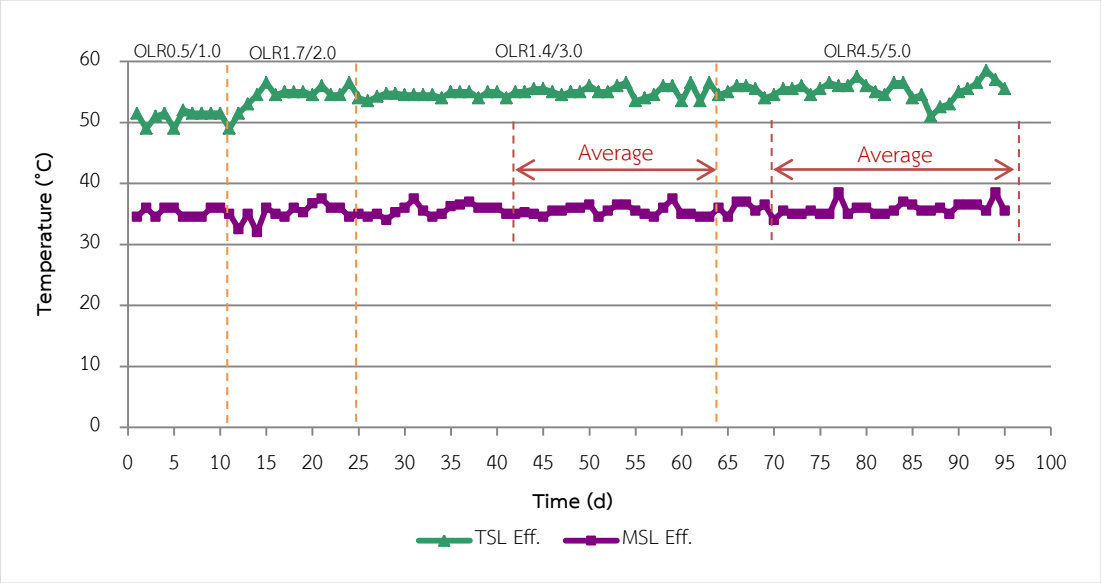


Figure 4.4 (b) Effluent temperatures of TSL and MSL reactors

4.2.2 pH

pH is an important indicator of stability for anaerobic digestion system. The suitable pH for anaerobic digestion process is around 6-8. pH lower than 6 or higher than 8 is restrictive and can be toxic to methane-forming bacteria (Gerardi., 2003). During start-up period, pH of TS and MS effluent were in ranges of 7.46-8.25 and 7.41-8.31, while pH of TSL and MSL effluent were in ranges of 7.43-7.76 and 7.4-7.74. These pH values were in the suitable range for anaerobic digestion process. Relatively higher pH value during the first 25 d was the result of all reactors being started-up by adding 70% of working volume with the high pH septage.

During the operation period, pH of TS influent was 7.92±0.27 while that of TSL influent was 6.84±0.08. Mixing septage with LW reduced the pH of the influent for TSL reactor as the average pH of LW was low (3.96±0.08). pH values of TS and MS effluent were 7.41-8.00 and 7.24-7.95, respectively (Figure 4.5(a)). Even though the influent pH of TPAD2 was significantly lower, pH values of TSL and MSL effluent (7.21-7.60 and 7.28-7.55, respectively (Figure 4.5(b)) were still within the suitable

range for normal anaerobic degradation. The average pHs of OLR1.5/3.0 were 7.48±0.05 and 7.42±0.04 for TS and MS effluent, and 7.28±0.04 and 7.34±0.03 at ORL1.4/3.0 for TSL and MSL effluent. The average pHs of OLR4.5/5.0 were 7.81±0.09 and 7.74±0.11 for TS and MS effluent, and 7.35±0.05 and 7.44±0.06 for TSL and MSL effluent. When OLR was increased to OLR4.5/5.0, higher pHs were observed especially from TS and MS effluent. Increase of pH at higher OLR was the result of changes of septage characteristics. As organic contents of septage were significantly reduced after long storage time, C/N ratio of septage used at OLR4.5/5.0 would be considerably decreased. Anaerobic biodegradation of the nitrogen-rich substrate could create high amounts of alkalinity as 3.6 g/l as $CaCO_3$ of alkalinity are anaerobically produced from 1 g/l nitrogen (Speece, 1996). This high amounts of alkalinity coupled with low VFAs created (as organic contents were lower) leading to higher pH of reactor effluent. Increase of pH of TSL and MSL effluent was not as obvious as that observed from TS and MS reactors as LW could maintain the relatively stable C/N ratio even though organic contents of septage was lower. Nevertheless, mixing of septage and LW had proved to be able to maintain pH of the reactor at the suitable level even when OLR was as high as 4.5 and 5.0 kgVS/m^3-d for TSL and MSL reactors, respectively.

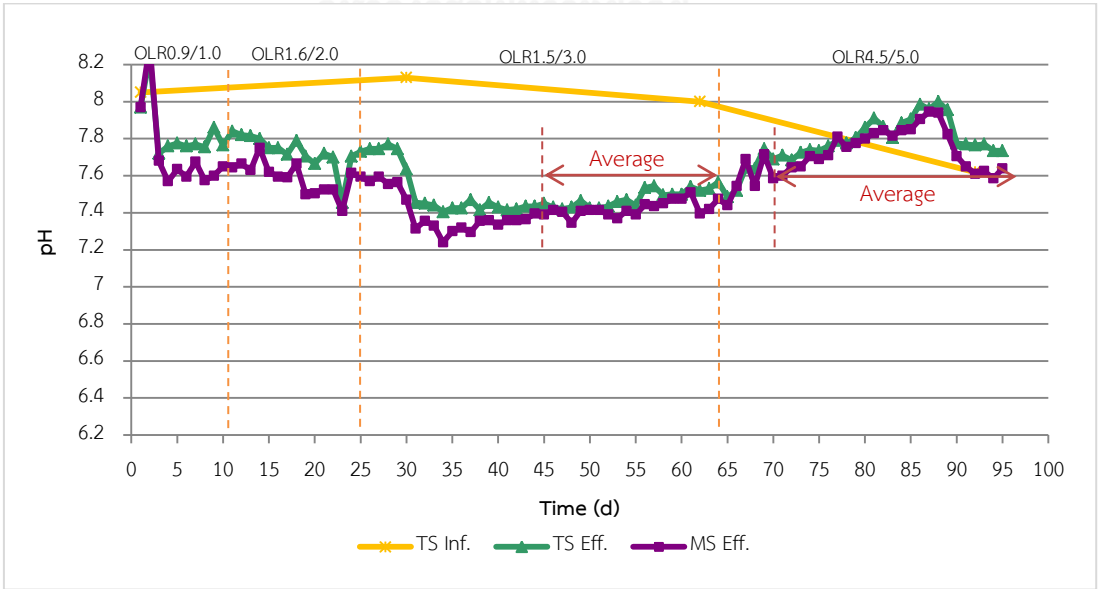


Figure 4.5 (a) pHs of TPAD1 reactors

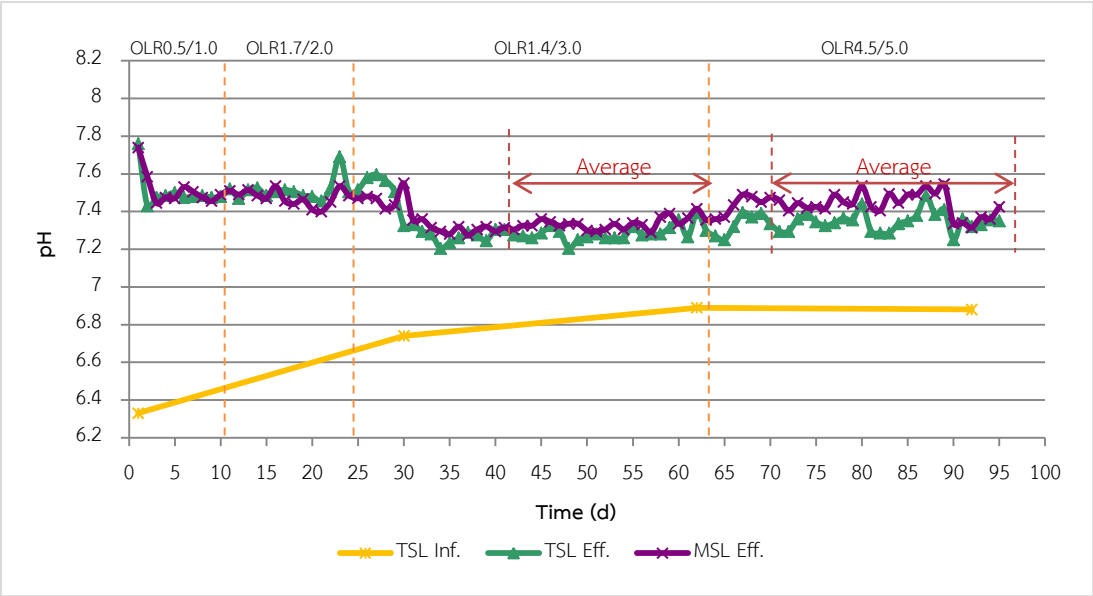


Figure 4.5 (b) pHs of TPAD2 reactors

4.2.3 Alkalinity and Volatile Fatty Acid (VFA)

Alkalinity in wastewater results from the presence of hydroxide (OH^-), carbonates (CO_3^{2-}) and bicarbonates (HCO^{3-}). The alkalinity in wastewater helps to resist changes in pH cause by the presence of acid. Alkalinity concentration of 2,000 to 3,000 mg/l as $CaCO_3$ may be needed in anaerobic process to maintain an acceptable pH (Metcalf & Eddy, 2004). The alkalinity concentrations in ranges of 2,781-4,352 mg$CaCO_3$/l and 0-3,143 mg$CaCO_3$/l were detected in the influent of TS and TSL during start-up period. The alkalinity concentrations of TS and MS were in ranges of 2,599-5,746 mg$CaCO_3$/l and 2,237-4,707 mg$CaCO_3$/l, while alkalinity of TSL and MSL effluent were in ranges of 1,511-3,851 mg$CaCO_3$/l and 2,055-3,484 mg$CaCO_3$/l, respectively.

During the operation period, alkalinity concentrations in ranges of 2,476-3,310 mg$CaCO_3$/l and 1,271-2,690 mg $CaCO_3$/l were found in the influent of TS and TSL, respectively. The alkalinity concentrations of TS and MS effluent were in ranges of 2,265-4,420 mg$CaCO_3$/l and 2,166-4,829 mg$CaCO_3$/l (Figure 4.6(a)), while the alkalinity concentrations of TSL and MSL were in ranges of 1,650-3,426 mg$CaCO_3$/l and 1,768-

3,426 mg$CaCO_3$/l (Figure 4.6(b)), respectively. The average alkalinity concentrations of OLR 1.5/3.0 were 3,873±367 mg$CaCO_3$/l and 3,835±504 mg$CaCO_3$/l for TS and MS effluent, and 2,921±306 mg$CaCO_3$/l and 2,972±208 mg$CaCO_3$/l at OLR 1.4/3.0 for TSL and MSL effluent. The average alkalinity concentrations of OLR4.5/5.0 were 2,747±416 mg$CaCO_3$/l and 2,776±545 mg$CaCO_3$/l for TS and MS effluent, and 1,974±286 mg$CaCO_3$/l and 2,147±399 mg$CaCO_3$/l for TSL and MSL effluent. As expected, effluent alkalinity of TSL and MSL reactors were lower than those of TS and MS reactors. This was, partly, due to the fact that mixture of septage and the low pH-LW were used as the feedstock for TSL and MSL reactors. However, alkalinity levels detected in the effluent of TSL and MSL reactors were still sufficient for maintaining pH levels within the workable range for anaerobic digestion. By mixing LW with septage at the proper mixture, biogas production could be occurred without any chemical addition.

Anaerobic reactor instability is generally manifested by a marked and rapid increase in VFA concentrations; this is frequently indicative of the failure of the methanogenic population due to other environmental disruptions. The methanogen was reported to tolerate both acetate and butyrate at concentrations of up to 10,000 mg/l although variable inhibitory levels for propionate of 1,000 mg/l and 5,000 mg/1 have been recorded (Gerardi., 2003). The VFA concentrations in ranges of 1,424-2,989 mgCH_3COOH/l and 1,922-10,249 mgCH_3COOH/l were detected in the influent of TS and TSL during start-up period. The VFA concentrations of TS and MS effluent were in ranges of 925-3,510 mgCH_3COOH/l and 1,037-4,413 mgCH_3COOH/l, while those found in TSL and MSL effluent were in ranges of 890-2,313 mgCH_3COOH/l and 925-2,074 mgCH_3COOH/l, respectively.

During the operation period, VFA concentration in ranges of 587-2,652 mgCH_3COOH/l and 880-2,629 mgCH_3COOH/l were found in the influent of TS and TSL. The VFA concentrations of TS and MS effluent were in ranges of 976-2,552 mgCH_3COOH/l and 1,127-2,704 mg CH_3COOH/l (Figure 4.7(a)), while the VFA concentration of TSL and MSL effluent were in ranges of 587-2,414 mgCH_3COOH/l and 734-1,878 mgCH_3COOH/l (Figure 4.7(b)), respectively. The average VFA

concentrations of OLR1.5/3.0 were 1,948±373 mgCH_3COOH/l and 1,916±376 mgCH_3COOH/l for TS and MS effluent, and 1,654±378 mgCH_3COOH/l and 1,649±217 mgCH_3COOH/l at OLR 1.4/3.0 for TSL and MSL effluent. The average VFA concentrations of OLR 4.5/5.0 were 1,291±294 mgCH_3COOH/l and 1,390±222 mgCH_3COOH/l for TS and MS effluent and 1,122±462 mgCH_3COOH/l and 1,010±233 mgCH_3COOH/l for TSL and MSL effluent. Corresponding to alkalinity levels, VFA concentrations of effluent from TS and MS reactors were higher than that found in TSL and MSL reactors effluent. However, considering that TPADs system was operated at the OLR as high as 4.5/5.0 kgVS/m^3-d, these VFA levels were still relatively and within the acceptable level for healthy anaerobic digestion (Sandra M. Stronach, 1986).

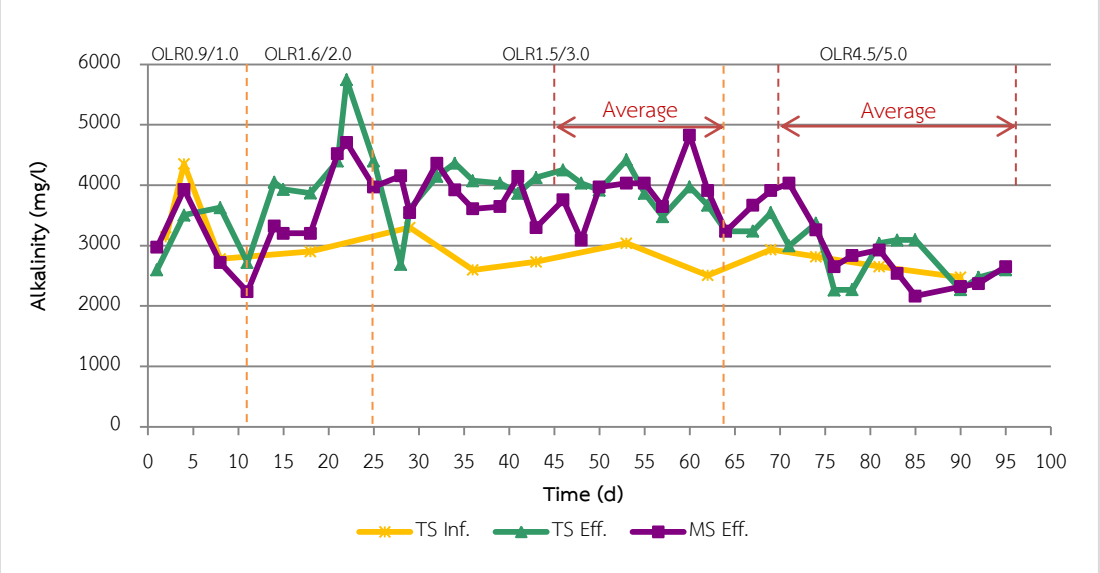


Figure 4.6 (a) Alkalinity concentrations of TPAD1 reactors

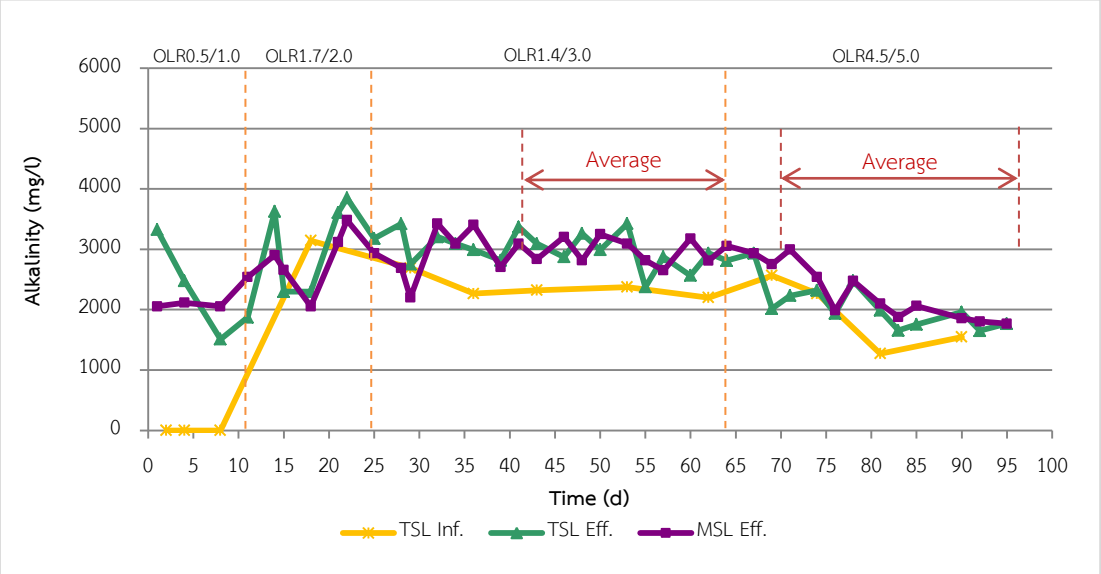


Figure 4.6 (b) Alkalinity concentrations of TPAD2 reactors

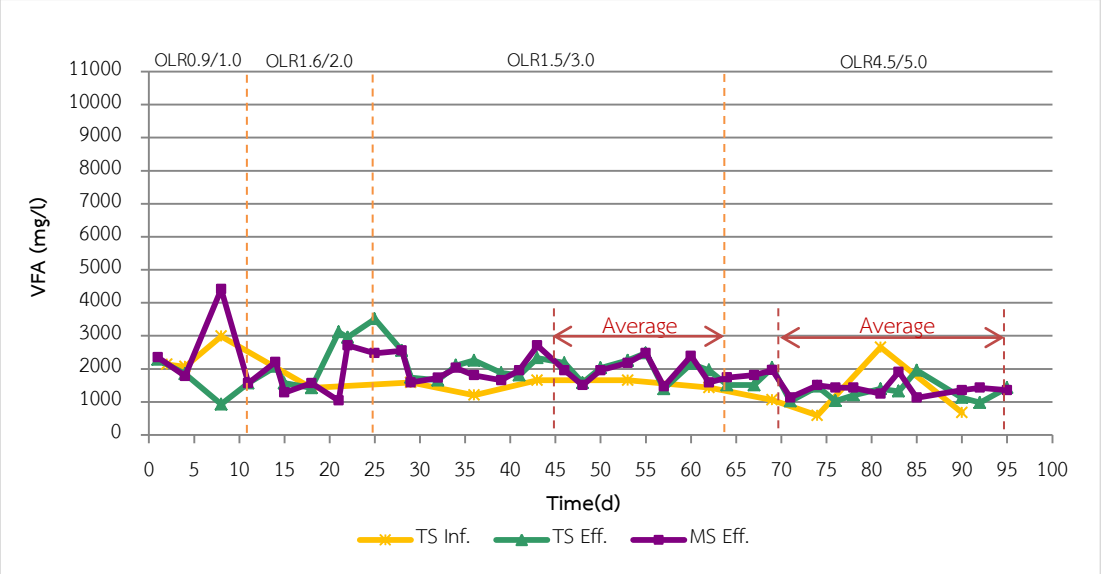


Figure 4.7 (a) VFA concentrations of TPAD1 reactors

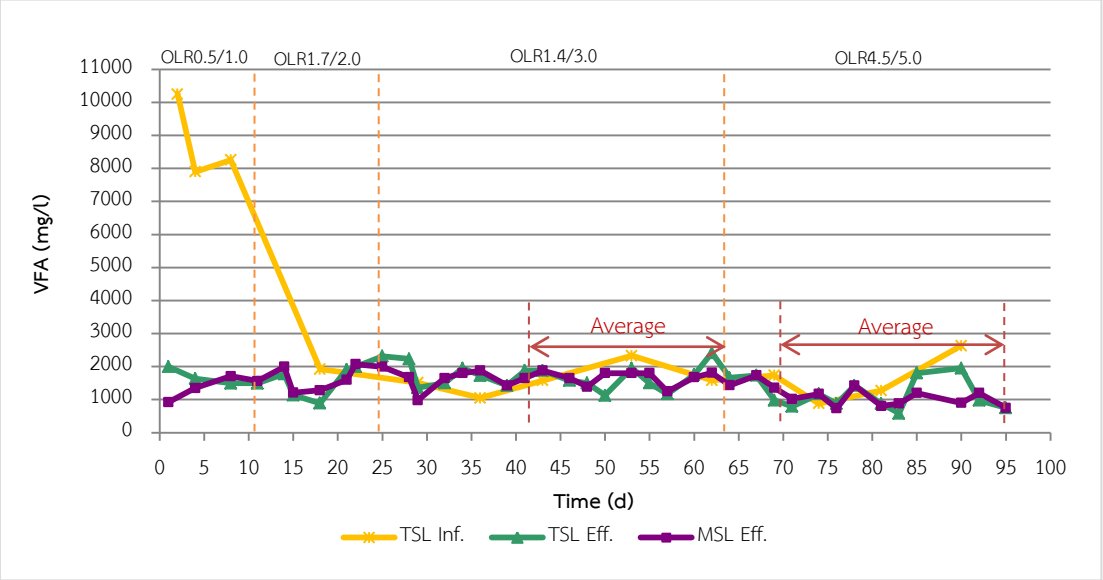


Figure 4.7 (b) VFA concentrations of TPAD2 reactors

The overall anaerobic conversion of biodegradable organic materials to end products, methane and carbon dioxide, is occurred from the co-operation of two types of bacteria; acid forming bacteria (VFA producer) and methanogens (CH_4 producer). Profile of influent VFA during 1-10 d was high due to lower amounts of septage (at COD:TKN of 100:1.1). McCarty (1986) stated that the suitable ratio of VFA to alkalinity for the anaerobic process activity should be less than 0.4; which over 0.8 of VFA to alkalinity ratio means the system has low buffer. The VFA:alkalinity (VFA:Alk) of TS and MS effluent during start-up period were in ranges of 0.26-0.88 and 0.23-0.79, while TSL and MSL effluent were in ranges of 0.39-0.99 and 0.45-0.83, respectively.

During the operated period, the VFA:Alk of TS and MS effluent were in ranges of 0.34-0.95 and 0.28-0.82 (Figure 4.8(a)), while TSL and MSL effluent were in ranges of 0.35-0.82 and 0.34-0.67 (Figure 4.8(b)). The average VFA:Alk of OLR1.5/3.0 were 0.50±0.08 and 0.50±0.07 for TS and MS effluent, while TSL and MSL effluent at OLR1.4/3.0 were 0.57±0.13 and 0.56±0.07. The average VFA:Alk of OLR 4.5/5 were

0.47±0.08 and 0.52±0.12 for TS and MS effluent, and 0.46±0.09 and 0.48±0.10 for TSL and MSL effluent.

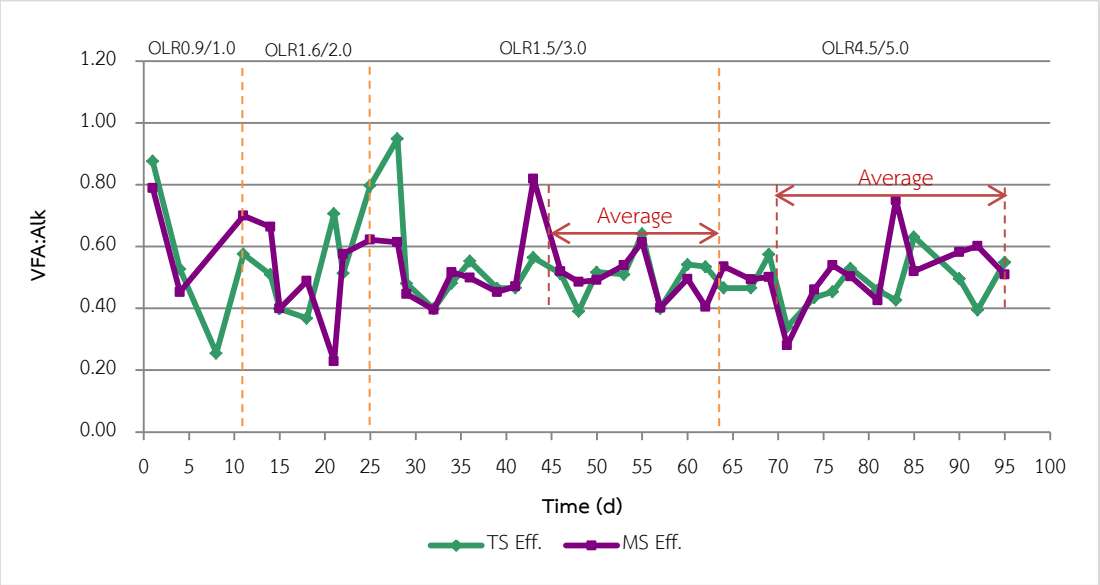


Figure 4.8 (a) VFA:Alk concentrations of TPAD1 reactors

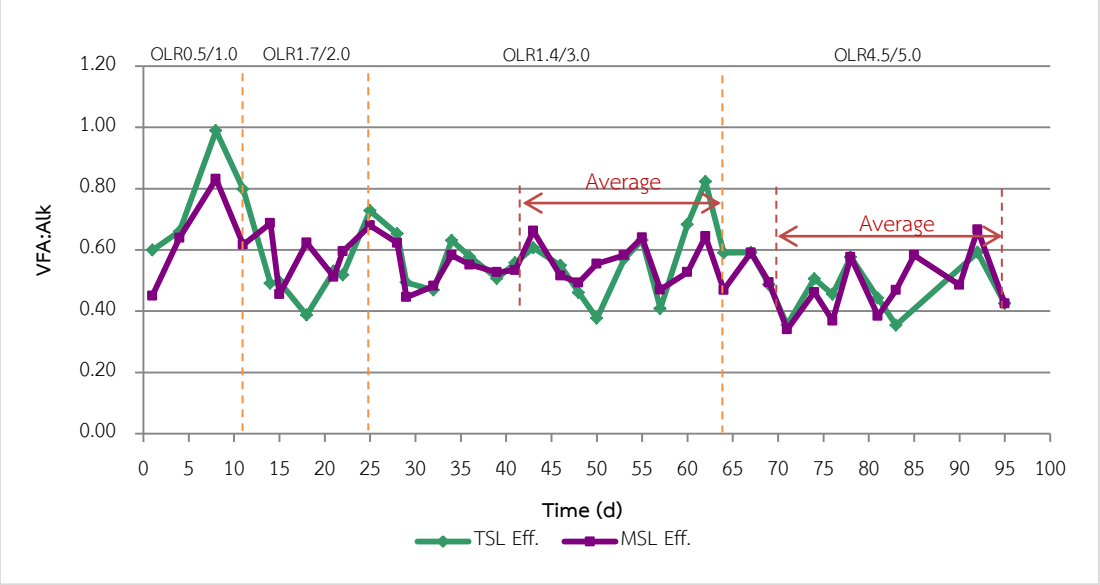


Figure 4.8 (b) VFA:Alk concentrations of TPAD2 reactors

Though VFA:Alk ratios of TSL and MSL reactors were somewhat high, they were considerably stable (RSD = 20.4% for TSL and 16.5% for MSL) throughout the

period of study regardless of the OLR (Figure 4.8(b)). This stable VFA:Alk ratio along with acceptable VFA and sufficient alkalinity concentrations suggested that TPAD2 system was functioning with satisfactory stability. Using alkalinity and VFA concentrations during pseudo-steady states with the measured pH and CO_2 composition, it was found that all amounts of alkalinity existed in TSL reactor were used up for neutralizing dissolved CO_2 and VFA at OLR1.4/3.0 and OLR4.5/5.0, respectively. For MSL, alkalinity was remained for buffering the possible increase of VFA up to 321 mg/l as CH_3COOH at OLR1.4/3.0, while all alkalinity was depleted at OLR4.5/5.0. Results from these calculations showed that even though operating with substantial stability, OLR4.5/5.0 tended to be the limit of TPAD2 system. Increase of OLR would lead to high risk of pH dropping lower than the suitable range for anaerobic digestion. Potential of having high VFA concentration for thermophilic anaerobic reactor leading to the possible higher VFA:Alk ratio has been reported by Smith (1964). However, as lower amounts of CO_2 can dissolve into the reactor content at thermophilic temperatures, only half as much alkalinity is required to buffer the CO_2 solubility as under mesophilic temperatures (Speece, 1996). As VFA:Alk ratios for both thermophilic and mesophilic reactors of TPAD2 were not significantly different from those of TPAD1, it could be concluded that codigestion of septage with LW at COD:TKN ratio of 100:5 did not destabilize system performance even it was operated at the OLR as high as 4.5 and 5.0 kgVS/m^3-d for TSL and MSL, respectively.

4.2.4 Total Solid (TS) and Volatile Solid (VS)

Anaerobic digesters are capable of treating insoluble wastes and soluble wastewaters. It is well known as a treatment process for sludge that contains large amounts of solids (particulate and colloidal wastes) (Evans, 2001). TS concentrations of TS and TSL influent were in ranges of 44,750-55,840 mg/l and 6,155-48,340 mg/l during start-up period. The measurement TS concentrations of TS and MS effluent were in ranges of 36,980-43,790 mg/l and 33,170-39,870 mg/l, while TSL and MSL effluent were in ranges of 10,530-30,300 mg/l and 11,520-26,820 mg/l, respectively.

During the operated period, TS concentrations of TS and TSL influent were in ranges of 18,050-35,960 mg/l and 14,810-29,210 mg/l. The TS concentrations of TS and MS effluent were in ranges of 11,200-46,990 mg/l and 10,420-44,300 mg/l (Figure 4.9(a)), while TSL and MSL effluent were in ranges of 8,420-41,350 mg/l and 8,210-39,060 mg/l (Figure 4.9(b)). The average TS concentrations of OLR1.5/3.0 were 41,847±3,351 mg/l and 41,652±1,880 mg/l for TS and MS effluent, and 26,717±7,071 mg/l and 29,581±1,969 mg/l at OLR1.4/3.0 for TSL and MSL effluent. The average TS concentrations of OLR4.5/5.0 were 22,742±7,620 mg/l and 24,112±7,292 mg/l for TS and MS effluent, and 16,989±10,724 mg/l and 16,878±6,455 mg/l for TSL and MSL effluent.

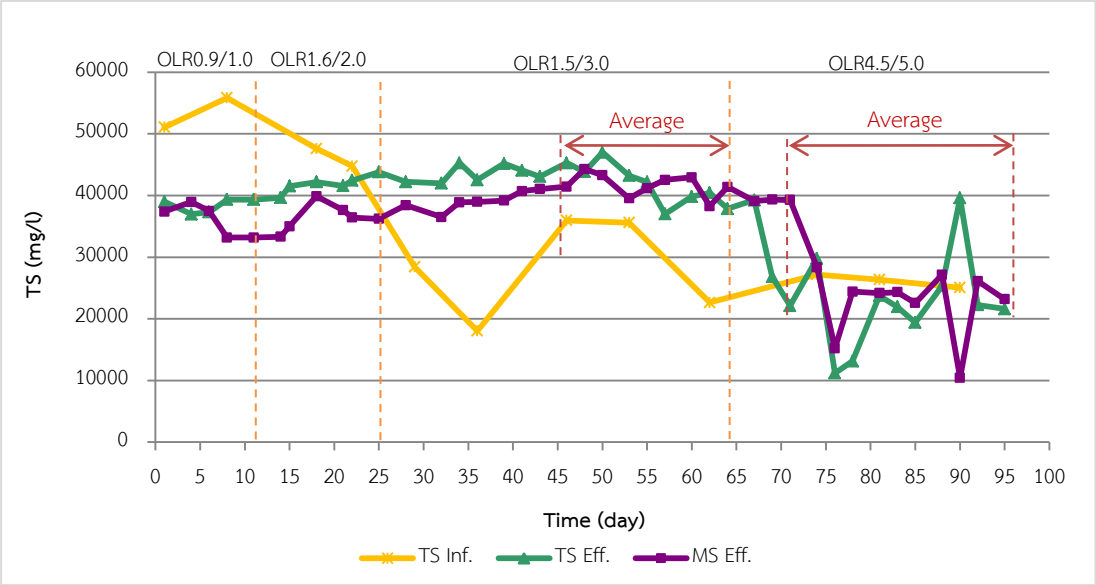


Figure 4.9 (a) TS concentrations of TPAD1 reactors

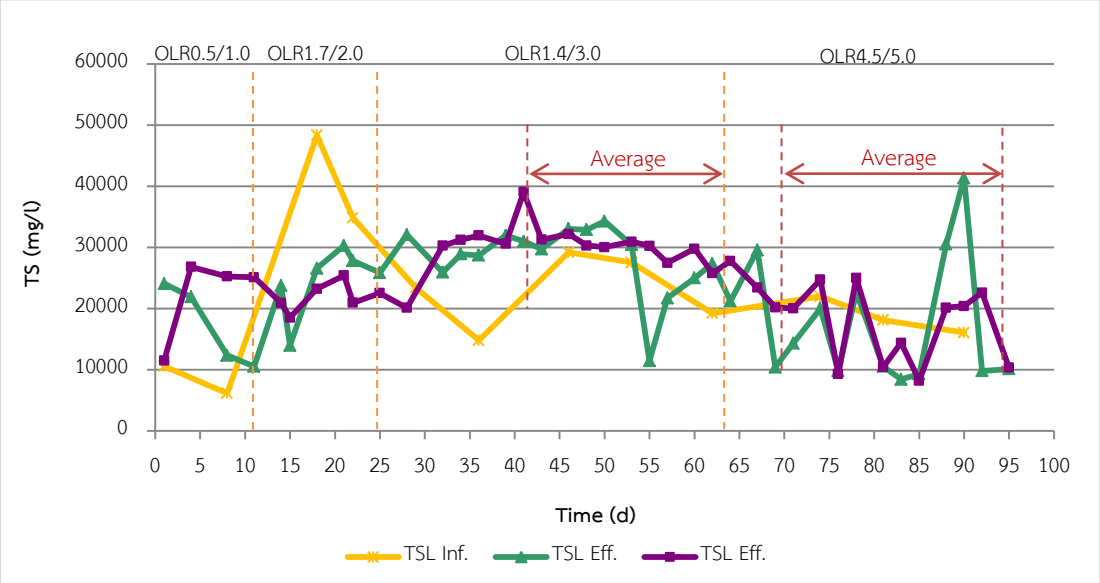


Figure 4.9 (b) TS concentrations of TPAD2 reactors

VS concentrations in ranges of 31,040-38,260 mg/l and 5,485-33,640 mg/l were found for TS and TSL influent during start-up period. The measurement VS concentrations of TS and MS were in ranges of 25,090-30,380 mg/l and 22,660-26,440 mg/l, while TSL and MSL effluent were in ranges of 7,610-20,670 mg/l and 8,050-18,950 mg/l.

During the operated period, VS concentrations in ranges of 8,860-24,830 mg/l and 10,550-20,620 mg/l were found for TS and TSL influence. The VS concentrations of TS and MS were in ranges of 8,050-34,010 mg/l and 7,380-31,820 mg/l (Figure 4.10(a)), while TSL and MSL effluent were in ranges of 6,250-29,450 mg/l and 5,990-30,800 mg/l (Figure 4.10(b)). The average VS concentrations of OLR1.5/3.0 were 30,022±2,607 mg/l and 29,573±1,581 mg/l for TS and MS effluent, and 18,584±4,909 mg/l and 21,037±1,440 mg/l at OLR1.4/3.0 for TSL and MSL effluent. The average VS concentrations of OLR4.5/5.0 were 15,843±4,921 mg/l and 17,188±5,380 mg/l for TS and MS effluent, and 12,150±7,436 mg/l and 12,042±4,484 mg/l for TSL and MSL effluent.

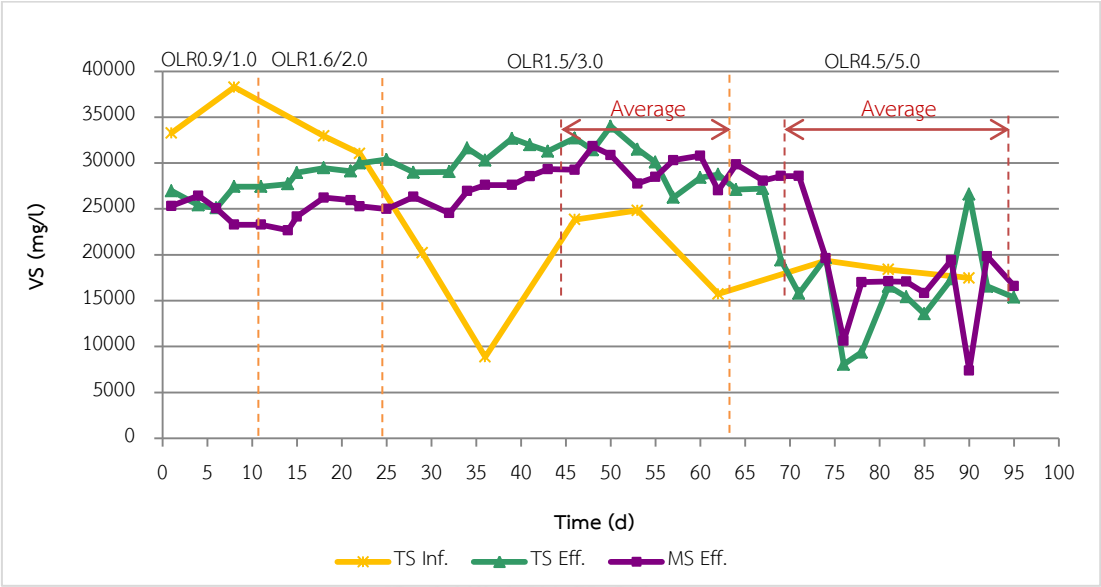


Figure 4.10 (a) VS concentrations of TPAD1 reactors

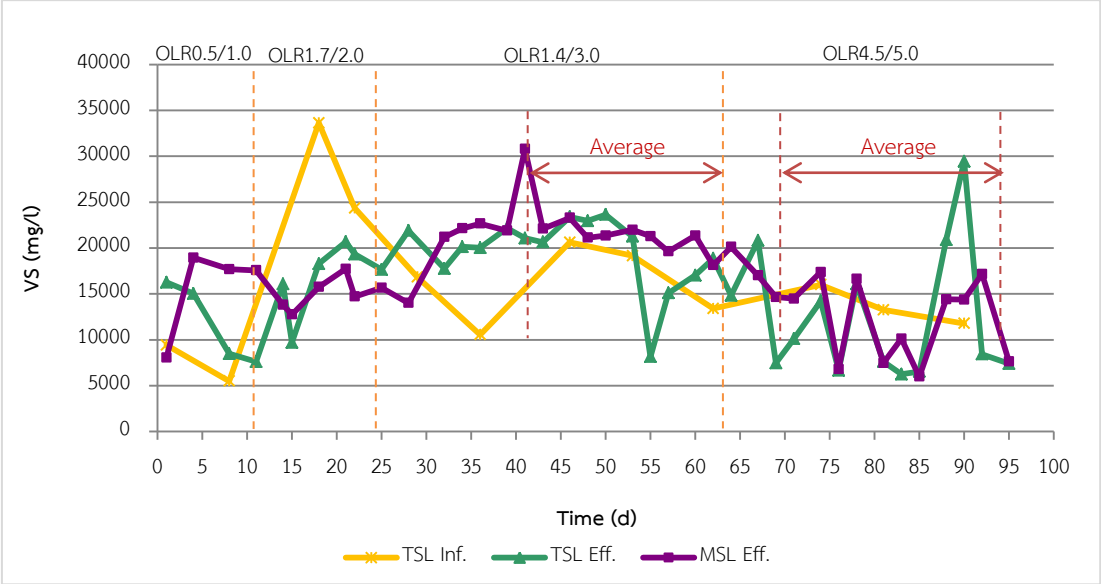


Figure 4.10 (b) VS concentrations of TPAD2 reactors

A CSTR, also known as continuous flow stirred tank reactor (CFSTR) or completely mixed reactor is used very frequently in wastewater treatment process. It is usually equipped with baffles and a mixer which is operated at a sufficiently high speed so that the mixing is assumed to be perfect. It is assumed that any reactant

carried into the reactor by the feed is dispersed evenly throughout the reactor without any time delay. In addition, the reaction is assumed to take place only in the reactor so that the effluent composition is the same as the reactor composition. Contrary to the ideal Plug-Flow reactor, in which all the fed feedstock will come out from the reactor after the hydraulic retention time (HRT) is reached, the Complete-Mix reactor required significantly longer time. It can be shown using Equation (19) by Metcalf & Inc. (2014) developed to describe the continuous step feeding of tracer to CSTR that at 1.5 times of HRT, the period used for indicating the pseudo-steady state in this work, approximately 78% of the feedstock is arrived at the outlet of the reactor.

$$C = C_0(1-e^{-\theta}) \qquad (19)$$

Where: C = concentration of the tracer in the reactor at time t, mg/l

C_0 = initial concentration of the tracer in the reactor, mg/l

Θ = the normalized detention time, t/HRT

It can be seen in Figure 4.9-4.10 that solid concentrations, both in forms of VS and TS, of the influent tended to be lower than those of the effluent, especially during the first 25-70 d of experiment. These results did not mean that there was no biodegradation reaction happened inside the reactor (because biogas was produced throughout the stated period) but it rather was the consequence of reactor start-up method and flow regime. According to Equation 19, it would take 4.6 times of HRT for 99% of the content of the CSTR to be replaced by the influent. As all reactors were started-up by adding 30% and 70% of working volume by inoculum and the high-solid septage, solid concentrations of the effluent during this period were influenced by high solid concentrations by the storage time of the reactor content. Decrease of septage solid concentrations also complicated the results when comparing solid concentrations of influent and effluent. Considering only the TS and VS concentrations of the reactor effluent, however, it could be seen that TPAD1 and

TPAD2 could produce the effluent that was quite stable in quality. Lower solid concentrations in the effluent detected during OLR4.5/5.0 of TPAD1 and TPAD2 was likely to be the result of decrease of solid concentrations of the raw septage used during the experiment.

In order to determine the organic content removal efficiency (in form of VS) of TPAD1 and TPAD2 systems considering reactor HRTs and decrease of septage VS contents, averaged influent VS concentrations were needed to be compared to the averaged effluent VS concentrations of the elapsed time (in this case, 1.5HRT was considered). Accordingly, for TPAD1 system, averaged influent VS concentrations during 1-25 d was compared with averaged VS of the effluent during 45-64 d, while averaged VS of the influent during 26-64 d was compared with averaged VS of the effluent during 70-95 d for OLR1.5/3.0 and OLR4.5/5.0, respectively (see Figure 4.10(a)). Likewise, for TPAD2 system, averaged influent VS concentrations during 15-25 d was compared with averaged VS of the effluent during 42-64 d, while averaged VS of the influent during 26-64 d was compared with averaged VS of the effluent during 70-95 d for OLR1.4/3.0 and OLR4.5/5.0, respectively (see Figure 4.10(b)). Results showed that TPAD1 system removed 12.7% and 41.9% of VS at OLR1.5/3.0 and OLR4.5/5.0, respectively, while 27.4% and 42.2% of VS were removed at OLR1.4/3.0 and OLR4.5/5.0, respectively, for TPAD2 system. Results showed that VS removal efficiency of TPAD2 was obviously higher than that of TPAD1, (at OLR1.5/3.0 and OLR1.4/3.0 for TPAD1 and TPAD2, respectively). This could be contributed by the fact that organic substances presented in septage used as the sole feedstock for TPAD1 was less biodegradable compared to the mixture of septage and LW used for TPAD2. The difference of VS removal efficiency became less obvious at OLR4.5/5.0 for both TPAD systems as the biodegradable portions of septage were depleted after long storage time. At this OLR, VS removal efficiencies obtained from both TPAD systems (41.9-42.2%) were relatively lower (see Table 4.7) than 56.0% when sewage sludge was used as the sole substrate for TPAD system (Song, 2004) and 71.0-83.3% when septage was treated by the temperature controlled septic tank (Pussayanavin, 2015)

Also, Valencia (2009) reported higher figure (60.0%) for VS removal efficiency from the co-digestion of septage and municipal solid waste in a biological landfill. Lower VS removal found in this current study was possibly the result of septage characteristic used during the experiment. As septage used in this study was collected from a household septic tank that had not been emptied for approximately 10 years, amounts of easily biodegradable organic matters would be much lower than the fresher one. It needs to be emphasized that although lesser VS was found to be removed by TPAD systems used in this study, the system was tested at a significantly higher OLR (OLR4.5/5.0) compared to 0.68-1.08 kgVS/m3-d and 1.38 kgVS/m3-d conducted using sewage sludge and septage by Song (2004) and Pussayanavin (2015) respectively.

Table 4.7 Comparisons of anaerobic digestion performance from previous works

Wastes	Reactor Types	Conditions		VS removal efficiency (%)	COD removal efficiency (%)	CH_4 Yield (ml/gV S_{added})	Pathogens removal efficiency (%)	References
		Temp. (°C)	OLR (kgVS/ m^3-d)					
Septage (S) and Municipal Solid Waste (MSW)	Bio-reactor Landfills	30±1	-	MSW+S=60	-	MSW= 192	TC[a] =99	(Valencia, 2009)
						MSW+S= 360	FC[b] =100	
Fruit and Vegetable	Plastic drums	30±2	38	-	-	270	-	(Viswanath, 1992)
Organic Fraction of Municipal Solid Waste	TPAD (3:6)	55-57; 35-37	29.9	81.3	59.8	130	-	(Fernández-Rodríguez, 2016)
	TPAD (4:10)		22.4	75.1	63.5	150		
Sewage sludge	TPAD	35; 55	0.68-1.08	56.0	66.4 (SCOD)	244	TC=98.5–99.6	(Song, 2004)

	Thermo philic	55	2.90	46.8	18.8	195		
	Mesophil ic	35	1.43	43.5	60.4	196		
Septage	Septic tank	30	1.38	71.0	74.2	16	-	(Pussayana vin, 2015)
		40		83.3	78.1	27		
Septage and Longan wastewat er (SL)	TPAD1 (S)	55±2; 35±2	1.5/3.0	12.7	32.3	2.83	TC=93.2 FC=92.6 E.coli= 91.5	This work
			4.5/ 5.5	41.9	31.5	0.74		
	TPAD2 (SL)		1.4/ 3.0	27.4	27.0	22.2	TC=91.1 FC=97.3 E.coli= 98.0	
			4.5/ 5.0	42.2	47.8	14.5		

4.2.5 COD

Similar to VS, COD concentration can be used to observe the performance of an anaerobic reactor in transforming organic substances into biogas. COD concentrations in ranges of 44,710-69,911 mg/l and 4,449-49,200 mg/l were found for TS and TSL influent during start-up period. The measurement COD concentrations of TS and MS effluent were in ranges of 30,829-68,004 mg/l and 28,516-64,614 mg/l, while TSL and MSL effluent were in ranges of 11,400-33,472 mg/l and 16,101-61,013 mg/l, respectively.

During the operated period, COD concentrations in ranges of 15,292-34,646 mg/l and 4,032-27,559 mg/l were found for TS and TSL influent. The COD concentrations of TS and MS effluent were in ranges of 11,290-42,520 mg/l and 4,032-49,190 mg/l (Figure 4.11(a)), TSL and MSL effluent were in ranges of 1,613-

30,643 mg/l and 806-32,256 mg/l (Figure 4.11(b)). The average COD concentrations of OLR1.5/3.0 were 37,979±4,048 mg/l and 39,486±5,389 mg/l for TS and MS, and25,315±5,064 mg/l and 27,237±3,566 mg/l at OLR1.4/3.0 for TSL and MSL. The average COD concentrations of OLR4.5/5.0 were 15,598±4,227 mg/l and 16,810±6,338 mg/l for TS and MS, and 11,124±8,232 mg/l and 10,983±8,496 mg/l for TSL and MSL.

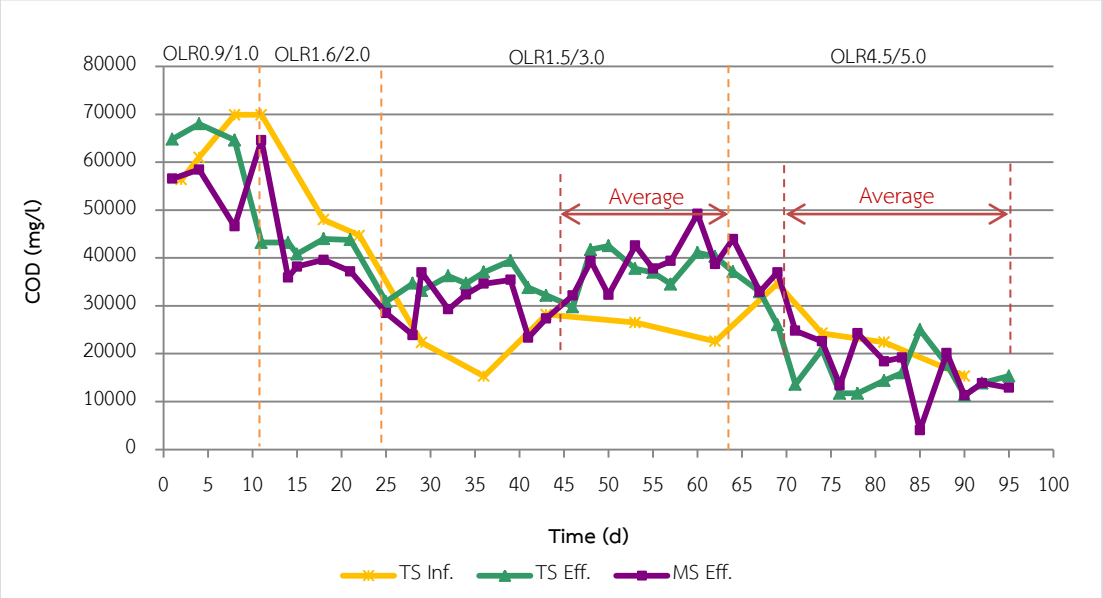


Figure 4.11 (a) COD concentrations of TPAD1 reactors

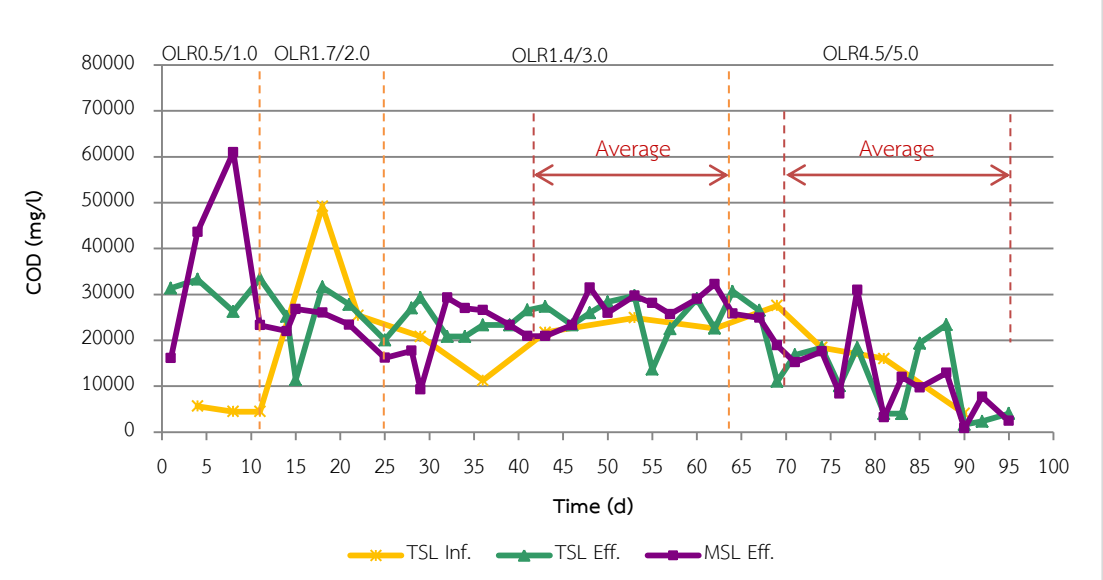


Figure 4.11 (b) COD concentrations of TPAD2 reactors

Changes of COD profiles for both TPAD1 and TPAD2 systems were similar to those of VS. Due to decrease of COD concentration of septage, influent COD for both TPAD systems was substantially fluctuated. This trend was more obvious for TPAD1 (Figure 4.11(a)) as septage was the sole substrate for this system. Relatively high influent COD concentration was detected during 1-10 d before it was decreased and stabilized from 25 d onwards. Stable influent COD was likely to be occurred as most of the biodegradable COD were utilized during septage storage time and only the recalcitrant COD was remained. Profile of influent COD for TPAD2 was similar to that of TPAD1, apart from that influent COD during 1-10 d was lower since lower amounts of septage were mixed with LW (at COD:TKN = 100:1.1). In order to determine COD removal efficiencies of the studied systems, averaged influent COD was needed to be compared with averaged COD effluent of the elapsed time, i.e. period of time according to system HRT. Results showed that TPAD1 system removed 32.3% and 31.5% of COD at OLR1.5/3.0 and OLR4.5/5.0, respectively, while 27.0% and 47.8% of COD were removed at OLR1.4/3.0 and OLR4.5/5.0, respectively, for TPAD2 system. Pattern of COD removal was similar to that of VS removal, in which higher amounts of COD were removed by TPAD2 compared to TPAD1 at OLR4.5/5.0. Fernández-Rodríguez (2016) found that 59.8-63.5% of COD were removed by TPAD using organic fraction of municipal solid waste as the feedstock (Table 4.7). Higher biodegradable fractions of feedstock used in their work could partly explain the difference of COD removal when compared to results of this current study.

4.2.5 Total Suspended Solid (TSS) and Volatile Suspended Solid (VSS)

TSS and VSS values are used to indicate amounts of suspended solids in the reactor. Samples were collected when reactor contents were completely mixed (at 50 rpm of stirrers), thus TSS and VSS could present total suspended solid concentrations and sludge (microorganisms) concentrations during the studied operating condition. The TSS and VSS concentrations are showed in Figure 4.12.

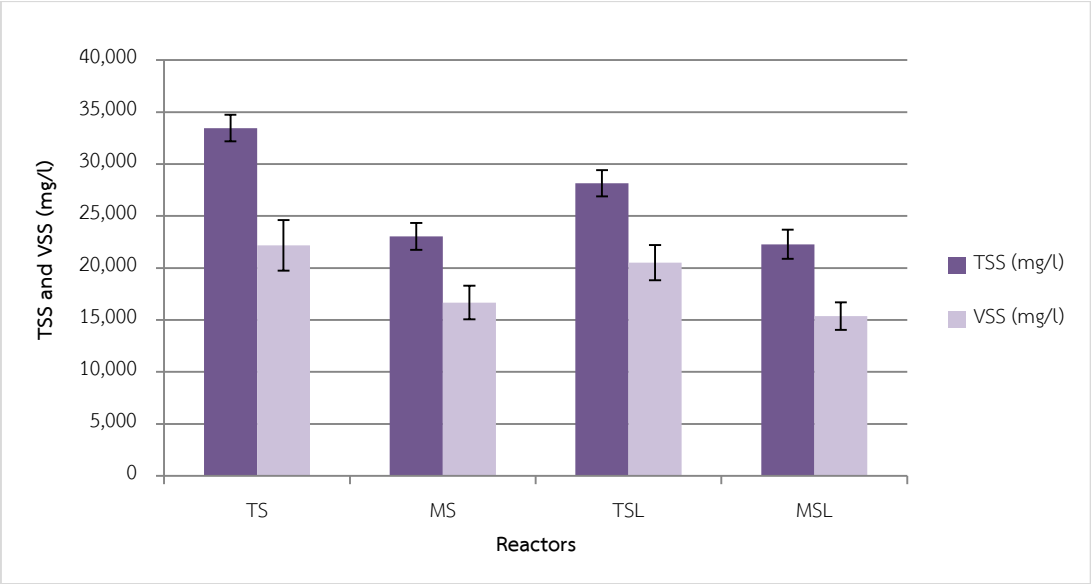


Figure 4.12 TSS and VSS concentrations of TPADs reactor

It can be seen that VSS concentrations of all studied reactors were in the range of 16,298-34,360 mg/l, well within the sludge concentration suitable for an anaerobic reactor (Tom D. Reynolds, 1996). The average VSS:TSS ratios for TS and MS were 0.66 and 0.72 while those for TSL and MSL were 0.73 and 0.69 implying that the majorities of suspended solids existed inside the reactor were microorganisms. These results showed that by operating the reactor in the anaerobic sequencing batch reactor (ASBR) mode, the system could satisfactorily retain sludge to the level that was in-line with that required by the anaerobic high rate reactor. This claim was supported by the average F/M ratios (0.17, 0.13, 0.16, and 0.4 gCOD/gVSS-d for TS, MS, TSL, and MSL effluent, respectively) which were within the lower range for those reported for normal AD operation (0.45-0.50; Tanaka (1997)).

4.2.7 Biogas volume and composition

The biogas volumes of TS and MS during start-up period were in ranges of 0.00-1.09 l/d and 0.00-0.57 l/d, while TSL and MSL were in ranges of 0.00-8.16 l/d and 0.00-0.12 l/d.

During the operation period, biogas volumes of TS and MS were in ranges of 0.00-0.95 l/d and 0.00-0.13 l/d (Figure 4.13(a)), while TSL and MSL were in ranges of 0.19-5.28 l/d and 0.00-0.55 l/d (Figure 4.13(b)). The average biogas volumes of OLR1.5/3.0 were 0.185±0.08 l/d and 0.016±0.02 l/d for TS and MS, and 1.64±0.421 l/d and 0.022±0.022 l/d at OLR1.4/3.0 for TSL and MSL. The average biogas volumes of OLR4.5/5.0 were 0.242±0.229 l/d and 0.016±0.02 l/d for TS and MS, and 1.64±0.421 l/d and 0.022±0.022 l/d at OLR1.4/3.0 for TSL and MSL.

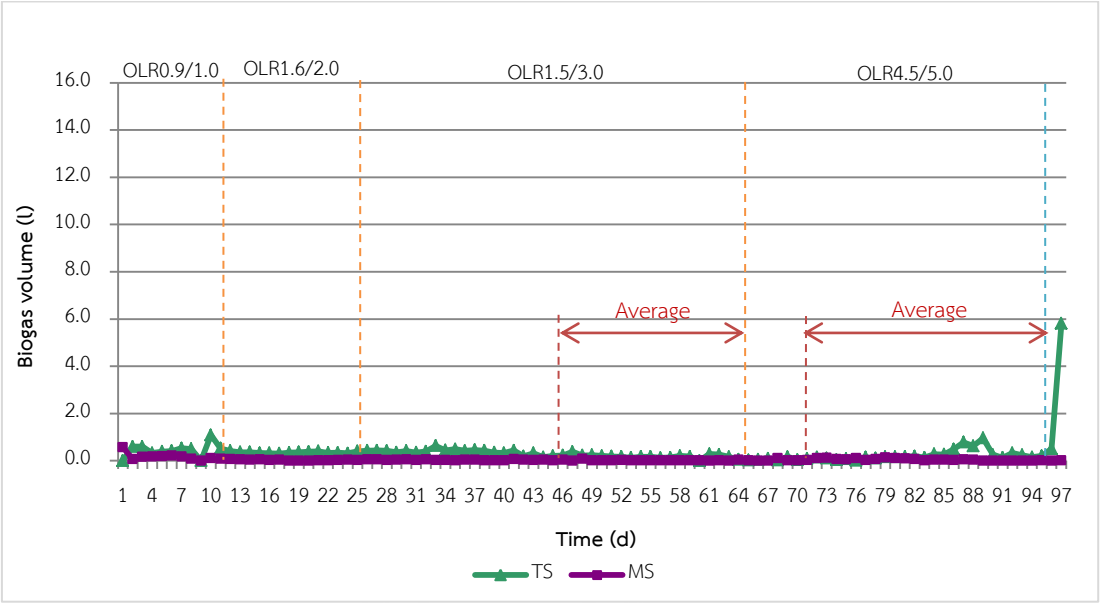


Figure 4.13 (a) Biogas volumes of TPAD1 reactors

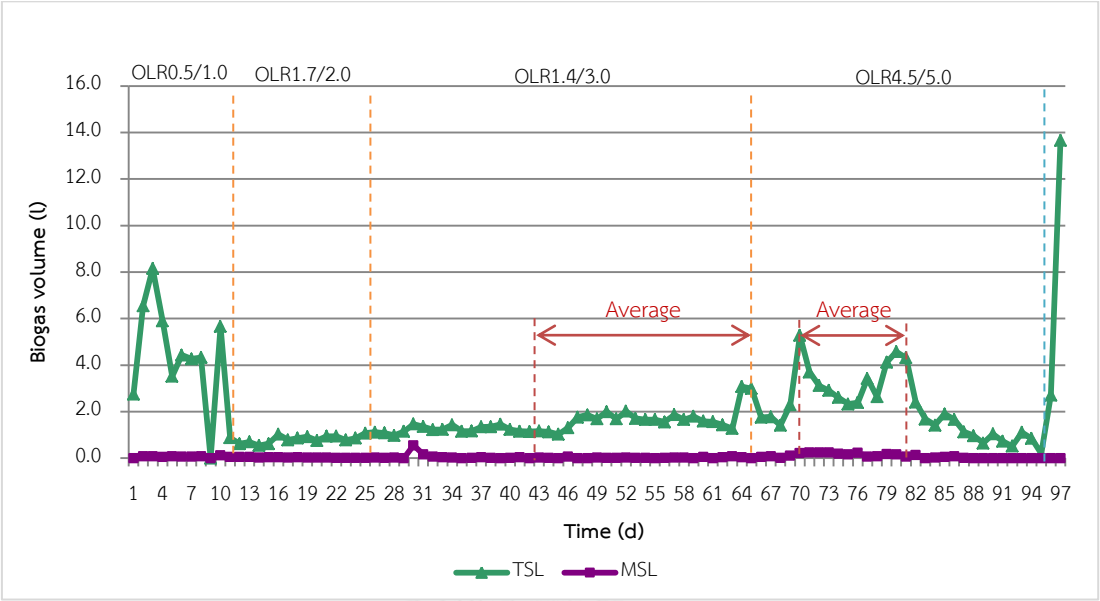


Figure 4.13 (b) Biogas volumes of TPAD2 reactors

Biogas produced from septage used as the sole substrate was low and fairly stable (Figure 4.13(a)). Higher volume of biogas observed from TS reactor during the first 40 d was because some easily degradable organic substances were still remained in septage. For TPAD2, biogas started to be produced right away from TSL after reactor operation, which was attributable to the use of acclimatized inoculum. High amounts of biogas were produced by TSL during the first 10 d was due to higher portion of LW used in the waste mixture. Relatively stable biogas production was found during OLR1.4/3.0 operation for TSL and 1,637(±421) ml/d of biogas was observed at pseudo-steady state. At increase OLR of 4.5/5.0, higher amounts of biogas were produced (during 64-81 d) before biogas volume was declined. The cause of this biogas reduction had been investigated and all measured parameters were brought into consideration. It was found that decrease of biogas production was not initiated by microbial causes as pH, VFA and alkalinity of the TPAD2 system during the problematic period were in the normally acceptable ranges and not substantially different from those at the previous conditions. Therefore, reactor physical aspects were examined and it was found that the biogas tubes connected

studied reactors to the gas bubble counters were blocked by the condensed water. This claim was supported by the fact that after the tubing was unblocked (and the condensate bottle was installed to prevent the future blocking) and TPAD2 was operated under the same OLR, biogas volume was immediately increased. However, as the problem was solved when the new batch of septage was used at COD:TKN ratio of 100:2.5 (rather than 100:5 used in the previous state), the measured biogas volume detected at this condition was not representing that at the previous condition. The biogas production during OLR4.5/5.0 was, therefore, the average of those (during 70-81 d) before biogas reduction was observed. Even though higher amount of biogas (3,452(±956) ml/d) was found to be produced at OLR4.5/5.0 by TSL, increased amount was not proportional to increase of OLR. This suggested that this OLR was likely to be the limit of TSL reactor if used as the single reactor. Nevertheless, it was found that MSL could produce 8 times more biogas when operated at OLR4.5/5.0 compared to that at OLR1.4/3.0 (176(±71.6) ml/d compared to 22(±22) ml/d, respectively). It was obvious that the mesophilic reactor could polish the remained carbon content, which is an advantage of using TPAD system.

The methane yields of TS and MS during start-up period were in ranges of 0.00-25.2 $mlCH_4/gVS_{added}$ and 0.00-29.2 $mlCH_4/gVS_{added}$, while TSL and MSL were in ranges of 0.00-682 $mlCH_4/gVS_{added}$ and 0.00-33.7 $mlCH_4/gVS_{added}$.

During the operated period, methane yields TS and MS were in ranges of 0.03-14.0 $mlCH_4/gVS_{added}$ and 0.00-3.39 $mlCH_4/gVS_{added}$ (Figure 4.14(a)), while TSL and MSL were in ranges of 0.58-37.1 $mlCH_4/gVS_{added}$ and 0.00-50.4 $mlCH_4/gVS_{added}$ (Figure 4.14(b)). The average methane yields of OLR1.5/3.0 were 2.29±1.34 $mlCH_4/gVS_{added}$ and 0.54±0.65 $mlCH_4/gVS_{added}$ for TS and MS, and 20.5±4.56 $mlCH_4/gVS_{added}$ and 1.73±1.17 $mlCH_4/gVS_{added}$ at OLR 1.4/3.0 for TSL and MSL. The average methane yields of OLR4.5/5.0 were 0.57±0.49 $mlCH_4/gVS_{added}$ and 0.17±0.17 $mlCH_4/gVS_{added}$ for TS and MS, and 13.8±3.82 $mlCH_4/gVS_{added}$ and 0.73±0.54 $mlCH_4/gVS_{added}$ for TSL and MSL.

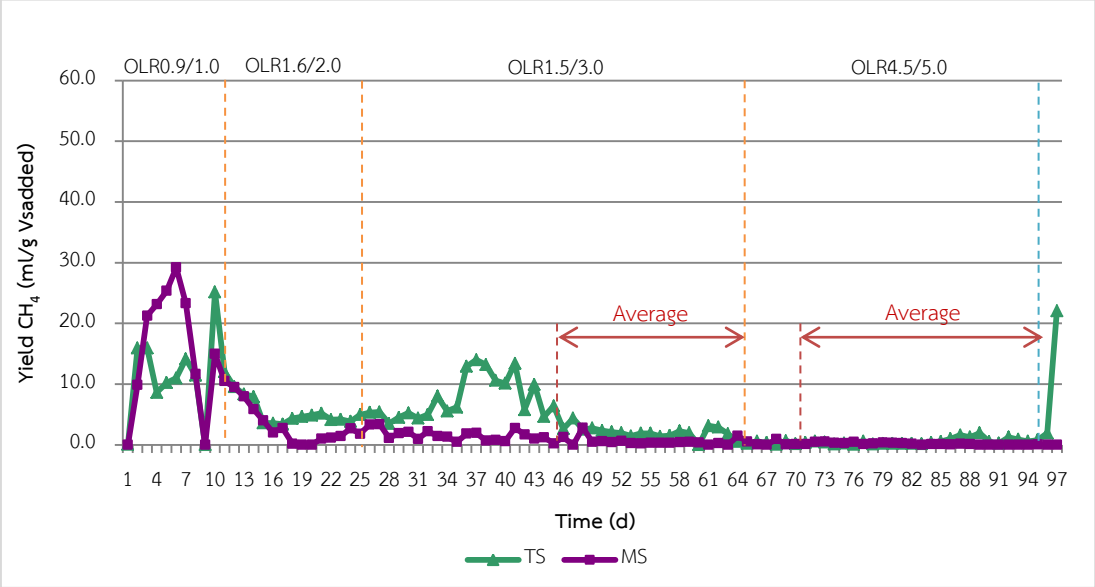


Figure 4.14 (a) Methane yields of TPAD1 reactors

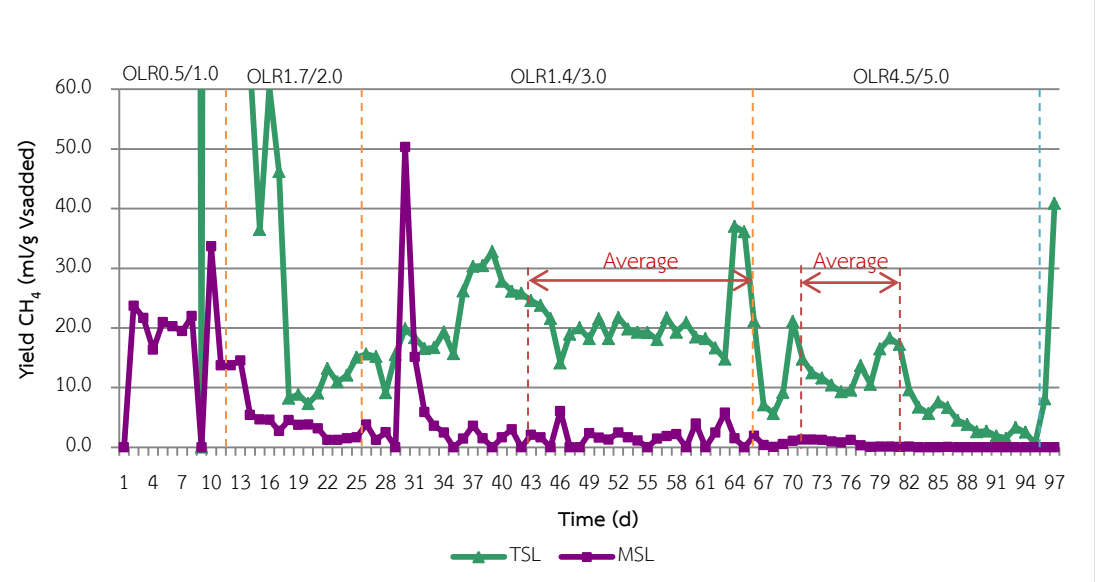


Figure 4.14 (b) Methane yields of TPAD2 reactors

Unsurprisingly, methane yields ($mlCH_4/gVS_{added}$) of TPAD1 system was significantly lower than those of TPAD2 throughout the experiment period. It was mainly contributed by more recalcitrant portions of organic substances presented in

septage especially at the end of the experiment. This assumption could be proved by the higher methane yields during the first 46 d of experiment (Figure 4.14(a)) as some trace amounts of biodegradable organic compounds were still existed in septage. After the degradable organic parts had been depleted, methane yield became lower and stable throughout the course of the remaining period of study. For TPAD2, very high methane yields obtained at the beginning part of study was the result of more LW portions present in the feedstock mixture. At OLR1.4/3.0, 20.5(±4.56) and 1.73(±1.71) $mlCH_4/gVS_{added}$ were produced by TSL and MSL and the total methane yield was 22.2 $mlCH_4/gVS_{added}$. Lower methane yields (calculated using the data during the same period as biogas volume, explained in the previous paragraph) were gained at OLR4.5/5.0 from TSL (13.8 $mlCH_4/gVS_{added}$) and MSL (0.73 $mlCH_4/gVS_{added}$) with the total methane yield of 14.5 $mlCH_4/gVS_{added}$. There have been studied of anaerobic digestion for biogas production showed in Table 4.7. Using septage as the sole substrate in 40°C and 30°C controlled septic tanks, Pussayanavin (2015) found that methane yields were 27 $mlCH_4/gVS_{added}$ and 16 $mlCH_4/gVS_{added}$, respectively. Lower methane yield found in this current study (2.83 $mlCH_4/gVS_{added}$ at OLR1.5/3.0), could be explained by the different characteristic of septage from different source. However, co-digestion of septage with LW improved methane yield up to 22.2 $mlCH_4/gVS_{added}$ at OLR1.4/3.0 (compared to 2.83 $mlCH_4/gVS_{added}$ from septage by TPAD1 at OLR1.5/3.0). Using fruit and vegetable (Viswanath, 1992), organic fraction of municipal solid waste (Fernández-Rodríguez, 2016), and sewage sludge (Song, 2004) as a single substrate could be generated over 12 times, 5 times, and 8 times of methane yields. Co-digesting of septage with municipal solid waste increased over 16 times of methane yield (Valencia, 2009). Considering that methane yield obtained from co-digestion of septage and LW could be increased up to 7 times compared to that gained from septage as the sole substrate, level of methane yield improvement found in this current study was in the same range as those found in the previously aforementioned works.

4.2.8 Pathogens

Pathogenic bacteria mainly found in the feces and sewage of a tropical community is Pathogenic E.coli, Salmonella ssp., and Shigella spp. (Feachem, 1983). During start-up period, total coliforms of TS and TSL influent were in ranges of 1.6×10^{8}–2.3×10^{9} MPN/100ml and 7.9×10^{3}–3.3×10^{5} MPN/100ml. The total coliforms of TS and MS effluent were in ranges of 490–1.7×10^{3} MPN/100ml and 2.4×10^{4}–9.2×10^{4} MPN/100ml, while TSL and MSL effluent were in ranges of 790–1.8×10^{3} MPN/100ml and 1.3×10^{4}–3.5×10^{4} MPN/100ml.

During the operated period, the total coliforms of TS and TSL influent were in ranges of 200-2.0×10^{5} MPN/100ml and 2.2×10^{3}-1.3×10^{5} MPN/100ml. The total coliforms of TS and MS effluent were in ranges of <18-120 MPN/100ml and 130-2.3×10^{7} MPN/100ml at OLR1.5/3.0, while TSL and MSL effluent were in ranges of <18-7.5×10^{3} MPN/100ml and 2.2×10^{4}-7.9×10^{5} MPN/100ml at OLR1.4/3.0. The total coliforms of TS and MS effluent at OLR4.5/5.0 were in ranges of <18-370 MPN/100ml and <18-450 MPN/100ml (Figure 4.15(a)), while TSL and MSL effluent were in ranges of <18-3.2×10^{3} MPN/100ml and 20-450 MPN/100ml (Figure 4.15(b)). The average total coliform removal efficiency of TS and TSL effluent were 93.2±11.5% and 89.9±16.3%.

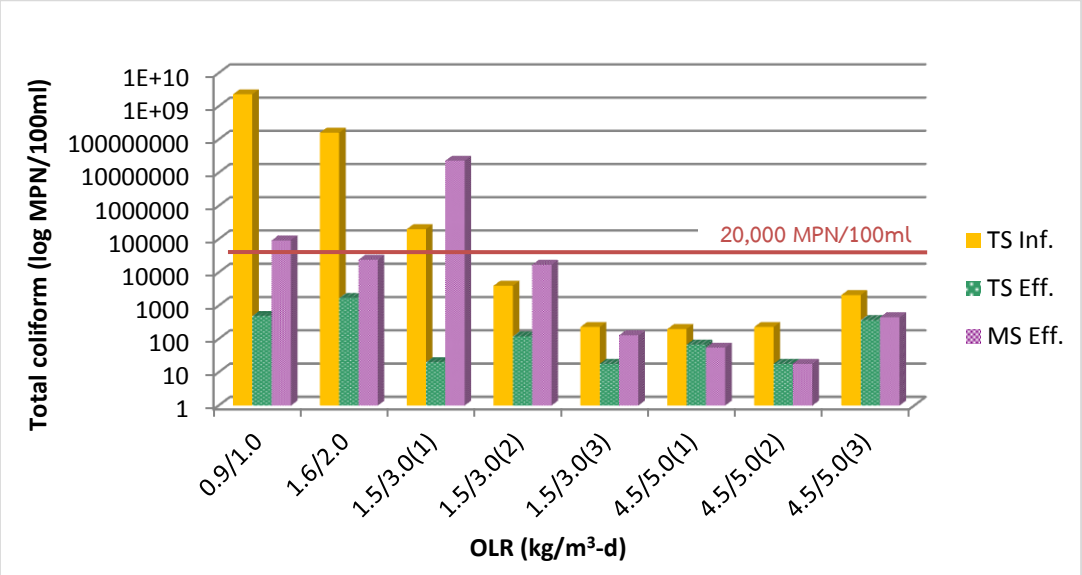


Figure 4.15 (a) Total coliform of TPAD1 reactors

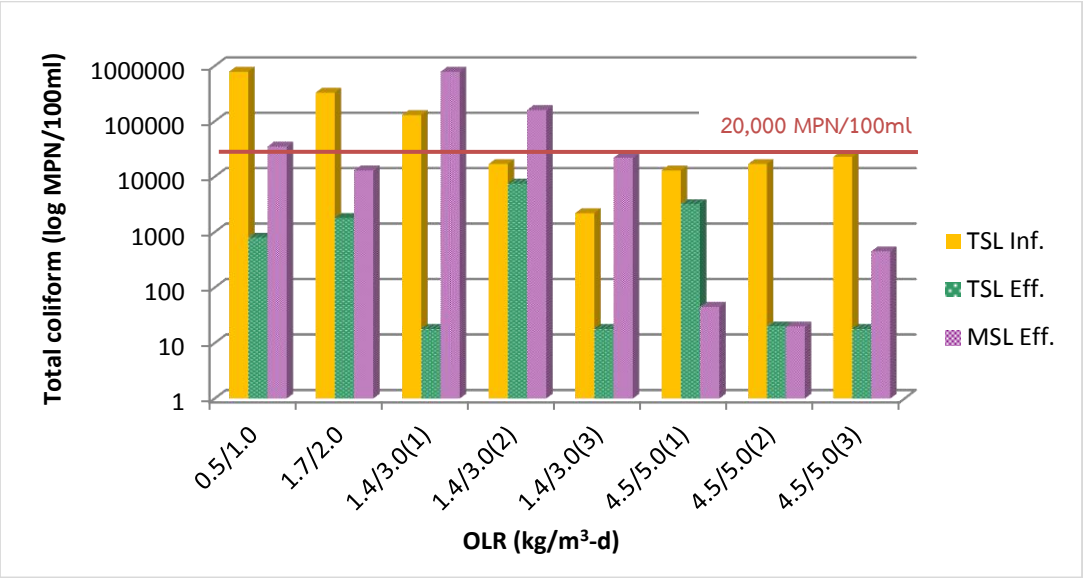


Figure 4.15 (b) Total coliform of TPAD2 reactors

Fecal coliforms of TS and TSL influent were in range of 1.7×10^{7}–6.3×10^{7} MPN/100ml and 7.9×10^{3}–3.3×10^{5} MPN/100ml during start-up period. The fecal coliforms of TS and MS effluent were in ranges of 490-780 MPN/100ml and 4.9×10^{3}-9.2×10^{4} MPN/100ml, while TSL and MSL effluent were in ranges of 18–490 MPN/100ml and 450–3.5×10^{4} MPN/100ml.

During the operated period, the fecal coliforms of TS and TSL influent were in ranges of 78-2.0×10^{5} MPN/100ml and 330-1.3×10^{5} MPN/100ml. The fecal coliforms of TS and MS effluent were in ranges of <18 MPN/100ml and <18-2.4×10^{4} MPN/100ml at OLR1.5/3.0, while TSL and MSL effluent were in ranges of <18 MPN/100ml and 165-4.9×10^{5} MPN/100ml at OLR1.4/3.0. The fecal coliforms of TS and MS effluent at OLR4.5/5.0 were in ranges of <18-45 MPN/100ml and <18-37 MPN/100ml (Figure 4.16(a)), while TSL and MSL effluent were in ranges of <18-170 MPN/100 ml and <18-61 MPN/100 ml (Figure 4.16(b)). The average fecal coliform removal efficiency of TS and TSL effluent were 92.6±9.91% and 96.6±4.61%.

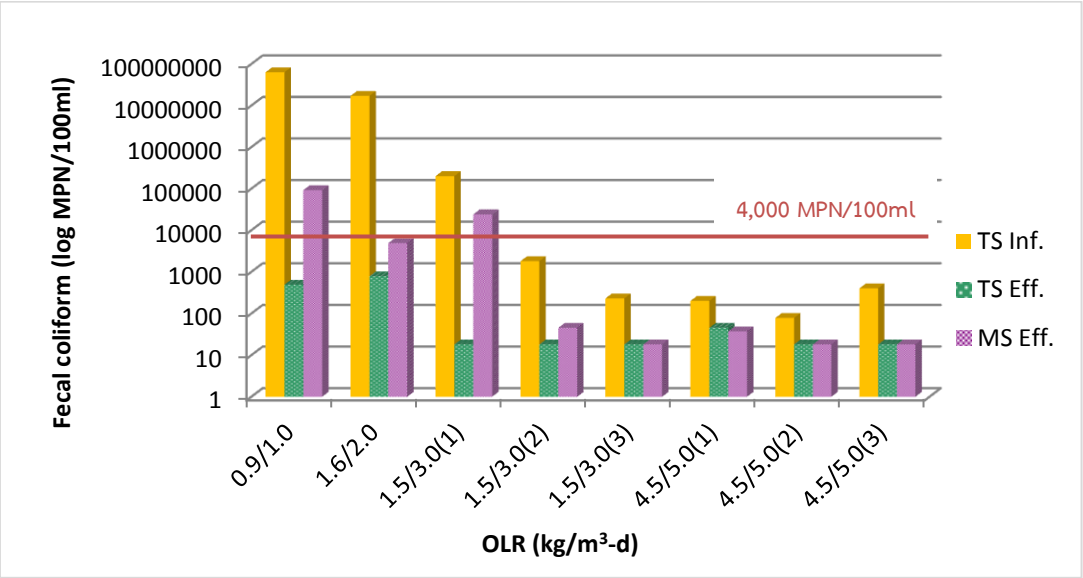


Figure 4.16 (a) Fecal coliform of TPAD1 reactors

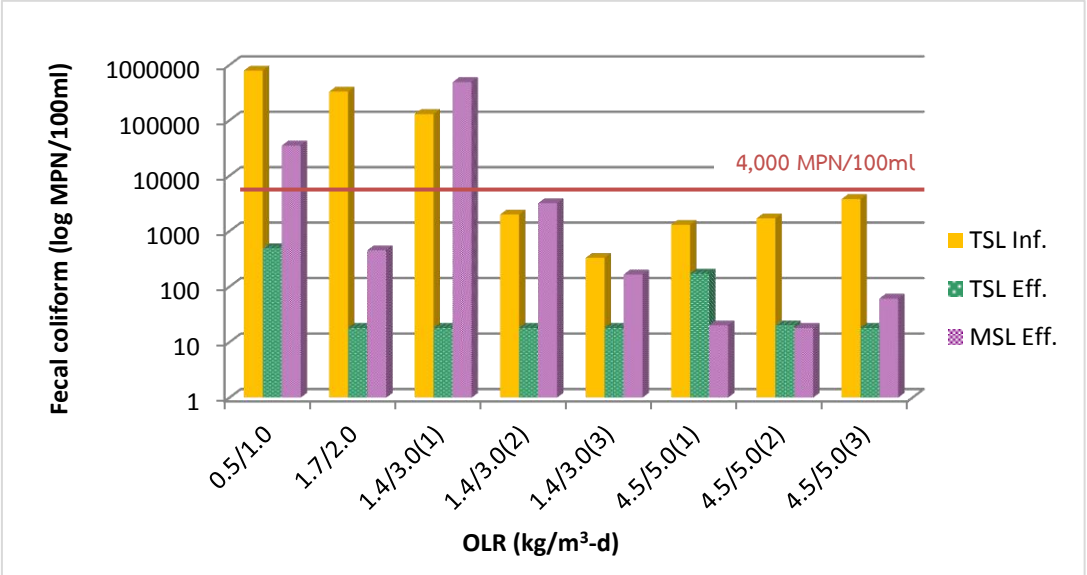


Figure 4.16 (b) Fecal coliform of TPAD2 reactors

E.coli of TS and TSL influent were in ranges of 1.7×10^{7} MPN/100ml and 790–2.3×10^{4} MPN/100ml during start-up period. The E.coli of TS and MS effluent were in

ranges of 490-780 MPN/100ml and 180–3.3×10^{3} MPN/100ml, while TSL and MSL effluent were in ranges of <18 MPN/100ml and 180–450 MPN/100ml.

During the operated period, the E.coli of TS and TSL influent were in ranges of 45-1.7×10^{4} MPN/100ml and 170-4.5×10^{3} MPN/100ml. The E.coli of TS and MS effluent were in ranges of <18 MPN/100ml and <18-230 MPN/100ml at OLR1.5/3.0, while TSL and MSL effluent were in ranges of <18 MPN/100ml and 68-2.3×10^{4} MPN/100ml at OLR1.4/3.0. The E.coli of TS and MS effluent at OLR4.5/5.0 were in ranges of <18-20 MPN/100ml and <18 MPN/100ml (Figure 4.17(a)), while TSL and MSL effluent were in ranges of <18-20 MPN/100ml and <18-21 MPN/100ml (Figure 4.17(b)). The average E.coli removal efficiency of TS and TSL effluent were 91.5±13.4% and 97.8±3.45%.

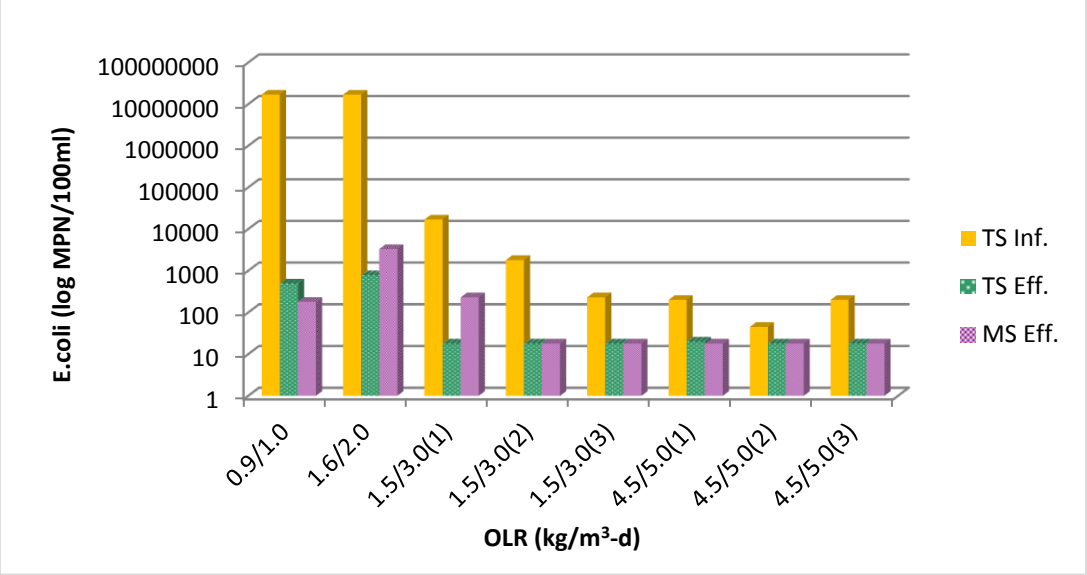


Figure 4.17 (a) E.coli of TPAD1 reactors

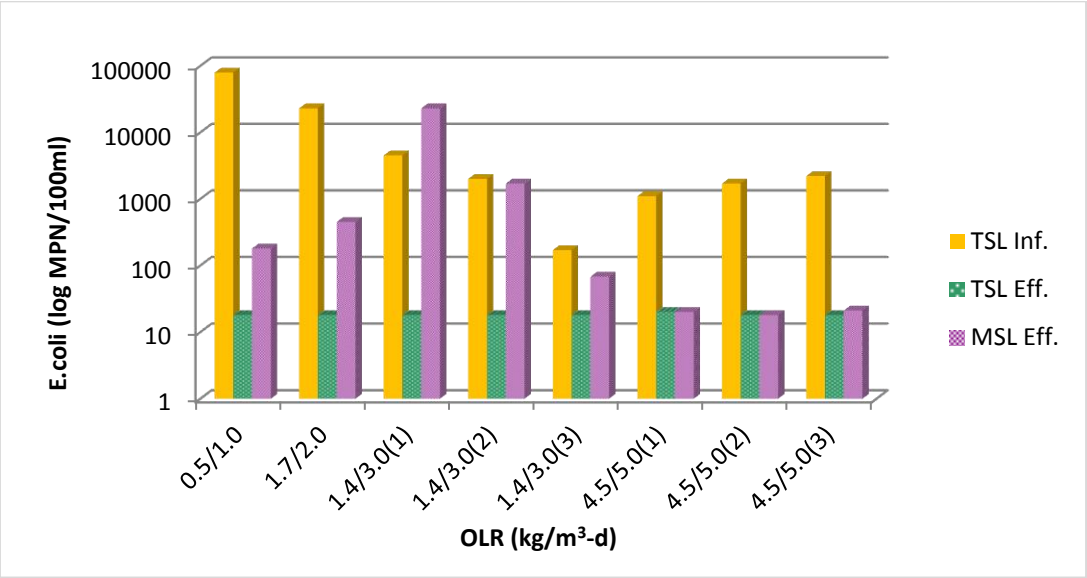


Figure 4.17 (b) E.coli of TPAD2 reactors

Total coliform bacteria were presented in the raw septage up to 2.3×10^{9} MPN/100ml while amounts of Salmonella ssp. and Shigella spp. were less than the detection limits. After 95 d, $2.1X10^{3}$ MPN/100ml of total coliform bacteria were detected in the septage. However, TPAD system could efficiently remove total coliform, fecal coliform and E.coli as reduction was around 1-2 log, regardless of the feedstock mixture and operating OLR. Apart from the high coliform bacteria detected in MSL at the OLR1.4/3.0(1) (the reactor was re-seeded with septage after physical reactor malfunction and sludge wash-out), <18-7.5×10^{3} MPN/100ml of total coliform, <18-170 MPN/100 of fecal coliform and <18-68 MPN/100 of E.coli were detected in the effluent of all studied reactors. These amounts of coliform bacteria were conformed with those of irrigation water set by the Pollution Control Department (PCD), Ministry of Natural Resources and Environment, which stated that the total coliform and fecal coliform should be under 20,000 MPN/100ml and 4,000 MPN/100ml for agricultural usage. Feachem (1983) demonstrated that a treatment process with time-temperature combinations effect falling within the 'safety zone' should be lethal to all excreted pathogens. Indicated time-temperature requirements

are at least: 1 h at ≥ 62°C, 1 d at ≥ 50°C and 1 week at ≥ 46°C. The results showed that pathogens were removed over 90% for TS and TSL effluent while MS and MSL effluent were rarely changed. These results suggested that pathogenic bacteria functioned with temperature and TPAD system could be used very efficiently for pathogens removal. Table 4.7 shows results obtained in some previous works using septage as the reactor feedstock. It was found that level of pathogen removal found in this current work was in the same ranges as those found using different kinds of anaerobic reactor.

4.2.9 Application of this work

In order to co-digest septage with LW generated within the area of Chiang Mai municipality (approximately 442 m^3/yr) using TPAD at OLR1.4/3.0 (the OLR that rendered the highest methane yield of 22.2 mlCH_4/gVSadded), 1,464 m^3/yr (equivalent to 4.0 m^3/d) of septage is required. The total amount of biogas that could be produced was 751 m^3/yr. This amount of biogas, though not great in quantity, will be generated during the golden dried longan production season which happens only around 2 months per year (thus, equivalent to the biogas generation of 375 m^3/month). The remained amounts of septage (approximately 50,366 m^3/yr) could still be used for co-digestion with other potential wastes, e.g. fruit peelings (in particular; longan and lychee peelings), food industrial wastes, to produce more biogas. Therefore, to effectively utilize septage, it is important to find suitable co-substrates so that the process can be operated during the entire year and not depend on only one kind of waste. These amounts of produced biogas (375 m^3/month) can generate 750 kWh of electricity or have the heat potential equal to 172 kg LPG or 225 l diesel, respectively. These amounts of electricity or heat can be used to heat up the reactor or as the supplementary fuel. Additionally, as effluent from both TPAD1 and TPAD2 contained significant amounts of plant nutrients, i.e. nitrogen (N), phosphorus (P) and potassium (K) (Table 4.8), it can be used for agriculture. Levels of nutrients contained in the effluent were conformed with the standard set for compost tea by the Ministry of Agriculture and Cooperatives,

Department of Agriculture, in which the total N, total P and total K should be over 0.5 % w/w, 0.5 % w/w and 0.5 % w/w, respectively. This liquid fertilizer can be considered as the added value of the system, apart from the biogas generated.

Table 4.8 Liquid fertilizer composition in effluent of TPAD1 and TPAD2 systems

Effluent	N (%)	P_2O_6 (%)	K_2O (%)
TS	0.13	0.06	0.40
MS	0.14	0.06	0.02
TSL	0.08	0.03	0.02
MSL	0.08	0.03	0.03

To make the system work, it is also important for the authority responsible in managing the use and disposal of septage to set the criteria for septage treatment and disposal. These criteria are still lacking in most provinces of Thailand, including Chiang Mai. The criteria should include the suitable method for septage collection, treatment and usage. The “tipping fee system”, as also used for solid waste management, needs to be implemented so that the efficient septage management can be operated. This tipping fee can be calculated from the difference between the system operating cost, values of products, e.g. biogas and liquid/solid fertilizer, and the government subsidy, if available.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

According to the research objectives, results gained from this research can be concluded as following;

1. The suitable COD:TKN ratio (v/v) between septage and golden dried longan producing wastewater was 100:5.

2. The modified Gompertz model could be effectively used to predict the biochemical methane potential of the anaerobic biodegradation of septage, golden dried longan producing wastewater and their mixture. The maximum ultimate specific methane yield was 143 $mlCH_4/gVS_{added}$ at the COD:TKN ratio of 100:5 with the shortest lag phase of 2.65 d.

3. TPAD system could be efficiently used for the treatment and biogas production from septage and mixture of septage and golden dried longan producing wastewater. At OLR of 1.4/3.0 $kgVS/m^3$-d, 22.2 $mlCH_4/gVS_{added}$ of methane yield was obtained while at OLR of 4.5/5.0 $kgVS/m^3$-d, the methane yield was 14.5 $mlCH_4/gVS_{added}$. Up to 47.8% of volatile solids were found to be removed by the studied TPAD system.

4. More than 90% of pathogens, i.e. Total Coliform and Fecal Coliform, were removed by TPAD system. Effluent of the system contained amounts of pathogens that met the standard of water capable of being used for irrigation. Moreover, system effluent also contained nutrients, i.e. nitrogen, phosphorus and potassium, for being used in agriculture.

5.2 Recommendations

1. The biogas tube of TPAD system should be large enough for gas flowing to avoid blockage by condensed water.
2. Due to the season of longan, this system could be useful when applied with other types of fruit waste to allow the continuous operation of this system.
3. As organic contents of septage were found to be reduced by the storage time, higher methane yield could be achieved if the fresh septage was utilized, i.e. by shortening the storage time. In addition, co-digesting septage with higher amounts of co-substrate should also increase the methane yield.
4. Results from this study revealed that only thermophilic reactor was sufficient for biogas production from the mixture of septage and LW. Therefore, to justify the advantage of TPAD, mixing septage with the co-substrate in the solid form, e.g. fruit peelings, would be more appropriate.
5. Results gained from this study should be used for some other wastes having similar characteristic to septage and LW. However, if different substrates are to be used, the suitable ratio should be determined by conducting the BMP test and the suitable OLR should be investigated with the TPAD operated in the continuous mode.

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APPENDIX A

Mass Balance Equation:

$$COD{:}TKN_{mix} = \frac{(Q_s \times COD_s) + (Q_{LW} \times COD_{LW})}{(Q_s \times TKN_s) + (Q_{LW} \times TKN_{LW})}$$

Where; Q_s = Flow of septage (m^3)

Q_{LW} = Flow of LW (m^3)

COD_s = COD of septage (mg/l)

COD_{LW} = COD of LW (mg/l)

TKN_s = TKN of septage (mg/l)

TKN_{LW} = TKN of LW (mg/l)

$COD{:}TKN_{mix}$ = COD to TKN mixture

Table A-1 Biogas accumulation results from each BMP test

Date		Biogas accumulation (ml)					
		Blank	S	LW	S:LW 1	S:LW 2	S:LW 3
1	11/1/2016	0	0	0	0	0	0
2	11/2/2016	0	3	31	23	16	8
3	11/3/2016	3	30	84	70	53	45
4	11/4/2016	14	50	93	81	70	68
5	11/5/2016	22	60	95	82	75	74
6	11/6/2016	33	76	102	97	97	99
7	11/7/2016	51	95	114	107	115	111
8	11/8/2016	61	106	120	116	134	121
9	11/9/2016	70	117	129	125	154	131
10	11/10/2016	79	128	144	141	177	141
11	11/11/2016	82	131	161	158	203	147
12	11/12/2016	91	137	183	178	234	150
13	11/13/2016	98	144	222	204	259	156
14	11/14/2016	104	151	257	247	282	162
15	11/15/2016	112	155	286	279	299	167
16	11/16/2016	116	159	311	305	308	170
17	11/17/2016	119	164	334	332	315	174
18	11/18/2016	122	176	354	354	318	187

Date		Biogas accumulation (ml)					
		Blank	S	LW	S:LW 1	S:LW 2	S:LW 3
19	11/19/2016	127	200	373	374	323	214
20	11/20/2016	127	200	393	383	323	214
21	11/21/2016	129	207	411	402	323	220
22	11/22/2016	132	215	428	419	328	228
23	11/23/2016	132	218	445	425	329	231
24	11/24/2016	138	223	462	431	331	236
25	11/25/2016	142	228	475	436	333	241
26	11/26/2016	149	233	482	443	336	245
27	11/27/2016	153	236	485	444	336	247
28	11/28/2016	156	238	486	448	336	251
29	11/29/2016	159	241	489	451	337	254
30	11/30/2016	160	243	489	453	337	255
31	12/1/2016	165	245	497	457	338	259
32	12/2/2016	167	247	497	457	338	259
33	12/3/2016	172	249	500	462	338	264
34	12/4/2016	176	252	501	463	338	266
35	12/5/2016	181	255	504	465	339	269
36	12/6/2016	183	257	507	466	342	271
37	12/7/2016	187	259	508	468	343	273
38	12/8/2016	191	263	511	471	345	276
39	12/9/2016	194	266	514	473	346	280
40	12/10/2016	197	266	514	474	346	280
41	12/11/2016	199	267	514	475	347	281
42	12/12/2016	203	270	515	477	349	284
43	12/13/2016	205	270	522	477	354	284
44	12/14/2016	207	271	522	477	354	284
45	12/15/2016	207	271	522	477	354	284
46	12/16/2016	208	271	523	477	357	285
47	12/17/2016	211	274	527	480	361	289
48	12/18/2016	211	274	527	480	361	289
49	12/19/2016	211	274	527	480	361	289
50	12/20/2016	211	274	527	480	361	289

Date		Biogas accumulation (ml)					
		Blank	S	LW	S:LW 1	S:LW 2	S:LW 3
51	12/21/2016	223	281	539	487	370	297
52	12/22/2016	223	281	539	487	370	297
53	12/23/2016	229	287	545	492	376	303
54	12/24/2016	229	287	545	492	376	303
55	12/25/2016	229	287	545	492	376	303
56	12/26/2016	234	289	547	493	379	306
57	12/27/2016	234	289	547	493	379	306
58	12/28/2016	237	290	549	493	380	306
59	12/29/2016	237	290	549	493	380	306
60	12/30/2016	238	290	550	493	381	306
61	12/31/2016	238	290	550	493	381	306
62	1/1/2017	238	290	550	493	381	306
63	1/2/2017	247	296	556	495	387	311
64	1/3/2017	247	296	556	495	387	311
65	1/4/2017	252	298	559	495	389	312
66	1/5/2017	252	298	559	495	389	312
67	1/6/2017	259	302	563	497	392	315
68	1/7/2017	259	302	563	497	392	315
69	1/8/2017	259	302	563	497	392	315
70	1/9/2017	261	305	563	501	392	319
71	1/10/2017	261	305	563	501	392	319
72	1/11/2017	266	306	568	501	398	319

Table A-2 Results of Methane composition from each BMP test

Date		CH_4 (%)					
		Blank	S	LW	S:LW 1	S:LW 2	S:LW 3
11	11/11/2016					22.2	
12	11/12/2016			11.6			
13	11/13/2016			24.6	15.0		
17	11/17/2016		18.5				19.1
19	11/19/2016			31.2			
20	11/20/2016			39.6	33.8		

Date		CH_4 (%)					
		Blank	S	LW	S:LW 1	S:LW 2	S:LW 3
21	11/21/2016				38.6		
23	11/23/2016	18.3					
25	11/25/2016	22.7					
32	12/2/2016	26.6					
35	12/5/2016					33.7	
72	1/11/2017	29.8	31.6	43.1	40.9	35.2	30.9

Table A-3 CH_4 yield results from each BMP test

Date		CH_4 yield ($mlCH_4/gVS_{added}$)					
		Blank	S	LW	S:LW 1	S:LW 2	S:LW 3
1	11/1/2016	0	0	0	0	0	0
2	11/2/2016	0	1	4	3	3	1
3	11/3/2016	0	6	10	10	9	9
4	11/4/2016	3	9	11	12	11	13
5	11/5/2016	4	11	11	12	12	14
6	11/6/2016	6	14	12	15	16	19
7	11/7/2016	9	18	13	16	19	21
8	11/8/2016	11	20	14	17	22	23
9	11/9/2016	13	22	15	19	25	25
10	11/10/2016	14	24	17	21	29	27
11	11/11/2016	15	24	19	24	46	28
12	11/12/2016	17	25	21	27	79	29
13	11/13/2016	18	27	56	31	87	30
14	11/14/2016	19	28	80	83	95	31
15	11/15/2016	21	29	89	94	101	32
16	11/16/2016	21	29	97	103	104	32
17	11/17/2016	22	30	104	112	106	33
18	11/18/2016	22	56	111	120	107	58
19	11/19/2016	23	63	116	126	109	66
20	11/20/2016	23	63	156	129	109	66
21	11/21/2016	23	66	177	156	109	68
22	11/22/2016	24	68	184	171	111	70

Date		CH_4 yield ($mlCH_4/gVS_{added}$)					
		Blank	S	LW	S:LW 1	S:LW 2	S:LW 3
23	11/23/2016	24	69	192	174	111	71
24	11/24/2016	32	71	199	176	112	73
25	11/25/2016	33	72	205	178	112	74
26	11/26/2016	41	74	208	181	113	76
27	11/27/2016	42	75	209	182	113	76
28	11/28/2016	43	75	209	183	113	77
29	11/29/2016	44	76	210	185	113	78
30	11/30/2016	44	77	211	185	113	79
31	12/1/2016	45	78	214	187	114	80
32	12/2/2016	46	78	214	187	114	80
33	12/3/2016	52	79	215	189	114	81
34	12/4/2016	53	80	216	189	114	82
35	12/5/2016	54	81	217	190	114	83
36	12/6/2016	55	81	218	191	120	84
37	12/7/2016	56	82	219	191	121	84
38	12/8/2016	57	83	220	192	121	85
39	12/9/2016	58	84	221	193	122	86
40	12/10/2016	59	84	221	194	122	86
41	12/11/2016	60	85	221	194	122	87
42	12/12/2016	61	85	222	195	123	88
43	12/13/2016	61	85	225	195	125	88
44	12/14/2016	62	86	225	195	125	88
45	12/15/2016	62	86	225	195	125	88
46	12/16/2016	62	86	225	195	126	88
47	12/17/2016	63	87	227	196	127	89
48	12/18/2016	63	87	227	196	127	89
49	12/19/2016	63	87	227	196	127	89
50	12/20/2016	63	87	227	196	127	89
51	12/21/2016	67	89	232	199	130	92
52	12/22/2016	67	89	232	199	130	92
53	12/23/2016	69	91	235	201	133	94
54	12/24/2016	69	91	235	201	133	94

Date		CH_4 yield ($mlCH_4/gVS_{added}$)					
		Blank	S	LW	S:LW 1	S:LW 2	S:LW 3
55	12/25/2016	69	91	235	201	133	94
56	12/26/2016	70	91	236	202	134	94
57	12/27/2016	70	91	236	202	134	94
58	12/28/2016	71	92	236	202	134	94
59	12/29/2016	71	92	236	202	134	94
60	12/30/2016	71	92	237	202	134	94
61	12/31/2016	71	92	237	202	134	94
62	1/1/2017	71	92	237	202	134	94
63	1/2/2017	74	94	240	202	136	96
64	1/3/2017	74	94	240	202	136	96
65	1/4/2017	76	94	241	203	137	96
66	1/5/2017	76	94	241	203	137	96
67	1/6/2017	77	96	242	203	138	97
68	1/7/2017	77	96	242	203	138	97
69	1/8/2017	77	96	242	203	138	97
70	1/9/2017	78	96	242	205	138	98
71	1/10/2017	78	96	242	205	138	98
72	1/11/2017	80	97	245	205	140	98

Table A-4 MG model results of Septage in BMP test

x	y	f(x)	y-f(x)	$(y-f(x))^2$	y-(avgY)	$(y-(avgY))^2$
Time	H_{exp}	$H_{predicted}$	H_{exp}- $H_{predicted}$	$error^2$	H_{exp}-(avgH_{exp})	$(H_{exp}-(avgH_{exp}))^2$
0	0.00	4.15	-4.15	17.26	-18.24	332.61
1	0.00	4.70	-4.70	22.08	-18.24	332.61
2	3.33	5.29	-1.96	3.85	-14.91	222.23
3	7.45	5.94	1.52	2.30	-10.78	116.31
4	9.71	6.63	3.08	9.51	-8.52	72.64
5	10.57	7.38	3.20	10.22	-7.66	58.72
6	11.67	8.18	3.49	12.16	-6.57	43.18

x	y	f(x)	y-f(x)	$(y-f(x))^2$	y-(avgY)	$(y-(avgY))^2$
Time	H_{exp}	$H_{predicted}$	H_{exp}- $H_{predicted}$	$error^2$	H_{exp}-(avgH_{exp})	$(H_{exp}-(avgH_{exp}))^2$
7	12.13	9.03	3.09	9.55	-6.11	37.35
8	12.59	9.95	2.65	7.01	-5.64	31.86
9	13.19	10.91	2.28	5.20	-5.05	25.46
10	13.49	11.93	1.56	2.45	-4.74	22.50
11	13.62	13.00	0.61	0.38	-4.62	21.33
12	13.62	14.13	-0.51	0.26	-4.62	21.32
13	13.62	15.31	-1.69	2.87	-4.62	21.32
14	13.62	16.55	-2.93	8.58	-4.62	21.32
15	13.62	17.83	-4.21	17.75	-4.62	21.32
16	13.62	19.17	-5.55	30.77	-4.62	21.32
17	13.62	20.55	-6.93	48.00	-4.62	21.32
18	17.29	21.98	-4.69	21.95	-0.95	0.90
19	26.80	23.45	3.36	11.27	8.57	73.40
20	27.09	24.96	2.12	4.52	8.85	78.28
21	29.93	26.51	3.42	11.68	11.69	136.70
22	32.32	28.10	4.21	17.76	14.08	198.20
23	33.83	29.73	4.10	16.82	15.59	243.05
24	33.83	31.38	2.45	5.99	15.59	243.12
25	34.58	33.07	1.51	2.29	16.34	267.12
26	34.58	34.78	-0.20	0.04	16.34	267.12
27	34.58	36.52	-1.93	3.74	16.34	267.12
28	34.58	38.27	-3.69	13.62	16.34	267.12

Table A-5 MG model results of LW in BMP test

x	y	f(x)	y-f(x)	$(y-f(x))^2$	y-(avgY)	$(y-(avgY))^2$
Time	H_{exp}	$H_{predicted}$	H_{exp}-$H_{predicted}$	$error^2$	H_{exp}-(avgH_{exp})	$(H_{exp}$-(avgH_{exp}))^2
0	0.00	0.00	0.00	0.00	-91.52	8376.01
1	0.00	0.00	0.00	0.00	-91.52	8376.01
2	4.76	0.00	4.76	22.66	-86.76	7527.36
3	10.42	0.00	10.42	108.53	-81.10	6577.64
4	10.42	0.00	10.42	108.57	-81.10	6577.30
5	10.42	0.00	10.42	108.54	-81.10	6577.30
6	10.42	0.02	10.40	108.26	-81.10	6577.30
7	10.42	0.09	10.33	106.67	-81.10	6577.30
8	10.42	0.39	10.03	100.63	-81.10	6577.30
9	10.42	1.24	9.18	84.33	-81.10	6577.30
10	10.42	3.14	7.28	53.00	-81.10	6577.30
11	10.42	6.64	3.78	14.26	-81.10	6577.30
12	10.42	12.14	-1.72	2.95	-81.10	6577.30
13	16.54	19.71	-3.17	10.06	-74.98	5622.08
14	30.75	29.12	1.63	2.66	-60.77	3693.50
15	41.84	39.84	2.00	4.00	-49.68	2467.77
16	52.29	51.28	1.01	1.02	-39.23	1539.04
17	61.75	62.82	-1.07	1.14	-29.77	886.10
18	69.88	73.96	-4.08	16.68	-21.64	468.33
19	77.10	84.34	-7.24	52.42	-14.42	207.83
20	89.11	93.74	-4.63	21.46	-2.41	5.81
21	100.20	102.06	-1.86	3.46	8.68	75.30
22	109.89	109.28	0.61	0.37	18.37	337.30
23	120.09	115.45	4.63	21.47	28.57	816.05

x	y	f(x)	y-f(x)	$(y-f(x))^2$	y-(avgY)	$(y-(avgY))^2$
Time	H_{exp}	$H_{predicted}$	$H_{exp}-H_{predicted}$	$error^2$	$H_{exp}-(avgH_{exp})$	$(H_{exp}-(avgH_{exp}))^2$
24	128.35	120.67	7.67	58.88	36.83	1356.22
25	134.88	125.04	9.84	96.76	43.36	1880.12
26	134.88	128.67	6.21	38.51	43.36	1880.04
27	134.88	131.67	3.21	10.30	43.36	1880.04
28	134.88	134.13	0.75	0.56	43.36	1880.04
29	134.88	136.14	-1.26	1.60	43.36	1880.04
30	134.88	137.78	-2.90	8.44	43.36	1880.04
31	138.92	139.12	-0.20	0.04	47.40	2246.62
32	138.92	140.20	-1.28	1.64	47.40	2246.71
33	138.92	141.08	-2.16	4.66	47.40	2246.71
34	138.92	141.79	-2.87	8.22	47.40	2246.71
35	138.92	142.36	-3.44	11.84	47.40	2246.71
36	138.92	142.82	-3.90	15.24	47.40	2246.71
37	138.92	143.20	-4.28	18.29	47.40	2246.71
38	138.92	143.50	-4.58	20.95	47.40	2246.71
39	138.92	143.74	-4.82	23.23	47.40	2246.71
40	138.92	143.94	-5.02	25.15	47.40	2246.71
41	138.92	144.09	-5.17	26.76	47.40	2246.71
42	138.92	144.22	-5.30	28.08	47.40	2246.71
43	138.92	144.32	-5.40	29.18	47.40	2246.71
44	142.94	144.40	-1.47	2.15	51.42	2643.57
45	149.23	144.47	4.77	22.71	57.71	3330.92
46	149.74	144.52	5.21	27.17	58.21	3388.99
47	150.91	144.57	6.35	40.30	59.39	3527.59
48	150.91	144.60	6.31	39.87	59.39	3527.59

x	y	f(x)	y-f(x)	$(y-f(x))^2$	y-(avgY)	$(y-(avgY))^2$
Time	H_{exp}	$H_{predicted}$	H_{exp}-$H_{predicted}$	$error^2$	H_{exp}-(avgH_{exp})	$(H_{exp}$-(avgH_{exp}))^2
49	150.91	144.63	6.29	39.52	59.39	3527.59
50	150.91	144.65	6.26	39.24	59.39	3527.59

Table A-6 MG model results of S:LW 1 in BMP test

x	y	f(x)	y-f(x)	$(y-f(x))^2$	y-(avgY)	$(y-(avgY))^2$
Time	H_{exp}	$H_{predicted}$	H_{exp}-$H_{predicted}$	$error^2$	H_{exp}-(avgH_{exp})	$(H_{exp}$-(avgH_{exp}))^2
0	0.00	0.00	0.00	0.00	-65.39	4276.45
1	0.00	0.00	0.00	0.00	-65.39	4276.45
2	6.02	0.00	6.02	36.26	-59.37	3525.18
3	13.05	0.00	13.05	170.21	-52.35	2740.33
4	13.05	0.00	13.05	170.20	-52.35	2740.37
5	13.05	0.00	13.05	170.20	-52.35	2740.37
6	13.05	0.00	13.04	170.14	-52.35	2740.37
7	13.05	0.03	13.02	169.40	-52.35	2740.37
8	13.05	0.22	12.82	164.46	-52.35	2740.37
9	13.05	1.00	12.04	145.02	-52.35	2740.37
10	13.05	3.17	9.87	97.51	-52.35	2740.37
11	13.05	7.63	5.42	29.37	-52.35	2740.37
12	13.25	14.89	-1.65	2.72	-52.15	2719.48
13	17.03	24.81	-7.79	60.63	-48.37	2339.30
14	36.24	36.63	-0.38	0.15	-29.15	849.79
15	49.39	49.29	0.10	0.01	-16.00	256.15
16	61.50	61.82	-0.31	0.10	-3.89	15.15
17	73.83	73.47	0.36	0.13	8.44	71.18
18	83.66	83.81	-0.15	0.02	18.26	333.59

19	92.04	92.67	-0.63	0.40	26.65	710.05
20	96.56	100.05	-3.49	12.18	31.17	971.27
21	107.05	106.07	0.98	0.95	41.65	1734.97
22	115.99	110.91	5.08	25.85	50.60	2559.91
23	119.43	114.74	4.69	21.95	54.03	2919.38
24	120.53	117.75	2.78	7.71	55.14	3040.00
25	120.53	120.11	0.43	0.18	55.14	3040.03
26	123.15	121.93	1.22	1.48	57.75	3335.18
27	123.15	123.34	-0.19	0.04	57.75	3335.23
28	123.54	124.43	-0.89	0.79	58.14	3380.56
29	124.08	125.26	-1.19	1.41	58.68	3443.60
30	124.11	125.90	-1.79	3.20	58.72	3447.95
31	124.98	126.39	-1.42	2.01	59.58	3550.17
32	124.98	126.77	-1.79	3.21	59.58	3550.17
33	124.98	127.06	-2.08	4.32	59.58	3550.17

Table A-7 MG model results of S:LW 2 in BMP test

x	y	f(x)	y-f(x)	$(y-f(x))^2$	y-(avgY)	$(y-(avgY))^2$
Time	H_{exp}	$H_{predicted}$	$H_{exp}-H_{predicted}$	$error^2$	$H_{exp}-(avgH_{exp})$	$(H_{exp}-(avgH_{exp}))^2$
0	0.00	0.00	0.00	0.00	-42.35	1793.29
1	0.00	0.00	0.00	0.00	-42.35	1793.29
2	5.11	0.01	5.10	25.96	-37.24	1386.64
3	10.75	0.11	10.65	113.39	-31.59	998.15
4	11.51	0.49	11.03	121.56	-30.83	950.79
5	11.51	1.58	9.93	98.59	-30.84	950.81
6	12.94	3.92	9.03	81.48	-29.40	864.54
7	12.94	7.87	5.08	25.76	-29.40	864.55

x	y	f(x)	y-f(x)	$(y-f(x))^2$	y-(avgY)	$(y-(avgY))^2$
Time	H_{exp}	$H_{predicted}$	$H_{exp}-H_{predicted}$	$error^2$	$H_{exp}-(avgH_{exp})$	$(H_{exp}-(avgH_{exp}))^2$
8	14.41	13.46	0.96	0.92	-27.93	780.22
9	16.54	20.33	-3.80	14.40	-25.81	666.03
10	19.50	27.94	-8.44	71.27	-22.85	522.21
11	27.80	35.67	-7.87	61.98	-14.55	211.67
12	40.41	43.05	-2.64	6.98	-1.94	3.76
13	50.87	49.75	1.12	1.26	8.52	72.67
14	60.15	55.61	4.54	20.62	17.80	316.92
15	66.16	60.58	5.58	31.10	23.81	566.90
16	69.83	64.71	5.12	26.22	27.48	755.11
17	72.51	68.07	4.44	19.73	30.16	909.91
18	73.21	70.78	2.44	5.94	30.87	952.81
19	73.92	72.93	0.99	0.98	31.58	997.11
20	73.92	74.64	-0.71	0.51	31.58	997.11
21	73.95	75.97	-2.02	4.10	31.60	998.70
22	75.48	77.02	-1.54	2.37	33.13	1097.87
23	75.86	77.83	-1.97	3.89	33.51	1123.23
24	75.86	78.47	-2.60	6.78	33.51	1123.23
25	75.86	78.96	-3.09	9.57	33.51	1123.23

Table A-8 MG model results of S:LW 3 in BMP test

x	y	f(x)	y-f(x)	$(y-f(x))^2$	y-(avgY)	$(y-(avgY))^2$
Time	H_{exp}	$H_{predicted}$	$H_{exp}-H_{predicted}$	$error^2$	$H_{exp}-(avgH_{exp})$	$(H_{exp}-(avgH_{exp}))^2$
0	0.00	7.36	-7.36	54.10	-22.46	504.32
1	0.00	8.09	-8.09	65.51	-22.46	504.32

x	y	f(x)	y-f(x)	$(y-f(x))^2$	y-(avgY)	$(y-(avgY))^2$
Time	H_{exp}	$H_{predicted}$	$H_{exp}-H_{predicted}$	$error^2$	$H_{exp}-(avgH_{exp})$	$(H_{exp}-(avgH_{exp}))^2$
2	4.83	8.88	-4.05	16.38	-17.62	310.62
3	11.94	9.71	2.23	4.97	-10.51	110.55
4	15.29	10.59	4.69	22.04	-7.17	51.42
5	15.29	11.52	3.77	14.19	-7.17	51.41
6	18.79	12.49	6.30	39.68	-3.66	13.42
7	18.79	13.52	5.28	27.85	-3.66	13.42
8	18.79	14.59	4.21	17.71	-3.66	13.42
9	18.79	15.70	3.09	9.58	-3.66	13.42
10	18.79	16.86	1.94	3.74	-3.66	13.42
11	18.97	18.06	0.91	0.83	-3.48	12.14
12	18.97	19.31	-0.34	0.11	-3.48	12.14
13	18.97	20.60	-1.62	2.63	-3.48	12.14
14	18.97	21.92	-2.95	8.71	-3.48	12.14
15	18.97	23.29	-4.32	18.64	-3.48	12.14
16	18.97	24.69	-5.72	32.73	-3.48	12.14
17	18.97	26.13	-7.16	51.26	-3.48	12.14
18	21.78	27.60	-5.83	33.98	-0.68	0.46
19	32.27	29.11	3.16	9.98	9.81	96.26
20	32.27	30.64	1.63	2.65	9.81	96.26
21	34.86	32.20	2.66	7.09	12.41	153.95
22	37.48	33.79	3.69	13.63	15.02	225.65
23	38.94	35.40	3.55	12.59	16.49	271.81
24	38.94	37.02	1.92	3.68	16.49	271.82
25	39.37	38.67	0.70	0.49	16.92	286.20
26	39.37	40.34	-0.96	0.93	16.92	286.20

x	y	f(x)	y-f(x)	$(y-f(x))^2$	y-(avgY)	$(y-(avgY))^2$
Time	H_{exp}	$H_{predicted}$	$H_{exp}-H_{predicted}$	$error^2$	$H_{exp}-(avgH_{exp})$	$(H_{exp}-(avgH_{exp}))^2$
27	39.37	42.02	-2.64	6.98	16.92	286.20

First order kinetic equation:

$$B_t = f_d(1 - \exp(-k_{hyd}t))$$

Where; $B_{(t)}$ **=** cumulative methane production at time t **(**ml**)**

f_d **=** methane potential obtained during stationary phase **(**mlCH_4**/**gVS**)**

k_{hyd} **=** the hydrolysis rate constant **(**1**/**d**)**

Table A-9 FO model results of Septage in BMP test

x	y	f(x)	y-f(x)	$(y-f(x))^2$	y-(avgY)	$(y-(avgY))^2$
Time	H_{exp}	$H_{predicted}$	$H_{exp}-H_{predicted}$	$error^2$	$H_{exp}-(avgH_{exp})$	$(H_{exp}-(avgH_{exp}))^2$
0	0.00	0.00	0.00	0.00	-18.24	332.61
1	0.00	1.30	-1.30	1.70	-18.24	332.61
2	3.33	2.61	0.72	0.53	-14.91	222.23
3	7.45	3.91	3.55	12.59	-10.78	116.31
4	9.71	5.20	4.51	20.36	-8.52	72.64
5	10.57	6.50	4.08	16.62	-7.66	58.72
6	11.67	7.79	3.87	15.01	-6.57	43.18
7	12.13	9.08	3.04	9.26	-6.11	37.35
8	12.59	10.37	2.22	4.93	-5.64	31.86
9	13.19	11.66	1.53	2.35	-5.05	25.46
10	13.49	12.94	0.55	0.30	-4.74	22.50
11	13.62	14.23	-0.61	0.37	-4.62	21.33

x	y	f(x)	y-f(x)	$(y-f(x))^2$	y-(avgY)	$(y-(avgY))^2$
Time	H_{exp}	$H_{predicted}$	$H_{exp}-H_{predicted}$	$error^2$	$H_{exp}-(avgH_{exp})$	$(H_{exp}-(avgH_{exp}))^2$
12	13.62	15.51	-1.89	3.57	-4.62	21.32
13	13.62	16.79	-3.17	10.03	-4.62	21.32
14	13.62	18.06	-4.44	19.75	-4.62	21.32
15	13.62	19.34	-5.72	32.71	-4.62	21.32
16	13.62	20.61	-6.99	48.89	-4.62	21.32
17	13.62	21.88	-8.26	68.28	-4.62	21.32
18	17.29	23.15	-5.86	34.35	-0.95	0.90
19	26.80	24.42	2.39	5.70	8.57	73.40
20	27.09	25.68	1.40	1.97	8.85	78.28
21	29.93	26.95	2.98	8.91	11.69	136.70
22	32.32	28.21	4.11	16.89	14.08	198.20
23	33.83	29.46	4.36	19.04	15.59	243.05
24	33.83	30.72	3.11	9.66	15.59	243.12
25	34.58	31.98	2.61	6.79	16.34	267.12
26	34.58	33.23	1.35	1.83	16.34	267.12
27	34.58	34.48	0.10	0.01	16.34	267.12
28	34.58	35.73	-1.15	1.31	16.34	267.12

Table A-10 FO model results of LW in BMP test

x	y	f(x)	y-f(x)	$(y-f(x))^2$	y-(avgY)	$(y-(avgY))^2$
Time	H_{exp}	$H_{predicted}$	$H_{exp}-H_{predicted}$	$error^2$	$H_{exp}-(avgH_{exp})$	$(H_{exp}-(avgH_{exp}))^2$
0	0.00	0.00	0.00	0.00	-91.52	8376.01
1	0.00	4.86	-4.86	23.64	-91.52	8376.01
2	4.76	9.65	-4.89	23.87	-86.76	7527.36
3	10.42	14.35	-3.93	15.46	-81.10	6577.64

x	y	f(x)	y-f(x)	$(y-f(x))^2$	y-(avgY)	$(y-(avgY))^2$
Time	H_{exp}	$H_{predicted}$	$H_{exp}-H_{predicted}$	$error^2$	$H_{exp}-(avgH_{exp})$	$(H_{exp}-(avgH_{exp}))^2$
4	10.42	18.98	-8.56	73.25	-81.10	6577.30
5	10.42	23.53	-13.11	171.89	-81.10	6577.30
6	10.42	28.01	-17.59	309.37	-81.10	6577.30
7	10.42	32.41	-21.99	483.73	-81.10	6577.30
8	10.42	36.75	-26.33	693.11	-81.10	6577.30
9	10.42	41.01	-30.59	935.70	-81.10	6577.30
10	10.42	45.20	-34.78	1209.78	-81.10	6577.30
11	10.42	49.33	-38.91	1513.68	-81.10	6577.30
12	10.42	53.38	-42.96	1845.80	-81.10	6577.30
13	16.54	57.37	-40.83	1667.36	-74.98	5622.08
14	30.75	61.30	-30.55	933.45	-60.77	3693.50
15	41.84	65.16	-23.32	543.64	-49.68	2467.77
16	52.29	68.96	-16.67	277.83	-39.23	1539.04
17	61.75	72.69	-10.94	119.71	-29.77	886.10
18	69.88	76.37	-6.49	42.12	-21.64	468.33
19	77.10	79.98	-2.88	8.30	-14.42	207.83
20	89.11	83.54	5.57	31.02	-2.41	5.81
21	100.20	87.04	13.16	173.17	8.68	75.30
22	109.89	90.48	19.41	376.62	18.37	337.30
23	120.09	93.86	26.22	687.65	28.57	816.05
24	128.35	97.19	31.15	970.57	36.83	1356.22
25	134.88	100.47	34.41	1184.22	43.36	1880.12
26	134.88	103.69	31.19	972.82	43.36	1880.04
27	134.88	106.86	28.02	785.18	43.36	1880.04
28	134.88	109.98	24.90	620.21	43.36	1880.04

x	y	f(x)	y-f(x)	$(y-f(x))^2$	y-(avgY)	$(y-(avgY))^2$
Time	H_{exp}	$H_{predicted}$	$H_{exp}-H_{predicted}$	$error^2$	$H_{exp}-(avgH_{exp})$	$(H_{exp}-(avgH_{exp}))^2$
29	134.88	113.04	21.84	476.89	43.36	1880.04
30	134.88	116.06	18.82	354.25	43.36	1880.04
31	138.92	119.03	19.89	395.76	47.40	2246.62
32	138.92	121.94	16.98	288.20	47.40	2246.71
33	138.92	124.81	14.11	198.97	47.40	2246.71
34	138.92	127.64	11.28	127.28	47.40	2246.71
35	138.92	130.42	8.50	72.32	47.40	2246.71
36	138.92	133.15	5.77	33.31	47.40	2246.71
37	138.92	135.84	3.08	9.51	47.40	2246.71
38	138.92	138.48	0.44	0.19	47.40	2246.71
39	138.92	141.08	-2.16	4.67	47.40	2246.71
40	138.92	143.64	-4.72	22.27	47.40	2246.71
41	138.92	146.16	-7.24	52.35	47.40	2246.71
42	138.92	148.63	-9.71	94.30	47.40	2246.71
43	138.92	151.07	-12.15	147.51	47.40	2246.71
44	142.94	153.46	-10.52	110.76	51.42	2643.57
45	149.23	155.82	-6.58	43.32	57.71	3330.92
46	149.74	158.13	-8.40	70.54	58.21	3388.99
47	150.91	160.41	-9.50	90.25	59.39	3527.59
48	150.91	162.66	-11.74	137.88	59.39	3527.59
49	150.91	164.86	-13.95	194.55	59.39	3527.59
50	150.91	167.03	-16.12	259.78	59.39	3527.59

Table A-11 FO model results of S:LW 1 in BMP test

x	y	f(x)	y-f(x)	$(y-f(x))^2$	y-(avgY)	$(y-(avgY))^2$
Time	H_{exp}	$H_{predicted}$	$H_{exp}-H_{predicted}$	$error^2$	$H_{exp}-(avgH_{exp})$	$(H_{exp}-(avgH_{exp}))^2$
0	0.00	0.00	0.00	0.00	-65.39	4276.45
1	0.00	4.21	-4.21	17.73	-65.39	4276.45
2	6.02	8.42	-2.40	5.76	-59.37	3525.18
3	13.05	12.63	0.42	0.18	-52.35	2740.33
4	13.05	16.83	-3.79	14.35	-52.35	2740.37
5	13.05	21.04	-7.99	63.86	-52.35	2740.37
6	13.05	25.24	-12.19	148.68	-52.35	2740.37
7	13.05	29.44	-16.39	268.76	-52.35	2740.37
8	13.05	33.64	-20.59	424.05	-52.35	2740.37
9	13.05	37.84	-24.79	614.50	-52.35	2740.37
10	13.05	42.03	-28.98	840.08	-52.35	2740.37
11	13.05	46.22	-33.18	1100.73	-52.35	2740.37
12	13.25	50.41	-37.17	1381.51	-52.15	2719.48
13	17.03	54.60	-37.58	1411.95	-48.37	2339.30
14	36.24	58.79	-22.55	508.44	-29.15	849.79
15	49.39	62.98	-13.59	184.64	-16.00	256.15
16	61.50	67.16	-5.66	32.04	-3.89	15.15
17	73.83	71.34	2.49	6.18	8.44	71.18
18	83.66	75.53	8.13	66.16	18.26	333.59
19	92.04	79.70	12.34	152.20	26.65	710.05
20	96.56	83.88	12.68	160.74	31.17	971.27
21	107.05	88.06	18.99	360.65	41.65	1734.97
22	115.99	92.23	23.76	564.52	50.60	2559.91
23	119.43	96.40	23.02	530.09	54.03	2919.38

x	y	f(x)	y-f(x)	$(y-f(x))^2$	y-(avgY)	$(y-(avgY))^2$
Time	H_{exp}	$H_{predicted}$	$H_{exp}-H_{predicted}$	$error^2$	$H_{exp}-(avgH_{exp})$	$(H_{exp}-(avgH_{exp}))^2$
24	120.53	100.57	19.96	398.34	55.14	3040.00
25	120.53	104.74	15.79	249.34	55.14	3040.03
26	123.15	108.91	14.24	202.74	57.75	3335.18
27	123.15	113.07	10.07	101.49	57.75	3335.23
28	123.54	117.23	6.30	39.72	58.14	3380.56
29	124.08	121.40	2.68	7.19	58.68	3443.60
30	124.11	125.56	-1.44	2.08	58.72	3447.95
31	124.98	129.71	-4.73	22.42	59.58	3550.17
32	124.98	133.87	-8.89	79.04	59.58	3550.17
33	124.98	138.02	-13.04	170.16	59.58	3550.17

Table A-12 FO model results of S:LW 2 in BMP test

x	y	f(x)	y-f(x)	$(y-f(x))^2$	y-(avgY)	$(y-(avgY))^2$
Time	H_{exp}	$H_{predicted}$	$H_{exp}-H_{predicted}$	$error^2$	$H_{exp}-(avgH_{exp})$	$(H_{exp}-(avgH_{exp}))^2$
0	0.00	0.00	0.00	0.00	-42.35	1793.29
1	0.00	3.53	-3.53	12.44	-42.35	1793.29
2	5.11	7.05	-1.94	3.76	-37.24	1386.64
3	10.75	10.57	0.19	0.03	-31.59	998.15
4	11.51	14.08	-2.57	6.59	-30.83	950.79
5	11.51	17.59	-6.08	36.93	-30.84	950.81
6	12.94	21.09	-8.15	66.40	-29.40	864.54
7	12.94	24.59	-11.65	135.69	-29.40	864.55
8	14.41	28.09	-13.67	186.95	-27.93	780.22
9	16.54	31.58	-15.04	226.17	-25.81	666.03
10	19.50	35.06	-15.57	242.40	-22.85	522.21

x	y	f(x)	y-f(x)	$(y-f(x))^2$	y-(avgY)	$(y-(avgY))^2$
Time	H_{exp}	$H_{predicted}$	$H_{exp}-H_{predicted}$	$error^2$	$H_{exp}-(avgH_{exp})$	$(H_{exp}-(avgH_{exp}))^2$
11	27.80	38.55	-10.75	115.52	-14.55	211.67
12	40.41	42.02	-1.62	2.61	-1.94	3.76
13	50.87	45.50	5.38	28.90	8.52	72.67
14	60.15	48.96	11.19	125.11	17.80	316.92
15	66.16	52.43	13.73	188.48	23.81	566.90
16	69.83	55.89	13.94	194.30	27.48	755.11
17	72.51	59.34	13.17	173.44	30.16	909.91
18	73.21	62.79	10.42	108.63	30.87	952.81
19	73.92	66.24	7.69	59.07	31.58	997.11
20	73.92	69.68	4.24	18.02	31.58	997.11
21	73.95	73.12	0.83	0.69	31.60	998.70
22	75.48	76.55	-1.07	1.14	33.13	1097.87
23	75.86	79.98	-4.12	16.94	33.51	1123.23
24	75.86	83.40	-7.54	56.84	33.51	1123.23
25	75.86	86.82	-10.96	120.09	33.51	1123.23

Table A-12 FO model results of S:LW 2 in BMP test

x	y	f(x)	y-f(x)	$(y-f(x))^2$	y-(avgY)	$(y-(avgY))^2$
Time	H_{exp}	$H_{predicted}$	$H_{exp}-H_{predicted}$	$error^2$	$H_{exp}-(avgH_{exp})$	$(H_{exp}-(avgH_{exp}))^2$
0	0.00	0.00	0.00	0.00	-22.46	504.32
1	0.00	2.01	-2.01	4.05	-22.46	504.32
2	4.83	3.97	0.86	0.74	-17.62	310.62
3	11.94	5.88	6.06	36.77	-10.51	110.55
4	15.29	7.74	7.55	57.01	-7.17	51.42
5	15.29	9.54	5.74	32.98	-7.17	51.41

x	y	f(x)	y-f(x)	$(y-f(x))^2$	y-(avgY)	$(y-(avgY))^2$
Time	H_{exp}	$H_{predicted}$	$H_{exp}-H_{predicted}$	$error^2$	$H_{exp}-(avgH_{exp})$	$(H_{exp}-(avgH_{exp}))^2$
6	18.79	11.30	7.49	56.10	-3.66	13.42
7	18.79	13.02	5.78	33.36	-3.66	13.42
8	18.79	14.69	4.11	16.87	-3.66	13.42
9	18.79	16.31	2.48	6.16	-3.66	13.42
10	18.79	17.89	0.90	0.81	-3.66	13.42
11	18.97	19.43	-0.46	0.21	-3.48	12.14
12	18.97	20.93	-1.96	3.84	-3.48	12.14
13	18.97	22.39	-3.42	11.69	-3.48	12.14
14	18.97	23.81	-4.84	23.42	-3.48	12.14
15	18.97	25.20	-6.22	38.73	-3.48	12.14
16	18.97	26.54	-7.57	57.31	-3.48	12.14
17	18.97	27.86	-8.88	78.89	-3.48	12.14
18	21.78	29.13	-7.36	54.11	-0.68	0.46
19	32.27	30.38	1.89	3.58	9.81	96.26
20	32.27	31.59	0.68	0.47	9.81	96.26
21	34.86	32.76	2.10	4.41	12.41	153.95
22	37.48	33.91	3.57	12.73	15.02	225.65
23	38.94	35.03	3.92	15.33	16.49	271.81
24	38.94	36.12	2.83	8.00	16.49	271.82
25	39.37	37.17	2.20	4.84	16.92	286.20
26	39.37	38.21	1.17	1.37	16.92	286.20
27	39.37	39.21	0.17	0.03	16.92	286.20

APPENDIX B

Table B-1 Temperature results from each TPAD system

Date		Temperature (°C)			
		TS Eff.	MS Eff.	TSL Eff.	MSL Eff.
1	20-Feb	51.0	34.5	51.5	34.5
2	21-Feb	49.5	35.5	49.0	36.0
3	22-Feb	51.5	32.5	51.0	34.5
4	23-Feb	50.5	36.5	51.5	36.0
5	24-Feb	49.5	35.5	49.0	36.0
6	25-Feb	51.5	32.5	52.0	34.5
7	26-Feb	51.0	34.5	51.5	34.5
8	27-Feb	51.5	32.5	51.5	34.5
9	28-Feb	49.5	35.5	51.5	36.0
10	1-Mar	50.5	36.5	51.5	36.0
11	2-Mar	49.0	37.0	49.0	35.0
12	3-Mar	51.0	34.5	51.5	32.5
13	4-Mar	51.5	33.0	53.0	35.0
14	5-Mar	53.0	34.5	54.5	32.0
15	6-Mar	55.0	35.5	56.5	36.0
16	7-Mar	55.0	35.5	54.5	35.0
17	8-Mar	55.0	36.0	55.0	34.5
18	9-Mar	55.0	35.5	55.0	36.0
19	10-Mar	54.5	35.0	55.0	35.3
20	11-Mar	54.8	35.0	54.5	36.8
21	12-Mar	54.5	37.0	56.0	37.5
22	13-Mar	54.5	35.5	54.5	36.0
23	14-Mar	54.0	36.0	54.5	36.0
24	15-Mar	55.0	34.5	56.5	34.5
25	16-Mar	54.0	36.0	54.0	35.0
26	17-Mar	54.0	36.0	53.5	34.5
27	18-Mar	53.5	36.0	54.3	35.0
28	19-Mar	54.0	34.5	54.8	34.0
29	20-Mar	54.5	34.0	54.8	35.3
30	21-Mar	55.0	35.0	54.5	36.0
31	22-Mar	55.0	37.0	54.5	37.5

Date		Temperature (°C)			
		TS Eff.	MS Eff.	TSL Eff.	MSL Eff.
32	23-Mar	55.0	34.5	54.5	35.5
33	24-Mar	55.0	34.0	54.5	34.5
34	25-Mar	55.0	36.0	54.0	35.0
35	26-Mar	55.5	36.0	55.0	36.3
36	27-Mar	55.0	34.5	55.0	36.5
37	28-Mar	55.5	37.5	55.0	37.0
38	29-Mar	54.5	37.0	54.0	36.0
39	30-Mar	54.5	35.5	55.0	36.0
40	31-Mar	55.0	35.5	55.0	36.0
41	1-Apr	55.0	34.5	54.0	35.0
42	2-Apr	55.5	36.5	55.0	35.0
43	3-Apr	55.5	35.0	55.0	35.3
44	4-Apr	55.0	35.0	55.5	35.0
45	5-Apr	55.0	37.0	55.5	34.5
46	6-Apr	55.5	36.0	55.0	35.5
47	7-Apr	55.5	37.0	54.5	35.5
48	8-Apr	55.5	39.0	55.0	36.0
49	9-Apr	56.0	36.5	55.0	36.0
50	10-Apr	55.5	36.0	56.0	36.5
51	11-Apr	56.0	35.5	55.0	34.5
52	12-Apr	55.5	36.0	55.0	35.5
53	13-Apr	55.5	37.0	56.0	36.5
54	14-Apr	55.0	36.5	56.5	36.5
55	15-Apr	56.0	36.0	53.5	35.5
56	16-Apr	55.0	34.0	54.0	35.0
57	17-Apr	54.5	34.5	54.5	34.5
58	18-Apr	55.5	36.0	56.0	36.0
59	19-Apr	55.5	37.5	56.0	37.5
60	20-Apr	46.5	35.5	53.5	35.0
61	21-Apr	31.0	36.5	56.5	35.0
62	22-Apr	55.0	35.0	53.5	34.5
63	23-Apr	55.5	35.5	56.5	34.5

Date		Temperature (°C)			
		TS Eff.	MS Eff.	TSL Eff.	MSL Eff.
64	24-Apr	55.0	36.0	54.5	36.0
65	25-Apr	55.0	37.0	55.0	34.5
66	26-Apr	55.0	37.5	56.0	37.0
67	27-Apr	55.5	35.5	56.0	37.0
68	28-Apr	56.0	36.0	55.5	35.5
69	29-Apr	54.5	34.5	54.0	36.5
70	30-Apr	55.5	35.0	54.5	34.0
71	1-May	56.0	34.5	55.5	35.5
72	2-May	56.0	35.0	55.5	35.0
73	3-May	55.5	36.0	56.0	35.0
74	4-May	56.0	45.5	54.5	35.5
75	5-May	54.5	36.5	55.5	35.0
76	6-May	56.5	37.0	56.5	35.0
77	7-May	54.5	35.5	56.0	38.5
78	8-May	57.0	35.0	56.0	35.0
79	9-May	54.5	34.5	57.5	36.0
80	10-May	55.5	34.5	56.0	36.0
81	11-May	54.5	37.0	55.0	35.0
82	12-May	55.0	36.5	54.5	35.0
83	13-May	56.5	35.0	56.5	35.5
84	14-May	54.0	35.0	56.5	37.0
85	15-May	54.0	35.5	54.0	36.5
86	16-May	52.0	36.0	54.5	35.5
87	17-May	51.0	35.5	51.0	35.5
88	18-May	52.5	33.5	52.5	36.0
89	19-May	55.0	37.0	53.0	35.0
90	20-May	55.0	36.0	55.0	36.5
91	21-May	56.0	36.5	55.5	36.5
92	22-May	57.0	36.5	56.5	36.5
93	23-May	57.0	34.5	58.5	35.5
94	24-May	54.0	37.5	57.0	38.5
95	25-May	56.0	36.0	55.5	35.5

Table B-2 pH results from Influent and Effluent of each TPAD system

Date		pH					
		TS Inf.	TS Eff.	MS Eff.	TSL Inf.	TSL Eff.	MSL Eff.
1	20-Feb	8.05	7.97	7.97	6.33	7.76	7.74
2	21-Feb		8.25	8.31		7.43	7.59
3	22-Feb		7.72	7.68		7.48	7.45
4	23-Feb		7.76	7.57		7.49	7.48
5	24-Feb		7.78	7.64		7.50	7.47
6	25-Feb		7.76	7.60		7.48	7.53
7	26-Feb		7.77	7.68		7.48	7.51
8	27-Feb		7.76	7.58		7.49	7.48
9	28-Feb		7.86	7.60		7.48	7.46
10	1-Mar		7.77	7.65		7.48	7.49
11	2-Mar		7.84	7.65		7.52	7.51
12	3-Mar		7.82	7.67		7.47	7.49
13	4-Mar		7.82	7.63		7.52	7.52
14	5-Mar		7.80	7.75		7.53	7.49
15	6-Mar		7.75	7.62		7.49	7.47
16	7-Mar		7.75	7.60		7.51	7.54
17	8-Mar		7.72	7.59		7.52	7.46
18	9-Mar		7.79	7.67		7.51	7.44
19	10-Mar		7.71	7.50		7.49	7.47
20	11-Mar		7.67	7.51		7.48	7.41
21	12-Mar		7.72	7.53		7.46	7.40
22	13-Mar		7.70	7.53		7.53	7.45
23	14-Mar		7.46	7.41		7.69	7.54
24	15-Mar		7.71	7.62		7.51	7.49
25	16-Mar		7.73	7.60		7.52	7.47
26	17-Mar		7.75	7.57		7.58	7.48
27	18-Mar		7.75	7.60		7.60	7.47
28	19-Mar		7.77	7.56		7.57	7.42
29	20-Mar		7.75	7.57		7.51	7.44
30	21-Mar	8.13	7.64	7.47	6.74	7.33	7.55
31	22-Mar		7.46	7.32		7.33	7.36

Date		pH					
		TS Inf.	TS Eff.	MS Eff.	TSL Inf.	TSL Eff.	MSL Eff.
32	23-Mar		7.45	7.36		7.30	7.36
33	24-Mar		7.44	7.33		7.28	7.32
34	25-Mar		7.41	7.24		7.21	7.30
35	26-Mar		7.43	7.30		7.24	7.28
36	27-Mar		7.43	7.32		7.26	7.32
37	28-Mar		7.47	7.30		7.29	7.28
38	29-Mar		7.42	7.36		7.28	7.31
39	30-Mar		7.46	7.36		7.25	7.32
40	31-Mar		7.43	7.34		7.31	7.30
41	1-Apr		7.42	7.36		7.31	7.32
42	2-Apr		7.42	7.36		7.28	7.31
43	3-Apr		7.44	7.37		7.27	7.33
44	4-Apr		7.44	7.40		7.26	7.33
45	5-Apr		7.45	7.39		7.29	7.36
46	6-Apr		7.43	7.42		7.33	7.35
47	7-Apr		7.42	7.41		7.30	7.33
48	8-Apr		7.43	7.35		7.21	7.34
49	9-Apr		7.47	7.41		7.25	7.34
50	10-Apr		7.43	7.42		7.27	7.30
51	11-Apr		7.43	7.42		7.28	7.30
52	12-Apr		7.44	7.39		7.26	7.31
53	13-Apr		7.46	7.37		7.26	7.34
54	14-Apr		7.47	7.41		7.26	7.31
55	15-Apr		7.44	7.39		7.32	7.34
56	16-Apr		7.54	7.45		7.28	7.33
57	17-Apr		7.55	7.44		7.28	7.29
58	18-Apr		7.50	7.45		7.28	7.37
59	19-Apr		7.50	7.48		7.32	7.39
60	20-Apr		7.50	7.48		7.36	7.34
61	21-Apr		7.54	7.51		7.27	7.37
62	22-Apr	8.00	7.52	7.40	6.89	7.40	7.42
63	23-Apr		7.53	7.42		7.30	7.36

Date		pH					
		TS Inf.	TS Eff.	MS Eff.	TSL Inf.	TSL Eff.	MSL Eff.
64	24-Apr		7.57	7.48		7.27	7.36
65	25-Apr		7.49	7.44		7.25	7.37
66	26-Apr		7.52	7.55		7.32	7.44
67	27-Apr		7.65	7.69		7.40	7.49
68	28-Apr		7.64	7.55		7.37	7.48
69	29-Apr		7.75	7.72		7.39	7.45
70	30-Apr		7.69	7.59		7.34	7.48
71	1-May		7.71	7.60		7.30	7.46
72	2-May		7.69	7.65		7.30	7.41
73	3-May		7.73	7.65		7.36	7.45
74	4-May		7.74	7.71		7.39	7.42
75	5-May		7.74	7.69		7.35	7.43
76	6-May		7.76	7.71		7.33	7.42
77	7-May		7.79	7.81		7.34	7.49
78	8-May		7.78	7.76		7.37	7.45
79	9-May		7.81	7.78		7.36	7.44
80	10-May		7.86	7.80		7.44	7.54
81	11-May		7.91	7.83		7.30	7.43
82	12-May		7.87	7.85		7.29	7.41
83	13-May		7.81	7.82		7.29	7.50
84	14-May		7.89	7.85		7.34	7.45
85	15-May		7.91	7.85		7.35	7.49
86	16-May		7.99	7.91		7.38	7.49
87	17-May		7.96	7.95		7.49	7.54
88	18-May		8.00	7.94		7.39	7.50
89	19-May		7.96	7.83		7.41	7.55
90	20-May		7.78	7.71		7.25	7.34
91	21-May		7.77	7.65		7.36	7.34
92	22-May	7.62	7.77	7.61	6.88	7.32	7.315
93	23-May		7.77	7.63		7.33	7.37
94	24-May		7.74	7.59		7.355	7.36
95	25-May		7.74	7.64		7.35	7.425

Table B-3 Alkalinity results from Influent and Effluent of each TPAD system

Date		Alkalinity ($mgCaCO_3/l$)					
		TS Inf.	TS Eff.	MS Eff.	TSL Inf.	TSL Eff.	MSL Eff.
1	20-Feb		2599	2974		3325	2055
2	21-Feb	3143			0		
4	23-Feb	4352	3506	3929	0	2478	2116
8	27-Feb	2781	3627	2720	0	1511	2055
11	2-Mar		2720	2237		1874	2539
14	5-Mar		4050	3325		3627	2902
15	6-Mar		3929	3204		2297	2660
18	9-Mar	2902	3869	3204	3143	2297	2055
21	12-Mar		4401	4523		3606	3117
22	13-Mar		5746	4707		3851	3484
25	16-Mar		4401	3973		3179	2934
28	19-Mar		2690	4157		3423	2690
29	20-Mar	3301	3606	3545	2690	2751	2201
32	23-Mar		4144	4365		3205	3426
34	25-Mar		4365	3923		3094	3094
36	27-Mar	2597	4074	3610	2265	2991	3404
39	30-Mar		4033	3647		2818	2707
41	1-Apr		3868	4144		3370	3094
43	3-Apr	2733	4126	3301	2321	3095	2837
46	6-Apr		4254	3757		2873	3205
48	8-Apr		4033	3094		3260	2818
50	10-Apr		3920	3971		2991	3249
53	13-Apr	3039	4420	4033	2376	3426	3094
55	15-Apr		3868	4033		2376	2818
57	17-Apr		3481	3647		2873	2652
60	20-Apr		3973	4829		2567	3179
62	22-Apr	2506	3668	3912	2201	2934	2812
64	24-Apr		3240	3240		2812	3056
67	27-Apr		3240	3668		2934	2934
69	29-Apr	2934	3545	3912	2567	2017	2751

Date		Alkalinity ($mgCaCO_3/l$)					
		TS Inf.	TS Eff.	MS Eff.	TSL Inf.	TSL Eff.	MSL Eff.
71	1-May		2995	4034		2231	2995
74	4-May	2818	3370	3260	2265	2321	2542
76	6-May		2265	2652		1934	1989
78	8-May		2269	2837		2476	2476
81	11-May	2652	3039	2928	1271	1989	2100
83	13-May		3094	2542		1658	1879
85	15-May		3095	2166		1754	2063
90	20-May	2476	2269	2321	1547	1960	1857
92	22-May		2476	2372		1650	1805
95	25-May		2597	2652		1768	1768

Table B-4 VFA results from Influent and Effluent of each TPAD system

Date		VFA ($mgCH_3COOH/l$)					
		TS Inf.	TS Eff.	MS Eff.	TSL Inf.	TSL Eff.	MSL Eff.
1	20-Feb		2278	2349		1993	925
2	21-Feb	2135			10249		
4	23-Feb	2064	1851	1779	7900	1637	1352
8	27-Feb	2989	925	4413	8256	1495	1708
11	2-Mar		1566	1566		1495	1566
14	5-Mar		2064	2206		1779	1993
15	6-Mar		1566	1281		1139	1210
18	9-Mar	1424	1424	1566	1922	890	1281
21	12-Mar		3111	1037		1914	1595
22	13-Mar		2951	2712		1994	2074
25	16-Mar		3510	2473		2313	1994
28	19-Mar		2552	2552		2233	1675
29	20-Mar	1584	1735	1584	1509	1358	981
32	23-Mar		1652	1728		1502	1652
34	25-Mar		2103	2028		1953	1803
36	27-Mar	1202	2253	1803	1052	1728	1878
39	30-Mar		1878	1652		1427	1427

Date		VFA ($mgCH_3COOH/l$)					
		TS Inf.	TS Eff.	MS Eff.	TSL Inf.	TSL Eff.	MSL Eff.
41	1-Apr		1803	1953		1878	1652
43	3-Apr	1652	2328	2704	1577	1878	1878
46	6-Apr		2178	1953		1577	1652
48	8-Apr		1577	1502		1502	1390
50	10-Apr		2028	1953		1127	1803
53	13-Apr	1652	2253	2178	2328	1953	1803
55	15-Apr		2479	2479		1502	1803
57	17-Apr		1394	1467		1174	1247
60	20-Apr		2154	2393		1755	1675
62	22-Apr	1434	1962	1584	1584	2414	1811
64	24-Apr		1509	1735		1660	1434
67	27-Apr		1509	1811		1735	1735
69	29-Apr	1056	2037	1962	1735	981	1358
71	1-May		1019	1132		792	1019
74	4-May	587	1467	1504	880	1174	1174
76	6-May		1027	1430		880	734
78	8-May		1202	1427		1427	1427
81	11-May	2652	1394	1247	1271	880	807
83	13-May		1320	1907		587	880
85	15-May		1953	1127		1803	1202
90	20-May	676	1127	1352	2629	1953	901
92	22-May		976	1427		976	1202
95	25-May		1427	1352		751	751

Table B-5 VFA/Alk results from effluent of each TPAD system

Date		VFA/Alk			
		TS Eff.	MS Eff.	TSL Eff.	MSL Eff.
1	20-Feb	0.9	0.8	0.6	0.5
4	23-Feb	0.5	0.5	0.7	0.6
8	27-Feb	0.3		1.0	0.8
11	2-Mar	0.6	0.7	0.8	0.6

Date		VFA/Alk			
		TS Eff.	MS Eff.	TSL Eff.	MSL Eff.
14	5-Mar	0.5	0.7	0.5	0.7
15	6-Mar	0.4	0.4	0.5	0.5
18	9-Mar	0.4	0.5	0.4	0.6
21	12-Mar	0.7	0.2	0.5	0.5
22	13-Mar	0.5	0.6	0.5	0.6
25	16-Mar	0.8	0.6	0.7	0.7
28	19-Mar	0.9	0.6	0.7	0.6
29	20-Mar	0.5	0.4	0.5	0.4
32	23-Mar	0.4	0.4	0.5	0.5
34	25-Mar	0.5	0.5	0.6	0.6
36	27-Mar	0.6	0.5	0.6	0.6
39	30-Mar	0.5	0.5	0.5	0.5
41	1-Apr	0.5	0.5	0.6	0.5
43	3-Apr	0.6	0.8	0.6	0.7
46	6-Apr	0.5	0.5	0.5	0.5
48	8-Apr	0.4	0.5	0.5	0.5
50	10-Apr	0.5	0.5	0.4	0.6
53	13-Apr	0.5	0.5	0.6	0.6
55	15-Apr	0.6	0.6	0.6	0.6
57	17-Apr	0.4	0.4	0.4	0.5
60	20-Apr	0.5	0.5	0.7	0.5
62	22-Apr	0.5	0.4	0.8	0.6
64	24-Apr	0.5	0.5	0.6	0.5
67	27-Apr	0.5	0.5	0.6	0.6
69	29-Apr	0.6	0.5	0.5	0.5
71	1-May	0.3	0.3	0.4	0.3
74	4-May	0.4	0.5	0.5	0.5
76	6-May	0.5	0.5	0.5	0.4
78	8-May	0.5	0.5	0.6	0.6
81	11-May	0.5	0.4	0.4	0.4
83	13-May	0.4	0.8	0.4	0.5
85	15-May	0.6	0.5		0.6

Date		VFA/Alk			
		TS Eff.	MS Eff.	TSL Eff.	MSL Eff.
90	20-May	0.5	0.6		0.5
92	22-May	0.4	0.6	0.6	0.7
95	25-May	0.5	0.5	0.4	0.4

Table B-6 TS results from influent and effluent of each TPAD system

Date		TS (mg/l)					
		TS Inf.	TS Eff.	MS Eff.	TSL Inf.	TSL Eff.	MSL Eff.
1	20-Feb	51080	39010	37400	10560	24060	11520
4	23-Feb		36980	38950		21900	26820
6	25-Feb		37310	37500			
8	27-Feb	55840	39330	33170	6155	12360	25260
11	2-Mar		39330	33170		10530	25130
14	5-Mar		39650	33300		23730	20930
15	6-Mar		41510	35010		13980	18530
18	9-Mar	47630	42190	39870	48340	26590	23240
21	12-Mar		41560	37610		30300	25400
22	13-Mar	44750	42450	36430	34830	27820	20950
25	16-Mar		43790	36220		25840	22530
28	19-Mar		42230	38440		32080	20120
29	20-Mar	28430			23420		
32	23-Mar		41990	36510		25930	30270
34	25-Mar		45270	38900		28920	31240
36	27-Mar	18050	42530	38980	14810	28710	31950
39	30-Mar		45190	39170		31970	30580
41	1-Apr		44100	40700		30970	39060
43	3-Apr		43070	41060		29730	31280
46	6-Apr	35960	45270	41430	29210	33060	32180
48	8-Apr		43850	44300		32900	30310
50	10-Apr		46990	43290		34290	30050
53	13-Apr	35590	43240	39540	27530	30420	30930
55	15-Apr		42180	41190		11450	30250
57	17-Apr		37000	42520		21730	27470

Date		TS (mg/l)					
		TS Inf.	TS Eff.	MS Eff.	TSL Inf.	TSL Eff.	MSL Eff.
60	20-Apr		39820	42940		25000	29780
62	22-Apr	22650	40420	38280	19230	27360	25770
64	24-Apr		37850	41380		21230	27790
67	27-Apr		39260	39110		29560	23420
69	29-Apr		26830	39340		10410	20210
71	1-May		22120	39290		14310	20020
74	4-May	27180	29780	28350	21980	20010	24740
76	6-May		11200	15220		9810	9300
78	8-May		13130	24400		22680	25020
81	11-May	26360	23770	24180	18120	10530	10430
83	13-May		21950	24340		8420	14390
85	15-May		19400	22560		9290	8210
88	18-May		25360	27160		30530	20160
90	20-May	25060	39590	10420	16070	41350	20420
92	22-May		22250	26133		9817	22600
95	25-May		21610	23180		10130	10370

Table B-7 VS results from influent and effluent of each TPAD system

Date		VS (mg/l)					
		TS Inf.	TS Eff.	MS Eff.	TSL Inf.	TSL Eff.	MSL Eff.
1	20-Feb	33270	26960	25320	9425	16260	8050
4	23-Feb		25410	26440		15040	18950
6	25-Feb		25090	25050			
8	27-Feb	38260	27430	23280	5485	8470	17690
11	2-Mar		27430	23280		7610	17570
14	5-Mar		27710	22660		16070	13810
15	6-Mar		28940	24160		9700	12750
18	9-Mar	32940	29450	26230	33640	18290	15760
21	12-Mar		29110	25950		20670	17730
22	13-Mar	31040	29970	25290	24350	19330	14710
25	16-Mar		30380	24980		17660	15670
28	19-Mar		28990	26310		21900	14000

Date		VS (mg/l)					
		TS Inf.	TS Eff.	MS Eff.	TSL Inf.	TSL Eff.	MSL Eff.
29	20-Mar	20200			16840		
32	23-Mar		29040	24530		17760	21200
34	25-Mar		31610	26950		20130	22130
36	27-Mar	8860	30310	27610	10550	20020	22660
39	30-Mar		32690	27610		22180	21900
41	1-Apr		31960	28570		21080	30800
43	3-Apr		31290	29340		20640	22100
46	6-Apr	23830	32710	29260	20620	23400	23290
48	8-Apr		31410	31820		22950	21130
50	10-Apr		34010	30870		23640	21360
53	13-Apr	24830	31500	27760	19150	21260	21980
55	15-Apr		30080	28480		8150	21280
57	17-Apr		26240	30310		15090	19630
60	20-Apr		28400	30790		17030	21360
62	22-Apr	15730	28760	27010	13400	18850	18130
64	24-Apr		27090	29860		14830	20110
67	27-Apr		27200	28070		20810	17000
69	29-Apr		19410	28580		7460	14650
71	1-May		15780	28590		10100	14480
74	4-May	19360	19700	19630	16000	14220	17380
76	6-May		8050	10620		6670	6810
78	8-May		9370	17010		16070	16650
81	11-May	18400	16560	17110	13250	7630	7460
83	13-May		15400	17060		6250	10110
85	15-May		13550	15830		6540	5990
88	18-May		17340	19400		20900	14400
90	20-May	17460	26600	7380	11780	29450	14380
92	22-May		16567	19833		8417	17167
95	25-May		15360	16600		7400	7640

Table B-8 COD results from influent and effluent of each TPAD system

Date		COD (mg/l)					
		TS Inf.	TS Eff.	MS Eff.	TSL Inf.	TSL Eff.	MSL Eff.
1	20-Feb		64826	56564		31354	16101
2	21-Feb	56352					
4	23-Feb	61013	68004	58471	5635	33260	43641
8	27-Feb	69911	64614	46607	4449	26269	61013
11	2-Mar	69911	43217	64614	4449	33472	23304
14	5-Mar		43200	35943		25200	22000
15	6-Mar		40800	38200		11400	26800
18	9-Mar	48000	44000	39600	49200	31600	26000
21	12-Mar		43800	37200		27800	23400
22	13-Mar	44701			25434		
25	16-Mar		30829	28516		20039	16185
28	19-Mar		34682	23892		26975	17726
29	20-Mar	22351	33141	36994	20809	29287	9249
32	23-Mar		36224	29287		20809	29287
34	25-Mar		34682	32370		20809	26975
36	27-Mar	15292	37022	34608	11268	23340	26559
39	30-Mar		39437	35412		23340	23340
41	1-Apr		33803	23340		26559	20926
43	3-Apr	28169	32193	27364	21730	27364	20926
46	6-Apr		29779	32193		23340	23340
48	8-Apr		41732	39370		25984	31496
50	10-Apr		42520	32283		28346	25984
53	13-Apr	26506	37751	42570	24900	29719	29719
55	15-Apr		36948	37751		13655	28112
57	17-Apr		34538	39357		22490	25703
60	20-Apr		41126	49190		29030	29030
62	22-Apr	22579	40320	38707	22579	22579	32256
64	24-Apr		37094	43949		30643	25805
67	27-Apr		32932	32932		26506	24900
69	29-Apr	34646	25984	37008	27559	11024	18898

Date		COD (mg/l)					
		TS Inf.	TS Eff.	MS Eff.	TSL Inf.	TSL Eff.	MSL Eff.
71	1-May		13600	24800		16800	15200
74	4-May	24268	20921	22594	18410	18410	17573
76	6-May		11715	13389		10042	8368
78	8-May		11715	24268		18410	30962
81	11-May	22400	14400	18400	16000	4000	3200
83	13-May		16000	19200		4000	12000
85	15-May		25000	4032		19355	9677
88	18-May		17742	20161		23387	12903
90	20-May	15323	11290	11290	4032	1613	806
92	22-May		13873	13873		2312	7707
95	25-May		15323	12903		4032	2419

Table B-9 TSS of each TPAD system

Date		TSS (mg/l)			
		TS	MS	TSL	MSL
46	6-Apr	32560	22120	27260	21280
78	8-May	34360	23940	29040	23260

Table B-10 VSS of each TPAD system

Date		VSS (mg/l)			
		TS	MS	TSL	MSL
46	6-Apr	20460	15520	19320	14440
78	8-May	23900	17820	21700	30962

Table B-11 VSS/TSS each TPAD system

Date		VSS/TSS			
		TS	MS	TSL	MSL
46	6-Apr	0.63	0.70	0.71	0.69
78	8-May	0.70	0.74	0.75	0.70

Table B-12 F/M of each TPAD system

Date		F/M ratio (gCOD/gVSS-d)			
		TS	MS	TSL	MSL
46	6-Apr	0.24	0.10	0.24	0.10
78	8-May	0.16	0.09	0.16	0.09

Table B-13 Biogas results of each TPAD system

Date		Biogas volume (l/d)			
		TS	MS	TSL	MSL
1	20-Feb	0.00	0.57	2.74	0.00
2	21-Feb	0.60	0.07	6.55	0.09
3	22-Feb	0.60	0.15	8.16	0.08
4	23-Feb	0.32	0.17	5.90	0.06
5	24-Feb	0.38	0.18	3.52	0.08
6	25-Feb	0.41	0.21	4.43	0.07
7	26-Feb	0.53	0.17	4.26	0.07
8	27-Feb	0.49	0.08	4.33	0.08
9	28-Feb	0.00	0.00	0.00	0.00
10	1-Mar	1.09	0.11	5.67	0.12
11	2-Mar	0.52	0.08	0.87	0.05
12	3-Mar	0.41	0.07	0.62	0.05
13	4-Mar	0.36	0.06	0.70	0.05
14	5-Mar	0.36	0.04	0.54	0.02
15	6-Mar	0.33	0.06	0.62	0.03
16	7-Mar	0.32	0.03	1.03	0.03
17	8-Mar	0.31	0.04	0.79	0.02
18	9-Mar	0.34	0.00	0.86	0.03
19	10-Mar	0.36	0.00	0.92	0.03
20	11-Mar	0.38	0.00	0.76	0.03
21	12-Mar	0.40	0.02	0.95	0.02
22	13-Mar	0.33	0.02	0.94	0.01
23	14-Mar	0.34	0.02	0.78	0.01
24	15-Mar	0.31	0.04	0.86	0.01
25	16-Mar	0.40	0.03	1.08	0.01

Date		Biogas volume (l/d)			
		TS	MS	TSL	MSL
26	17-Mar	0.43	0.05	1.11	0.03
27	18-Mar	0.44	0.05	1.08	0.01
28	19-Mar	0.42	0.02	0.98	0.03
29	20-Mar	0.36	0.04	1.15	0.00
30	21-Mar	0.41	0.05	1.47	0.55
31	22-Mar	0.34	0.02	1.36	0.17
32	23-Mar	0.39	0.05	1.22	0.06
33	24-Mar	0.63	0.03	1.23	0.04
34	25-Mar	0.44	0.03	1.43	0.03
35	26-Mar	0.49	0.01	1.16	0.00
36	27-Mar	0.42	0.04	1.16	0.02
37	28-Mar	0.46	0.04	1.34	0.04
38	29-Mar	0.43	0.02	1.35	0.02
39	30-Mar	0.34	0.02	1.45	0.00
40	31-Mar	0.33	0.01	1.23	0.02
41	1-Apr	0.44	0.06	1.16	0.03
42	2-Apr	0.19	0.04	1.14	0.00
43	3-Apr	0.32	0.03	1.17	0.02
44	4-Apr	0.15	0.04	1.13	0.02
45	5-Apr	0.21	0.01	1.02	0.00
46	6-Apr	0.23	0.04	1.31	0.07
47	7-Apr	0.38	0.00	1.76	0.00
48	8-Apr	0.22	0.08	1.86	0.00
49	9-Apr	0.24	0.01	1.69	0.03
50	10-Apr	0.20	0.02	2.00	0.02
51	11-Apr	0.18	0.01	1.69	0.01
52	12-Apr	0.17	0.02	2.02	0.03
53	13-Apr	0.13	0.01	1.71	0.02
54	14-Apr	0.17	0.01	1.66	0.01
55	15-Apr	0.17	0.01	1.66	0.00
56	16-Apr	0.13	0.01	1.56	0.02
57	17-Apr	0.14	0.01	1.87	0.03

Date		Biogas volume (l/d)			
		TS	MS	TSL	MSL
58	18-Apr	0.21	0.01	1.66	0.03
59	19-Apr	0.18	0.01	1.80	0.00
60	20-Apr	0.00	0.01	1.59	0.06
61	21-Apr	0.28	0.00	1.57	0.00
62	22-Apr	0.26	0.01	1.44	0.03
63	23-Apr	0.16	0.00	1.27	0.08
64	24-Apr	0.05	0.05	3.08	0.04
65	25-Apr	0.02	0.02	3.00	0.00
66	26-Apr	0.05	0.00	1.75	0.05
67	27-Apr	0.09	0.00	1.78	0.08
68	28-Apr	0.02	0.11	1.41	0.01
69	29-Apr	0.16	0.01	2.30	0.11
70	30-Apr	0.04	0.01	5.28	0.22
71	1-May	0.09	0.03	3.71	0.25
72	2-May	0.15	0.11	3.12	0.25
73	3-May	0.11	0.12	2.91	0.25
74	4-May	0.03	0.07	2.61	0.19
75	5-May	0.08	0.06	2.33	0.16
76	6-May	0.01	0.11	2.39	0.24
77	7-May	0.15	0.02	3.43	0.07
78	8-May	0.11	0.06	2.64	0.08
79	9-May	0.16	0.13	4.12	0.18
80	10-May	0.17	0.11	4.58	0.16
81	11-May	0.17	0.09	4.31	0.07
82	12-May	0.19	0.06	2.41	0.13
83	13-May	0.13	0.01	1.68	0.00
84	14-May	0.28	0.03	1.42	0.02
85	15-May	0.27	0.04	1.90	0.05
86	16-May	0.49	0.02	1.67	0.08
87	17-May	0.78	0.05	1.13	0.01
88	18-May	0.62	0.03	0.96	0.00
89	19-May	0.95	0.00	0.65	0.00

Date		Biogas volume (l/d)			
		TS	MS	TSL	MSL
90	20-May	0.26	0.00	1.04	0.00
91	21-May	0.13	0.00	0.73	0.00
92	22-May	0.33	0.00	0.52	0.00
93	23-May	0.24	0.00	1.11	0.00
94	24-May	0.15	0.00	0.85	0.00
95	25-May	0.21	0.01	0.19	0.00

Table B-14 Gas composition results of each TPAD systems

Date		TS			MS		
		CH_4	CO_2	O_2	CH_4	CO_2	O_2
3	22-Feb	65.4	25	1.6			
10	1-Mar	62.4	28.7	1.7	62.6	13.7	7.4
18	9-Mar	56.8	28.1	2.1			
25	16-Mar	56.8	28.1	2.1	45.2	13.7	7.4
32	23-Mar	60.3	27.8	1.6			
53	13-Apr	60.8	23.3	2.6			
60	20-Apr	60.7	22.8	1.5			
67	27-Apr				44.4	10.4	5.5
74	4-May	59.8	13.5	3.3	23	7.6	5.3
81	11-May	19.4	10.2	10.6			
88	18-May	30.6	13.9	5	15.6	6.7	5.2
94	24-May	56.9	20	3.1	40.2	12	4.2
Date		TSL			MSL		
		CH_4	CO_2	O_2	CH_4	CO_2	O_2
3	22-Feb	57.1	38.4	0.2	57.7	20.6	2.4
10	1-Mar	55.9	34.3	1.3			
25	16-Mar	59.1	32.5	0.9			
32	23-Mar	61.8	30.5	0.6	56.4	11.5	5.3
53	13-Apr	57.7	36	0.1			
60	20-Apr	56.6	33.2	0.7	44.7	10.5	7.2
67	27-Apr	59.9	28.6	0.9			
74	4-May	59.9	28.6	0.9	25.9	12.2	5.6
88	18-May	39.3	23.1	4.8	3.9	6.5	8.7
94	24-May	44.9	43.9	1.1			

Table B-15 CH_4 yield results of each TPAD system

Date		CH_4 yield ($mlCH_4/gVS_{added}$)			
		TS	MS	TSL	MSL
1	20-Feb	0.0	0.0	89.4	0.0
2	21-Feb	15.9	9.9	213.3	23.7
3	22-Feb	15.9	21.3	265.7	21.7
4	23-Feb	8.6	23.1	192.2	16.4
5	24-Feb	10.2	25.4	114.5	21.0
6	25-Feb	11.0	29.2	144.3	20.3
7	26-Feb	14.1	23.3	138.9	19.5
8	27-Feb	11.4	11.7	520.9	22.0
9	28-Feb	0.0	0.0	0.0	0.0
10	1-Mar	25.2	15.0	681.6	33.7
11	2-Mar	12.0	10.5	105.1	13.7
12	3-Mar	9.6	9.5	74.4	13.7
13	4-Mar	8.4	8.0	83.9	14.6
14	5-Mar	7.9	5.9	63.8	5.5
15	6-Mar	3.6	4.0	36.5	4.7
16	7-Mar	3.6	2.0	60.4	4.6
17	8-Mar	3.4	2.8	46.2	2.7
18	9-Mar	4.4	0.2	8.2	4.6
19	10-Mar	4.6	0.0	8.9	3.8
20	11-Mar	4.9	0.0	7.3	3.8
21	12-Mar	5.2	1.0	9.1	3.2
22	13-Mar	4.1	1.2	13.2	1.2
23	14-Mar	4.2	1.4	10.9	1.2
24	15-Mar	3.9	2.7	12.1	1.5
25	16-Mar	4.9	1.8	15.1	1.7
26	17-Mar	5.3	3.3	15.6	3.8
27	18-Mar	5.4	3.4	15.2	1.2
28	19-Mar	3.5	1.1	9.1	2.5
29	20-Mar	4.5	1.9	15.5	0.0
30	21-Mar	5.2	2.1	19.9	50.3

Date		CH_4 yield ($mlCH_4/gVS_{added}$)			
		TS	MS	TSL	MSL
31	22-Mar	4.4	1.0	18.4	15.2
32	23-Mar	5.0	2.2	16.5	5.9
33	24-Mar	8.0	1.5	16.7	3.6
34	25-Mar	5.6	1.3	19.3	2.5
35	26-Mar	6.2	0.5	15.7	0.0
36	27-Mar	12.9	1.8	26.2	1.5
37	28-Mar	14.0	1.9	30.3	3.6
38	29-Mar	13.2	0.7	30.4	1.5
39	30-Mar	10.6	0.8	32.8	0.0
40	31-Mar	10.1	0.6	27.8	1.7
41	1-Apr	13.4	2.8	26.2	3.0
42	2-Apr	5.8	1.7	25.8	0.0
43	3-Apr	9.9	1.0	24.6	2.1
44	4-Apr	4.6	1.2	23.8	1.7
45	5-Apr	6.4	0.2	21.6	0.0
46	6-Apr	2.6	1.3	14.1	6.1
47	7-Apr	4.4	0.0	19.0	0.0
48	8-Apr	2.6	2.8	20.0	0.0
49	9-Apr	2.7	0.5	18.2	2.4
50	10-Apr	2.3	0.6	21.6	1.6
51	11-Apr	2.1	0.4	18.2	1.3
52	12-Apr	1.9	0.6	21.8	2.5
53	13-Apr	1.4	0.3	19.8	1.7
54	14-Apr	1.9	0.2	19.3	1.2
55	15-Apr	1.9	0.3	19.2	0.0
56	16-Apr	1.4	0.3	18.1	1.4
57	17-Apr	1.5	0.3	21.7	1.9
58	18-Apr	2.3	0.4	19.3	2.2
59	19-Apr	2.0	0.5	20.9	0.0
60	20-Apr	0.0	0.4	18.5	4.0
61	21-Apr	3.1	0.0	18.2	0.0
62	22-Apr	2.9	0.3	16.7	2.5

Date		CH_4 yield ($mlCH_4/gVS_{added}$)			
		TS	MS	TSL	MSL
63	23-Apr	1.8	0.0	14.8	5.8
64	24-Apr	0.5	1.5	37.1	1.5
65	25-Apr	0.2	0.6	36.1	0.0
66	26-Apr	0.6	0.1	21.1	2.0
67	27-Apr	0.4	0.0	7.1	0.4
68	28-Apr	0.1	0.9	5.6	0.1
69	29-Apr	0.7	0.1	9.2	0.6
70	30-Apr	0.2	0.1	21.1	1.1
71	1-May	0.4	0.1	14.8	1.3
72	2-May	0.6	0.5	12.5	1.3
73	3-May	0.4	0.5	11.6	1.3
74	4-May	0.1	0.3	10.4	1.0
75	5-May	0.3	0.3	9.3	0.8
76	6-May	0.1	0.5	9.5	1.2
77	7-May	0.6	0.1	13.7	0.3
78	8-May	0.1	0.2	10.5	0.1
79	9-May	0.2	0.4	16.5	0.1
80	10-May	0.2	0.3	18.3	0.1
81	11-May	0.2	0.3	17.2	0.1
82	12-May	0.2	0.2	9.6	0.1
83	13-May	0.2	0.0	6.7	0.0
84	14-May	0.4	0.1	5.7	0.0
85	15-May	0.5	0.1	7.6	0.0
86	16-May	1.0	0.1	6.7	0.1
87	17-May	1.6	0.1	4.5	0.0
88	18-May	1.3	0.1	3.9	0.0
89	19-May	1.9	0.0	2.6	0.0
90	20-May	0.5	0.0	2.7	0.0
91	21-May	0.3	0.0	1.9	0.0
92	22-May	1.3	0.0	1.5	0.0
93	23-May	0.9	0.0	3.3	0.0
94	24-May	0.6	0.0	2.5	0.0

Date		CH_4 yield ($mlCH_4/gVS_{added}$)			
		TS	MS	TSL	MSL
95	25-May	0.8	0.0	0.6	0.0

Table B-16 Total coliform results from influent and effluent of each TPAD system

Date		Total coliform (MPN/100ml)					
		TS Inf.	TS Eff.	MS Eff.	TSL Inf.	TSL Eff.	MSL Eff.
1	1-Mar	2300000000	490	92000	790000	790	35000
2	12-Mar	160000000	1700	24000	330000	1800	13000
3	20-Mar	200000	20	23000000	130000	18	790000
4	3-Apr	4000	120	17000	17000	7524	160000
5	22-Apr	230	18	130	2200	18	22000
6	29-Apr	200	68	55	13000	3200	45
7	11-May	230	18	18	17000	20	20
8	22-May	2100	370	450	23000	18	450

Table B-17 Fecal coliform results from influent and effluent of each TPAD system

Date		Fecal coliform (MPN/100ml)					
		TS Inf.	TS Eff.	MS Eff.	TSL Inf.	TSL Eff.	MSL Eff.
1	1-Mar	63000000	490	92000	790000	490	35000
2	12-Mar	17000000	780	4900	330000	18	450
3	20-Mar	200000	18	24000	130000	18	490000
4	3-Apr	1800	18	45	2000	18	3200
5	22-Apr	230	18	18	330	18	165
6	29-Apr	200	45	37	1300	170	20
7	11-May	78	18	18	1700	20	18
8	22-May	400	18	18	3800	18	61

Table B-18 E.coli results from influent and effluent of each TPAD system

Date		E.coli (MPN/100ml)					
		TS Inf.	TS Eff.	MS Eff.	TSL Inf.	TSL Eff.	MSL Eff.
1	1-Mar	17000000	490	180	79000	18	180
2	12-Mar	17000000	780	3300	23000	18	450

Date		E.coli (MPN/100ml)					
		TS Inf.	TS Eff.	MS Eff.	TSL Inf.	TSL Eff.	MSL Eff.
3	20-Mar	17000	18	230	4500	18	23000
4	3-Apr	1800	18	18	2000	18	1700
5	22-Apr	230	18	18	170	18	68
6	29-Apr	200	20	18	1100	20	20
7	11-May	45	18	18	1700	18	18
8	22-May	200	18	18	2200	18	21

VITA

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