

**KINETIC STUDY OF TWO-PHASE MESOPHILIC ANAEROBIC
DIGESTION OF ORGANIC FRACTION MUNICIPAL SOLID
WASTE BY USING CHEN-HASHIMOTO METHANE
PRODUCTION MODEL**

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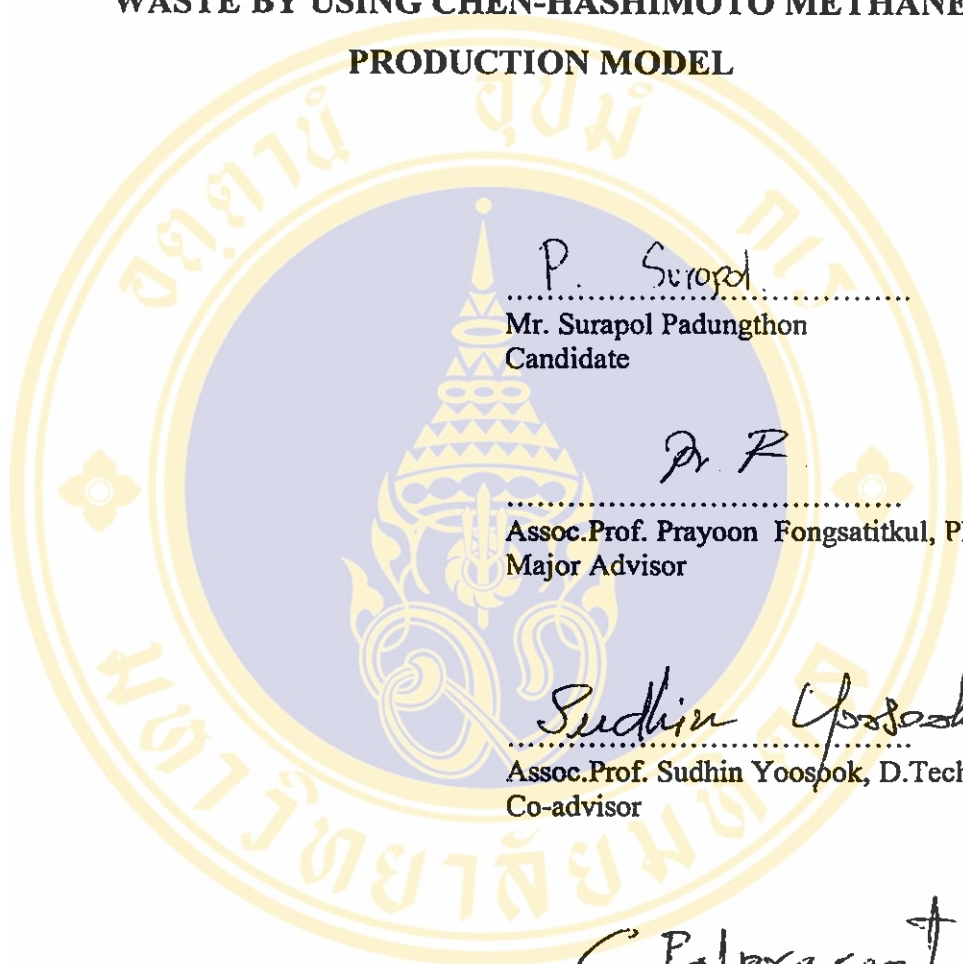
SURAPOL PADUNGTHON

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OF THE REQUIREMENTS FOR
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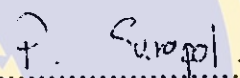
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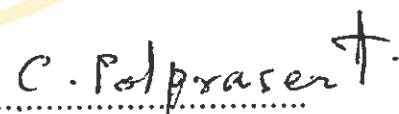
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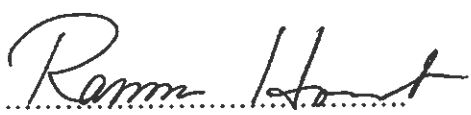

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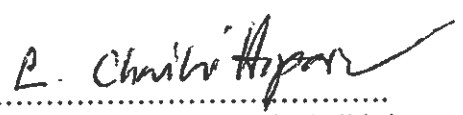

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Surapol Padungthon

March, 2005

KINETIC STUDY OF TWO-PHASE MESOPHILIC ANAEROBIC DIGESTION OF ORGANIC FRACTION MUNICIPAL SOLID WASTE BY USING CHEN-HASHIMOTO METHANE PRODUCTION MODEL

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ABSTRACT

The objective of this research was to carry out a kinetic evaluation of the two-phase mesophilic anaerobic digestion of organic fraction municipal solid waste (OFMSW). Two main parts of the experimental runs were designated. System performance operating was done under three different feed substrate concentrations: 8, 12, and 15 %TS. The hydraulic retention time (HRT) varied between 18 to 33 days (including 3 days in acidogenic reactors), and results were evaluated using the Chen-Hashimoto methane production model to determine the kinetic constants, a dimensionless kinetic parameter (K) and maximum specific microbial growth rate ($\mu_{\max}$) of the process. Furthermore, prediction of minimum retention time ($\theta_{\min}$) and maximum volumetric methane production rate ($\delta_{\max}$) and demonstration of anaerobic digestion design based on kinetic parameters of waste using in these experiments were carried out.

Base on the experimental results, total solid removal, volatile solid removal and methane yields were in the ranges of 59.5-77.8%, 72-89.4% and 0.15-0.48 l.CH₄STP/gVS_{added}, respectively. From the statistical analysis, total solid, volatile solid removal efficiency and methane yield at HRTs of 30 days were significantly higher than those at 25, 20 and 15 days ($p < 0.05$). The total solid, volatile solid removal efficiency and methane yield at removal efficiency at total solids concentration of 80,000 mg/l were significantly higher than those at 120,000 and 150,000 mg/l ($p < 0.05$).

Results were then evaluated by using the Chen-Hashimoto methane production model to determine the kinetic constants of the process. The kinetic constants as being fed with total solid concentrations of about 8, 12 and 15 %; $\mu_{\max}$ values were 0.095, 0.084 and 0.078 per day and K values were 0.867, 0.846 and 0.814, respectively. Finally the minimum hydraulic retention time, $\theta_{\min}$ (day), at which the wash out of the micro-organisms occurred, were 10.9, 11.9 and 12.8 days, and maximum volumetric methane production rate was found to be 1.14, 1.50 and 1.62 l CH₄STP/l_{reactor}·day for substrate concentrations of about 8, 12 and 15 %TS, respectively.

The optimum running condition was found at the HRTs of 30 days and the total solids concentration of 80,000 mg/l (8%) with total solid removal, volatile solid removal and methane yields of 77.1%, 88.5 % and 0.45 l.CH₄STP/ gVS_{added}, respectively.

KEY WORDS: ANAEROBIC DIGESTION / CHEN-HASHIMOTO MODEL /
/ SOLID WASTE MANAGEMENT / TWO-PHASE MESOPHILIC
ORGANIC FRACTION MUNICIPAL SOLID WASTE

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การศึกษาทางจลศาสตร์ของระบบหมักไร้อากาศ แบบสองขั้นตอน ภายใต้อุณหภูมิปานกลาง โดยใช้ส่วนที่เป็นสารอินทรีย์ที่ได้จากขยะชุมชน โดยใช้แบบจำลองการเกิดก๊าซมีเทนของ เซน-ฮาชิโมโตะ (A KINETIC STUDY OF TWO-PHASE MESOPHILIC ANAEROBIC DIGESTION OF ORGANIC FRACTION MUNICIPAL SOLID WASTE BY USING CHEN-HASHIMOTO METHANE PRODUCTION MODEL)

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บทคัดย่อ

งานวิจัยนี้มีวัตถุประสงค์เพื่อที่จะประเมินค่าทางจลศาสตร์ ของระบบหมักไร้อากาศ แบบสองขั้นตอน ภายใต้อุณหภูมิ ปานกลาง โดยใช้ส่วนที่เป็นสารอินทรีย์ที่ได้จากขยะชุมชน การทดลองนี้แบ่งเป็น 2 ส่วน โดยส่วนที่หนึ่ง เป็นการศึกษาถึงสมรรถนะของระบบภายใต้การทดลองโดยใช้ความเข้มข้นของสารอินทรีย์ที่เข้าระบบแตกต่างกันคือ 8, 12 และ 15 เปอร์เซ็นต์ และช่วงระยะเวลาเก็บกักที่ 18 ถึง 33 วัน ซึ่งรวมถึงระยะเวลาเก็บกักในถังหมักกรดด้วย 3 วัน และในส่วนที่ 2 นั้นเป็นการหาค่าคงที่ทางจลศาสตร์ (K and μ_{max})

จากผลการทดลองพบว่า ค่าประสิทธิภาพในการกำจัดของแข็งทั้งหมด, ของแข็งระเหย และ ค่าปริมาณการเกิดก๊าซมีเทน อยู่ในช่วง 59.5 - 77.8 เปอร์เซ็นต์, 72.0 - 89.4 เปอร์เซ็นต์ และ 0.15 - 0.48 l CH₄STP/gVSadded ตามลำดับ จากการวิเคราะห์ค่าทางสถิติ พบว่า การกำจัดของแข็งทั้งหมด, ของแข็งระเหย และปริมาณการเกิดก๊าซมีเทน ที่ระยะเวลากักเก็บ 30 วันมีค่าเฉลี่ยสูงกว่าระยะเวลากักเก็บ 25, 20 และ 15 วัน อย่างมีนัยสำคัญทางสถิติ ($p < 0.05$) และ สมรรถนะของระบบในรูปของ การกำจัดของแข็งทั้งหมด, ของแข็งระเหย และปริมาณการเกิดก๊าซมีเทน ที่ความเข้มข้น ของสารอินทรีย์ที่เข้าระบบ 8 เปอร์เซ็นต์ มีค่าเฉลี่ยสูงกว่าความเข้มข้น ของสารอินทรีย์ที่เข้าระบบ 12 และ 15 เปอร์เซ็นต์อย่างมีนัยสำคัญทางสถิติ ($p < 0.05$)

จากการประเมินค่าคงที่ทางจลศาสตร์พบว่า ค่าคงที่ทางจลศาสตร์ μ_{max} มีค่า 0.095, 0.084 และ 0.078 ต่อวัน ส่วนค่า K มีค่า 0.867, 0.846 และ 0.814 เมื่อทำการทดลองโดยใช้ความเข้มข้นของสารอินทรีย์เข้าระบบ 8, 12 และ 15 ตามลำดับ จากนั้นเมื่อนำค่าที่ได้มาใช้ในการทำนายระยะเวลากักเก็บต่ำสุดจะได้ค่าเท่ากับ 10.9, 11.9 และ 12.8 วัน และอัตราการผลิตก๊าซมีเทนสูงสุด เท่ากับ 1.14, 1.50 และ 1.62 l CH₄STP /l_{reactor}.day เมื่อทำการทดลองโดยใช้ความเข้มข้นของสารอินทรีย์เข้าระบบ 8, 12 และ 15 ตามลำดับ

สภาวะของการเดินระบบที่เหมาะสม คือระยะเวลาเก็บกักที่ 30 วัน และความเข้มข้นของของแข็งเข้าระบบอยู่ที่ 8 % ซึ่งจะช่วยให้ ค่าประสิทธิภาพในการกำจัดของแข็งทั้งหมด, ของแข็งระเหย และ ค่าปริมาณการเกิดก๊าซมีเทน เท่ากับ 77.1 เปอร์เซ็นต์, 88.5 เปอร์เซ็นต์ และ 0.45 l CH₄STP /gVSadded ตามลำดับ

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CHAPTER I

INTRODUCTION

1.1 Rationales and Justifications

The depletion of non-renewable energy sources leads to the need to search for other renewable resources available at local conditions. There exist many renewable sources, such as sunlight, wind and biomass, while agricultural wastes represent an important source of bioenergy. The anaerobic digestion process is one of the technologies used to produce energy as well as to reduce the organic content of waste. The climate problems due to the greenhouse effect, the recognized need for sustainable development and problems due to the ozone layer depletion have all contributed to the recognition of the value of anaerobic digestion as a technique to produce renewable energy (1)(2).

Waste biomass includes forestry wastes, agricultural residues, sewage sludge, industrial organic residues and municipal solid waste (MSW). Such wastes present a growing threat to the health of the environment and represent a substantial source of Greenhouse Gas (GHG) emissions (3). The interest in alternative municipal solid waste (MSW) management strategies will likely intensify because the production of MSW continues to grow, while the disposal capacity via traditional landfilling and incineration is diminishing. Recovery through recycling and composting already has increased substantially since the late 1980s and is expected to divert 30 to 40% of MSW streams in 2010 (4)(5).

12345678An alternative MSW treatment strategy is anaerobic biological treatment, either in anaerobic digesters or in landfill bioreactors (6). Anaerobic biological treatment can be an acceptable alternative to current disposal strategies because it reduces the volume of MSW, stabilizes MSW, produces a residue that can be used for soil conditioning, and recovers energy from MSW in the form of methane (7).

Anaerobic sludge digestion is one of the most difficult and expensive processes in wastewater engineering. The cost of sludge management comprises

approximately 35% of the capital cost and 55% of annual operation and maintenance costs of a wastewater treatment plant. Sludge quantities continue to increase, but the options for sludge disposal are limited due to the more stringent regulations enacted to protect the environment (8).

Anaerobic digestion emerges as another alternative for treating the organic fraction of solid wastes. Anaerobic microbial processes occur in environments that are devoid of oxygen including the bottom of lakes, in swamps and in landfills. Anaerobic processes are recreated at the industrial scale by controlling parameters such as temperature, humidity, microbial activity and the waste used as feedstock. Anaerobic processes can convert the organic biodegradable fraction of the municipal solid waste (OFMSW) into a high methane content biogas and a stable residue that can be upgraded to compost quality. Anaerobic digestion does not release green house gases (GHG) to the atmosphere, but captures them for energy generation purposes. Another aspect that can be enhanced is that the use of biogas as an energy source helps to offset the GHG emission associated with energy production using fossil fuels (9).

By isolating the two key phases in two separate reactors, a two-phase anaerobic digestion system was used to avert the imbalance between processes of acidogenesis and methanogenesis. Lissens et al, 1998 compared the most common types of anaerobic digesters for solid wastes. They concluded that batch systems had the simplest design and are the least expensive solid waste digesters. Two-stage systems are more complex and more expensive systems; but these systems are more stable and improve process stability due to the better working conditions of acidogenic and methanogenic bacteria and it reduces significantly any risk of digester overloading (10).

In order to be able to design and operate anaerobic digestion systems appropriately, mathematical models need to be developed. Since Thailand is quite different from Europe countries, in terms of waste compositions, climate or temperature/ humidity, lifestyle, etc., an evaluated strategy for anaerobic digestion under mesophilic conditions using the organic fraction of municipal solid waste (OFMSW) should be made. Several observations presented in this study are linked to microbial population dynamics using results obtained and then evaluated using the

Chen-Hashimoto methane production model to determine the kinetic constants: a dimensionless kinetic parameter (K) and maximum specific microbial growth rate ($\mu_{\max}$) of the process (11) and using of two kinetic parameters to predict the minimum hydraulic retention time ($\theta_{\min}$) and the maximum volumetric methane production rate ($\delta_{\max}$).

1.2 Research Objectives

1.2.1 General objective

To carry out a kinetic evaluation of the two phases mesophilic anaerobic digestion of organic fraction municipal solid waste (OFMSW) from the integrated waste management center, Chonburi.

1.2.2 Specific objectives

- 1) To investigate the values of a dimensionless kinetic parameter (K) for the three substrate concentrations used an influent.
- 2) To investigate the values of the maximum specific microbial growth rate ($\mu_{\max}$) for the three substrate concentrations used an influent.
- 3) To predict the minimum hydraulic retention time ($\theta_{\min}$) and the maximum volumetric methane production rate ($\delta_{\max}$).
- 4) To set design criteria for treatment of organic fraction of municipal solid waste by using of two-phase mesophilic anaerobic digestion based on kinetic parameters.

1.3 Research Hypotheses

The hypotheses of the study include:

1.3.1 Kinetic parameter, a dimensionless kinetic parameter (K) decreases with the increasing influent substrate concentrations (%TS).

1.3.2 Kinetic parameter, the maximum specific microbial growth rate ($\mu_{\max}$) decreases with the increasing influent substrate concentrations (%TS).

1.4 Research Variables

1.4.1 Independent variables

- 1) Hydraulic Retention Time in methanogenic reactors (days)
- 2) Total solids concentration of feed substrate (%TS)

1.4.2 Dependent variables

- 1) Total solid removal efficiency (%TS removal)
- 2) Volatile solid removal efficiency (%VS removal)
- 3) Methane yields (l CH₄ STP/g.VS added.)

1.4.3 Control variables

- 1) Hydraulic retention time of acidogenic reactors (3 day) (12)
- 2) Substrate (OFMSW) from Chonburi plant.
- 3) Completely mixed condition (CSTR type)
- 4) Quasi-continuous mode (feed once per day)
- 5) pH in methane reactors (6.8-7.8)

1.5 Scope of Study

This research was an experimental research involving an operation of 3 similar lab-scale anaerobic digestion systems made from stainless steel. The scopes of this research include the followings:

1.5.1 Organic fraction of municipal solid waste (OFMSW) was obtained from the integrated waste management center located in Chonburi.

1.5.2. The raw OFMSW was mixed with tap water within mixing device for desired total solid concentration (% TS) and stored in laboratory cold room at 4 °c before fed to the experimental system.

1.5.3. The reactors used in this study were a completely stirred type reactor CSTR type and feed substrate in once a day (Quasi-continuous mode).

1.5.4. Methanogenic reactors were controlled temperature in mesophilic range 35 °c whereas acidogenic reactors were operated temperature in ambient temperature.

1.6 Conditions and Limitations of the Study

1.6.1. The OFMSW obtained by grabs sampling at a specific time. The raw substrate was taken using plastic containers and carried back to the Laboratory Section of Sanitary Engineering Department, Faculty of Public Health, Mahidol University for further usage in the experiment.

1.6.2. Acidogenic reactors were carried out under the natural conditions at the unit operation room of seventh building the fourth floor, Faculty of Public Health, Mahidol University. The natural conditions were recorded at temperature of 27 ± 3.0 °C .And methane reactors were carried out under mesophilic range (35 ± 1 °C) with insulation outside the reactors.

1.6.3. Overall anaerobic digestion systems were operated at anaerobic condition by being sealed with o-ring at the upper part of reactors and fed once a day (Quasi continuous).

1.6.4. Biogas generated from anaerobic digestion was measured by water displacement method.

1.6.5. The cost of VFA analysis using gas chromatography method is expensive, thus we then have to analyze the VFA by a simple titration procedure according to Buchauer (13).

1.6.6. The cost analysis of methane content in biogas using gas chromatography method is expensive, thus we then have to estimate the methane content during steady state is 60% CH₄ in Biogas (14).

1.7 Definition of Keywords

1.7.1 OFMSW: Organic fraction of municipal solid waste from integrated waste management center Chonburi province.

1.7.2. Anaerobic digestion: The process used for the stabilization of OFMSW .It involves the decomposition of organic and inorganic matter in absence of molecular oxygen.

1.7.3. Mesophilic condition: Temperature in anaerobic digestion bioreactor especially in methane reactors. The operational temperature is kept within mesophilic range 35 ± 1 °C.

1.7.4. Two phase anaerobic digestion: Anaerobic digestion is composing of 2 difference growth of microorganism so for effectiveness of process to separate acid phase and methanogenic phase in difference reactors.

1.7.5. MPR (Methane production rate): The MPR is the total volume of liter CH_4 @STP produced per liter reactor volume per day.

1.7.6. Methane yield (B): The methane yield is the liter of CH_4 @STP produced per grams of volatile solid added to the digesters.

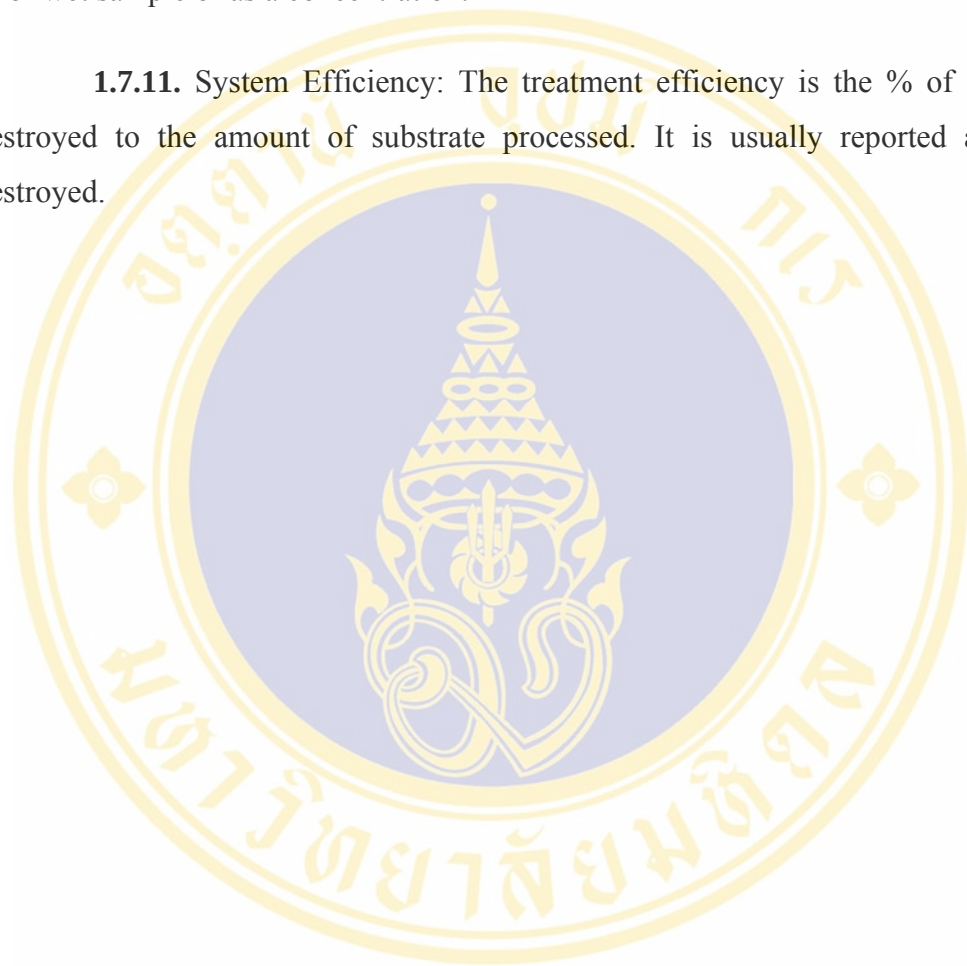
1.7.7. VFA: The productions of the acidogenic anaerobic digestion are mainly short-chain fatty acids with two to five carbon atoms. The volatile fatty acids including acetic, propionic, butyric acid etc.

1.7.8. BPR (Biogas production rate): Biogas production rate is the total volume of liter biogas @ STP produced per liter reactor volume per day.

1.7.9. HRT (Hydraulic retention time): The HRT is a measure of the average amount of time which an ideal soluble compound would remain in the reactor and is calculated by dividing the liquid volume by the average feed volume flow rate and is normally presented in either days or hours.

1.7.10. VS (Volatile solids): VS is a measure of the organic fraction of a sample which can be burned at 550 °C. And is found by removing the weight of the organic fraction from the weight of dry sample. VS may be reported as a % of TS or a % of wet sample or as a concentration.

1.7.11. System Efficiency: The treatment efficiency is the % of substrate destroyed to the amount of substrate processed. It is usually reported a % VS destroyed.



1.8 Conceptual framework

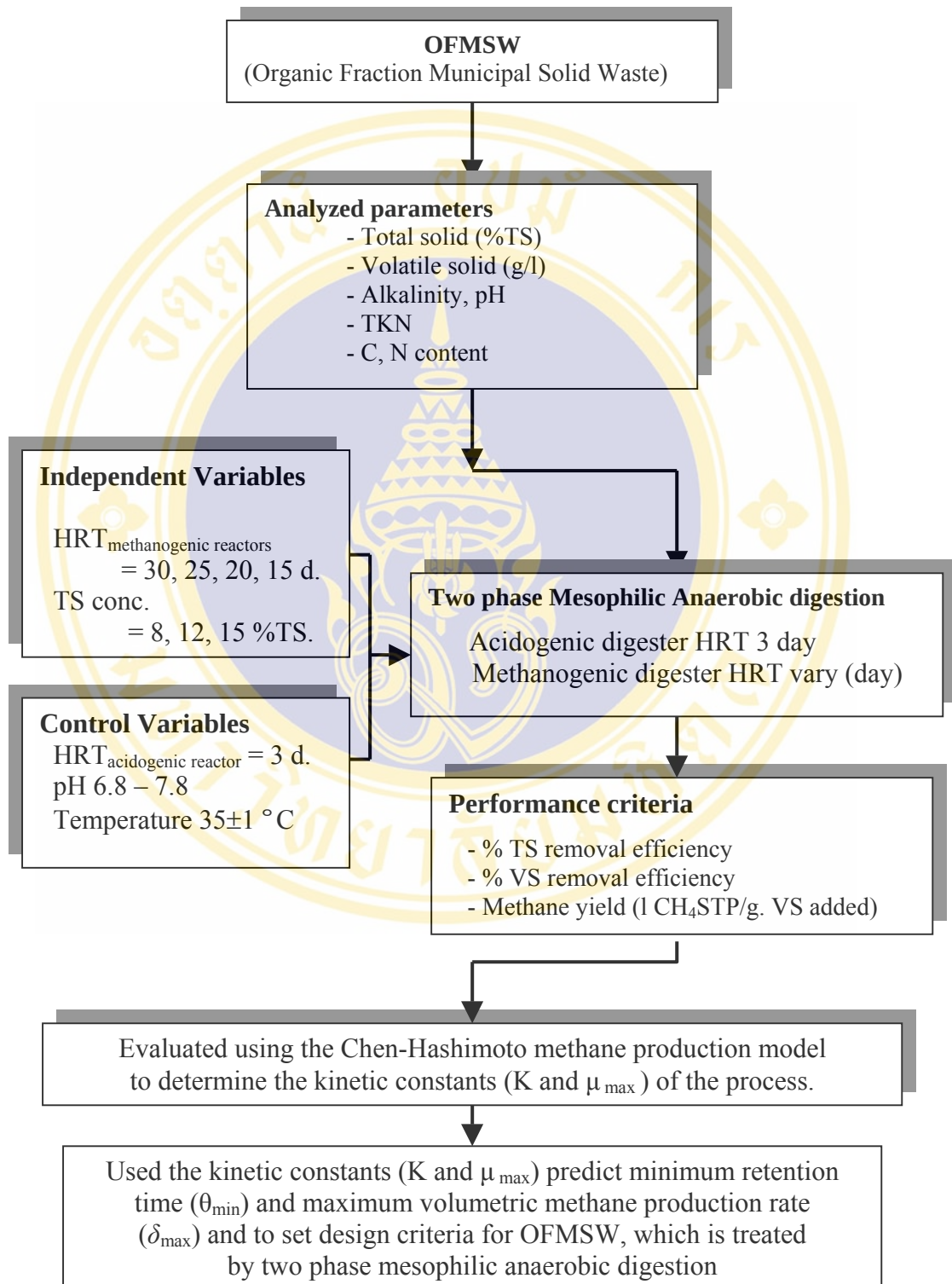


Figure 1.1 Conceptual frameworks.

CHAPTER II

LITERATURE REVIEWS

2.1 Introduction

In the last decade of the 20th century, the use of Anaerobic Digestion (AD) technology for the processing of organic wastes has expanded appreciably. Between 1996 and 2000, the number of new AD plants increased from 2 to 7 plants per year. Europe is far ahead in AD technology and Germany and Denmark, are leading in the use of AD technology.

AD technology has seen a remarkable progress in reactor and process design. Earlier, long periods of time were required for a completed degradation. Mesophilic temperatures (about 35°C) would require up to 20-25 days for digestion.

2.2 History of Anaerobic Digestion (15) (16)

In late 70's, most of the AD plants were designed to treat sewage and were predominantly low-solids operations. However, during the last decade the number of high solids processes has increased appreciably to include organic MSW treatment. If one of the goals of new plants is energy generation, then high solids are more promising. The DRANCO and Valorga companies' case studies are representatives of good strategies for obtaining revenues by supplying energy to nearby operations and by creating a market for compost. For example, the Tilburg plant (40,000tons/year MSW capacity) has an estimated annual income of \$1.16 million. The advantage offered by HS (High Solid) includes higher methane production (Valorga, 220-250 m³/ton of feed) as compared with LS operations (Waasa, 100-150 m³/ton of feed). In addition, the reported organic loading rate for HS (DRANCO, 15 kg VS per m³ per day) is about twice that of LS (Waasa, 6 kg VS/ m³.d).

The possibility of digesting the organic fraction of municipal solid waste (OFMSW) has only been studied in the last 10 to 15 years, (13) in spite of pioneering work by Barbit. More recent studies include these of Golueke and Pfeffer and

Liebmann who demonstrated the advantages of mixing municipal solid waste with sewage sludge, while Klass studied the efficiency of the process and the effect of temperature was investigated by Pfeffer. Cooney and Wise made a comprehensive study of factors affecting gas production, while Kispert et al. developed a detailed engineering analysis of fuel gas production from solid waste. The anaerobic digestion of the organic fraction of MSW and sewage sludge mixed at different ratios was carried out by Diaz et al.

More recently, Buivid *et al.* examined several ways of enhancing gas production in controlled landfill test cells, by manipulation of environmental parameters. Methane production was significantly increased with a conversion of over 50% of the biodegradable MSW to methane. The effect of water, buffer and sludge addition on the enhancement of gas production was also studied by Emcon Associates. They suggested that an increase in moisture content coupled with buffering to a pH of around 7 and the addition of nutrients and bacteria will decrease lag time, while increasing both the yield and rate of methane generation. Klink and Ham, from the Argonne National Laboratory, also looked at the effect of leachate movement on methane production. They concluded that leachate recycling coupled with the management of nutrients and pH, yields a higher production than that under enhanced static conditions.

2.3 Fundamental of Anaerobic Treatment

Anaerobic treatment consists of the biochemical conversion of organic materials by a consortium of microorganisms, typically in the absence of oxygen, to methane and carbon dioxide

1) General Process Description: Generally the overall AD process can be divided into three stages: Pretreatment, waste digestion, gas recovery and residue treatment. Most digestion systems require pre-treatment of waste to obtain homogeneous feedstock. The preprocessing involves separation of non-digestible materials and shredding. The waste received by AD digester is usually source separated or mechanically sorted. The separation ensures removal of undesirable or recyclable materials such as glass, metals, stones etc. In source separation, recyclables

are removed from the organic wastes at the source. Mechanical separation can be employed if source separation is not available. However, the resultant fraction is then more contaminated leading to lower compost quality. The waste is shredded before it is fed into the digester. Inside the digester, the feed is diluted to achieve desired solids content and remains in the digester for a designated retention time. For dilution, varying ranges of water sources can be used such as clean water, sewage sludge, or re-circulated liquid from the digester effluent. A heat exchanger is usually required to maintain temperature in the digesting vessel (Figure 2.1). The biogas obtained in AD is scrubbed to obtain pipeline quality gas. In case of residue treatment, the effluent from the digester is dewatered, and the liquid recycled for use in the dilution of incoming feed. The biosolids are aerobically cured to obtain a compost product.

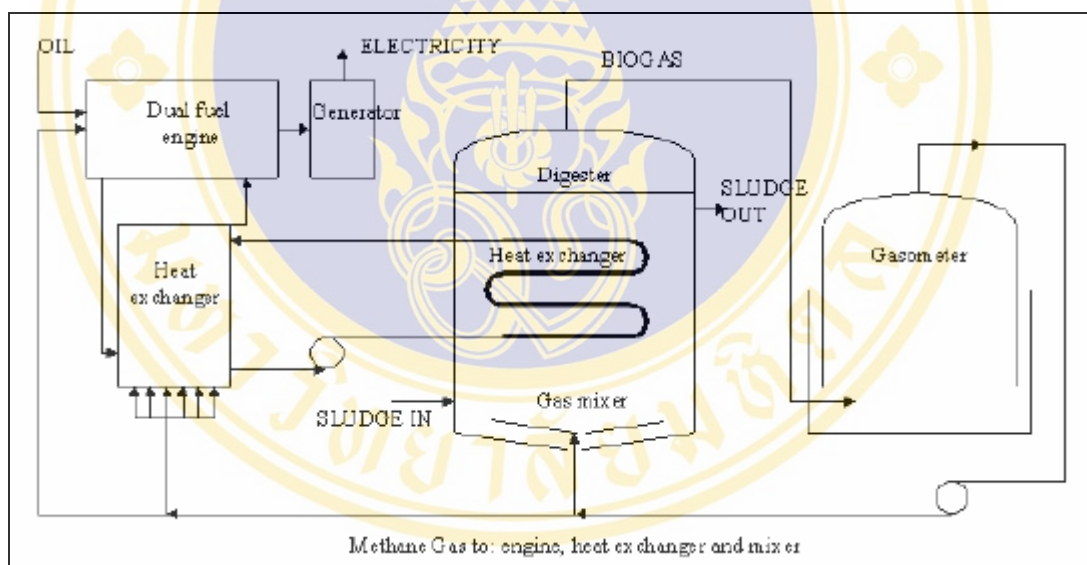


Figure 2.1 The flow diagram of low solids anaerobic digestion (16)

2) The Anaerobic Digestion Process: Anaerobic biodegradation of organic material proceeds in the absence of oxygen and the presence of anaerobic microorganisms. AD is the consequence of a series of metabolic interactions among various groups of microorganisms. It occurs in three stages, hydrolysis/liquefaction, acidogenesis and methanogenesis. The first group of microorganism secretes enzymes, which hydrolyses polymeric materials to monomers such as glucose and

amino acids. These are subsequently converted by second group i.e. acetogenic bacteria to higher volatile fatty acids, H_2 and acetic acid. Finally, the third group of bacteria, methanogenic, converts H_2 , CO_2 , and acetate, to CH_4 . These stages are described in detail below. The AD is carried out in large digesters (Figure 2.2) that are maintained at temperatures ranging from $30^\circ C$ - $65^\circ C$.



Figure 2.2 The digesters at Tilburg Plant in The Netherlands (17)

2.1) Hydrolysis/liquefaction: In the first stage of hydrolysis, or liquefaction, fermentative bacteria convert the insoluble complex organic matter, such as cellulose, into soluble molecules such as sugars, amino acids and fatty acids. The complex polymeric matter is hydrolyzed to monomer, e.g., cellulose to sugars or alcohols and proteins to peptides or amino acids, by hydrolytic enzymes, (lipases, proteases, cellulases, amylases, etc.) secreted by microbes. The hydrolytic activity is of significant importance in high organic waste and may become rate limiting. Some industrial operations overcome this limitation by the use of chemical reagents to enhance hydrolysis. The application of chemicals to enhance the first step has been found to result in a shorter digestion time and provide a higher methane yield (18).

Hydrolysis/Liquefaction reactions

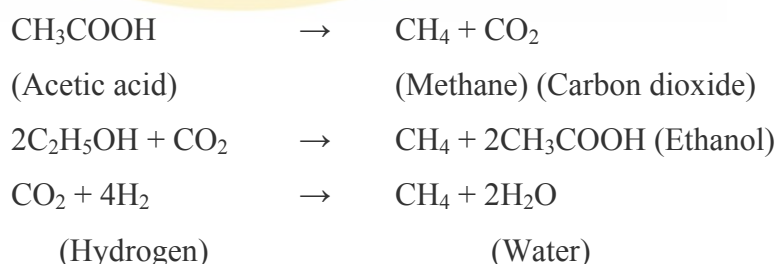
Lipids	→	Fatty Acids
Polysaccharides	→	Monosaccharides
Protein	→	Amino Acids
Nucleic Acids	→	Purines & Pyrimidines

2.2) Acetogenesis: In the second stage, acetogenic bacteria, also known as acid formers, convert the products of the first phase to simple organic acids, carbon dioxide and hydrogen. The principal acids produced are acetic acid (CH_3COOH), propionic acid ($\text{CH}_3\text{CH}_2\text{COOH}$), butyric acid ($\text{CH}_3\text{CH}_2\text{CH}_2\text{COOH}$), and ethanol ($\text{C}_2\text{H}_5\text{OH}$). The products formed during acetogenesis are due to a number of different microbes, e.g., *syntrophobacter wolinii*, a propionate decomposer and *syntrophomonas wolfei*, and a butyrate decomposer. Other acid formers are *clostridium* spp., *peptococcus anerobus*, *lactobacillus*, and *actinomyces*.

An acetogenesis reaction is shown below:



2.3) Methanogenesis: Finally, in the third stage methane is produced by bacteria called methane formers (also known as methanogens) in two ways: either by means of cleavage of acetic acid molecules to generate carbon dioxide and methane, or by reduction of carbon dioxide with hydrogen. Methane production is higher from reduction of carbon dioxide but limited hydrogen concentration in digesters results in that the acetate reaction is the primary producer of methane (19). The methanogenic bacteria include *methanobacterium*, *methanobacillus*, *methanococcus* and *methanosarcina*. Methanogens can also be divided into two groups: acetate and H_2/CO_2 consumers. *Methanosarcina* spp. and *methanothrix* spp. (also, *methanosaeta*) are considered to be important in AD both as acetate and H_2/CO_2 consumers. The methanogenesis reactions can be expressed as follows:



In the case of series metabolism, the transformation of organics and intermediates are rate-controlled by the slowest reaction in the process. For optimum conditions, the anaerobic series metabolism requires that each group of organisms collaborate to prevent intermediate concentration build up. Commonly, the slowest groups of anaerobic organisms are the methanogens; therefore, accumulation of

organic acids (propionic or acetic) may result. The acid buildup can consume any reserve alkalinity and the pH of the system decreases, inhibiting the entire process (20).

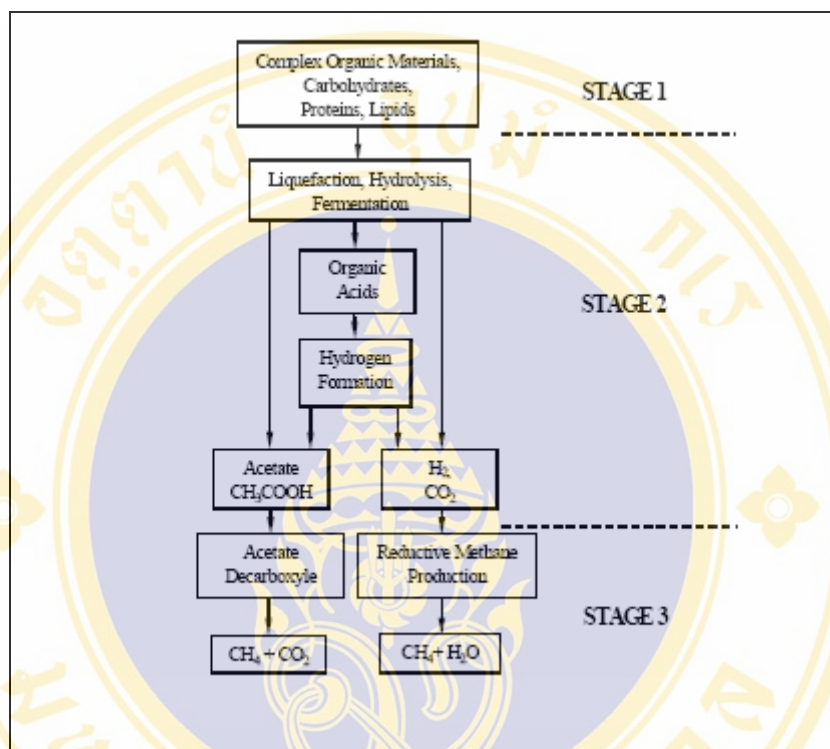


Figure 2.3 Multi step methanogenesis in anaerobic digestion.

A second item of importance in the series metabolism is that the conversion of propionate to acetate and hydrogen is only thermodynamically possible at hydrogen concentrations below 10^{-4} atmospheres. Additionally, hydrogen conversion to methane is only thermodynamically possible at hydrogen concentrations above 10^{-6} atmospheres (1 ppm). Therefore, these conditions may cause a “bottleneck” in the anaerobic system if the hydrogen concentration is less than 10^{-6} or greater than 10^{-4} atm. Microbes responsible for converting hydrogen to methane must maintain hydrogen concentrations between 10^{-4} and 10^{-6} to provide favorable conditions for the conversion of propionate.

3) Various Anaerobic Digestion Systems: AD processes can be classified according to the total solids (TS) content of the slurry in the digester reactor. Low solids systems (LS) contain less than 10 % TS, medium solids (MS) contain about 15%-20%, and high solids (HS) processes range from 22% to 40%. AD processes can be categorized further on the basis of number of reactors used, into single-stage and multi-stage. In single stage processes, the three stages of anaerobic process occur in one reactor and are separated in time (i.e., one stage after the other) while multi-stage processes make use of two or more reactors that separate the acetogenesis and methanogenesis stages in space. Batch reactors are used where the reactor is loaded with feedstock at the beginning of the reaction and products are discharged at the end of a cycle. The other type of reactor used, mostly for low solids slurries, is continuous flow where the feedstock is continuously charged and discharged. As noted earlier, the AD systems treat various types of waste-streams and in some plants MSW is mixed with sewage sludge or other type of waste. These types of processes will be discussed in more detail later (21).

2.4 Thermophilic-Mesophilic Process of Anaerobic Digestion

An important achievement in the application of anaerobic digestion to municipal wastes was the development of a thermophilic process (22). Thermophilic digestion has the advantage of being capable of producing large volumes of gas at high organic loadings and short retention times, along with a high degree of pathogen destruction. Thermophilic (55°C) and conventional mesophilic (35°C) systems were thoroughly compared using multiple laboratory units. The systems (4 liters working volume each) were examined over a wide range of hydraulic Retention times (6-16 days) and feed-solids concentrations (3-18% total solids), i.e. organic solids loading of up to 24 g of volatile solids/liter/d. The results of these experiments are shown in Fig. 2.4.

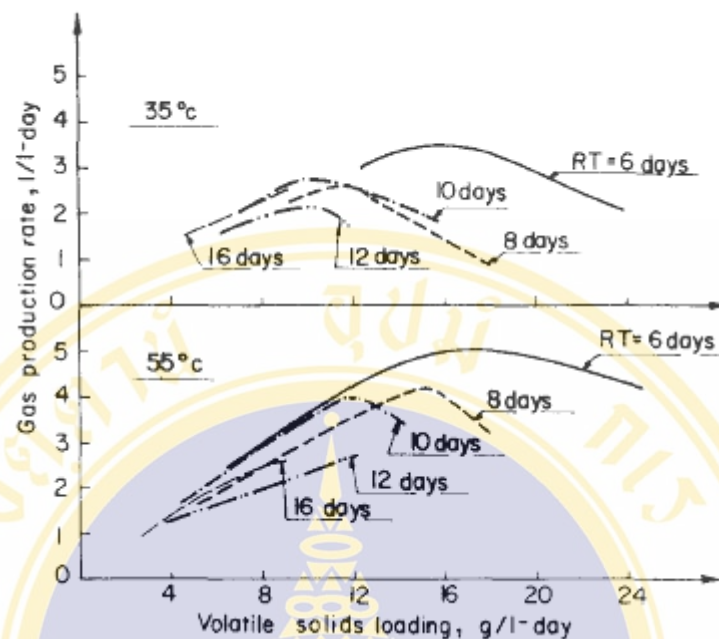


Figure 2.4 Thermophilic (55°C) vs. mesophilic (35°C) gas production rates under various operational conditions.

From the results, it can be seen that at longer retention times (12 and 16 days) there was little or no difference in gas production rates (liters gas/ liters vol. /d) for the mesophilic and thermophilic systems. However, at short retention times and higher organic loadings, there was a significant advantage to thermophilic operation. The highest thermophilic biogas production rate obtained was 5.5 liters/liter-d, at an organic loading rate of 16 g/liter-d, while at the same loading rate the maximum mesophilic biogas production rate was 3.5 liters/liter-d. These performance data indicate that thermophilic anaerobic digestion more efficiently converts organic material to biogas under intensive conditions. The average methane concentration in the biogas ranged from 60 to 70% by volume. (23)

2.5 Co-digestion of Anaerobic Digestion

An interesting option for improving yields of anaerobic digestion of solid wastes is co-digestion. That is, the use of a co-substrate that in most cases improves the biogas yields due to positive synergisms established in the digestion medium and the supply of missing nutrients by the co-substrates. In addition, economic advantages

derived from the fact of sharing equipment are quite significant. Sometimes the use of a co-substrate can also help to establish the required moisture contents of the digester feed. Other advantages are the easier handling of mixed wastes, the use of common access facilities and the known effect of economy of scale. However, some drawbacks also exist, mainly due to slurry transport costs and the problems arising from the harmonization of different policies of the waste generators.

The advantages of co-digestion have been sung for some time. For instance, Mata-Alvarez and Cecchi (24) referred to the co-digestion of OFMSW with sewage sludge in existing digesters. Both wastes are produced in large quantities and in many places, and much research has focused on this particular issue. Co digestion of manure and industrial organic wastes has been widespread in Denmark around 20 centralized co-digestion plants since the late 1980s, with very interesting results. However, apart from this, few reports on industrial applications of this concept have been published. Most industrial co-digestion plants treat OFMSW plus (in a relatively small percentage) some other organic waste, such as sewage sludge. However, despite the positive results in the studies listed here the scarce industrial application of co-digestion is surprising.

The presence of organic waste residues improves the dewaterability measured as specific resistance. With the same components, Demirekler and Anderson recommended a ratio for primary sewage sludge: OFMSW of 80:20, after testing ratios of 100:0, 80:20 and 60:40 on a TSs basis (25). The experimental work was carried out in three laboratory-scale semi-batch anaerobic digesters, operated at 35°C. Addition of SS significantly decreased the imbalances observed during the start-up and improved the process performance. In all cases inoculums from an operating anaerobic digester was used, enabling both a quick start-up and the capacity for handling high organic loading rates (OLRs) from the beginning of the experiment. Working with unsorted MSW, Borghi et al. examined co-digestion with sewage sludge, and also the digestion enhancement experienced with different chemical, biological and thermal pre-treatments.

2.6 Important Operating Parameter (26)

The rate at which the microorganisms grow is of paramount importance in the AD process. The operating parameters of the digester must be controlled so as to enhance the microbial activity and thus increase the anaerobic degradation efficiency of the system. Some of these parameters are discussed in the following section.

1) Waste composition/Volatile Solids (VS) : The wastes treated by AD may comprise a biodegradable organic fraction, a combustible and an inert fraction. The biodegradable organic fraction includes kitchen scraps, food residue, and grass and tree cuttings. The combustible fraction includes slowly degrading lignocellulosic organic matter containing coarser wood, paper, and cardboard. As these lignocellulosic organic materials do not readily degrade under anaerobic conditions, they are better suited for waste-to-energy plants. Finally, the inert fraction contains stones, glass, sand, metal, etc. This fraction ideally should be removed, recycled or used as landfill.

The removal of inert fraction prior to digestion is important as otherwise it increases digester volume and wear of equipment. In waste streams high in sewage and manure, the microbes thrive and hydrolyse the substrate rapidly whereas for the more resistant waste materials, such as wood, digestion is limited. The volatile solids (VS) in organic wastes are measured as total solids minus the ash content, as obtained by complete combustion of the feed wastes. The volatile solids comprise the biodegradable volatile solids (BVS) fraction and the refractory volatile solids (RVS). Kayhanian showed that knowledge of the BVS fraction of MSW helps in better estimation of the biodegradability of waste, of biogas generation, organic loading rate and C/N ratio. Lignin is a complex organic material that is not easily degraded by anaerobic bacteria and constitutes the refractory volatile solids (RVS) in organic MSW. Waste characterized by high VS and low non-biodegradable matter, or RVS, is best suited to AD treatment. The composition of wastes affects the yield and biogas quality as well as the compost quality.

2) pH Level: Anaerobic bacteria, specially the methanogens, are sensitive to the acid concentration within the digester and their growth can be inhibited by acidic

conditions. The acid concentration in aqueous systems is expressed by the pH value, i.e. the concentration of hydrogen ions. At neutral conditions, water contains a concentration of 10^{-7} hydrogen ions and has a pH of 7. Acid solutions have a pH less than 7 while alkaline solutions are at a pH higher than 7. It has been determined that an optimum pH value for AD lies between 5.5 and 8.5. During digestion, the two processes of acidification and methanogenesis require different pH levels for optimal process control. The retention time of digestion affects the pH value and in a batch reactor acetogenesis occurs at a rapid pace. Acetogenesis can lead to accumulation of large amounts of organic acids resulting in pH below 5. Excessive generation of acid can inhibit methanogens, due to their sensitivity to acid conditions. Reduction in pH can be controlled by the addition of lime or recycled filtrate obtained during residue treatment. In fact, the use of recycled filtrate can even eliminate the lime requirement. As digestion reaches the methanogenesis stage, the concentration of ammonia increases and the pH value can increase to above 8. Once methane production is stabilized, the pH level stays between 7.2 and 8.2.

3) Temperature: There are mainly two temperature ranges that provide optimum digestion conditions for the production of methane – the mesophilic and thermophilic ranges. The mesophilic range is between 20°C-40°C and the optimum temperature is considered to be 30°C-35°C. The thermophilic temperature range is between 50°C-65°C. It has been observed that higher temperatures in the thermophilic range reduce the required retention time.

4) Carbon to Nitrogen Ratio (C/N)

The relationship between the amount of carbon and nitrogen present in organic materials is represented by the C/N ratio. Optimum C/N ratios in anaerobic digesters are between 20 – 30. A high C/N ratio is an indication of rapid consumption of nitrogen by methanogens and results in lower gas production. On the other hand, a lower C/N ratio causes ammonia accumulation and pH values exceeding 8.5, which is toxic to methanogenic bacteria. Optimum C/N ratios of the digester materials can be achieved by mixing materials of high and low C/N ratios, such as organic solid waste mixed with sewage or animal manure.

5) Total solids content (TS)/Organic Loading Rate (OLR): As discussed earlier, Low solids (LS) AD systems contain less than 10 % TS, medium solids (MS)

about 15-20% and high solids (HS) processes range from 22% to 40%. An increase in TS in the reactor results in a corresponding decrease in reactor volume. Organic loading rate (OLR) is a measure of the biological conversion capacity of the AD system. Feeding the system above its sustainable OLR results in low biogas yield due to accumulation of inhibiting substances such as fatty acids in the digester slurry. In such a case, the feeding rate to the system must be reduced. OLR is a particularly important control parameter in continuous systems. Many plants have reported system failures due to overloading. Vandevivere reports OLR is twice in HS in comparison to LS (27).

6) Retention (or residence) Time: The required retention time for completion of the AD reactions varies with differing technologies, process temperature, and waste composition. The retention time for wastes treated in mesophilic digester range from 10 to 40 days. Lower retention times are required in digesters operated in the thermophilic range. A high solids reactor operating in the thermophilic range has a retention time of 14 days.

7) Mixing: The purpose of mixing in a digester is to blend the fresh material with digested containing microbes. Furthermore, mixing prevents scum formation and avoids temperature gradients within the digester. However excessive mixing can disrupt the microbes so slow mixing is preferred. The kind of mixing equipment and amount of mixing varies with the type of reactor and the solids content in the digester.

8) Compost: When the digestion is complete, the residue slurry, also known as digested, is removed, the water content is filtered out and re-circulated to the digester, and the filter cake is cured aerobically, usually in compost piles, to form compost. The compost product is screened for any undesirable materials, (such as glass shards, plastic pieces etc) and sold as soil amendment. The quality of compost is dependent on the waste composition. Some countries have prescribed standards for compost quality. The U.S. Department of Agriculture has set standards for heavy metals in the compost (Table 2.1). These standards are for compost treated by the aerobic process but may also be applied to AD compost product.

Table 2.1 US Department of Agriculture Compost Heavy Metals Standards (ppm)

Table 1. US Department of Agriculture Compost Heavy Metals Standards (ppm)	
Heavy Metal	Standard*
Cadmium (Cd)	10
Nickel (Ni)	200
Lead (Pb)	250
Copper (Cu)	1000
Chromium (Cr)	1000
Zinc (Zn)	2500
Source : USEPA 1995 * standard for compost produced by aerobic process	
Ref: Hickman, L.H., (1999) Principles of Integrated Solid Waste Management, American Academy of Environmental Engineers Publication	

2.7 Characteristic of Biogas from Anaerobic Digestion

1) Biogas Composition: The gas obtained during AD comprises of methane, carbon dioxide, some inert gases and sulfur compounds (Table 2.2). Usually 100-200 m³ of total gas are produced per ton of organic MSW digested. Untreated biogas fresh from the reactor is a mixture of several different gases (Table 2.3). When organic matter is degraded anaerobically the result is carbon in its most oxidized form (CO₂) and its most reduced form (CH₄). The CH₄/CO₂ ratio depends on the oxidation state of the organic material. The more reduced the carbon in the organic material is the more CH₄ will be produced relative to CO₂. The composition of the biogas exiting the reactor also depends upon the pH in the reactor because part of the CO₂ will dissolve (CO₂ (aq)) or be present as HCO₃³⁻ in solution. Almost all of the methane generated will be present as gas due to the low solubility of methane. This means that the methane content in the gas phase always will be larger than predicted based on the stoichiometry of degradation. In addition to CH₄ and CO₂ trace amounts of other gases are generated. Hydrogen sulfide (H₂S) is of most interest because this gas usually needs to be removed before the biogas can be used for energy production due to highly corrosive acids generated by oxidation of H₂S.

Table 2.2 Typical Biogas Compositions.

Table 3. Typical Biogas Composition	
Methane	55-70% by vol.
Carbon dioxide	30-45% by vol
Hydrogen sulphide	200-4000 ppm by vol
Energy content of AD gas product	20-25MJ/standard m ³
Energy content of CH ₄ per ton MSW	167-373MJ/Ton MSW
Reference: Regional Information Service Centre for South East Asia on Appropriate Technology (RISE-AT) (Nov 1998), Review of current status of Anaerobic Digestion Technology for treatment of MSW	

2) Energy conversion: Conversion of biogas to heat and power is a clean and environmentally friendly process. Only water and carbon dioxide is produced. The energy conversion itself does not contribute to the global loading of carbon dioxide to the atmosphere because the energy source is organic matter, which is CO₂ neutral (the same amount of CO₂ is released during degradation and gas combustion as was taken up during growth of plant tissue). The energy content of methane is 27.5 MJ/kg, which is approximately twice that of food wastes. Biogas with 65% methane has an energy content of 6.5 kWh per Nm³.

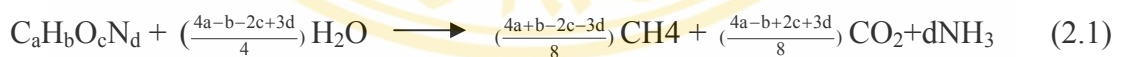
In modern high-tech biogas plants conversion of the energy contained in the methane is done in combined heat and power (CHP) plants. The energy conversion unit is often located at the biogas plant to save costs for construction of transmission pipes and because some of the heat produced at the CHP unit is used for heating the digester. The biogas is normally used to drive a gas motor connected to a power generator. The system produces electricity that is sold to the grid. Cooling of the gas engine produces heat that is used to produce hot water. The water is then used for remote heating of nearby residential homes and businesses via a piping system and for heating the digester and hygienization tanks at the biogas plant.

The CHP technology provides very high-energy utilization efficiency and it is therefore optimal for utilization of the biogas. Up to 90% of the energy contained in the biogas can be converted to either heat or electricity in a CHP plant. Smaller quantities of methane are usually lost from the biogas plants and the CHP plant due to leaks in piping and pumps etc. These losses are typically on the order of 2% for the biogas plant and 3% for the CHP plant. Greater losses may be encountered if the gas

is transported over long distances for energy utilization away from the biogas plant. In modern plants approximately 36 - 40% of the energy contained in the biogas can be converted to electricity and about 50% to useful heat (hot water) yielding an energy utilization efficiency of 86 - 90%. Part of the power and heat generated is used to run the biogas plant this normally amounts to 10% of the heat and power generated.

3) Biogas and methane potential: One of the most important issues in anaerobic waste treatment is the quantity and composition of gas produced. Often the economy of the treatment facilities depends on the sales of gas or energy (heat, electricity) derived from the biogas. The biogas potential (the amount of gas that can be produced from a given quantity of organic waste) is therefore an essential parameter. The following section discusses biogas potential and gas composition as related to the design and operation of the digester as well as composition of the organic material digested. Because biogas typically is a mixture of different gases and methane is the compound that is of interest (seen from an energy perspective at least) the term methane potential will be used rather than the more diffuse term biogas potential.

4) Ultimate methane potential (28): If the chemical composition of the input organic matter is known the ultimate quantity of methane that can be produced may be estimated based upon the stoichiometry of the degradation reaction using Buswells formula.



The specific theoretical methane yield (B_{th}) in terms of normal cubic meters, Nm^3 CH_4 per ton volatile solids (VS defined as ignition loss at 550°C) under standard conditions (0°C 1 atm) can be calculated from

$$B_{th} = 22,400 \frac{\left(\frac{4a + b - 2c - 3d}{8}\right)}{12a + b + 16c + 14d} \quad (2.2)$$

5) Actual methane potential: The theoretical methane potential calculated from Eqs. (2.1) and (2.2) gives the maximum of methane that can possibly be generated from the given organic matter. It can therefore only be used as an estimate of the possible methane production that can be achieved in a full-scale digester. The actual methane yield from digesters is always lower due to the following factors:

Part of the organic input (substrate) will be used for generation of new biomass (bacteria). This fraction is typically on the order of 5-10 % of the input VS. Part of the organic matter will exit the reactor without being degraded. This fraction is typically on the order of 10%. The lignin containing part of the organic matter cannot be degraded under anaerobic conditions. For lignin containing materials the biodegradable fraction (BF) can be estimated as where LC is the lignin content as a percentage of VS (Table 2.3)

$$BF = 0.83 - 0.028 LC \quad (2.3)$$

Table 2.3 Lignin content of selected organic materials

Component	Lignin content % of VS
Food wastes	0.4
Newspaper	21.9
Office paper	0.4
Cardboard	12.9
Yard wastes	4.1
Chicken manure	3.4
Pig manure	2.2
Cow manure	8
Wheat straw	13
Whey acid	0
Pine wood	28

Part of the organic matter is bound to inorganic particles and will not be available for microbial degradation. The degradation of the organic matter may be restricted due to lack of sufficient nutrients for microbial growth. It is therefore in general advisable to use actual measured methane potentials under the conditions that one wishes to run the digester. Such measurements can be difficult to carry out in practice as many full-scale biogas plants are using mixtures of different organic materials as substrates. In general about 50-70% of the biodegradable materials will

be converted into biogas in an average biogas reactor depending on process conditions. This interval is applicable to manure, sewage sludge, restaurant waste and household waste. Special industrial wastes consisting of easily degradable materials such as sugars, fats and proteins will normally show an even higher rate of turnover.

The methane yield can also be estimated if the reactor design and the biodegradation properties of the organic material being digested are known. Hashimoto et al. (11) proposed the following model for methane yield (B) per mass of COD or VS input as a function of design parameters and type of organic material.

$$B = \frac{B_0 S_0}{HRT} \left(1 - \frac{K}{HRT \mu_m - 1 + K} \right) \quad (2.4)$$

Where B_0 is the ultimate methane yield, S_0 is the input biodegradable substrate concentration in terms of COD or VS concentration; μ_m is the maximum specific growth rate of the microorganisms in the reactor (a lumped parameter) and K is a dimensionless kinetic parameter. B_0 can be found by plotting the steady-state methane production against $1/HRT$ for different levels of HRT for a given constant temperature and extend the plot to infinity ($1/HRT = 0$). The maximum specific growth rate for the anaerobic microorganisms in terms of d^{-1} can be estimated as $\mu_m = 0.013T - 0.129$ where T is temperature. The expression is valid in the temperature interval $20 - 60^\circ C$. The constant K can be found by plotting the HRT vs. $(S_0 - S_e)/S_e$ where S_e is the effluent COD or VS concentration. The slope is equal to K/μ_m and the intercept is $1/\mu_m$. Even if the organic matter is biodegradable under anaerobic conditions part of it will still not be degraded due to the finite hydraulic retention time. If 100% of the degradable matter were to be converted into biogas it would require an infinite HRT. Under normal circumstances about 50 – 70% of the degradable matter will be converted into biogas.

2.8 Digester design and operation (29)

Reactors for anaerobic digestion can be both complete mixed or plug flow reactors. Here we will focus on complete mixed reactors, as they are the most widely

used for biogas production. This section will discuss reactor analysis, reactor sizing and mode of operation.

1) Reactor analysis: If it is assumed that the growth of the bacteria in the reactor is limited only by substrate availability (well functioning reactor) a mass balance for the complete mixed reactor of volume V can be set up as shown in Fig 2.5 where S_0 is the input biodegradable substrate concentration, S_e is the exit biodegradable substrate concentration (and the substrate concentration in the reactor) and Q is the volumetric flow through the system.



Figure 2.5 Schematic of mass balance for a complete mix reactor system

Assuming that the degradation of substrate follows first order kinetics, the rate of change with time of substrate mass within the reactor can be calculated as follows.

$$V \frac{dS_e}{dt} = QS_0 - QS_e - KVS_e \quad (2.5)$$

Where K is the first-order degradation constant dividing through with volume V yields

$$\frac{dS_e}{dt} = \frac{S_0}{HRT} - \frac{S_e}{HRT} - KS_e \quad (2.6)$$

At steady state conditions the rate of change in substrate concentration within the reactor is zero and we get

$$\frac{S_e}{S_0} = \frac{1}{1 + K HRT} \quad (2.7)$$

This can be rearranged into a linear form.

$$S_0 - S_e = K S_e HRT \quad (2.8)$$

Running a series of tests using the organic substrate that is to be digested for varying HRT and plotting $S_0 - S_e$ versus S_e HRT will yield a straight line with slope K if the assumption of first-order kinetics is valid. If K is known Eq. (2.8) can be used to estimate the required HRT to obtain a desired substrate removal rate in the reactor.

2) Design approach based on reactor analysis: An anaerobic digester can very well be designed based on reactor analysis using a laboratory bench scale reactor digesting the organic material in question. The first step is to determine the degradation constant K based on experimental data from the lab reactor. The second step is to choose the desired substrate removal efficiency i.e. $(S_0 - S_e)/S_0$. Given S_0 the design HRT can be computed from Eq. (2.8). The required reactor volume can then be calculated if the volumetric flow rate Q is known as $V = \text{HRT} \cdot Q$. Given the chemical composition of the biodegradable matter, the methane yield can be estimated using Eqs. (2.3) in combination with Table 2.3 and Eq. (2.4)

The methane yield could alternatively have been calculated using Eq. (2.4) if the parameters K and μ_m are known. At present the knowledge about the biodegradation parameters used in the different models is scarce. Often digester design is based on experiences from existing plants. Here we could for instance have selected the HRT based on the data. In this case we could only have obtained an estimate of the theoretical methane potential from Eq. (2.4).

2.9 The development of kinetic modeling (30)

The development of kinetic models to describe the anaerobic treatment process has continued over the last fifty years. Although early work consisted mainly of “black box” (descriptive) modeling, it was quickly realized that the greater sophistication was needed if the model were to be further developed into better predictors of process performance. The predictions of unstructured models such as the black box can not meaningful be extrapolated

Each type of model has major advantages and disadvantage and some are better suited than others particular applications. Dynamic models are recognized as

being the most useful type. They can be used for control purposes and to predict process failure, unlike steady state models, which are only useful for process design applications.

The most popular models can be divided into four groups, depending on the type of kinetic assumed: Monod, Modified Monod, First order and modified Contois (Chen-Hashimoto methane production model). In all cases of models are based on microbial kinetics, it being implicitly assumed that rates of substrate utilization and product yield can be predicted on this basis alone. Enzyme kinetics and variations in enzyme concentration are rarely considered. Furthermore monoculture kinetics are assumed as a basis for predicting specific population growth rates even in the more complex mixed culture condition found in anaerobic digesters. Models based on monoculture kinetics can be divided into four groups.

2.9.1 Monod kinetics

The Monod expression is the one most commonly selected as a basis for predicting the performance of anaerobic digesters. The rate of substrate utilization accounting for saturation kinetics is given by.

$$\frac{d[S]}{dt} = \frac{k[X][S]}{K_s + [S]} \quad (2.9)$$

An expression for microbial growth rate is:

$$\frac{d[X]}{dt} = a \frac{d[S]}{dt} - b[X] \quad (2.10)$$

(i.e. the net growth rate = theoretical growth rate- decay rate) and this, when combined with equation (1) results in the overall equation for specific growth rate:

$$\mu = \frac{d[X]}{dt} \frac{1}{[X]} = \frac{ak[S]}{K_s + [S]} - b \quad (2.11)$$

The growth yield coefficient (a) and the maximum specific rate of substrate utilization (k) can be replaced by the maximum specific growth rate, $\mu_{\max}$, when $b = 0$, to give.

$$\mu = \frac{\mu_{\max}[S]}{K_s + [S]} \quad (2.12)$$

For continuously operated digesters this equation can be used to determine the minimum retention time, which ensures the avoidance of “washout” (where the retention time is the reciprocal of the specific growth rate for the slowest growing microbial species)

Although the use of Monod expressions for dynamic modeling, as in these cases is the questionable, the major drawback is in the suitability of these models for treatment of solid wastes. The three significant disadvantages are:

(a) The Monod term in the mass balances is applicable only to balanced microbial growth. It is therefore not a good choice for dynamic modeling or more specifically for predicting a digester's response to a change in inputs, or for predicting digester failure or performance on start up and shut down.

(b) Monod kinetics was developed for monocultures and they ignore the interactive effects between species that occurred in mixed cultures such as those present in digesters.

(c) The hydrolysis step is either ignored or not considered in enough detail to enable the model to be used predictively when treating agriculture waste. The Monod expression is empirically based, being derived from Michaelis-Menten saturation kinetics, which assumes that the growth limiting substrate is in the solution. With many solid wastes the energy source for microbial growth is derived from complex organic compounds in suspension, which are solubilized. The hydrolysis step constrains operators to a maximum dilution rate for continuous operation.

The Monod expression has been used primarily for dynamic modeling work, regardless of the limitations outlined, and especially where the computer solution is necessary. Slight modifications have been made to the models in some cases, to improve predicting power and to reduce the number of parameters. These modified models are the most accurate of the models for predicting dynamic process performance, particularly of gas yields. However experimental results, mainly with laboratory scale digesters, have shown that the models are poor at predicting volatile solids reduction, especially at high solids loadings.

To summarize, although the Monod type model has been applied extensively, there are still major problems when using it for the dynamic modeling of the digestion of lignocellulosic wastes.

2.9.2 Modified Monod kinetics

In many cases, especially at high substrate concentrations, enzyme reactions no longer obey Michaelis-Menten kinetics and substrate inhibition occurs. In particular, with solid wastes, this can occur at high ammonia or high volatile acid concentrations, depending on the nature of waste. However, the problem is most acute with highly soluble wastes, where acidogenic reaction rates are so much faster than methanogenic ones leading to an accumulation of volatile acids. This is caused by competitive inhibition of the enzyme by the substrate. A theoretical derivation of this kinetic effect has been provided by Reberts and is given by:

$$v = \frac{k[E]}{1 + \frac{K}{[S]} + \frac{[S]}{KI}} \quad (2.13)$$

This equation has been adapted, in a similar way to the derivation of the Monod equation, from Michaelis-Menten relationship, by Andrews who used the empirical expressions:

$$\frac{d[S]}{dt} = \frac{k[X]}{1 + \frac{K}{[S]} + \frac{[S]}{KI}} \quad (2.14)$$

And

$$\mu = \frac{\mu_{\max}}{1 + \frac{K_s}{[S]} + \frac{[S]}{KI}} \quad (2.15)$$

As the basis of this model and applied those to assess the inhibition effect of un-ionized volatile acids on methane formation. Andrews and Graef developed this work further into a dynamic model to predict volatile acid variation, alkalinity, pH, and gas flow rate and gas composition. Most of the kinetic data used by Andrew and Graef were provided by work from Lawrence and McCarty and Buswell. Three causes of digester instability were outlined: (a) hydraulic overload, (b) organic overload and (c) toxic overload. Andrew and Graef to assess digester response to independent step changes in these three factors used the model. From these results they propose control strategies for ensuring the operational stability of working digesters. However, no results are presented to indicate how effective the strategies can be on large-scale plant.

To summarize, the substrate inhibition kinetics model is a modified from the saturation kinetic model, allowing for end product inhibition effect. However, although it may be an improvement over conventional Monod kinetic for predicting process performances at high organic concentrations, it still suffers from the major drawbacks of Monod models, as many of assumptions used in the model formulation are the same.

2.9.3 First order kinetics

Pfeffer and Grady have proposed first order kinetic models for prediction models for the prediction of the digester performance under steady state conditions. Their simulation results compared well with experimental data for volatile solids destruction at low substrate concentrations, where a first order approximates to Monod kinetics. Gaddy using results from the digestion of corn Stover and Baccay and Hashimoto using caustic soda treated straw as a digester feedstock, also found good agreement between the predicted and experimental results, assumption reaction rates were controlled by first order kinetics. This is a good assumption because the highly lignified material they were working with gave only low concentrations of soluble substrate.

Pfeffer found it difficult to quantify concentrations of biomass and available substrate for use in the modeling of municipal digesters assuming Monod kinetics, and he therefore used the first order expression for the rate of substrate utilization:

$$\frac{d[S]}{dt} = -k[S] \quad (2.16)$$

As it was difficult to measure the substrate concentration [S] directly, he used the ultimate gas yield as an indicator of substrate concentration. The initial concentration, [S₀], was equated to the potential gas yield at 0.5 m³/kg VS fed and the substrate removal rate could be determined by monitoring the gas flow rate and concentration of carbon dioxide in solution, and carrying out mass balance calculation. For defined operating temperature, plotting ([S₀] - [S])/[S] against retention

time indicated that the reaction rate at retention times above 10 days was distinctly lower than the rate at times below 10 days.

Singh et al. realized that the Monod model is based on the concentration of soluble limiting substrate and hence cannot be easily applied to the digestion of high solids agricultural wastes. Working with cattle slurry, digested over detention time from 5 to 40 day, Singh et al found that a perfect first order relationship did not apply. Because solid degradation rates depend on the type of waste in the digester, and because more resistant fractions accumulate in the digester with time, they incorporated a time function into their kinetics expression. They also allowed for the gas production rate to be proportional to the substrate utilization rate, and to increase to a maximum only after a minimum substrate amount has been degraded. Such behavior is not accounted for in Contois models. The algebraic expression

$$\frac{d[S]}{dt} = \frac{K[S]}{(1+t)} \quad (2.17)$$

When integrated, gives

$$[S_t] = [S_0](1+t)^{-K} \quad (2.18)$$

And hence

$$\ln[S_t] = \ln[S_0] - K \ln(1+t) \quad (2.19)$$

By curve fitting to the experimental data they determined the constant, $K=0.14$, for cattle slurry. They concluded that the model could account successfully for degradation rates falling much faster than the substrate concentration and for gas production rates not proportional to the substrate utilization rate. This improvement to the basic first order model is well justified. However, the limitations of the first order model are still inherent and restrict application.

2.9.4 Modified Contois kinetic: Chen-Hashimoto kinetic model

Contois proposed a bacterial growth model in an attempt to simulate the effects on specific growth rates of mass transfer limitations due to variations in population density. The Contois model, which can be regarded as a development of the Monod model, is based upon the expression

$$\mu = \frac{\mu_{\max}[S]}{K([X] + [S])} \quad (2.20)$$

In modified from this has been used by Chen and Hashimoto as the basis of anaerobic digestion simulations. For steady state well mixed digesters the methane production rate (v) ($m^3/m^3.d$) can be predicted from:

$$v = \frac{B_0[S_0]}{\theta} \left\{ 1 - \frac{K}{(\theta\mu_{\max}) - 1 + K} \right\} \quad (2.20)$$

This from of the equation was selected by Chen and Hashimoto so that methane yield could be used as an indicator of substrate concentration, as the monitoring of volatile solids concentration is difficult with the inaccurate analyses available.

The model was tested by Chen and Hashimoto using sewage sludge data of O'Rourke, municipal refuse data of Pfeffer, and animal waste data from several investigations. Chen and Hashimoto achieved predictions of volatile solid reductions. Equation (13), in an alternative from:

$$B = B_0 \left\{ 1 - \frac{K}{(\theta\mu_{\max}) - 1 + K} \right\} \quad (2.21)$$

can be used to predict methane production at defined residence times. B_0 , a waste-specific term, is measured either by long term batch digestion or by extrapolation to infinite time of a plot of methane production against the reciprocal of residence time. The maximum specific growth rate, $\mu_{\max}$, depends on temperature and obeys the empirical equation.

$$\mu_{\max} = 0.013 T - 0.129 \quad (2.22)$$

Surprisingly, $\mu_{\max}$ remains relatively constant from waste to waste and can be thought of as the maximum specific growth rate of the slowest growing bacteria in

the digester. The kinetic parameter, K , is a function of the influent volatile solid concentration. It is fairly constant for low concentrations but increase with increasing concentration to a maximum when solid overloading and inhibition occur. Plot of residence time against gas yield can be used to determine $\mu_{\max}$ and K for an experimentally evaluated ultimate gas yield, B_0 . The ultimate gas yield, B_0 gives an indicator of the relative biodegradability of specific waste streams and accounts for the physical and chemical nature of the organic solids. It is independent of both temperature and volatile solid concentrations.

The above model was successfully used by Hill to determine the optimum operational parameters (temperature, organic solid loading rate and residence time) for continuous digestion of dairy, beef, pig and municipal wastes. The model can therefore be use to optimize a treatment process for specific waste type.

The model is a better predictor of volatile solids reduction than the Monod model, as it takes account of the relative recalcitrance of various types of waste. However, its predictions of gas yield must be used with care, particularly at low substrate concentrations, owing to the inherent limitations of the Contois model.

2.10 Chen-Hashimoto kinetic model of anaerobic digestion (31)

Chen-Hashimoto model is used for kinetic analysis of the experimental data. In a completely mixed continuous digester the rates of change of cell mass and substrate concentration are expressed by the following equations:

$$\frac{dX}{dt} = \mu X - \frac{X}{\theta} \quad (2.23)$$

$$\frac{dS}{dt} = -r + \frac{S_0 - S}{\theta} \quad (2.24)$$

where X is the concentration of cell mass, μ the specific microbial growth rate, θ the hydraulic retention time, S_0 the concentration of substrate in the influent, S the concentration of substrate in the effluent, and r is the volumetric substrate utilization rate.

The relationship between r and μ is defined by the following equation:

$$\mu = \frac{Yr}{X} \quad (2.25)$$

where Y is the yield coefficient (cell mass/substrate mass) and is considered constant. In the steady-state, $dX/dt = 0$ and $dS/dt = 0$, hence

$$\mu = \frac{1}{\theta} = D \quad (2.26)$$

Where D is the dilution rate

$$r = \frac{S_0 - S}{\theta} \quad (2.27)$$

And

$$X = Y(S_0 - S) \quad (2.28)$$

Substituting these expressions in Contois 'equation:

$$\mu = \frac{\mu_{\max} S}{\beta X + S} \quad (2.29)$$

where $\mu_{\max}$ is the maximum specific microbial growth rate and β is a dimensionless kinetic parameter, one obtains:

$$\frac{S}{S_0} = \frac{K}{\mu_{\max} \theta - 1 + K} \quad (2.30)$$

where K is a dimensionless kinetic parameter equal to $Y\beta$.

Eq. (2.30) shows that effluent substrate concentration depends on the influent substrate concentration. The minimum retention time indicating when the washout of micro-organisms occurs is numerically equal to the reciprocal of the maximum growth rate:

$$\theta_{\min} = \frac{1}{\mu_{\max}} \quad (2.31)$$

To study the kinetics of methane fermentation of complex substrates, two different approaches are generally used: one approach is to find the rate-limiting substrate for the kinetic evaluation; another approach is using chemical oxygen demand or volatile solids concentration as an indicator of the substrate concentration. The later approach evaluates the overall process performance and is convenient to use. However, a portion of the COD or VS is not available to the microbes as substrate.

There are difficulties in using COD or VS as the gross substrate. The laboratory test for COD of high strength residues requires at least 100 times dilution which generally yields unreliable data. Also, some of the volatile acids in the effluent are volatilized during the VS determination. Because the volatile acids are precursors of methane fermentation, their volatilization during the VS determinations causes errors in the calculated amount of substrate utilized.

A reduction of 1 g VS is equivalent to the production of 0.35 l of methane at STP. Knowing the VS loading to the reactor and the volume of methane produced, the remaining COD in the digester can be calculated. If B denotes the volume (in liters) of methane produced under normal conditions of pressure and temperature per gram of substrate (VS) added to the digester, and B_0 is the volume of methane produced under normal conditions of pressure and temperature per gram of substrate added at infinite retention time or for complete utilization of substrate, the biodegradable VS in the reactor will be directly proportional to $(B_0 - B)$, and B_0 will be directly proportional to the biodegradable VS loading. Therefore, from Eq. (2.30) one obtains:

$$\frac{B_0 - B}{B_0} = \frac{K}{\mu_{\max} \theta - 1 + K} \quad (2.32)$$

From Eq. (2.32) one obtains:

$$\theta = \frac{1}{\mu_{\max}} + \frac{K}{\mu_{\max}} \frac{B}{B_0 - B} \quad (2.33)$$

Thus, by first calculating the value of B_0 , the graph of θ versus $B/(B_0 - B)$ produces a straight line with an intercept of $1/\mu_{\max}$ and with a slope of $K/\mu_{\max}$. To obtain the parameter B_0 one uses the following equation, which is easily derived from Eq. (2.30):

$$B = B_0 \left| 1 - \frac{K}{\mu_{\max} \theta - 1 + K} \right| \quad (2.34)$$

such that when $\theta/\theta_{\min} = \mu_{\max} \theta \gg |1 - K|$, the graphs of B versus $1/\theta$ are straight lines in which B coincides with B_0 when the retention time is infinite, which is to say the intercept of the lines coincides with B_0 . Since B is the methane production per gram of added COD, the volumetric methane production rate (δ) equals B multiplied by the loading rate:

$$\delta = \frac{BS_0}{\theta} = \frac{B_0S_0}{\theta} \left| 1 - \frac{K}{\mu_{\max} \theta - 1 + K} \right| \quad (2.35)$$

where δ has the dimensions of volume CH₄ per volume digester per unit time. The maximum volumetric methane production rate, $\delta_{\max}$, is obtained by taking the derivative of δ in terms of θ and equating it to zero. So,

$$\delta_{\max} = \frac{B_0S_0}{\theta_{\min}} \left| \frac{1 - (K / (K + K^{1/2}))}{1 + K^{1/2}} \right| \quad (2.36)$$

Eq. (2.34) was used to determine B_0 . This equation shows that, if $\mu_{\max}\theta \gg [1 - K]$, the plot of B versus $1/\theta$ should be a straight line with $B \rightarrow B_0$ as $\theta \rightarrow \infty$. Fig. 1 shows a graph of B (l CH₄ STP/g VS) against $1/\theta$ (per day). Since the plot of B versus $1/\theta$ was found to be linear for the above-mentioned range of retention times, linear regressions (least squares method) were used to determine the intercept B_0 .

The values of θ plotted against the quotient $B / (B_0 - B)$ for the three-substrate concentrations studied. The pairs of values $(\theta, B/(B_0 - B))$ fall on straight lines, when using the least squares method, in such a way that values for the kinetic parameters $\mu_{\max}$ and K can be obtained from the intercept and the slope of the adjusted lines. Thus, according to Eq. (2.33), $\mu_{\max} = 1/\text{intercept}$, and $K = \text{slope}/\text{intercept}$.

Values for the two kinetic parameters ($\mu_{\max}$ and K) with their confidence limits at 95% are shown for the three substrate concentrations used. The values corresponding to the most concentrate substrates used (II and III) are of the same order of magnitude with those obtained in the anaerobic digestion process of some complex solid wastes such as sewage sludge, dairy and beef wastes. However, higher values for these kinetic parameters were reported in the literature [15] when the digesters operated at thermophilic temperature (60 °C) or when more biodegradable substrates were processed.

The theoretical B values were calculated by using Eq. (2.34). As can be seen in the values of both parameters decreased when influent substrate concentration increased. Therefore, the kinetic parameters were found to be influenced by the

influent substrate concentration, which shows the occurrence of an inhibitor in the waste material.

2.11 Related Research

R. Borja et al. (31) A kinetic study of the anaerobic digestion of two-phase olive mill solid waste (OMSW) was carried out in a laboratory-scale completely stirred tank reactor at mesophilic temperature (35 °C). The reactor was operated at three different feed substrate concentrations: 34.5, 81.1 and 113.1 g VS/l. The hydraulic retention time (HRT) varied between 40.0 and 8.3 days for the first feed used and between 50 and 10 days for the other two feed substrate concentrations. The results were evaluated using the Chen–Hashimoto methane production model to determine the kinetic constants of the process. The kinetic constants ($\mu_{\max}$ and K) were affected by the feed substrate concentration and decreased by 63 and 65%, respectively, when the feed concentration increased from 34.5 to 113.1 g VS/l.

V. Blonskaja et al. (32) anaerobic digestion of distillery waste was studied in a mesophilic two-stage system consisting of an anaerobic filter (AF) and an upflow anaerobic sludge blanket (UASB) reactor. The experiments were conducted with hydraulic retention times (HRT) ranging from 10 to 19 days at loading rates of 2.5–5.1 kg COD/(m³ day) in the first stage, and up to 20–39 days, corresponding to loading rates 0.6–2.5 kg COD/(m³ day) in the second stage. The treatment efficiencies (COD removals) achieved was 54 and 93% in the first and second stage, respectively. The acidogenic reactor provided satisfactory conversion of initial COD to volatile fatty acids (VFAs), averaging 20.5%. As a result of self-regulation, pH in the methanogenic reactor was in the range of 7.2–7.8. The generation of biogas in the second stage was significantly higher (6 l/day) than that in the first stage (1 l/day). The bacterial growth rate of acetogenic/methanogenic populations, determined by microcalorimetry, was higher in the separated methanogenic stage (average $\mu_{\max}$ 0.433 1/h) as compared to the single-stage reactor (acidogenic stage, average $\mu_{\max}$ 0.159 1/h). To accelerate start-up of the process, increase gas generation and retard production of VFAs in the acidogenic stage small amounts of the algal preparation *Biotreat 100* were used.

Saikat Banerjee et al. (33) Distillery wastes from alcohol manufacturing units such as breweries etc. are highly polluted with organic substances. It is necessary to decrease the pollution load to have eco-friendly environment and simultaneously to recover energy from the distillery slop, which possesses enormous energy potential. In view of these experimental studies on biomethanation of distillery wastes have been carried out in a semi-batch digester having different BOD loading of 1.54, 2.12, 2.74, 3.28 and 4.45 kg/m³ at different digestion temperatures in the range of 35–55 °C for hydraulic retention time of 14 days under controlled pH in the range of 6.8–7.2. Generated biogas has been collected at different retention days, and analysis of the gas has been made accordingly. It has been observed that biogas yields as well as methane yield have increased gradually giving maximum yield on 7th day after which biogas generation has gradually decreased. The present study deals with the mathematical analysis of the experimental data on biomethanation and suggests model equations relating maximum specific growth rate and kinetic parameter with digestion temperatures and BOD loading.

W.C. Hu et al. (34) The process kinetics of the mesophilic (35 °C) anaerobic digestion of ice-cream wastewater was investigated. The Monod equation and the Contois equation were used to develop two basic steady-state models. The kinetic parameters required for the application for the steady-state models were determined using a laboratory-scale continuously stirred tank reactor (5 l) fed with a synthetic ice-cream wastewater at a range of hydraulic retention times (2.99–7.45 days). Both models were evaluated with a set of routine analytical data obtained from a pilot-scale (5 m³) anaerobic contact digester treating the ice-cream wastewater at a commercial site. The steady-state model obtained with the Contois equation was more suitable than that obtained with the Monod equation for describing the process kinetics of the pilot-scale anaerobic contact process. The main reason for this is that the kinetic model based on the Contois equation considers the effect of any changes in influent substrate concentration in its prediction.

A. Keshtkar et al (35). Most conventional digesters used for animal wastewater treatment include continuously stirred-tank reactors. While imperfect

mixing patterns are more common than ideal ones in real reactors, anaerobic digestion models often assume complete mixing conditions. Therefore, their applicability appears to be limited. In this study, a mathematical model for anaerobic digestion of cattle manure was developed to describe the dynamic behavior of non-ideal mixing continuous flow reactors. The microbial kinetic model includes an enzymatic hydrolysis step and four microbial growth steps, together with the effects of substrate inhibition, pH and thermodynamic considerations. The bio-kinetic expressions were linked to a simple two-region liquid mixing model, which considered the reactor volume in two separate sections, the flow-through and the retention regions. Deviations from an ideal completely mixed regime were represented by changing the relative volume of the flow-through region (a) and the ratio of the internal exchange flow rate to the feed flow rate (b). The effects of the hydraulic retention time, the composition of feed, the initial conditions of the reactor and the degree of mixing on process performance can be evaluated by the dynamic model. The simulation results under different conditions showed that deviations from the ideal mixing regime decreased the methane yield and resulted in a reduced performance of the anaerobic reactors. The evaluation of the impact of the characteristic mixing parameters (a) and (b) on the anaerobic digestion of cattle manure showed that both liquid-mixing parameters had significant effects on reactor performance.

CHAPTER III

MATERIALS AND METHODS

3.1 Introduction

This study is an experimental research to carry out a kinetic evaluation of two-phase mesophilic anaerobic digestion of organic fraction of municipal solid waste (OFMSW). There are consisted of two main parts of the experimental runs; a) performance of the system by operated with three different feed substrate concentrations: 8, 12, 15 %TS. The hydraulic retention time (HRT) varied between 33 and 18 day (include acidogenic reactors 3 day). The results are evaluated using the Chen-Hashimoto methane production model to determine the kinetic constants (K and $\mu_{\max}$) of the process. And b) prediction of minimum retention time ($\theta_{\min}$) and maximum volumetric methane production rate ($\delta_{\max}$) and demonstration of anaerobic digestion design based on kinetic parameters of waste using in this experiments. The pH, volatile fatty acid, alkalinity, methane yield (l CH₄ STP/gVS added), total solid (TS), volatile solids (VS) will be analyzed.

3.2 Experimental Design

A laboratory-scale two-phase mesophilic anaerobic digestion of organic fraction of municipal solid waste (OFMSW) is set up and conducted in Laboratory Section of Sanitary Engineering Department, Faculty of Public Health Mahidol University. This experimental research is scheduled to determine the kinetic constants; dimensionless kinetic parameter (K) and the maximum specific microbial growth rate ($\mu_{\max}$) of the process using the Chen-Hashimoto methane production model. The experiment was divided in to two main parts; a) performance of the system by operated with three different feed substrate concentrations: 8, 12, and 15 %TS. The total hydraulic retention time (HRT) in acidogenic reactor was set 3 day and methanogenic reactors varied 30, 25, 20 and 15 day corresponding to 12

experimental conditions. Operational conditions during experimental runs were shown in Table 3.1.

Table 3.1 Operational conditions during experimental runs

Group	Experimental Condition	HRTs (d)		Total solid conc. (%TS)
		Acid	Methane	
1	1		30	8
	2		25	8
	3	3	20	8
	4		15	8
2	5		30	12
	6		25	12
	7	3	20	12
	8		15	12
3	9		30	15
	10		25	15
	11	3	20	15
	12		15	15

Remark

* Acidogenic reactors operated at ambient temperature.

** Methanogenic digesters reactors operated at mesophilic range 35 °C.

Table 3.2 Operational conditions during experimental runs feed flow rate of each mixed substrates concentration, which is correspond to hydraulic retention time of methanogenic reactors.

Parameters	Substrate I	Substrate II	Substrate III
Total solid (%)	8	12	15
HRT _{METHANE}	Flow (ml.)	Flow (ml)	Flow (ml)
30.0	400.0	400.0	400.0
25.0	480.0	480.0	480.0
20.0	600.0	600.0	600.0
15.0	800.0	800.0	800.0

Volume of Reactor 12 liters.

$$\text{Flow rate formula (Q)} = \frac{\text{Volume of reactor (12 l.)}}{\text{HRT}_{\text{methane}} \text{ (d.)}}$$

3.3 Research Model

3.3.1 Substrate preparation and characterization

Organic fraction of municipal solid waste (OFMSW) is obtained from the integrated solid management center located in Chonburi. This waste obtains from the last process of sorting station after sorting out of inorganic waste with sorting processes. The characteristics of each waste are measured immediately before two waste streams are mixed. The OFMSW was diluted with tap water to varied total solid concentrations 8, 12, 15 % in three 50 L capacity of storage tank and then stored in refrigerator at 4 °C.

The organic fraction of municipal solid waste (OFMSW) is analyzed by using the procedures prescribed in the Standard Method (36). After the mixed substrate is carried out in each experiment, the pH was control by buffer solution (NaHCO₃). Then, the final alkalinity of the test solutions is in range 3000-5000 mg/l.

3.3.2 Equipment and Materials.

3.3.2.1 Two-phase Mesophilic Anaerobic Digestion systems

1) Reactors: three anaerobic digestion systems were operated in a parallel sequence. This unit divided into two types of reactors.

1.1) Three acidogenic reactors are made of acrylic with dimension of 16 centimeter (diameter) X 25 centimeter (height) as illustrated in Figure 3.2. The reactor has a working volume of 8 liters.

1.2 Three methanogenic reactors are made of stainless steel with dimension of 22 centimeter (diameter) X 45 centimeter (height) as illustrated in Figure 3.2. The reactor has a working volume of 13 liters.

2) Stirrers: the reactor was completely mixed by central stirrer shaft connected with speed motor.

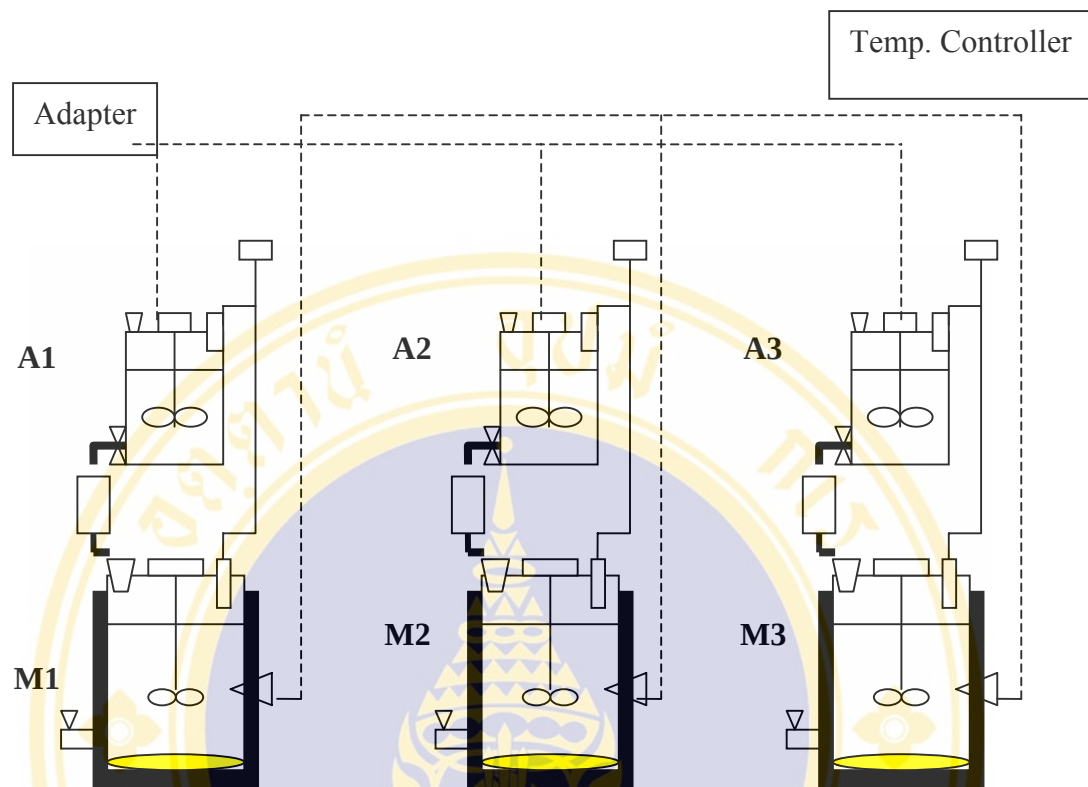
3) Timer: the equipment was used to set time for feeding and mixing the system.

4) Heater and temperature controller: heater 1000 W couple with temperature sensor and link information to temperature controller at 35 °C.

5) Influent and effluent container: the influent container and effluent container were made of plastic with volume of 50 liters and 10 liters respectively.

6) Feeder: the reactor was fed with OFMSW from influent container by feeder device (Quasi-continuous)

7) Gas collectors: gas meter used by liquid displacement method.



Sizing and Dimension

1. Acidogenic reactors have total volume 10 liters, active volume 8 liters, diameter 16 cm and height 25 cm.
2. Methanogenic reactors have total volume 17 liters, active volume 12 liters, diameter 22 cm. height 45 cm.

Figure 3.1 A schematic drawing of the experimental units.

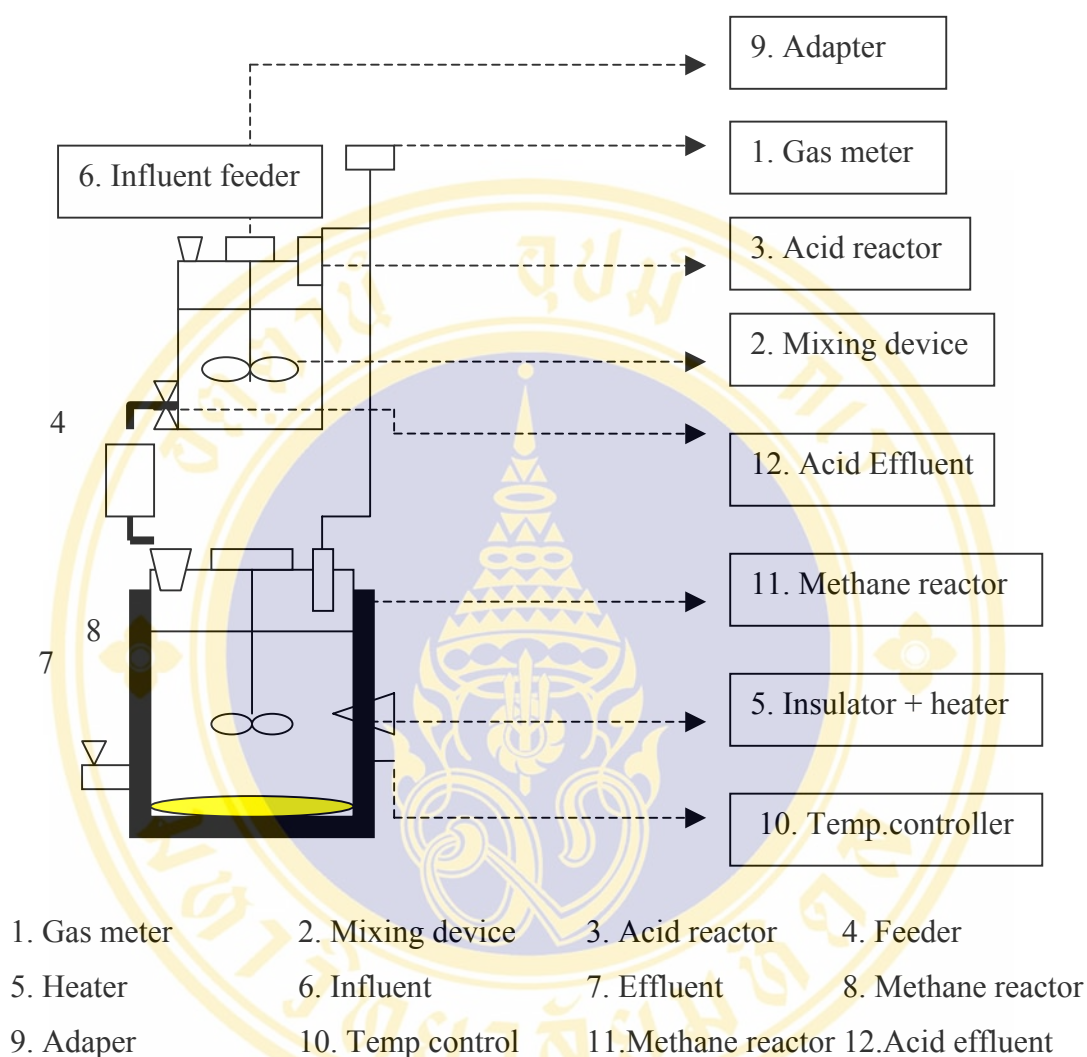


Figure 3.2 A schematic drawing of the anaerobic digestion dimension.

3.3.2.2 Equipment and materials for laboratory analysis

- 1) pH meter
- 2) Hot-air oven, Desiccators, Muffle furnace
- 3) Pipette size 5 and 10 ml
- 4) Beaker size 50, 100, 500 and 1,000 ml
- 5) Cylinder size 50, 100 and 1,000 ml
- 6) Volumetric flask size 50, 100, 500 and 1,000 ml
- 7) Erlenmeyer flask size 150, 250 ml
- 8) Volumetric pipette size 25 ml

3.4 Procedures and Analytical Methods

The experiments are carried out to evaluate a kinetic of two-phase mesophilic anaerobic digestion of organic fraction of municipal solid waste (OFMSW). The results are evaluated using the Chen-Hashimoto methane production model to determine the kinetic constants (K and $\mu_{\max}$) of the process. The pH, volatile fatty acid, alkalinity, methane yield ($l\ CH_4STP/gVS$ added), total solid (TS), volatile solids (VS) will be analyzed.

3.4.1 Experimental procedures

1) Seeding and Acclimatization

The reactors were seeded with anaerobic digester sludge from Nuang Kham sludge treatment plant having a TS content of 43,000 mg/l or 4.3 % TS. Three methanogenic digester was seed with 12 liters of dilution seed containing 43,000 mg/l (4.3 %TS).

During this acclimatization period, the organic loading rate (OLR) was gradually increased with 3.0 g VS/l per day between 1 and 15 days, 4.0 g VS/l per day between 16 and 30 days, 5 g VS/l per day between 31 and 45 days and finally 6 g VS/l per day between 46 and 60 days.

Table 3.3 The start-up of the reactor involved stepwise increases in VS loading using an influent substrate concentration of 127 g VS/l. (TS 15%)

Date	OLR (g VS/l per day)	Feed flow rate ml./day
1-15	3.0	283
16-30	4.0	378
31-45	5.0	472
46-60	6.0	567

This seeding and acclimatization period was followed by a series of continuous experiments using feed flow-rates of 400, 480, 600 and 800 ml per day for the three feed concentration 8, 12, 15 %TS each of feed substrate correspond to hydraulic retention times of 30, 25, 20 and 15 respectively.

The initial acclimatization period took place of about 2 months. In each experimental run, the reactors were considered to reach the steady-state when both volatile solid reduction and pH exhibited signs of stability (31)

3.4.1.2 Experimental process

The experimental process was divided into three major groups in each experimental run by used of OFMSW from integrated waste management center Chonburi province : Performance study of two phase mesophilic anaerobic digestion of OFMSW and then dilute with tap water for desired total solid concentration; the total solid concentration was divided into 3 conditions (reactors) as followed:

- **Group 1**, the total solid concentration were used at 8 %TS; whereas the hydraulic retention times (HRTs) were varied at 3 day in acidogenic reactors and 30, 25, 20, 15 day in methanogenic reactors).
- **Group 2**, the total solid concentration were used at 12 %TS; whereas the hydraulic retention times (HRTs) were varied at 3 day in acidogenic reactors and 30, 25, 20, 15 day in methanogenic reactors).
- **Group 3**, the total solid concentration were used at 15 %TS; whereas the hydraulic retention times (HRTs) were varied at 3 day in acidogenic reactors and 30, 25, 20, 15 day in methanogenic reactors).

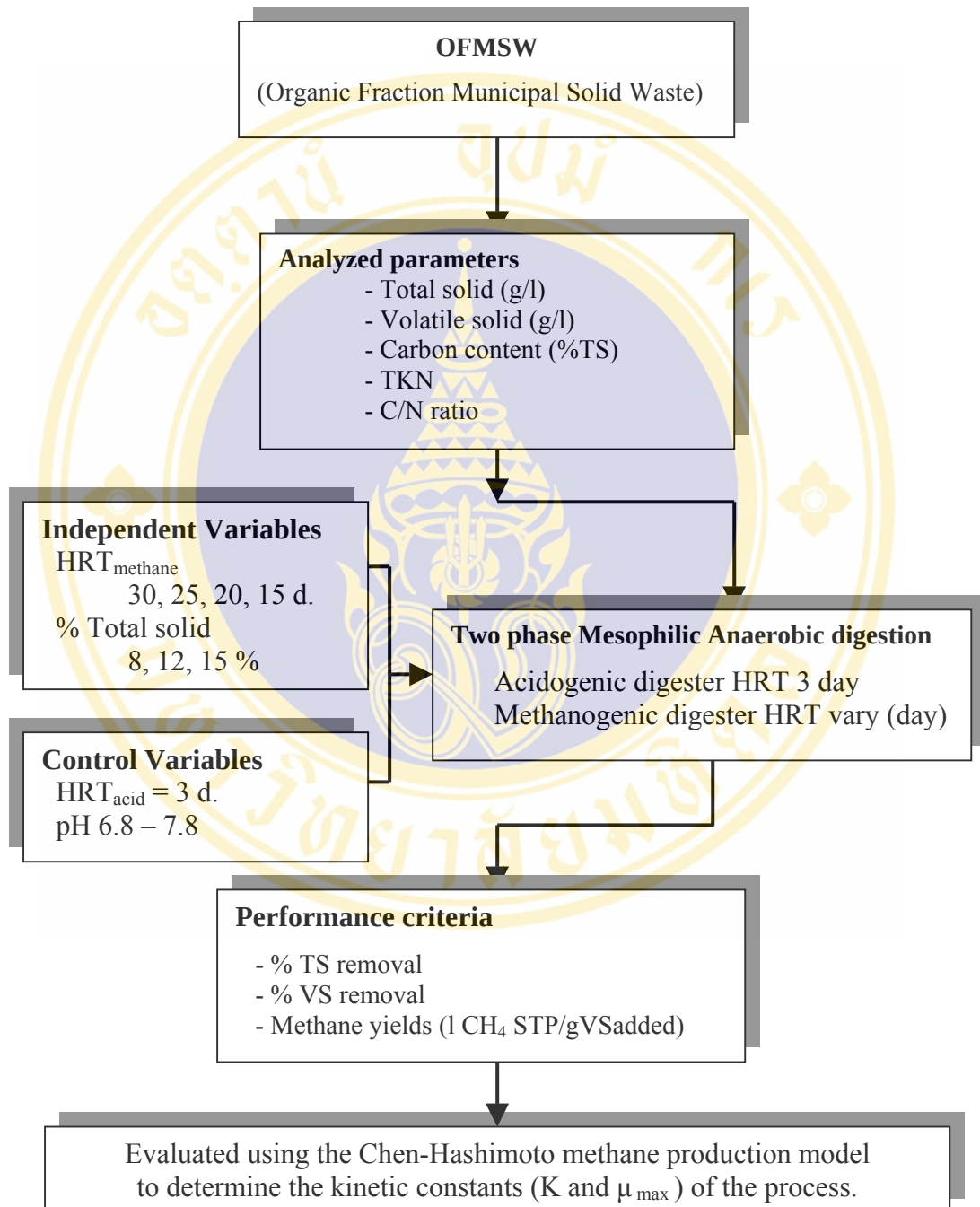
In each group, HRTs were maintained constantly HRT by flow rate of influent as calculated in equation below and summarized in Table 3.3 while the total solid concentration were varied as calculated in below as well.

$$\text{Hydraulic retention time (day)} = \frac{\text{Working volume of reactor (liter)}}{\text{Flow rate (liter/day)}}$$

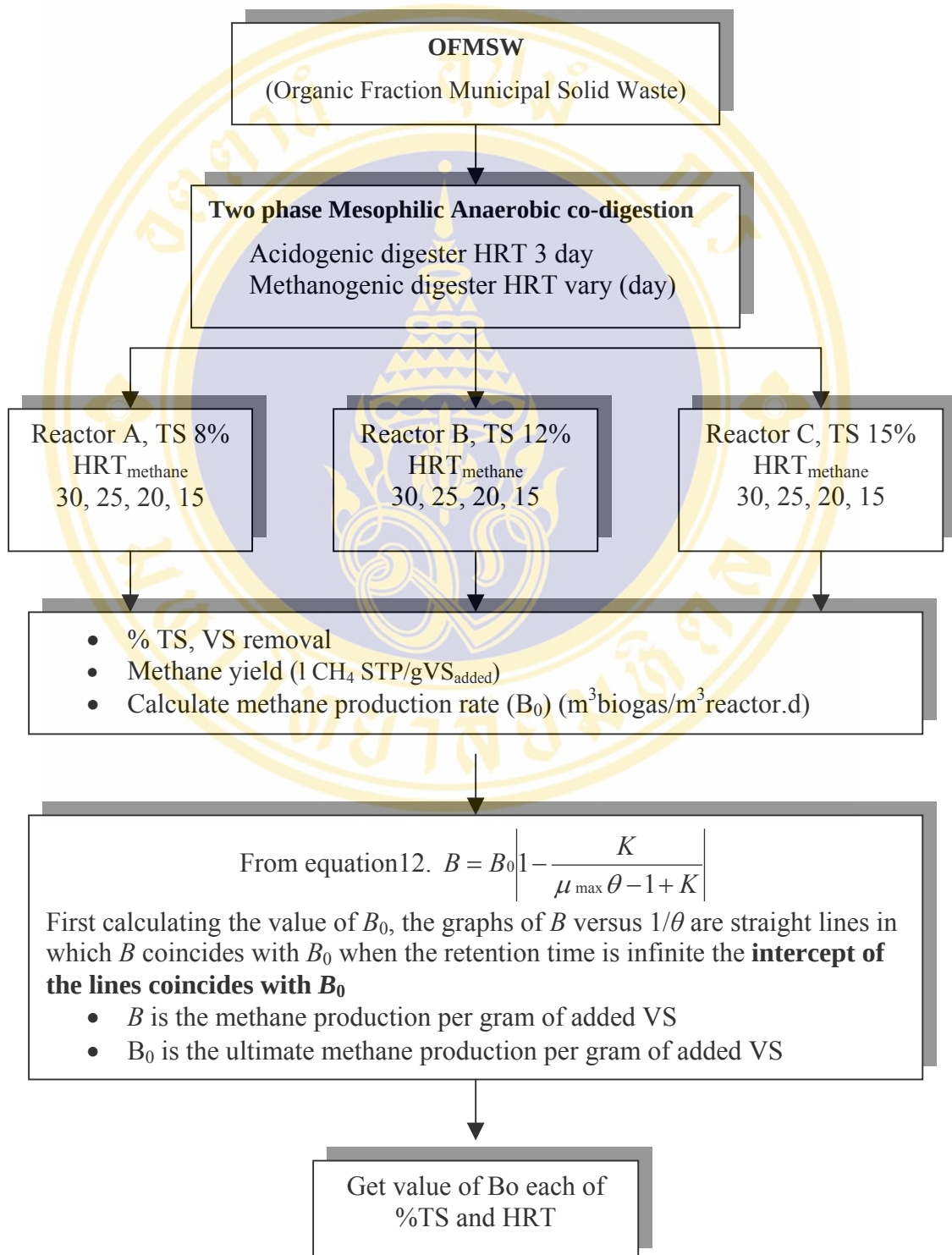
Dilution formula

$$C_1V_1 = C_2V_2$$

PART I: Kinetic studies operating with three total solid concentrations (%TS) and varied HRT 18-33day. (Included 3 days in acidogenic reactors)



Part II: Procedure used in evaluate the Chen-Hashimoto methane production model to determine the kinetic constants (K and $\mu_{\max}$) of the process and prediction of minimum hydraulic retention time ($\theta_{\min}$) and the maximum volumetric methane production rate ($\delta_{\max}$)



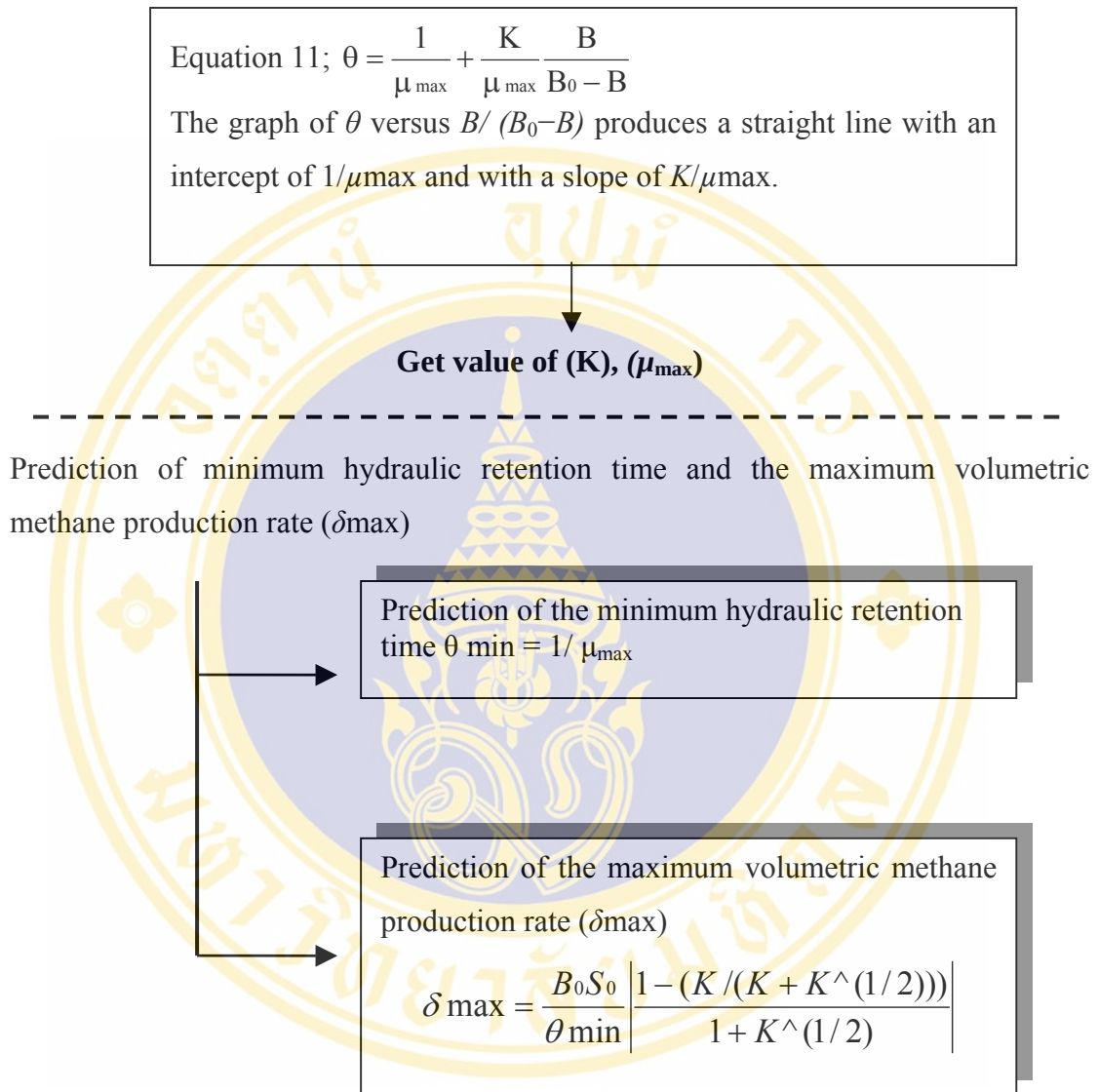


Figure 3.3 Summary of the experimental procedures

3.4.2 Analytical Methods

The influent and effluent samples were collected by grab sampling daily. Influent and effluent samples were collected from the influent container and effluent container, respectively. The samples were analyzed for total solid (TS), Volatile Solids (VS), Volatile fatty acid (VFA), Alkalinity, and pH, according to Standard Methods for the Examination of Water and Wastewater.

The parameters and analytical methods were described in Table 3.3. The chemical reagents and analytical apparatus used in this experiment were summarized in Table 3.4.

Table 3.3 Analytical methods and sampling intervals

Parameters	Methods	Sampling Points	
		Acid reactors	Methane reactors
TS	Total solid dried at 103-105 °C	**	**
VS	Volatile solid dried at 550 °C	**	**
TKN	Kjeldahl digestion method	****	****
pH	Glass electrode method	*	*
VFA	Titration method	*	*
Alkalinity	Titration method	*	*
Biogas production	Water displacement method	-	****

Note

- No
- * Analyzed 2 times/week
- ** Analyzed 3 times/week
- *** Daily
- **** Analyzed 3 times/run

Table 3.4 Chemical reagents and analytical apparatus

Parameter	Apparatus	Chemical reagent
TS	• Evaporation dish	
	• Analytical balance	
	• Drying oven, 103-105 °C	
	• Hot plate	
	• Measuring device	
	• Muffle furnace	
VS	• Hot-air oven	
	• Analytical balance	
	• Desiccators	
	• Evaporation dish	
pH	• pH meter	
VFA & Alkalinity	• pH electrode	• 0.05 N NaOH
	• magnetic stirrer	• 0.1 N H ₂ SO ₄
TKN	• Digestion Apparatus	• Sulfuric acid (conc.)
	➤ Digestion tubes	• Potassium sulfate
	➤ Digestion heating	• Mercuric(II)oxide (red)
	• Distillation Apparatus	• Sodium hydroxide
		• Sodium thiosulfate pentahydrate
		• Boric acid

3.5 Statistical Analysis

3.5.1 Descriptive Analysis: The productions of TS, VS, methane yield, from anaerobic digestion were described as mean values, minimum values, maximum values and standard deviation (S.D.).

3.5.2 The Two- Way ANOVA at 0.05 level of significance was used to test for statistically significant differences among the levels of dependent variables. All data were analyzed by using the package program of SPSS 11.0.

3.5.3 Regression analysis was performed to decide whether HRTs or total solid concentration in feed substrate affecting the production of methane yield and TS, VS removal by using forward stepwise regression and predict them by using polynomial regression.

3.6 Chen-Hashimoto kinetic model of anaerobic digestion

Chen-Hashimoto model is used for kinetic analysis of the experimental data. In a completely mixed continuous digester The rates of change of cell mass and substrate concentration are expressed by the following equations:

$$\frac{dX}{dt} = \mu X - \frac{X}{\theta} \quad (3.1)$$

$$\frac{dS}{dt} = -r + \frac{S_0 - S}{\theta} \quad (3.2)$$

$$\mu = \frac{Yr}{X} \quad (3.3)$$

Where;

- X = the concentration of cell mass
- μ = the specific microbial growth rate
- θ = the hydraulic retention time
- S_0 = the concentration of substrate in the influent
- S = the concentration of substrate in the effluent
- R = the volumetric substrate utilization rate.
- Y = the yield coefficient (cell mass/substrate mass)

In the steady-state, $dX/dt = 0$ and $dS/dt = 0$, hence

$$\frac{dX}{dt} = \mu X - \frac{X}{\theta} \longrightarrow \mu X = \frac{X}{\theta} \longrightarrow \mu = \frac{1}{\theta} = D \quad (3.4)$$

Where D is the dilution rate

$$\frac{dS}{dt} = r + \frac{S_0 - S}{\theta} \longrightarrow r = \frac{S_0 - S}{\theta} \quad (3.5)$$

And from eq. 3

$$\mu = \frac{Yr}{X} \longrightarrow X = \frac{Yr}{\mu} \longrightarrow \frac{Y(S_0 - S)}{\frac{1}{\theta}} \longrightarrow X = Y(S_0 - S) \quad (3.6)$$

Substituting these expressions in Contois' equation:

$$\mu = \frac{\mu_{\max} S}{\beta X + S} \quad (3.7)$$

$\mu_{\max}$ = the maximum specific microbial growth rate.

β = a dimensionless kinetic parameter, one obtains:

K = a dimensionless kinetic parameter equal to $Y\beta$.

μ = specific microbial growth rate (per day)

θ = hydraulic retention time (day)

$\mu_{\max}$ = maximum specific microbial growth rate (per day)

$\theta_{\min}$ = the minimum hydraulic retention time (days)

K = a dimensionless kinetic parameter

S_0 = feed volatile solid concentration (gVS/l)

S = volatile solid concentration in the effluent (gVS/l)

B = methane yield: volume of methane produced under normal conditions of pressure and temperature per grams of substrate (VS) added to the digester (l CH₄ STP/ gVS_{add})

B_0 = ultimate methane yield: volume of methane produced under normal conditions of pressure and temperature per gram of substrate added at infinite retention time (l CH₄ STP / gVS_{add})

$$\begin{aligned}\delta &= \text{volume CH}_4 \text{ per volume digester per unit time} \\ &\quad (\text{l CH}_4 \text{ STP} / \text{l}_{\text{reactor}} \text{ per day}) \\ \delta_{\max} &= \text{the maximum volumetric methane production rate} \\ &\quad (\text{l. CH}_4 \text{ STP} / \text{l}_{\text{reactor}} \text{ per day})\end{aligned}$$

$$\begin{aligned}\text{Eq. 3.7} \quad \mu &= \frac{\mu_{\max} S}{\beta X + S} \\ \frac{1}{\theta} &= \frac{\mu_{\max} S}{\beta Y(S_0 - S) + S} \quad \text{---} \rightarrow \text{BY } (S_0 - S) + S = \mu_{\max} \theta S \\ K(S_0 - S) + S &= \mu_{\max} \theta S \\ S &= \frac{KS_0 - KS + S}{\mu_{\max} \theta} \quad \text{---} \rightarrow \frac{KS_0 - S(K-1)}{\mu_{\max} \theta} \\ \mu_{\max} \theta S &= KS_0 - S(K-1) \quad \text{---} \rightarrow S\mu_{\max} \theta + S(K-1) = KS_0 \\ S(\mu_{\max} \theta + K - 1) &= KS_0 \quad \text{---} \rightarrow \frac{S}{S_0} = \frac{K}{\mu_{\max} \theta + K - 1} \quad (3.8)\end{aligned}$$

Eq. (3.8) shows that effluent substrate concentration depends on the influent substrate concentration.

The minimum retention time indicating when the washout of micro-organisms occurs is numerically equal to the reciprocal of the maximum growth rate:

$$\theta_{\min} = \frac{1}{\mu_{\max}} \quad (3.9)$$

A reduction of 1 g VS is equivalent to the production of 0.35 l of methane at STP. Knowing the VS loading to the reactor and the volume of methane produced, the remaining VS in the digester can be calculated. If B denotes the volume (in liters) of methane produced under normal conditions of pressure and temperature per gram of substrate (VS) added to the digester, and B_0 is the volume of methane produced under normal conditions of pressure and temperature per gram of substrate added at infinite retention time or for complete utilization of substrate, the biodegradable VS in the reactor will be directly proportional to $(B_0 - B)$, and B_0 will be directly proportional to the biodegradable VS loading. Therefore, from Eq. (3.8) one obtains:

$$\frac{B_0 - B}{B_0} = \frac{K}{\mu_{\max} \theta - 1 + K} \quad (3.10)$$

From Eq. (3.10) one obtains:

$$\theta = \frac{1}{\mu_{\max}} + \frac{K}{\mu_{\max}} \frac{B}{B_0 - B} \quad (3.11)$$

Thus, by first calculating the value of B_0 , the graph of θ versus $B/(B_0 - B)$ produces a straight line with an intercept of $1/\mu_{\max}$ and with a slope of $K/\mu_{\max}$.

To obtain the parameter B_0 one uses the following equation, which is easily derived from Eq. (3.10):

$$B = B_0 \left| 1 - \frac{K}{\mu_{\max} \theta - 1 + K} \right| \quad (3.12)$$

such that when $\theta/\theta_{\min} = \mu_{\max} \theta \gg |1 - K|$, the graphs of B versus $1/\theta$ are straight lines in which B coincides with B_0 when the retention time is infinite, which is to say the intercept of the lines coincides with B_0 . Since B is the methane production per gram of added VS, the volumetric methane production rate (δ) equals B multiplied by the loading rate:

$$\delta = \frac{BS_0}{\theta} = \frac{B_0 S_0}{\theta} \left| 1 - \frac{K}{\mu_{\max} \theta - 1 + K} \right| \quad (3.13)$$

where δ has the dimensions of volume CH_4 per volume digester per unit time. The maximum volumetric methane production rate, $\delta_{\max}$, is obtained by taking the derivative of δ in terms of θ and equating it to zero. So,

$$\delta_{\max} = \frac{B_0 S_0}{\theta_{\min}} \left| \frac{1 - (K / (K + K^{(1/2)}))}{1 + K^{(1/2)}} \right| \quad (3.14)$$

Since the plot of B versus $1/\theta$ was found to be linear for the above-mentioned range of retention times, linear regressions (least squares method) were used to determine the intercept B_0 .

Once the parameters for B_0 and the values for B were determined, θ against $B/(B_0 - B)$ can be plotted. The kinetic parameters, $\mu_{\max}$ and K , can be calculated for each influent substrate concentration.

The theoretical B values were calculated by using Eq. (3.12). As can be seen in the values of both parameters decreased when influent substrate concentration increased. Therefore, the kinetic parameters were found to be influenced by the influent substrate concentration, which shows the occurrence of an inhibitor in the waste material.

CHAPTER IV

RESULTS

This experimental research was carried out to evaluate a kinetic study of two-phase mesophilic anaerobic digestion of organic fraction of municipal solid waste (OFMSW). There are consisted of two main parts of the experimental runs; a) the results are evaluated using the Chen-Hashimoto methane production model to determine the kinetic constants (K and $\mu_{\max}$) of the process and prediction of minimum retention time ($\theta_{\min}$) and maximum volumetric methane production rate ($\delta_{\max}$). And b) removal efficiency of the system by operated with three different feed substrate concentrations: 8, 12, and 15 %TS. The hydraulic retention times (HRTs) varied between 33 and 18 day (include acidogenic reactors 3 day). The pH, Volatile Fatty Acid, Alkalinity, methane yields ($l\ CH_4\ STP/gVS_{\text{added}}$), Total Solid, and Volatile Solids (VS) will be analyzed.

4.1 Influent Substrate Characteristics

General characteristics of organic fraction of municipal solid waste from the Integrated waste management center Chonburi, as an influent used in this study, were presented in Table 4.1

Table 4.1 Characteristics of organic fraction of municipal solid waste (OFMSW) from the integrated waste management center, Chonburi.

Parameter	Range	Mean	S.D.
Total solids (g/L)	320-325	322	2.65
Volatile solids (g/L)	272-276	273	2.25
Carbon (% C)	15.11-15.35	15.21	0.12
TKN (mg/L)	4317-4737	4523	210
C/N ratio	32-35	33.7	1.53

4.2 Seeding and Acclimatization

The experiment was started with seeding and acclimatization periods. Anaerobically digested sludge was obtained from Nuang Kham Wastewater Treatment Plants. The initial feed digested concentration was around 43,000 mg/l as presented in Table 4.2

In acclimatization period, the organic fraction of municipal solid waste (OFMSW) is gradually feed, which increased organic loading rate step by step, starting 3 gVS/l.d to 4.0, 5.0 and 6.0 gVS/l.d at the final step. The initial acclimatization period took place of about 2 month. In each experimental run, the reactors were considered to reach the steady-state when both volatile solid reduction and pH exhibited signs of stability.

Table 4.2 Characteristics of seed sludge during the research period.

Parameter	Range	Mean	S.D.
Total solids (g/L)	40-48	43	3.6
Volatile solid (g/L)	24-28.3	25.6	1.9
Carbon (% C)	1.33-1.57	1.4	0.1
TKN (mg/L)	1443-1604	1540.3	69.9
C/N ratio	8.47-9.80	9.2	0.6

4.3 Determination of Kinetic Coefficients

To determine the kinetic coefficients using Chen-Hashimoto methane production model, two phase mesophilic anaerobic digestion system was operated. The important parameters must be available were B , $\theta_{\min}$, B_0 , K , $\mu_{\max}$ and $\delta_{\max}$.

In determining these coefficients, several different HRTs were selected for the operation at 30, 25, 20, and 15 day using the data collected at steady state conditions, and mean values should be determined for B , B_0 .

The equations using to calculate the coefficients, K , $\mu_{\max}$, $\theta_{\min}$ and $\delta_{\max}$ are as followed:

$$\theta_{\min} = \frac{1}{\mu_{\max}} \quad \text{----- (4.1)}$$

$$B = B_0 \left| 1 - \frac{K}{\mu_{\max} \theta - 1 + K} \right| \quad \text{----- (4.2)}$$

$$\frac{B_0 - B}{B_0} = \frac{K}{\mu_{\max} \theta - 1 + K} \quad \text{----- (4.3)}$$

$$\theta = \frac{1}{\mu_{\max}} + \frac{K}{\mu_{\max}} \frac{B}{B_0 - B} \quad \text{----- (4.4)}$$

$$\delta = \frac{BS_0}{\theta} = \frac{B_0 S_0}{\theta} \left| 1 - \frac{K}{\mu_{\max} \theta - 1 + K} \right| \quad \text{----- (4.5)}$$

$$\delta_{\max} = \frac{B_0 S_0}{\theta_{\min}} \left| \frac{1 - (K / (K + K^{(1/2)}))}{1 + K^{(1/2)}} \right| \quad \text{----- (4.6)}$$

Where,

- μ = specific microbial growth rate (per day)
- θ = hydraulic retention time (day)
- $\mu_{\max}$ = maximum specific microbial growth rate (per day)
- $\theta_{\min}$ = the minimum hydraulic retention time (days)
- K = a dimensionless kinetic parameter
- S_0 = feed volatile solid concentration (gVS/l)
- S = volatile solid concentration in the effluent (gVS/l)
- B = methane yield: volume of methane produced under normal conditions of pressure and temperature per grams of substrate (VS) added to the digester (l CH₄ STP/ gVS_{added})
- B_0 = ultimate methane yield: volume of methane produced under normal conditions of pressure and temperature per gram of substrate added at infinite retention time (l CH₄ STP / gVS_{added})
- δ = volume CH₄ per volume digester per unit time (l CH₄ STP / l_{reactor} per day)
- $\delta_{\max}$ = the maximum volumetric methane production rate (l. CH₄ STP / l_{reactor} per day)

4.3.1. Evaluation of ultimate methane yield (B_0) from experimental runs

To obtain the parameter B_0 one uses the following equation.

$$B = B_0 \left[1 - \frac{K}{\mu_{\max} \theta - 1 + K} \right] \quad (4.2)$$

Thus, by first calculating the value of B_0 , the graphs of B versus $1/\theta$ are straight lines in which B coincides with B_0 when the retention time is infinite, which is to say the intercept of the lines coincides with B_0 .

Table 4.3 Mean values for determining kinetic coefficient (B_0) of two phase mesophilic anaerobic digestion.

HRT (days)	$1/\theta$	B (l CH ₄ STP/gVSadded)		
		TS 8%	TS 12%	TS 15%
30	0.033	0.45	0.41	0.37
25	0.040	0.39	0.38	0.31
20	0.050	0.33	0.26	0.22
15	0.067	0.23	0.17	0.14

The values of B_0 can be determined by plotting the term $(1/\theta)$ versus B . The intercept of the straight line was equal to B_0 . Charts showed in Figure 4.1.

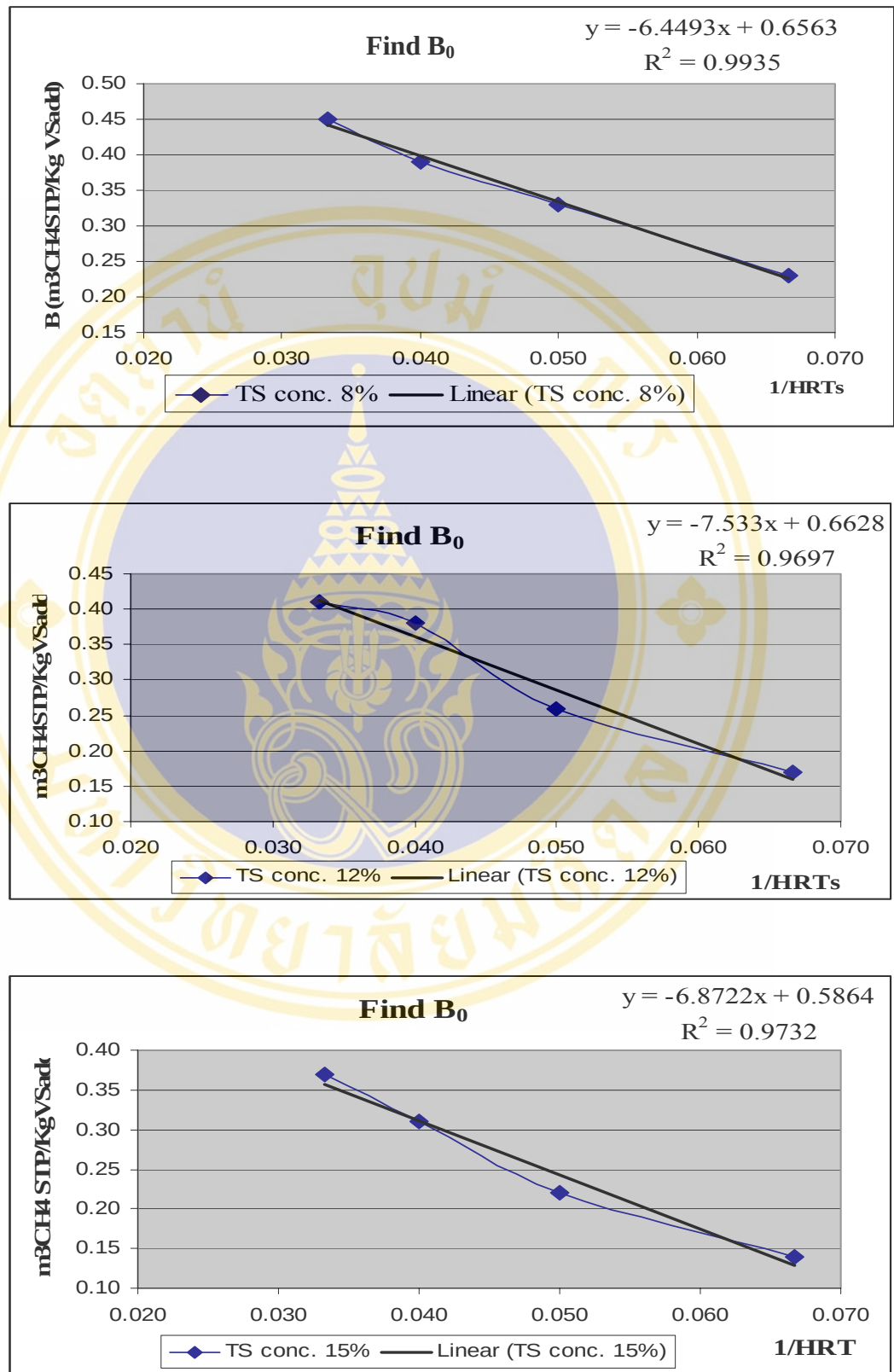


Figure 4.1 Plotting the term $(1/\theta)$ versus B for TS conc. 8, 12, 15 %

From Figure 4.1, equations and R^2 were used to determine the coefficients, B_0 . Equations 4.7, 4.8, 4.9 were the equations from plotting term $(1/\theta)$ versus (B)

$$Y = -6.4493 X + 0.6563, \quad R^2 = 0.9935 \quad (4.7)$$

$$Y = -7.533 X + 0.6628, \quad R^2 = 0.9697 \quad (4.8)$$

$$Y = -6.8722 X + 0.5864, \quad R^2 = 0.9732 \quad (4.9)$$

The equation from 4.7 to 4.9 indicates the linear correlation between $1/\text{HRTs}$ and B . The Y intercept of the vertical axis is equal to B_0 which is 0.6563, 0.6628, 0.5864 l $\text{CH}_4 \text{ STP/g VS}_{\text{added}}$ from total solid concentration 8, 12, 15 %, respectively.

4.3.2. Evaluation of kinetic constants of the process (μ_{max} and K) by using the Chen-Hashimoto methane production model.

From these coefficients (B_0) can be evaluated kinetic constant of the process (μ_{max} and K) by the following equation 4.4

$$\theta = \frac{1}{\mu_{\text{max}}} + \frac{K}{\mu_{\text{max}}} \frac{B}{B_0 - B} \quad (4.4)$$

The graph of θ versus $B/(B_0 - B)$ produces a straight line with an intercept of $1/\mu_{\text{max}}$ and with a slope of K/μ_{max} . Charts showed in Figure 4.2

Table 4.4 Mean values for determining kinetic coefficient (B_0) of two phase mesophilic anaerobic digestion.

HRT	B /(B_0 -B)		
	8	12	15
30	2.181	1.622	1.710
25	1.465	1.344	1.122
20	1.011	0.645	0.600
15	0.540	0.345	0.314

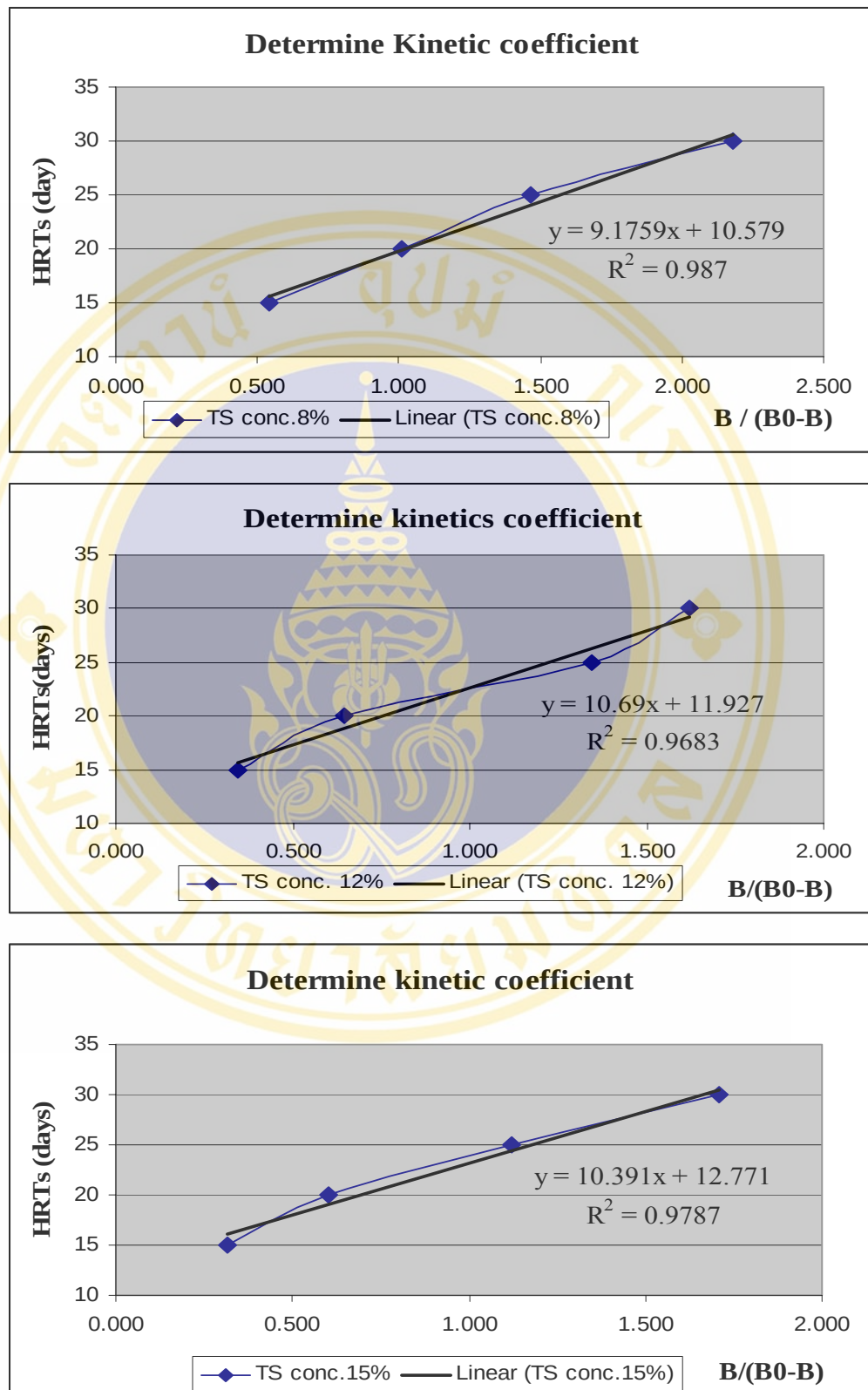


Figure 4.2 Plotting the term $B / (B_0 - B)$ versus HRTs for TS conc.8, 12, 15 %

From Figure 4.2, equations and R^2 were used to determined the coefficients, K and $\mu_{\max}$. Equation 4.10, 4.11 and 4.12 were the equation from plotting term $B/(B_0-B)$ versus HRTs for TS conc. 8, 12, 15 %, respectively.

$$Y = 9.1759 X + 10.579 \quad R^2 = 0.9870 \quad (4.10)$$

$$Y = 10.69 X + 11.927 \quad R^2 = 0.9683 \quad (4.11)$$

$$Y = 10.391X + 12.771 \quad R^2 = 0.9787 \quad (4.12)$$

The equation 4.10 - 4.12 indicated the linear correlation between $B/(B_0-B)$ and HRTs. the graph of θ versus $B/(B_0-B)$ produces a straight line with an intercept of $1/\mu_{\max}$ and with a slope of $K/\mu_{\max}$. So $\mu_{\max}$ can be finding from 1/intercept of the vertical axis, which is 0.095, 0.084, and 0.078 d^{-1} from total solid concentration 8, 12, and 15 %, respectively. The slope of the straight line is 9.1759, 10.69, and 10.391 from total solid concentration 8, 12, and 15 %, respectively. Therefore the K is equal to slope of straight line multiply by $\mu_{\max}$, which is 0.867, 0.846, and 0.814 from total solid concentration 8, 12, and 15 %, respectively.

4.3.3 Prediction of minimum retention time and maximum volumetric methane production rate

The minimum retention time indicating when the washout of micro-organisms occurs is numerically equal to the reciprocal of the maximum growth rate:

$$\theta_{\min} = \frac{1}{\mu_{\max}} \quad 4.1$$

When $\theta/\theta_{\min} = \mu_{\max}\theta \gg |1 - K|$, Since B is the methane production per gram of added VS, the volumetric methane production rate (δ) equals B multiplied by the loading rate:

$$\delta = \frac{BS_0}{\theta} = \frac{B_0S_0}{\theta} \left| 1 - \frac{K}{\mu_{\max}\theta - 1 + K} \right| \quad 4.5$$

Where δ has the dimensions of volume CH₄ per volume digester per unit time. The maximum volumetric methane production rate, $\delta_{\max}$, is obtained by taking the derivative of δ in terms of θ and equating it to zero. So,

$$\delta_{\max} = \frac{B_0 S_0}{\theta_{\min}} \left| \frac{1 - (K / (K + K^{1/2}))}{1 + K^{1/2}} \right| \quad 4.6$$

From these coefficients can calculate $\theta_{\min}$, $\delta_{\max}$ by following the equation 4.1 and 4.6, and summarized the value in Table 4.5.

Table 4.5 summarized the values of kinetic coefficient by Chen-Hashimoto methane production model.

Parameters	Unit	TS concentration		
		8%	12%	15%
S_0	g VS/l	68.63	102.48	127.27
B_0	l CH ₄ STP/gVS added	0.6563	0.6628	0.5864
K	-	0.867	0.846	0.814
$\mu_{\max}$	day ⁻¹	0.095	0.084	0.078
$\theta_{\min}$	day	10.579	11.927	12.771
$\delta_{\max}$	l CH ₄ STP / l _{reactor} .d	1.14	1.50	1.62

4.4 Removal Efficiency of Anaerobic Digestion of OFMSW

The experiments were divided into 3 groups of the two-phase anaerobic digestion system, consisting of 12 experimental conditions. Hydraulic retention times in methanogenic tanks were set at 30, 25, 20 and 15 day. Total solids concentrations in methanogenic tanks were set at 8% (80,000 mg/L), 12% (120,000 mg/L), and 15 % (150,000 mg/L). The total solids (TS), volatile solids (VS) and methane yield (l CH₄STP/ g VS added), pH, Volatile Fatty Acid (VFA), Alkalinity, will be analyzed.

The result presentations were divided into three groups namely group 1, group 2 and group 3. The details of results were described as follows

4.4.1 Group 1: Removal efficiency of anaerobic digestion of OFMSW at TS 8% (80,000 mg/L) and 30, 25, 20, 15 days HRT

The experiments were performed with total solid concentration 8 % (80,000 mg/l) and 30, 25, 20, 15 day HRT. The results of total solid removal, volatile solid removal and methane yield (B) were presented in Table 4.6 and 4.7. Removal efficiency of total solids, volatile solids and methane yields (B) were shown in Figure 4.3.

4.4.1.1 Experimental condition 1: The experiment was performed with total solid concentration 80,000 mg/L and HRT of 30 days. The average removal efficiency of total solids, volatile solids and methane yields were 77.08 % (SD.=0.52), 88.49 % (SD.=0.47) and 0.45 l.CH₄STP/gVS_{added} (SD.=0.01), respectively.

4.4.1.2 Experimental condition 2: The experiment was performed with total solid concentration 80,000 mg/L and HRT of 25 days. The average removal efficiency of total solids, volatile solids and methane yields were 74.96 % (SD.=0.66), 87.81 % (SD.=0.36) and 0.39 l.CH₄STP/gVS_{added} (SD.=0.01), respectively.

4.4.1.3 Experimental condition 3: The experiment was performed with total solid concentration 80,000 mg/L and HRT of 20 days. The average removal efficiency of total solids, volatile solids and methane yields were 72.25 % (SD.=0.42), 82.89 % (SD.=1.07) and 0.33 l.CH₄STP/gVS_{added} (SD.=0), respectively.

4.4.1.4 Experimental condition 4: The experiment was performed with total solid concentration 80,000 mg/L and HRT of 15 days. The average removal efficiency of total solids, volatile solids and methane yields were 68.69 % (SD.=0.91), 78.44 % (SD.=0.54) and 0.23 l.CH₄STP/gVS_{added} (SD.=0), respectively.

Table 4.6 The average of TS, VS removal efficiency and Methane yields of two-phase anaerobic digestion in group 1. (Total solid concentration 8 %, HRT of 30, 25, 20 and 15 days)

Parameter		Condition 1 (HRT 30 d)	Condition 2 (HRT 25 d)	Condition 3 (HRT 20 d)	Condition 4 (HRT 15 d)
TS removal (% removal)	Min	76	73.3	71.5	66.6
	Max	77.8	76.1	73	69.6
	Mean	77.08	74.96	72.25	68.69
	SD.	0.52	0.66	0.42	0.91
VS removal (% removal)	Min	87.5	87.1	81	77.7
	Max	89.4	88.4	84.4	79.6
	Mean	88.49	87.81	82.89	78.44
	SD.	0.47	0.36	1.07	0.54
Methane yields (l. CH ₄ STP /g.VS _{added})	Min	0.46	0.44	0.34	0.23
	Max	0.48	0.45	0.34	0.24
	Mean	0.45	0.39	0.33	0.23
	SD.	0.01	0.01	0	0

Table 4.7 The average of monitoring parameter: pH, VFA, Alkalinity, of two-phase anaerobic digestion in group 1. (Total solid concentration 8 %, HRT of 30, 25, 20 and 15 days)

Parameter		Condition 1 (HRT 30 d)	Condition 2 (HRT 25 d)	Condition 3 (HRT 20 d)	Condition 4 (HRT 15 d)
pH	Min	7.38	7.44	7.23	7.16
	Max	7.4	7.5	7.3	7.2
	Mean	7.3	7.4	7.1	7.1
	SD.	0.038	0.052	0.071	0.053
VFA mg/l as Acetic	Min	398	525	600	1045
	Max	468	575	675	1845
	Mean	438	555	639	1531
	SD.	19.41	16.26	28.85	282.19
Alkalinity mg/l as CaCO ₃	Min	1328	1528	1714	2210
	Max	1517	1833	2109	3372
	Mean	1447	1631	1847	2978
	SD.	59.95	100.36	126.03	439.36

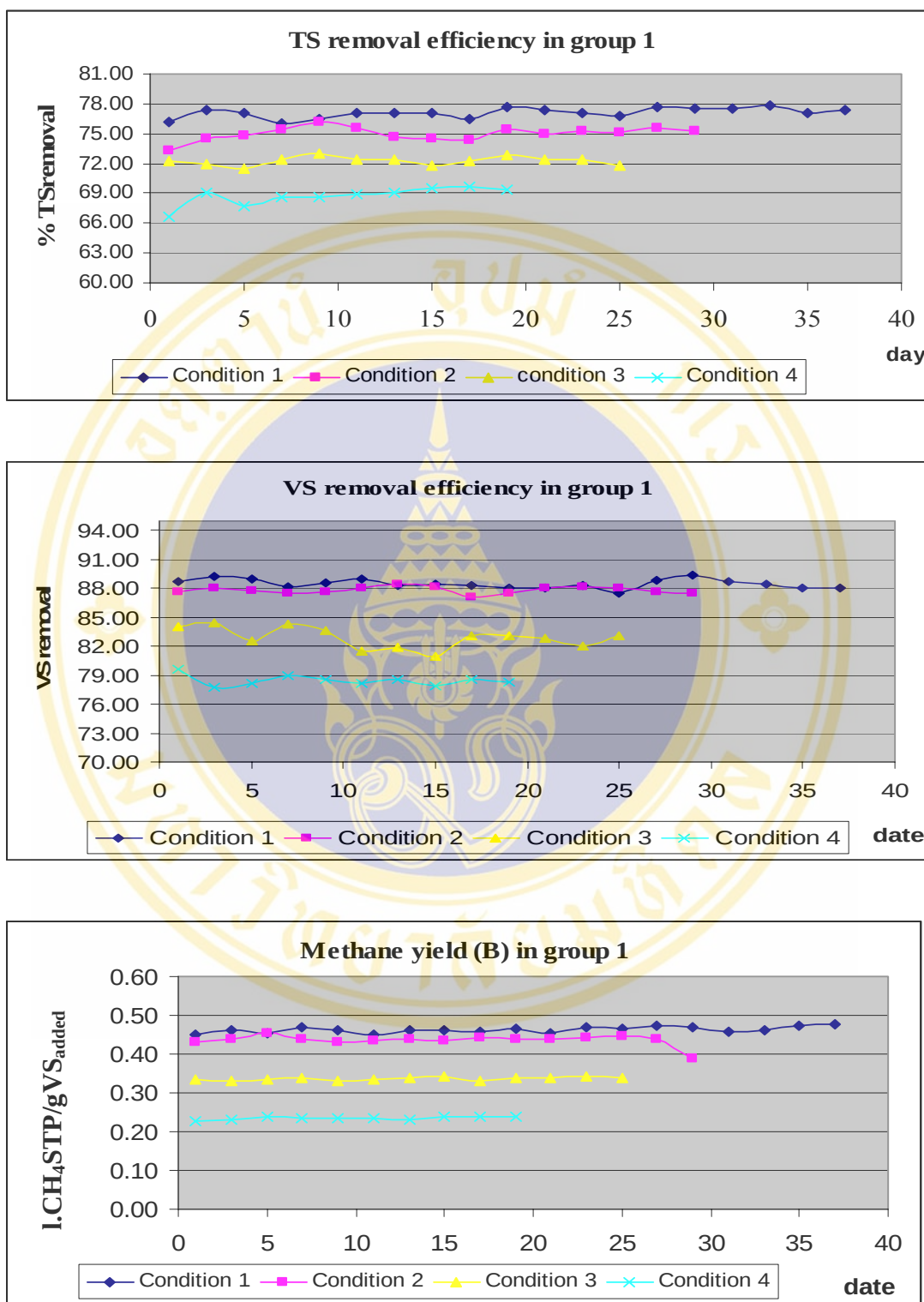


Figure 4.3 The removal efficiency of total solids, volatile solids and methane yields under condition 1, 2, 3 and 4 (total solids conc. 80,000 mg/l, HRTs of 30, 25, 20 and 15 days)

4.4.2 Group 2: Removal efficiency of anaerobic digestion of OFMSW at TS 12% (120,000 mg/L) and 30, 25, 20 and 15 days HRT.

The experiments were performed with total solid concentration 12 % (120,000 mg/l) and 30, 25, 20 and 15 day HRT. The results of total solid removal efficiency, volatile solid removal efficiency and methane yield (B) were presented in Table 4.8 and 4.9. Removal efficiency of total solids, volatile solids and methane yields (B) were shown in Figure 4.4.

4.4.2.1 Experimental condition 5: The experiment was performed with total solid concentration 120,000 mg/L and HRT of 30 days. The average removal efficiency of total solids, volatile solids and methane yields were 75.8 % (SD.=0.65), 88.35 % (SD.=0.98) and 0.41 l.CH₄STP/gVS_{added} (SD.=0.01), respectively.

4.4.2.2 Experimental condition 6: The experiment was performed with total solid concentration 120,000 mg/L and HRT of 25 days. The average removal efficiency of total solids, volatile solids and methane yields were 74.71 % (SD.=0.41), 87.66 % (SD.=0.47) and 0.38 l.CH₄STP/gVS_{added} (SD.=0.01), respectively.

4.4.2.3 Experimental condition 7: The experiment was performed with total solid concentration 120,000 mg/L and HRT of 20 days. The average removal efficiency of total solids, volatile solids and methane yields were 70.08 % (SD.=0.52), 80.08 % (SD.=0.73) and 0.26 l.CH₄STP/gVS_{added} (SD.=0.01), respectively.

4.4.2.4 Experimental condition 8: The experiment was performed with total solid concentration 120,000 mg/L and HRT of 15 days. The average removal efficiency of total solids, volatile solids and methane yields were 63.4 % (SD.=0.65), 76.85 % (SD.=0.43) and 0.17 l.CH₄STP/gVS_{added} (SD.=0), respectively.

Table 4.8 The average of TS and VS removal efficiency, Methane yields of two-phase anaerobic digestion in group 2. (Total solid concentration 12 %, HRT of 30, 25, 20 and 15 day)

Parameter		Condition 5 (HRT 30 d)	Condition 6 (HRT 25 d)	Condition 7 (HRT 20 d)	Condition 8 (HRT 15 d)
TS removal (% removal)	Min	74.7	74.1	69.1	62
	Max	77	75.3	71.4	64.5
	Mean	75.8	74.71	70.08	63.4
	SD.	0.65	0.41	0.73	0.65
VS removal (% removal)	Min	86.5	86.8	79.1	76.1
	Max	89.8	88.2	81.4	77.4
	Mean	88.35	87.66	80.08	76.85
	SD.	0.98	0.47	0.73	0.43
Methane yields (l. CH ₄ STP /g.VS _{added})	Min	0.41	0.39	0.27	0.17
	Max	0.43	0.41	0.28	0.18
	Mean	0.41	0.38	0.26	0.17
	SD.	0.01	0.01	0.01	0

Table 4.9 The average monitoring parameters: pH, VFA, Alkalinity, of two-phase anaerobic digestion in group 2. (total solid concentration 12 %, HRT of 30, 25, 20 and 15 day)

Parameter		Condition 5 (HRT 30 d)	Condition 6 (HRT 25 d)	Condition 7 (HRT 20 d)	Condition 8 (HRT 15 d)
pH	Min	7.46	7.47	7.01	6.87
	Max	7.5	7.6	7.2	6.9
	Mean	7.4	7.4	6.9	6.8
	SD.	0.051	0.067	0.105	0.049
VFA mg/l as Acetic	Min	618	712	1565	1993
	Max	693	890	1850	2840
	Mean	656	786	1766	2380
	SD.	23.09	53.82	95.66	305.33
Alkalinity mg/l as CaCO ₃	Min	2069	1978	3010	3322
	Max	2250	2697	3413	4303
	Mean	2135	2389	3276	3755
	SD.	50.86	214.41	115.9	367.42

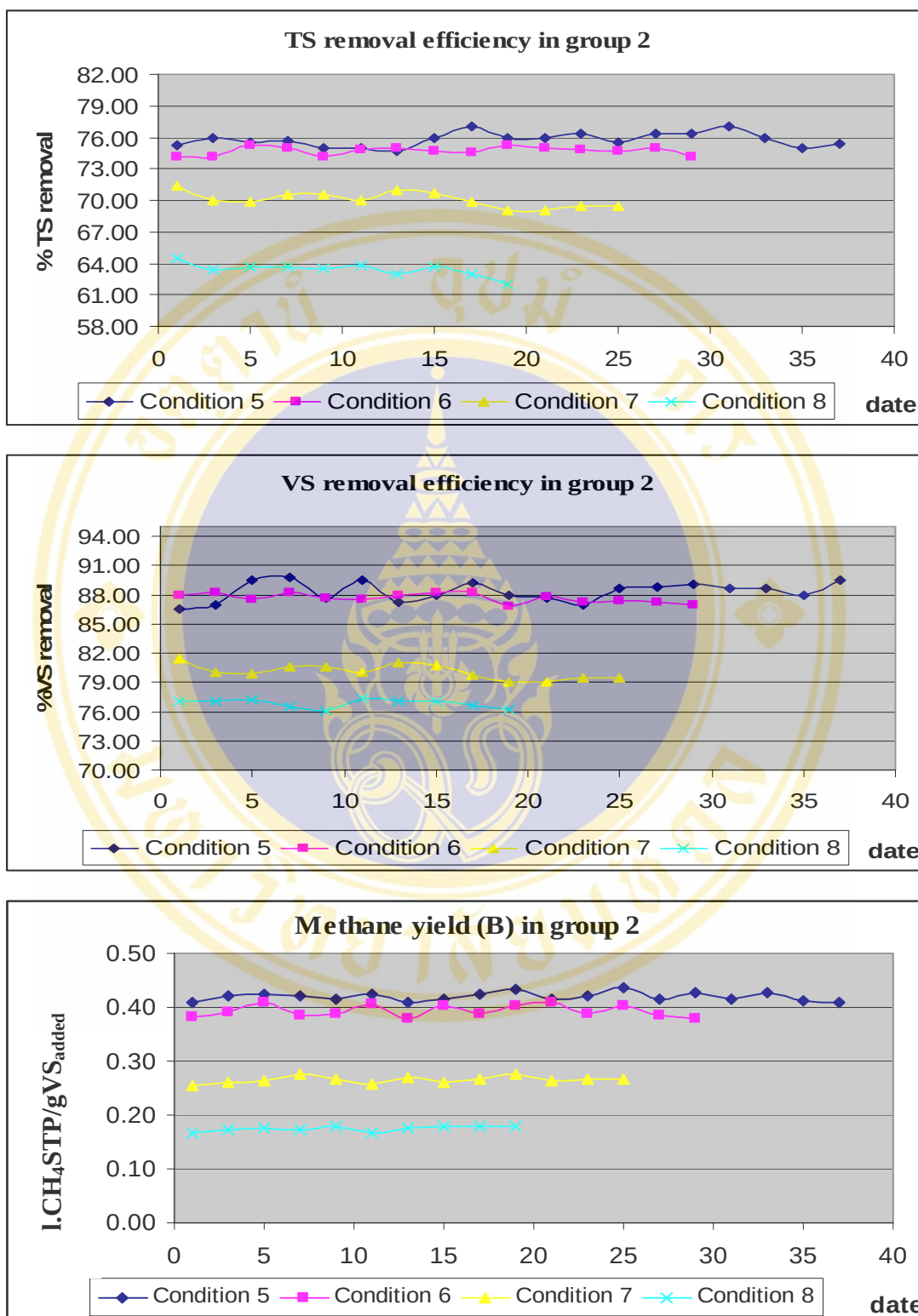


Figure 4.4 The removal efficiency of total solids, volatile solids and methane yields under condition 5, 6, 7 and 8 (total solids conc. 120,000 mg/l, HRTs of 30, 25, 20 and 15 days)

4.4.3 Group 3: Removal efficiency of anaerobic digestion of OFMSW at TS 15% (150,000 mg/L) and 30, 25, 20 and 15 days HRT

The experiments were performed with total solid concentration 15 % (150,000 mg/l) and 30, 25, 20, 15 day HRT. The results of total solid removal, volatile solid removal and methane yield (B) were presented in Table 4.10 and 4.11. Removal efficiency of total solids, volatile solids and methane yields (B) were shown in Figure 4.5.

4.3.3.1 Experimental condition 9: The experiment was performed with total solid concentration 150,000 mg/L and HRT of 30 days. The average removal efficiency of total solids, volatile solids, methane yields were 75.75 % (SD.=0.65), 87.77 % (SD.=0.85) and 0.37 l CH₄STP/gVS_{added} (SD.=0.01), respectively.

4.3.3.2 Experimental condition 10: The experiment was performed with total solid concentration 150,000 mg/L and HRT of 25 days. The average removal efficiency of total solids, volatile solids and methane yields were 73.0 % (SD.=0.93), 86.02 % (SD.=0.74) and 0.31 l CH₄STP/gVS_{added} (SD.=0), respectively.

4.3.3.3 Experimental condition 11: The experiment was performed with total solid concentration 150,000 mg/L and HRT of 20 days. The average removal efficiency of total solids, volatile solids and methane yields were 69.67 % (SD.=0.4), 79.67 % (SD.=0.4) and 0.22 l CH₄STP/gVS_{added} (SD.=0), respectively.

4.3.3.4 Experimental condition 12: The experiment was performed with total solid concentration 150,000 mg/L and HRT of 15 days. The average removal efficiency of total solids, volatile solids, methane yields were 60.98 % (SD.=0.93), 73.28 % (SD.=0.87) and 0.14 l CH₄STP/gVS_{added} (SD.=0), respectively.

Table 4.10 The average of TS and VS removal efficiency, Methane yields of two-phase anaerobic digestion in group 3. (Total solid concentration 15 %, HRT of 30, 25, 20 and 15 day)

Parameter		Condition 9 (HRT 30 d)	Condition 10 (HRT 25 d)	Condition 11 (HRT 20 d)	Condition 12 (HRT 15 d)
TS removal (% removal)	Min	75.30	71	68.9	59.5
	Max	76.20	74.3	70.3	62.7
	Mean	75.75	73	69.67	60.98
	SD.	0.28	0.93	0.4	0.93
VS removal (% removal)	Min	85.50	84.90	78.9	72
	Max	89.50	87.60	80.3	74.7
	Mean	87.77	86.02	79.67	73.28
	SD.	0.85	0.74	0.4	0.87
Methane yields (l. CH ₄ STP /Kg.VS _{added})	Min	0.38	0.32	0.22	0.15
	Max	0.41	0.33	0.23	0.16
	Mean	0.37	0.31	0.22	0.14
	SD.	0.01	0	0	0

Table 4.11 The average monitoring parameters: pH, VFA, Alkalinity, of two-phase anaerobic digestion in group 3. (Total solid concentration 15 %, HRT of 30, 25, 20, 15 day)

Parameter		Condition 9 (HRT 30 d)	Condition 10 (HRT 25 d)	Condition 11 (HRT 20 d)	Condition 12 (HRT 15 d)
pH	Min	7.45	7.5	6.91	6.77
	Max	7.5	7.7	7	6.8
	Mean	7.4	7.4	6.8	6.7
	SD.	0.052	0.082	0.06	0.049
VFA mg/l as Acetic	Min	825	1150	1693	2565
	Max	880	1575	2500	3215
	Mean	865	1409	2077	2783
	SD.	17.02	160.85	285.59	235.99
Alkalinity mg/l as CaCO ₃	Min	2667	2956	3215	4141
	Max	2933	3640	4101	49581
	Mean	2839	3287	3662	4460
	SD.	77.63	248.9	314.12	339.6

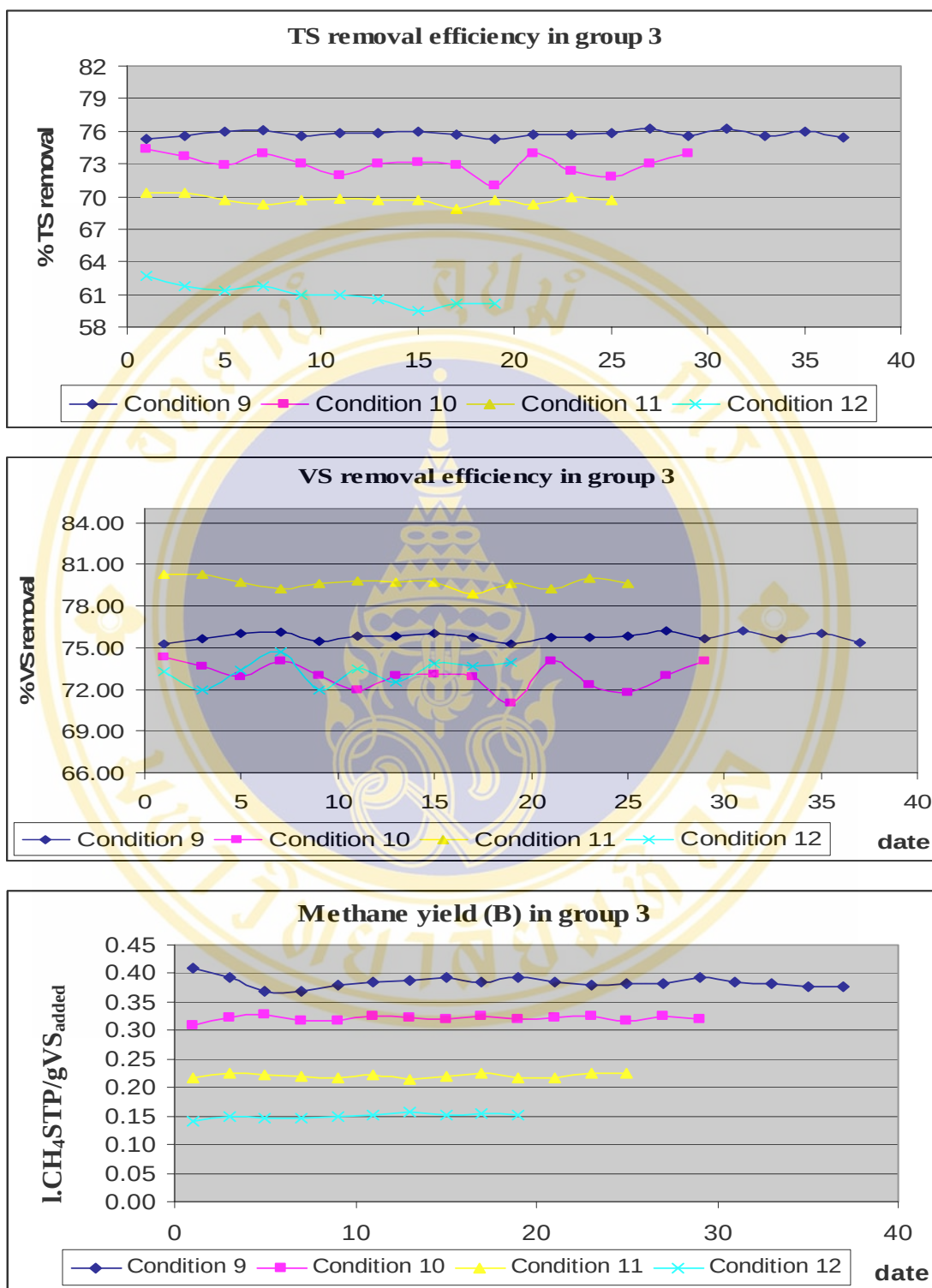


Figure 4.5 The removal efficiency of total solids, volatile solids and methane yields under condition 9, 10, 11 and 12 (total solids 150,000 mg/l, HRTs of 30, 25, 20 and 15 days)

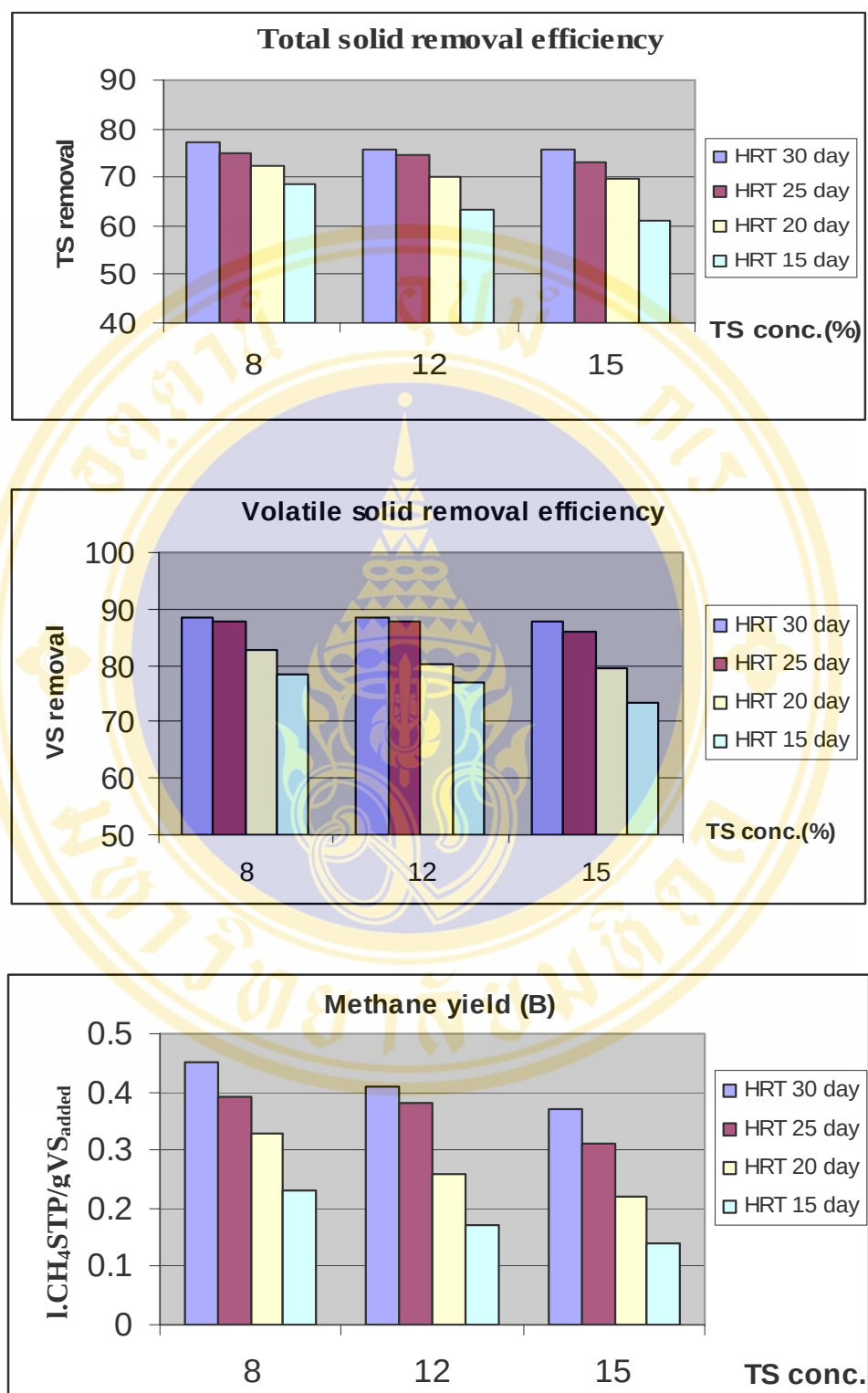


Figure 4.6 The total solids, volatile solids removal efficiency, methane yield of two phase mesophilic anaerobic digestion of OFMSW under steady state condition.

4.5 Statistical Analysis

4.5.1 Statistical Analysis for Total solids concentration

The results of statistical analysis of TS, VS removal efficiency and methane yields under steady state of two-phase mesophilic anaerobic digestion at total solids concentration of 8, 12, and 15% were summarized in Table 4.12 to 4.13

The average of TS removal efficiency at total solids concentration of 8, 12 and 15% were 73.95 % (SD=3.09), 72.02 % (SD=4.6), 71.05 % (SD=5.24), respectively. It was found that TS removal efficiency at TS concentration 8 % was significantly higher than those at 12 % ($p < 0.05$) and 15 % ($p < 0.05$) whereas, the TS removal at TS concentration 12 % was significantly higher than that at 15 % ($p < 0.05$).

The average of VS removal efficiency at total solids concentration of 8, 12 and 15% were 85.27 % (SD=3.91), 84.26 % (SD=4.81), 82.92 % (SD=5.49), respectively. It was found that VS removal efficiency at TS concentration 8 % was significantly higher than those at 12 and 15 % ($p < 0.05$). Whereas, the VS removal at TS concentration 12 % was significantly higher than that at 15 % ($p < 0.05$).

The average of methane yield ($\text{l CH}_4\text{STP/gVS}_{\text{added}}$) at total solids concentration of 8, 12 and 15% were 0.39 (SD=0.09), 0.33 (SD=0.095), 0.29 (SD=0.09), respectively. It was found that methane yield at TS concentration 8 % was significantly higher than those at 12 and 15 % ($p < 0.05$). Whereas, the methane yield at TS concentration 12 % was significantly higher than that at 15 % ($p < 0.05$).

Table 4.12 The results of TS, VS removal efficiency and specific gas production under total solids concentration of 8, 12 and 15%

TS conc.	%TS removal efficiency		%VS removal efficiency		Methane Yields ($\text{l CH}_4\text{STP/gVS}_{\text{added}}$)	
	Mean	SD	Mean	SD	Mean	SD
8% (Condition 1,2,3,4)	73.95	3.09	85.27	3.91	0.39	0.09
12% (Condition 5,6,7,8)	72.02	4.6	84.26	4.81	0.33	0.10
15% (Condition 9,10,11,12)	71.05	5.24	82.92	5.49	0.29	0.09

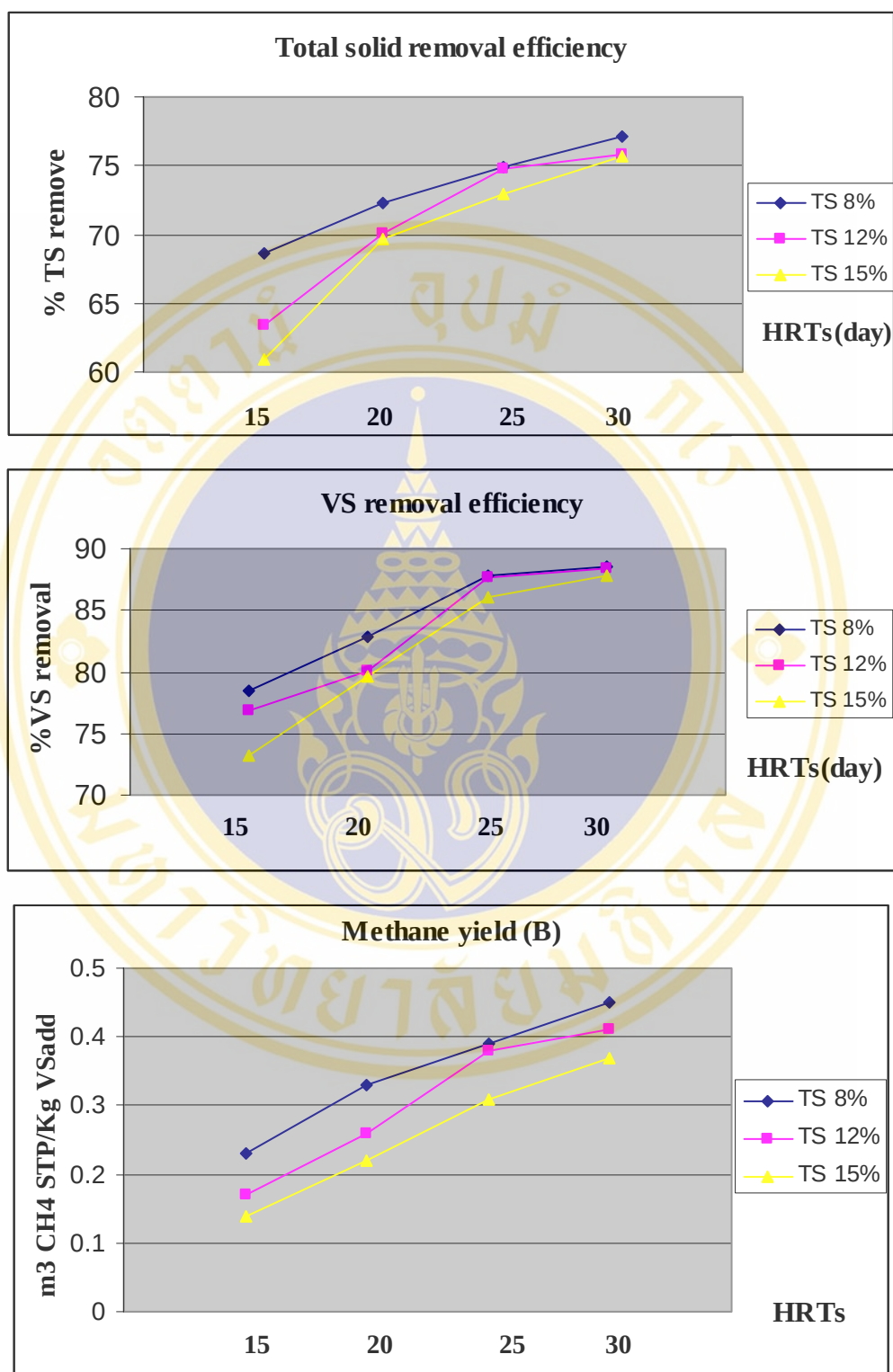


Figure 4.7 The relationship between total solid concentration (%TS) and total solid, volatile solid removal and methane yield in two phase mesophilic anaerobic digestion.

4.5.2 Statistical for HRTs

The results of statistical analysis of TS, VS removal efficiency and methane yields under steady state of two-phase mesophilic anaerobic digestion at HRTs of 15, 20, 25 and 30 days were summarized in Table 4.13 and Figure 4.8.

The average of TS removal efficiency at HRTs of 15, 20, 25 and 30 days were 64.36% (SD.=3.37), 70.67% (SD=1.26), 74.22% (SD=1.11) and 76.2% (SD=0.80), respectively. It was found that the TS removal efficiency at HRT 30 day was significantly higher than those at 25, 20 and 15 day ($p < 0.05$), the TS removal efficiency at HRT 25 day was significantly higher than that at 20 and 15 days ($p < 0.05$) and the TS removal efficiency at HRT 20 day was significantly higher than that at 15 days ($p < 0.05$).

The average of VS removal efficiency at HRTs of 15, 20, 25 and 30 days were 76.19% (SD.=2.28), 80.88% (SD=1.64), 87.16% (SD=0.98) and 88.20% (SD=0.84), respectively. It was found that VS removal efficiency at HRT 30 day was significantly higher than those at 25, 20 and 15 day ($p < 0.05$), the VS removal efficiency at HRT 25 day was significantly higher than that at 20 and 15 days ($p < 0.05$) and the VS removal efficiency at HRT 20 day was significantly higher than that at 15 days ($p < 0.05$).

The average of methane yields ($\text{l CH}_4\text{STP/gVS}_{\text{added}}$) at HRTs of 15, 20, 25 and 30 days were 0.19 (SD.=0.04), 0.27 (SD=0.05), 0.38 (SD=0.05) and 0.42 (SD=0.03), respectively. It was found that methane yields at HRT 30 day was significantly higher than those at 25, 20 and 15 day ($p < 0.05$), the methane yields at HRT 25 day was significantly higher than that at 20 and 15 days ($p < 0.05$) and the methane yields at HRT 20 day was significantly higher than that at 15 days ($p < 0.05$).

Table 4.13 The results of TS, VS removal efficiency and specific gas production under HRTs of 20, 25 and 30 days

HRTs	%TS removal efficiency		%VS removal efficiency		Methane yields l CH ₄ STP/gVS _{added}	
	Mean	SD	Mean	SD	Mean	SD
15 days	64.36	3.37	76.19	2.28	0.19	0.04
20 days	70.67	1.26	80.88	1.64	0.27	0.05
25 days	74.22	1.11	87.16	0.98	0.38	0.05
30 days	76.20	0.80	88.20	0.84	0.42	0.03

Table 4.14 The results of statistical analysis of the total solid removal, volatile solid removal and methane yield (B)

Parameters	Variables	ANOVA test	Multiple Comparison
TS removal	HRTs	DS	30>25>20>15
	TS conc.	DS	8>12>15
	HRTs * TS conc.	DS	30x8>30x12,30x8>30x15, 30x12=30x15
VS removal	HRTs	DS	30>25>20>15
	TS conc.	DS	8>12>15
	HRTs * TS conc.	DS	30x8>30x15,30x12>30x15, 30x8=30x12
Methane yields	HRTs	DS	30>25>20>15
	TS conc.	DS	8>12>15
	HRTs * TS conc.	DS	30x8>30x12 >30x15

Remark: NS means non significant difference among level, $\alpha = 0.05$

DS means difference significantly among the level, $\alpha = 0.05$

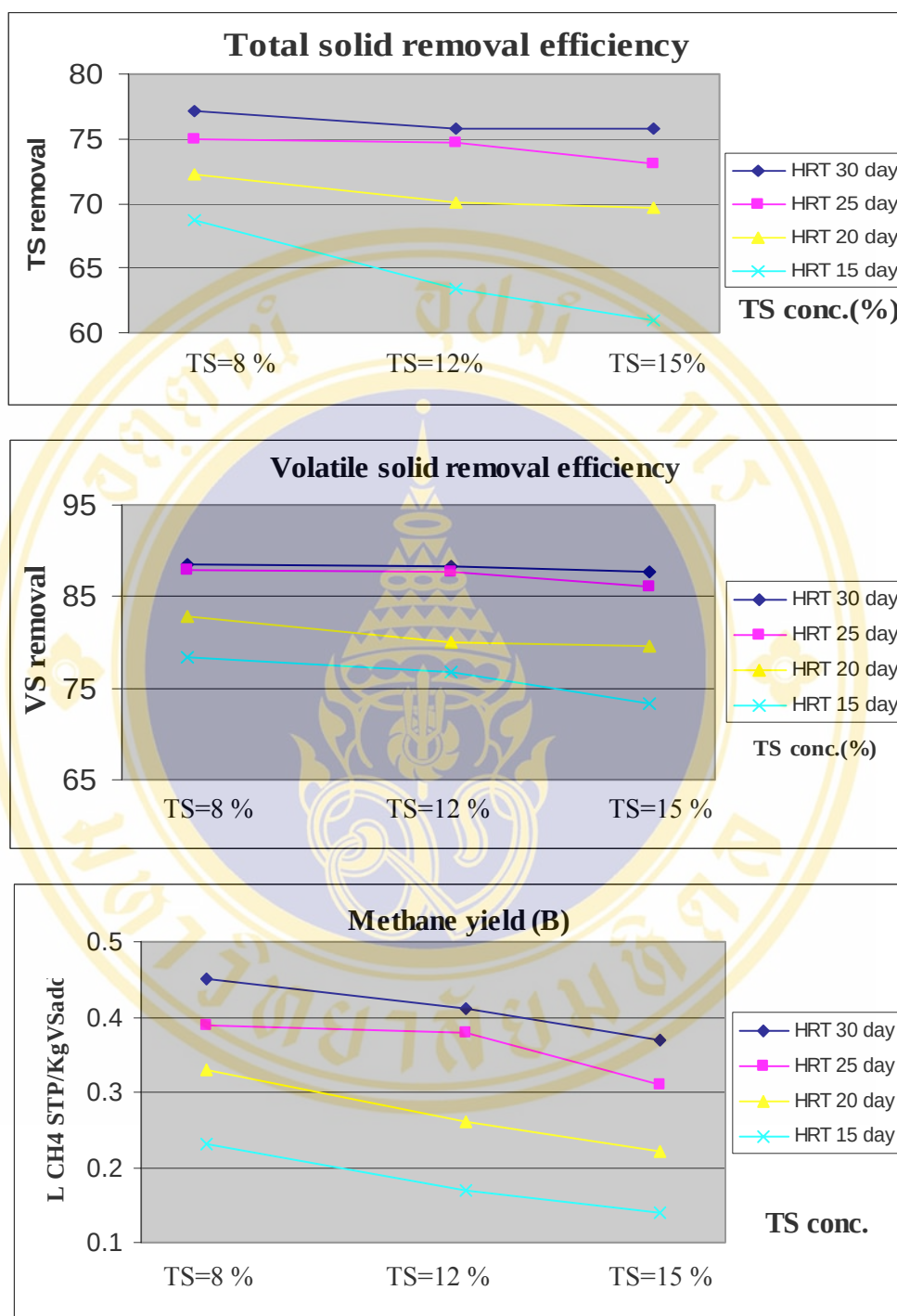


Figure 4.8 The relationship between total solid concentration (%TS) and total solid removal, volatile solid removal and methane yield in two phase mesophilic anaerobic digestion.

4.5.3 Statistical Analysis for Combination Effect of HRTs and total solids concentration

The results of statistical analysis for combination effect of HRTs and total solids concentration were found as shown in Table 4.14. The combination effect of HRTs and total solids concentration were significantly found in the TS, VS removal efficiency and specific gas production ($p < 0.05$).

The combination effect of 30 days HRT and 8% total solids concentration on the TS removal efficiency was significantly higher than those of 30 days HRT and 12% total solids concentration and 30 days HRT and 15% total solids concentration ($p < 0.05$). Whereas, the combination effect of 30 days HRT and 12, 15% total solids concentration were not significantly difference of TS removal efficiency.

The combination effect of 30 days HRT and 8% total solids concentration on the VS removal efficiency was significantly higher than of 30 days HRT and 15% total solids concentration ($p < 0.05$). The combination effect of 30 days HRT and 12% total solids concentration on the VS removal efficiency was significantly higher than of 30 days HRT and 15% total solids concentration ($p < 0.05$). Whereas, the combination effect of 30 days HRT and 8, 12% total solids concentration were not significantly difference of VS removal efficiency.

The combination effect of 30 days HRT and 8% total solids concentration on the methane yield was significantly higher than of 30 days HRT and 12% total solids concentration ($p < 0.05$). The combination effect of 30 days HRT and 8% total solids concentration on the methane yield was significantly higher than of 30 days HRT and 15% total solids concentration ($p < 0.05$). The combination effect of 30 days HRT and 12% total solids concentration on the methane yield was significantly higher than of 30 days HRT and 15% total solids concentration ($p < 0.05$).

4.5.4 Regression Analysis for TS, VS removal efficiency and specific gas production from Two-Phase Mesophilic Anaerobic Digestion of OFMSW

Regression analysis was performed to decide whether or not HRTs and/or total solids concentration affecting the TS, VS removal efficiency and specific gas production by using forward stepwise regression and predicting them by using polynomial regression.

From the results of the forward stepwise regression analysis, it was found that the TS, VS removal efficiency and specific gas production from two-phase mesophilic anaerobic digestion of OFMSW can be predicted using a linear combination of the HRTs and total solids concentration ($p < 0.05$). These relationships can be predicted as followed:

- **TS removal efficiency in this experiment can be predicted from the equation:**

$$\text{TS removal efficiency (\%)} = 59.56 + 0.743 \cdot \text{HRTs} - 0.418 \cdot \text{TSconc.} \text{ ----- (4.11)}$$

$$(R^2=0.877, N=171)$$

- **VS removal efficiency in this experiment can be predicted from the equation:**

$$\text{VS removal efficiency (\%)} = 68.69 + 0.813 \cdot \text{HRTs} - 0.332 \cdot \text{TSconc.} \text{ ----- (4.12)}$$

$$(R^2=0.888, N = 171)$$

- **Methane yields in this experiment can be predicted from the equation:**

$$\text{Methane yields} = 0.121 + (1.585 \times 10^{-2}) \cdot \text{HRTs} - (1.38 \times 10^{-2}) \cdot \text{TS conc.} \text{ ----- (4.13)}$$

$$(\text{l CH}_4\text{STP /g VS}_{\text{added}})$$

$$(R^2= 0.957, N = 171)$$

CHAPTER V

DISCUSSION

5.1 Organic Fraction of Municipal Solid Waste Characteristics

In this study, organic fraction of municipal solid waste (OFMSW) was collected from integrated waste management centre at Chonburi province and selected as representatives of feed substrate for two phase mesophilic anaerobic digestion. Organic fraction of municipal solid waste (OFMSW) from integrated waste management centre Chonburi were TS, VS, Carbon, TKN, and C/N ratio equal 322 g/l, 237.7 g/l, 15.21 of %TS, 4.52 g/l and 33.7 respectively.

Comparing with other sources, the TS concentration and VS/TS ratio were similar as 60-80 % reported by Cecchi, (37) of OFMSW collected in canteen. Whereas TKN concentration seems to be more than literature slightly. The average C/N ratio in OFMSW was about 35. This ratio was defined as sufficient and suitable for anaerobic digestion processes (38).

Table 5.1 Comparing organic fraction of municipal solid waste OFMSW characteristics from different sources. (39),(40),(41),(42)

Parameter	Europe country			Thailand	
	De Baere 2000	Kubler et al 1999	CITEC 2000	Food waste 2003	This experiment
TS (g/l)	310	290	170-250	351.3	322
VS (g/l)	70	63	70-90	326.9	273.7
Carbon (%TS)	-	-	-	-	15.21
TKN (mg/l)	-	-	-	5753	4523
C/N ratio	25	40	35	-	33.7

5.2 Determination of Kinetic Coefficients

From determining kinetic coefficients of three two phase mesophilic anaerobic digestion systems which were operated at three different feed substrate concentrations: 68.63, 102.48, and 127.27 gVS/l. The hydraulic retention time (HRT) varied between 33 and 18 day and kinetic coefficients of two phase mesophilic anaerobic digestion systems were summarized in Table 5.2.

Table 5.2 Mean values for determining kinetic coefficient (B_0) of two phase mesophilic anaerobic digestion.

HRT (days)	B ($\text{l CH}_4\text{STP/gVS}$)		
	TS 8%	TS 12%	TS 15%
30	0.45	0.41	0.37
25	0.39	0.38	0.31
20	0.33	0.26	0.22
15	0.23	0.17	0.14
B_0	0.6563	0.6628	0.5864

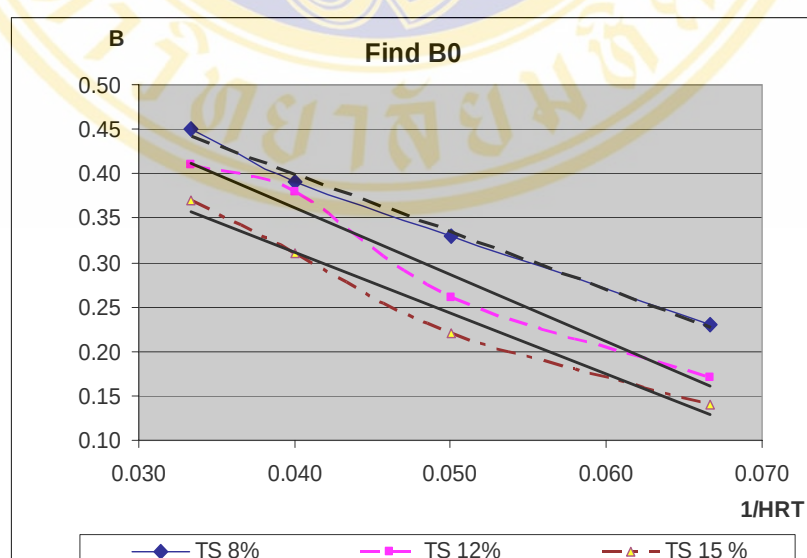


Figure 5.1 The effect of retention time on methane production in the anaerobic digestion of the three substrate concentrations used as influent.

Table 5.3 Summarized the values of kinetic parameters, $\mu_{\max}$ (per day) and K for the three substrate concentrations used as influent

Feed substrates	Volatile solids (g/l)	K	$\mu_{\max}$ (day ⁻¹)	$\theta_{\min}$ (day)	$\delta_{\max}$ l CH ₄ STP/l.d
Substrate I	68.63	0.867	0.095	10.58	1.14
Substrate II	102.48	0.846	0.084	11.93	1.50
Substrate III	127.27	0.814	0.078	12.77	1.62

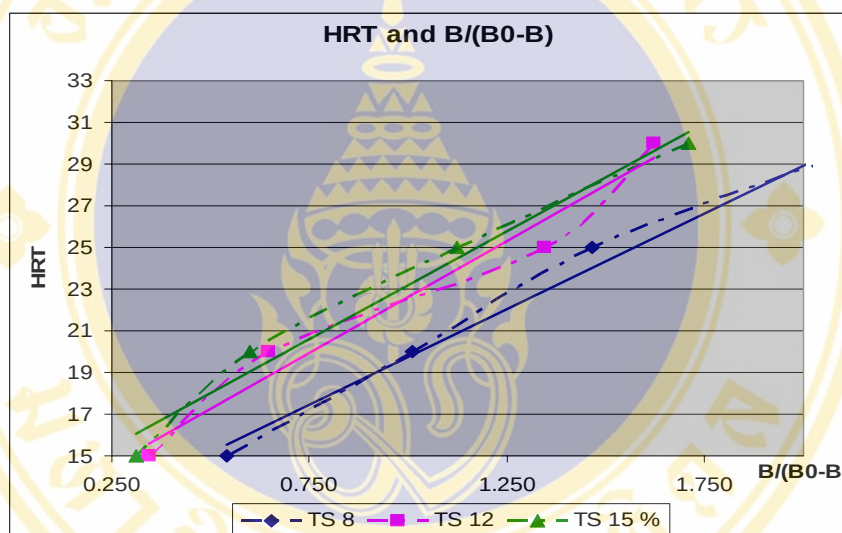


Figure 5.2 Experimental data plotted according to Eq. (4.3) from which the kinetic parameters $\mu_{\max}$ and K can be derived for the three substrate concentrations used as influent.

As can be seen in Table 5.2 and 5.3, the values of kinetic parameter: B, K and $\mu_{\max}$ decreased when influent substrate concentration increased. The value of the kinetic constant K for the substrate II (VS= 102.48 g/l) and III (VS= 127.27 g/l) is 2.42 and 6.11 % lower, respectively, than that obtained for the substrate I (VS= 68.63 g/l). The maximum specific growth rate, $\mu_{\max}$, is 11.58 and 17.89 % lower than that obtained with lowest S_0 . Therefore, the kinetic parameters were found to be influenced by the influent substrate concentration, with shows the occurrence of an inhibitor during the processes. When the influent substrate concentration increase

from 68.63 to 127.27 gVS/l, the B_0 values also decreased from 0.6563 to 0.5864 l $\text{CH}_4\text{STP/VS}$ added

This inhibitory effect on the kinetics of anaerobic digestion of two phase mesophilic OFMSW was clearly seen by increased the volatile fatty acid from 437.54 to 1531, 665.69 to 2379.54, and 864.62 to 2782.86 when operated at 8, 12, 15 %TS.

A similar behavior was observed in the anaerobic digestion process of olive mill solid waste (mesophilic anaerobic digestion of the two-phase olive mill solid waste). In this work, the overall kinetic constant of the anaerobic process was influenced by the volatile fatty acid content present during the experimental runs.

The minimum hydraulic retention times, $\theta_{\min}$ (day), at which the washout of the micro-organisms occurs were: 10.9, 11.9 and 12.8 days, for the Substrates I, II and III, respectively. These values were calculated by using Eq. 4.1 and taking into account that this retention time is numerically equal to the reciprocal of the minimum micro-organisms growth rate ($\mu_{\max}$).

Finally, the maximum volumetric methane production rates obtained from Eq.4.6 were found to be 1.14, 1.50, 1.62 l CH_4 STP/l per day for the substrate I, II and III, respectively. These values were somewhat higher than those obtained in the anaerobic digestion of sewage sludge and of the same order of magnitude than those appreciated in the anaerobic digestion of beef and dairy waste (43).

5.3 Removal Efficiency

The two phase mesophilic anaerobic digestion of OFMSW has been used to investigate removal efficiencies and methane yields. The comparison of productions at overall performances were illustrated in Table 5.4

Table 5.4 The overall productions of two phase mesophilic anaerobic digestion of OFMSW under steady state condition.

HRTs (days)	TS conc.	TS removal		VS removal		Methane yields	
	(%)	Ave.	SD.	Ave.	SD.	Ave.	SD.
30 (Condition 1,2,3)	8	77.08	0.52	88.5	0.47	0.46	0.01
	12	75.8	0.65	88.3	0.98	0.41	0.01
	15	75.8	0.28	87.8	0.85	0.38	0.01
25 (Condition 4,5,6)	8	74.96	0.66	87.8	0.36	0.41	0.01
	12	74.7	0.41	87.7	0.47	0.39	0.01
	15	73	0.93	86	0.74	0.32	0.00
20 (Condition 7,8,9)	8	72.3	0.42	82.9	1.07	0.34	0.00
	12	70.1	0.73	80.1	0.73	0.27	0.01
	15	69.7	0.4	79.7	0.4	0.22	0.00
15 (Condition 10,11,12)	8	68.69	0.91	78.44	0.54	0.23	0.00
	12	63.40	0.65	76.85	0.43	0.17	0.00
	15	60.98	0.93	73.28	0.87	0.15	0.00

5.3.1 Effect of TS conc. on TS, VS removal efficiency and methane yield

Statistical analysis of TS, VS removal efficiency and methane yields under steady state of two-phase mesophilic anaerobic digestion at total solids concentration of 8, 12 and 15% were summarized in Table 4.12 to 4.13 and Figure 4.7

TS Removal Efficiency: From the overall performances of two-phase mesophilic anaerobic digestion of OFMSW under steady state conditions, it was found that the TS removal efficiency at total solids concentration of 8, 12 and 15% were in the average of 73.95, 72.02 and 71.05 %, respectively According to statistical analysis, it was indicated that the TS removal efficiency at total solids concentration 8% was significantly higher than those at 12 and 15% total solids concentration ($p <$

0.05). At the same time the VS removal efficiency at TS concentration 12 % was significantly higher than that at 15 % ($p < 0.05$).

One reason could be explained that major danger for overall anaerobic conversion is presented when micro-organism populations are not balanced. Methane formers have a growth rate much slower than acidogenic bacteria; the problem is that acid formers outgrow methane formers and acidic conditions may be prevalence in the digester, which would slow down the activity of methanogenic bacteria and eventually totally inhibit their activity (38).

In this study the experiment was set feeding substrate concentration 8, 12, 15 %. At total solid concentration 8 % (80 g/l), the two phase mesophilic anaerobic digestion can be obtain higher total solid removal efficiencies. Under the different TS concentration mean that the different of organic loading rate. So have an accumulation of inhibiting substance such as VFA when OFMSW was added in to the system more than utilized by methanogen.

These results agree with Hamzawi N. (44), who reported that the total solids concentration of feed had a significant impact on the performance of the process.

VS Removal Efficiency: At the overall performance of two-phase mesophilic anaerobic digestion of OFMSW under steady state condition, it was indicated that the VS removal efficiency at total solids concentration of 8, 12 and 15% were in the average of 85.27, 84.26 and 82.92 %, respectively. According to statistical analysis, it was found that the VS removal efficiency at total solids concentration 8% was significantly higher than those at 12 and 15% total solids concentration ($p < 0.05$). At the same time the VS removal efficiency at 12% total solids concentration was significantly higher than that at 15% total solids concentration ($p < 0.05$).

The reason why lower VS removal efficiency was achieved when increasing total solids concentration may be due to the organic loading rate (OLR). The higher OLR would generate the accumulation of VFA. This means that an accumulation of VFA indicate process imbalance which in turn cause the pH to drop. Methane-former have a growth rate much slower than acidogenic bacteria; the problem is that acid-formers outgrow methane-formers and acidic conditions may be prevalent in the digester, which would slow down the activity of methanogenic bacteria and eventually totally inhibit their activity. (45).

This result is similar to the studies of Schober G. (38), which note that during experiments at mesophilic increasing the organic loading rate (OLR) by reducing the hydraulic retention and HRT 11 day the maximum VS reduction under steady state condition reach 72 % at mesophilic the yield of gas reached about 800 l gas KgVS-1 . A simple mathematical model was set up to describe digestion performance adequately designating the process conditions for most effective turnover.

Schober (38) concluded that stable process conditions with the CSTR were achieve at maximum OLR of 6 kgVS/m³d and HRT 24 days resulting in a VS degradation of 64 %. These values were comparable to data in the literature obtained for the digestion of fractionated bio-waste where OLR were kept in a range between 6 and 12 kgVS/m³d in order to ensure stable digestion. In this trial, HRT were between 18 and 21 days and leading to the 50-72 % VS reduction and methane yield 0.52 lg-1 VS degrade. Thus lipids may have preferentially been degraded in the CSTR.

Methane Yield: At the overall performance of two-phase mesophilic anaerobic digestion of OFMSW under steady state condition, it was indicated that the methane yield at total solids concentration of 8, 12 and 15% were in the average of 0.39, 0.33 and 0.29 l CH₄ STP/g VS added, respectively

According to statistical analysis, it was found that the methane yield at total solids concentration 8% was significantly higher than those at 12 and 15% total solids concentration ($p < 0.05$). And the same time the VS removal efficiency at 12% total solids concentration was significantly higher than that at 15% total solids concentration ($p < 0.05$).

These results of methane yield were nearly closed to those conducted by having a ranged from 0.2 to 0.63 m³ CH₄/KgVS with OLR ranging from 3 to 12.5 kgVS/m³d. Furthermore, according to Owens and Chynoweth, 1993; Oleszkiewicz and Poggi –Varaldo (46) they show that the 60% CH₄ in the biogas achieved for the methane yield (0.25 m³/KgVS) is very close to this study.

5.3.2 Effect of HRT on TS, VS removal efficiency and methane yield

TS Removal Efficiency: From the overall performances of two-phase mesophilic anaerobic digestion of OFMSW under steady state conditions, it was found that the TS removal efficiency at HRTs 15, 20, 25 and 30 days were in the average of 64.36, 70.67, 74.22 and 76.2 %, respectively. According to statistical analysis, it was indicated that the TS removal efficiency at HRTs 30 days was significantly higher than those at 25, 20 and 15 days ($p < 0.05$), the TS removal efficiency at HRTs 25 days was significantly higher than that at HRTs 20 and 15 days ($p < 0.05$), the TS removal efficiency at HRTs 20 days was significantly higher than that at HRTs 15 days ($p < 0.05$).

From the results of this study of TS removal efficiency among the 4 HRTs, it indicated that the increased HRTs would result in the increasing of removal efficiency, because the longer retention times would allow the microorganism more time to degrade the organic matter. According to the result, it can be seen that at HRTs 30 days the TS removal efficiency was achieved with 76.6% and at HRTs 15 days the TS removal efficiency was the lowest with 64.36%. This result is similar to the study of Jae Kyoung Cho et al (47), which noted that the removal efficiency increased when increasing hydraulic retention times.

VS Removal Efficiency: The VS removal efficiency at HRTs 15, 20, 25 and 30 days under steady state conditions were in the average of 76.19, 80.88, 87.16 and 88.2 %, respectively. According to statistical analysis, it was found that the VS removal efficiency at HRTs 30 days was significantly higher than those at 25, 20 and 15 days ($p < 0.05$), the VS removal efficiency at HRTs 25 days was significantly higher than that at HRTs 20 and 15 days ($p < 0.05$), the VS removal efficiency at HRTs 20 days was significantly higher than that at HRTs 15 days ($p < 0.05$).

From the results of this study of VS removal efficiency among the 4 HRTs, it indicated that the increased HRTs would result in the increasing of removal efficiency, because the longer retention times would allow the microorganism more time to degrade the organic matter. According to the result, it can be seen that at HRTs 30 days the VS removal efficiency was achieved with 88.2% and at HRTs 15 days the VS removal efficiency was the lowest with 76.19%. This result is similar to

the study of Jae Kyoung Cho et al (47), which noted that the removal efficiency increased when increasing hydraulic retention times.

Methane Yield: From the overall performances of two-phase mesophilic anaerobic digestion of OFMSW under steady state conditions, it was found that the methane yield at HRTs 15, 20, 25 and 30 days were in the average of 0.19, 0.27, 0.38 and 0.42 l CH₄ STP / g VS added, respectively. According to statistical analysis, it was found that methane yield at HRTs 30 days was significantly higher than those at 25, 20 and 15 days ($p < 0.05$), methane yield at HRTs 25 days was significantly higher than that at HRTs 20 and 15 days ($p < 0.05$), methane yield at HRTs 20 days was significantly higher than that at HRTs 15 days ($p < 0.05$).

From the results of this study of methane yield among the 3 total solids concentration, it indicated that the decreased HRTs would result in the decreasing of methane yield, because the reactor is overloaded the gas production will initially increase and then suddenly decrease after a period of time due to accumulation of inhibiting products (acids). According to the result, it can be seen that, it can be seen that at 30 days HRT the methane yield was achieved with 0.42 l CH₄ STP / g VS added and at 15 days HRT the methane yield was achieved with 0.19 l CH₄ STP / g VS added.

5.3.3 Combined effect of HRT and total solid concentration on TS, VS removal efficiency and methane yield

TS Removal Efficiency: Considering of combination effects of HRTs and total solids concentration, it was found that the combination effect of 30 days HRT and 8% total solids concentration was higher than those of 30 days HRT and 12% total solids concentration and 30 days HRT and 15% total solids concentration ($p < 0.05$), but the combination effect of 30 days and 12, 15% total solids concentration were not significantly difference of TS removal efficiency.

For 30 days HRT and the total solids concentration 8% gave the highest TS removal efficiency ($p < 0.05$).

For 25 days HRT. It indicated that there was no significant difference between 8 and 12% and the total solids concentration 8, 12% gave higher TS removal efficiency than total solids concentration 15% ($p < 0.05$).

For 20 days HRT and the total solids concentration 8% gave the highest TS removal efficiency ($p < 0.05$).

For 15 days HRT and the total solids concentration 8% gave the highest TS removal efficiency ($p < 0.05$).

VS Removal Efficiency: Considering the combination effects of 30 days HRT and 8% total solids concentration on the VS removal efficiency was significantly higher than of 30 days HRT and 15% total solids concentration ($p < 0.05$) and the combination effect of 30 days HRT and 12% total solids concentration on the VS removal efficiency was significantly higher than of 30 days HRT and 15% total solids concentration ($p < 0.05$). Whereas, the combination effect of 30 days HRT and 8, 12% total solids concentration were not significantly difference of VS removal efficiency.

For 30 days HRT. It indicated that there was no significant difference between 8 and 12% and the total solids concentration 8, 12% gave higher VS removal efficiency than total solids concentration 15% ($p < 0.05$).

For 25 days HRT. It illustrated that there was no significant difference between 8 and 12% and the total solids concentration 8, 12% gave higher VS removal efficiency than total solids concentration 15% ($p < 0.05$).

For 20 days HRT and the total solids concentration 8% gave the highest VS removal efficiency ($p < 0.05$).

For 15 days HRT and the total solids concentration 8% gave the highest VS removal efficiency ($p < 0.05$).

Methane Yield: Considering of combination effect of HRTs and total solids concentration, it was found that the combination effect of 30 days HRT and 8% total solids concentration was higher than those of 30 days HRT and 12% total solids concentration and 30 days HRT and 15% total solids concentration. As a result of 30

days HRT, it gave the highest methane yield and total solids concentration at 8 % also gave the highest methane yield.

For 30 days HRT and the total solids concentration of 8% gave the highest methane yield ($p < 0.05$).

For 25 days HRT and the total solids concentration of 8% gave the highest methane yield ($p < 0.05$).

For 20 days HRT and the total solids concentration of 8% gave the highest methane yield ($p < 0.05$).

5.3.4 Discussion for the Other Observed Results in Two-phase Mesophilic Anaerobic Digestion of OFMSW

pH: Process imbalance in an anaerobic digester will normally lead to accumulation of volatile fatty acids (VFA) resulting in a decrease in pH. The increase in acid concentration may not register as a drop in pH immediately if the buffer capacity of the material in the reactor is high. Most organic wastes have often a high content of weak acids and bases resulting in high buffer capacity. The organic acid accumulation therefore has to reach a high level before it is detected as a drop in pH. At that point the organic acids already significantly inhibit the process. pH is therefore difficult to use as it only reacts slowly to process imbalance. It is mentioned that pH is easy and inexpensive to measure and it is therefore an effective indicator in systems with low buffer capacity.

VFA/Alkalinity ratio; The fatty acids and the alkalinity concentrations show fast changes, when the stability of the anaerobic digestion process is upset. Because, when the process is not stable, the volatile fatty acid concentration increases, whereas the alkalinity decreases, the ratio of these two parameters can be a good tool for the observation of the stability of the anaerobic process. In this ratio, the VFAs are expressed in term of acetic acid concentration and the alkalinity in term of calcium carbonate concentration. Values of the ratio around 0.3 are index of good stability of the process, whereas larger values suggest an upset of the stability process. (38)

Ammonia: It is well known that ammonia/ammonium ($\text{NH}_3/\text{NH}_4^+$) can inhibit the anaerobic processes. This can especially become a problem during treatment of animal manure that contains high concentrations of urea. There are at present no guidelines for maximum concentrations of $\text{NH}_3/\text{NH}_4^+$. Often the anaerobic process can be adapted to high concentrations. It is especially the methane producing bacteria that are sensitive to high $\text{NH}_3/\text{NH}_4^+$ concentrations. The bacteria are more sensitive to $\text{NH}_3/\text{NH}_4^+$ at high temperatures. This is because the inhibiting component is NH_3 and the equilibrium $\text{H}^+ + \text{NH}_3 \leftrightarrow \text{NH}_4^+$ will be shifted toward the left at increasing temperatures. Also an increase in pH will result in increased NH_3 concentrations. This will cause increased inhibition of the methane production and an increase in the concentration of organic acids, which in turn cause the pH to drop again. This will reduce the NH_3 concentration and the degree of inhibition and will result in the phenomenon 'inhibited steady state'. (38)

5.4 The Optimum Running Condition

The comparison of TS, VS removal efficiency and methane yields among 12 experimental conditions, it could be concluded that the optimum running condition was total solids 8 %TS (80,000 mg/l) and HRTs at 30 day giving the removal efficiency (%) of TS and VS at 77.08, 88.49 and the methane yield of 0.45 l $\text{CH}_4\text{STP/gVS}_{\text{added}}$, respectively.

The contour graphs in Figure 5.7-5.9 illustrated the relationship between HRTs and total solids concentration on total solid, volatile solid removal efficiency and methane yields. These indicated that total solid concentration and HRTs were the influence variables on performance of two-phase mesophilic anaerobic digestion of OFMSW.

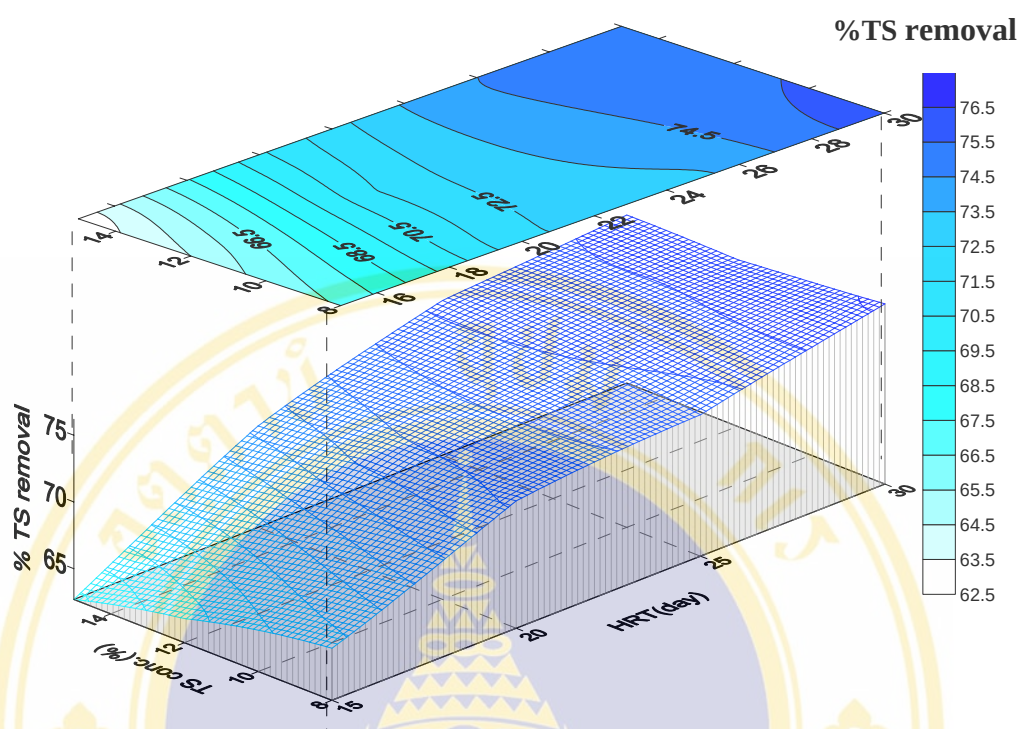


Figure 5.7 Contour graph for total solid removal during experimental runs

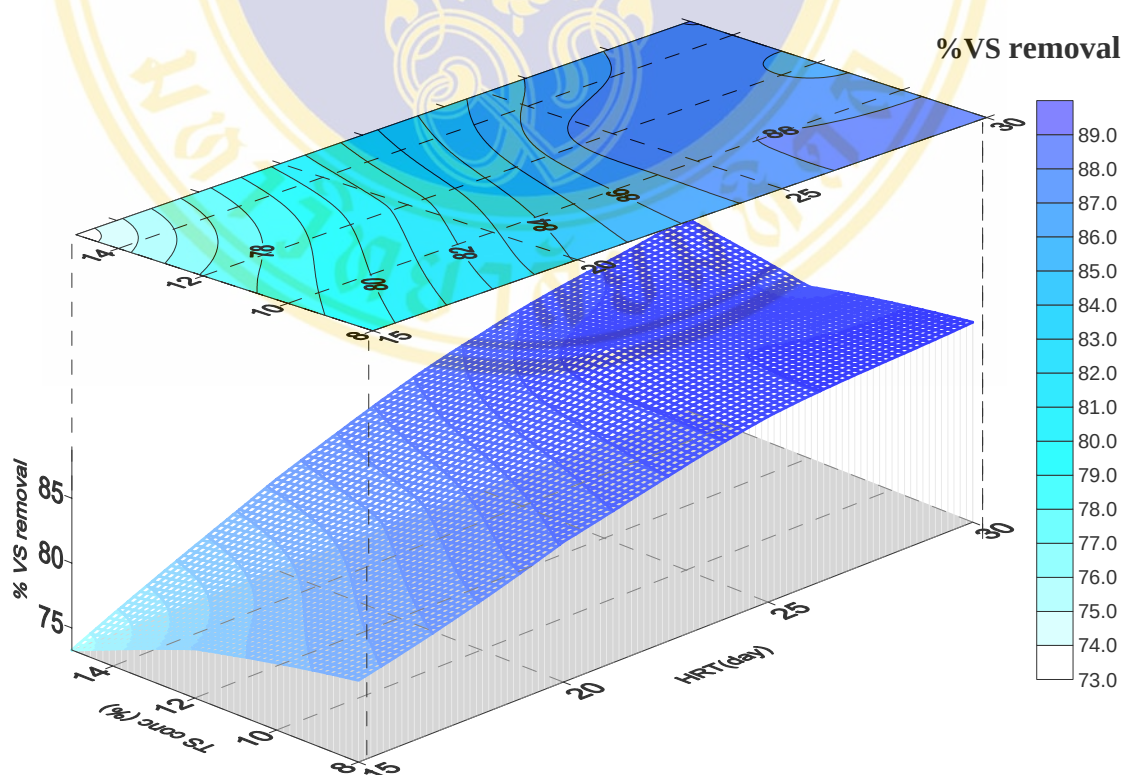


Figure 5.8 Contour graph for volatile solid removal during experimental runs

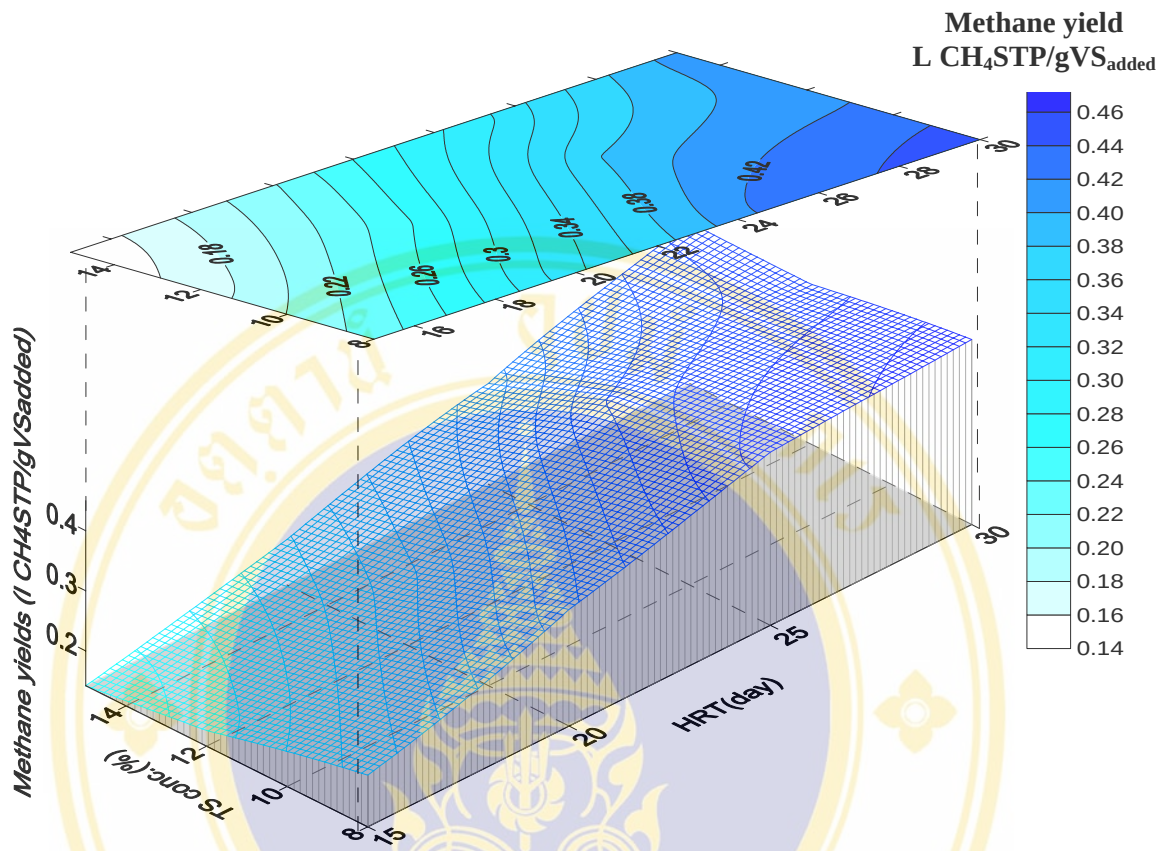


Figure 5.9 Contour graph for methane yield during experimental runs

5.5 Application of Kinetic study from Two-phase Mesophilic Anaerobic Digestion of OFMSW: Design procedure (26)

An anaerobic digester can very well be designed, based on reactor analysis using a laboratory bench scale reactor digesting the organic material in question.

The first step is to determine the degradation constant K based on experimental data from the lab reactor.

The second step is to choose the desired substrate removal efficiency i.e.

- $(S_0 - S_e)/S_0$.
- Given S_0 the design HRT can be computed from Eq. $S_0 - S_e = K S_e \text{ HRT}$
- The required reactor volume can then be calculated if the volumetric flow rate Q is known as $V = \text{HRT} \cdot Q$.

- Given the chemical composition of the biodegradable matter, the methane yield can be estimated in combination with Table 5.4 and Eq. of BF
- $BF = 0.83 - 0.028LC$ Where LC is the lignin content as a percentage of VS (Table 5.4)

Table 5.4 Lignin content of selected organic materials (48)

Component	Lignin content % of VS
Food wastes	0.4
Newspaper	21.9
Office paper	0.4
Cardboard	12.9
Yard wastes	4.1
Chicken manure	3.4
Pig manure	2.2
Cow manure	8
Wheat straw	13
Whey acid	0
Pine wood	28

Example: Designing a complete mixed digester for municipal solid wastes.

Parameters:

- Digester temperature is 35 °C
- Input 36,500 tons (wet weight) of OFMSW per year
- Inert solids (sand) 5% of dry weight
- Chemical composition 52% C, 8% H, 37% O, 3% N by weight
- Water content 70%
- Design dry matter content 8 % by weight
- Design biodegradable VS reduction efficiency 80%

1. Calculate the necessary quantity of dilution water

- The dry matter mass is $0.3 \times 36,500 = 10,950$ tons corresponding to 8% of the total input mass including dilution water.
- The total amount of water necessary is then $(10,950/8\%) \times 92\% = 125,925$ tons water.

- The amount of dilution water necessary is then 125,925 tons water total - (36,500 tons wet waste – 10,950 tons dry matter) = 78,475 tons water.
- The total input volume is then 114,975 m³.

2. Calculate the biodegradable fraction of the input material

$$BF = 0.83 - 0.028LC$$

Where LC is the lignin content as a percentage of VS

Lignin content from Table 5.4: LC = 0.4

- Biodegradable fraction from Eq.: $BF = 0.83 - 0.028 \times 0.4 = 0.82$

3. Calculate the input biodegradable substrate concentration S_0 and design effluent biodegradable substrate concentration S_e .

- $S_0 = \frac{10,950 \text{ tons dry matter} \times (1 - 0.05) \times 0.82 \text{ biodegradable fraction}}{114,975 \text{ m}^3 \text{ input volume}}$
 $= 74.19 \text{ kg/m}^3$
- $S_e = (1 - 80\%) \times 74.19 \text{ kg/m}^3 = 14.8 \text{ kg/m}^3$

4. Calculate the annual loading of biodegradable volatile solids

$$M_0 = 74.19 \text{ kg/m}^3 \times 114,975 \text{ m}^3 \times 1 \text{ m}^3/\text{ton} = 8,593 \text{ tons/yr}$$

5. Calculate the design HRT using Eq.

$$\begin{aligned} \text{HRT} &= (S_0 - S_e) / (K \times S_e) \\ &= (74.19 - 14.8) / (0.25 \times 14.8) = 16 \text{ d.} \end{aligned}$$

If K is not known HRT can be selected from Fig. 5.3 yielding 13-16d.

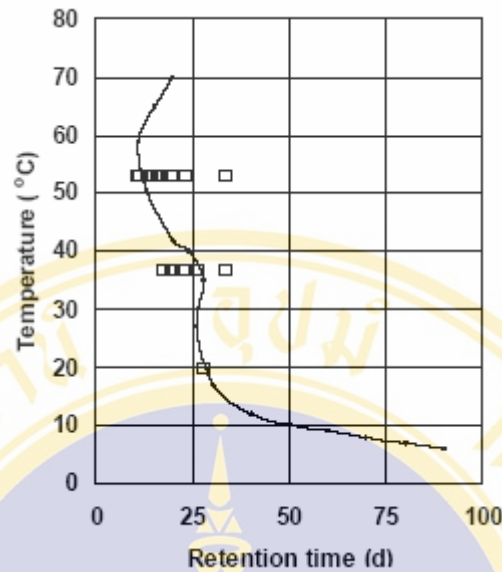


Figure 5.3. Relationship between hydraulic retention time and temperature in anaerobic digesters treating animal manure and biodegradable wastes, general trend (49)

6. Calculate the reactor design volume

$$V = \text{HRT} \cdot Q = (16\text{d} \cdot 114,975\text{m}^3/\text{yr}) / (365\text{d}/\text{yr}) = 5,040 \text{ m}^3$$

7. Calculate an approximate molecular formula for the input material.

For every gram of waste (dry matter) we have 0.45g C, 0.07g H, 0.32g O, and 0.03g N. This means that we have 0.45/12 moles of C, 0.07 moles of H, 0.32/16 moles of O, and 0.03/14 moles of N. An approximate chemical formula can therefore be expressed as $\text{C}_{0.043}\text{H}_{0.08}\text{O}_{0.023}\text{N}_{0.0021}$

8 Calculate the theoretical methane yield per ton of biodegradable volatile solids degraded in the reactor using Eq.

$$B_{\text{th}} = 22400 \frac{\left(\frac{4a+b-2c-3d}{8} \right)}{12a+b+16c+14d}$$

$$B_{\text{th}} = 22400 \frac{\left(\frac{4 \cdot 0.043 + 0.08 - 2 \cdot 0.023 - 3 \cdot 0.0021}{8} \right)}{12 \cdot 0.043 + 0.08 + 16 \cdot 0.023 + 14 \cdot 0.0021} = 563 \text{ Nm}^3$$

$$\text{Annual methane yield} = 8593 \times 563 = 4,837,859 \text{ Nm}^3/\text{yr}$$

9. Calculate the methane yield per ton of total solids entered into reactor

$$B = 4,837,859 \text{ Nm}^3/\text{yr} \times 10,950 \text{ tons}/\text{yr} = 441.8 \text{ Nm}^3/\text{ton}$$

The methane yield could alternatively have been calculated using this Eq.

$$B = \frac{B_0 S_0}{\text{HRT}} \left(1 - \frac{K}{\text{HRT} \mu_m - 1 + K} \right)$$

if the parameters K and μ_m are known. At present the knowledge about the biodegradation parameters used in the different models is scarce. Often digester design is based on experiences from existing plants. Here we could for instance have selected the HRT based on the data in Fig 5.3.

CHAPTER VI

CONCLUSION AND RECOMMENDATION

6. 1 Conclusion

The research aims to carry out a kinetic evaluation of two-phase mesophilic anaerobic digestion of organic fraction of municipal solid waste (OFMSW). The two-phase mesophilic anaerobic digestion system was operated at three different feed substrate concentrations: 68.63, 102.48 and 127.27 g VS/l. The hydraulic retention time (HRT) varied between 33.0 and 18 days for the three feed substrate concentrations. The results were evaluated using the Chen–Hashimoto methane production model to determine the kinetic constants of the process.

6.1.1 Evaluation of Kinetic Coefficients by using Chen–Hashimoto methane production model

The kinetic constants ($\mu_{\max}$ and K) were affected by the feed substrate concentration and decreased by 17.89 and 6.11 %, respectively, when the feed concentration increased from 68.63 to 127.27 g V/l. This behaviour is believed to be due to the higher levels of VFA and other inhibiting substances present in the most concentrated substrate used.

Finally, the minimum hydraulic retention times, $\theta_{\min}$ (day), at which the washout of the micro-organisms occurs were: 10.9, 11.9 and 12.8 days, for the Substrates I, II and III, respectively. These values were calculated by using Eq. 4.1 and taking into account that this retention time is numerically equal to the reciprocal of the minimum micro-organisms growth rate ($\mu_{\max}$). At the same time the maximum volumetric methane production rates obtained from Eq.4.6 were found to be 1.14, 1.50, 1.62 l CH₄ STP/l per day for the substrate I, II and III, respectively. The kinetic coefficient follow by Chen–Hashimoto methane production model of each substrate concentration were summarized as shown in Table 6.1

Table 6.1 Summarized the kinetic coefficients follow by Chen–Hashimoto methane production model

Parameter	unit	Substrate concentration		
		I	II	III
S_0	g.VS/l	68.63	102.48	127.27
B_0	l CH ₄ STP/gVS _{added}	0.656	0.663	0.586
K	-	0.867	0.846	0.814
$\mu_{\max}$	day ⁻¹	0.095	0.084	0.078
$\theta_{\min}$	day	10.58	11.93	12.77
$\delta_{\max}$	l CH ₄ STP/l.d	1.14	1.5	1.62

6.1.2 The Optimum Running Condition

The optimum running condition of two phase mesophilic anaerobic digestion of OFMSW was at the HRT of 30 days and the total solids concentration of 80,000 mg/l with the total solid removal efficiency, volatile solid removal efficiency, and methane yields of 77.08 %, 88.49% and 0.46 l CH₄STP/gVS_{added}, respectively.

6.2 Recommendations

The following recommendations are drawn for further considerations:

6.2.1 Application of anaerobic digestion on a pilot scale operation by using other configuration such as operated with thermophilic temperature.

6.2.2 Variation of the influent factors on the anaerobic digestion system such as temperature, reactor configuration, particle size of feed substrate.

6.2.3 Anaerobic digestion should be applied to digest the different types of waste from different sources.

REFERENCES

1. Hamed M. El-Mashad. Effect of temperature and temperature fluctuation on thermophilic anaerobic digestion of cattle manure. *Bioresource Technology* 2004; 95: 191–201.
2. De Baere, L. Anaerobic digestion of solid waste: state-of-the art. *Water Sci. Technol.* 2000; 41 (3): 283–290.
3. G.M. Vogt and B.E. Holbein. Canada's SUBBOR, Enhanced Anaerobic Digestion Technology: Utilization of Waste Biomass Avoids GHG Emission and Provides Alternative Presented at Climate Change 2: Canadian Technology Development Toronto, Oct. 2001.
4. Peter G. Stroot, Katherine D. Anaerobic Co-digestion of Municipal Solid waste and Bio-solid under Various Mixing Conditions; Digester Performance. University of Illinois at Urbana-Champaign .2000.
5. Williams M. E. Integrated solid waste management. In *Handbook of Solid Waste Management*, ed F. Kreith. McGraw-Hill, Inc., New York. 1994.
6. Pohland F. G. Landfill bioreactors: fundamentals and practice. *Water Qual. Int.* 1996: 18-22.
7. Tchobanoglous G., Theisen H. and Vigil S. *Integrated Solid Waste Management*. McGraw-Hill Inc, New York. 1993.
8. Knezevic, Z., Pilot-scale evaluation of anaerobic co-digestion of primary and pretreated waste-activated sludge. *Water Environ. Res.* 1995; 67: 835–841.
9. Ghosh, S., Ombregt, J. P. & Pipyn, P. Methane production from industrial wastes by two-phase digestion. *Wat. Res.* 1985; 19, 1083-8.
- 10 Kayhanian, M. Biodegradability of the organic fraction of municipal solid waste in a high solids anaerobic digester, *Waste Management & Research*. 1995; 13: 123-136
11. Y.R. Chen, A.G. Hashimoto, Kinetics of methane fermentation, *Biotechnol. Bioeng. Symp.* 8 (1978); 269-2825.

12. Rantala J. and Ahring B. A two-stage thermophilic anaerobic process for the treatment of source sorted household solid waste. *Biotechnol. Lett.* 1994; 16: 1097–1102.
13. Buchauer K. A comparison of two sample titration procedures to determine volatile fatty acid influents to wastewater and sludge treatment processes. *Water SA*.1998; 24(1): 49-56.
14. Hawkes, D. L. Factors affecting net energy production from mesophilic anaerobic digestion. In *Anaerobic Digestion*, eds D. A. Stratford, B. I. Wheatley and D. E. Hughes. 1980;pp. 131-150.
- 15 F. Cecchi, E G. Traverso, J. Mata-Alvarez and J. Clancy. State of the Art of R&D in the Anaerobic Digestion Process of Municipal Solid Waste in Europe. *Biomass*. 1988;16 : 257-284.
16. www.soton.ac.uk/~sunrise/anaerobicdig.htm#ADsolidwaste.
17. Shefali Verma. *Anaerobic Digestion of Biodegradable Organics in Municipal Solid Wastes*. Fu Foundation School of Engineering & Applied Science Columbia University May 2002.
18. Regional Information Service Centre for South East Asia on Appropriate Technology (RISE-AT). *Review of current status of Anaerobic Digestion Technology for treatment of MSW*. 1998.
19. www.biogasworks.com
20. S. Kimchie, S. Tarre. Developments in Anaerobic Digestion of Organic Wastes in Israel. *Biological Wastes*.1988;(26): 275-284.
21. De Baere, L., *Anaerobic Digestion of Solid Waste: State of the Art*, Water, Science Technology. 1999; 41(3): 283-290.
22. Shelef, G., Kimchie, S. & Grynberg, H. High-rate thermophilic digestion of agricultural wastes. *Biotechnology and Bioengineering Symp* .1980;(10): 341-51.
23. S. Kimchie, S. Tarre. Developments in Anaerobic Digestion of Organic Wastes in Israel. *Biological Wastes*.1988;(26): 275-284.
24. Cecchi F., Traverso P. G., Mata-Alvarez J., Clancy J. and Zaror C. State of the art of R&D in the anaerobic digestion process of municipal solid waste in Europe. *Biomass*.1988; 16: 57–284.

25. Anderson G. K. and Yang G. Determination of bicarbonate and total volatile acid concentration in anaerobic digesters using a simple titration. *Water Environ. Res.* 1992; 64:53–59.
26. Tjalfe G. Poulsen Anaerobic digestion Solid waste management, Chapter 5 Aalborg University, June 2003.
- 27 A. Keshtkar and B. Meyssami. Mathematical modeling of non-ideal mixing continuous flow reactors for anaerobic digestion of cattle manure. *Bioresource Technology* .2003; 87: 113–124.
28. W.C. Hu, K. Thayanithy. A kinetic study of the anaerobic digestion of ice-cream wastewater. *Process Biochemistry*. 2002; 37: 965–971.
29. Tchobanoglous, G., Theisen, H., and Vigil, S., *Integrated Solid Waste Management*, chapter 9, 1993; McGraw-Hill, New York.
30. De Baere, L., *Anaerobic Digestion of Solid Waste: State of the Art*, *Water, Science Technology* .1999; 41(3): 283-290.
- 31 R. Borja and B. Rincón. Kinetics of mesophilic anaerobic digestion of the two-phase olive mill solid waste *Biochemical Engineering Journal* .2003; 15: 139–145.
32. V. Blonskaja and A. Menert. Use of two-stage anaerobic treatment for distillery waste *Advances in Environmental Research*. 2003; 7: 671–678.
33. Saikat Banerjee, G.K. Biswas. Studies on biomethanation of distillery wastes and its mathematical analysis. *Chemical Engineering Jr.*2004; 102:193–201.
- 34 Kayhanian, M, and Tchobanoglous, G, Computation of C:N ratios for various organic fractions. *Biocycle* 1992;33(5),58-60.
- 35 Kayhanian, M, and Tchobanoglous, G, Computation of C:N ratios for various organic fractions. *Biocycle* 1992;33(5),58-60.
36. APHA, AWWA and WEF. *Standard methods for the Examination of Water and Wastewater*. 20th ed. Washington D.C.: American Public Health Association; 1998.
37. Cecchi, F., Paven, P. and Mata-Alvarez, J. Kinetic study of the thermophilic anaerobic digestion of the fresh and pre-composted mechanically selected organic fraction of MSW. *Envi Sci and Health A32* (1), 195-213.

38. J. Mata-Alvarez Biomethanization of the organic fraction of municipal solid wastes. 2003.
39. De Baere, L. Anaerobic digestion of solid waste ; state of the art. Wat. Sci Tech. 2000; 41(3):283-290
40. Kubler et al, Full scale co-digestion of organic waste., In: Proc. II ISAD-SW, Barcelona, Spain, 1999;175-182.
41. CITEC Le linee guida per la progettazione, la realizzazione e la gestione degli impianti a tecnologia complessa per lo smaltimento dei rifiuti urbani.
42. Tjalfe G. Poulsen Anaerobic digestion Solid waste management, Chapter 5 Aalborg University, June 2003.
43. Y.R. Chen, A.G. Hashimoto, Kinetics of methane fermentation, Biotechnol. Bioeng. Symp. 8 (1978) 269–282.
44. Hamzawi, N., Kennedy, K.J., Mc Lean, D.D., 1998. Technical feasibility of anaerobic co-digestion of sewage sludge and municipal solid waste. Environ. Technol. 19, 993–1003.
45. Anna C. Palmisano and Morton A. Barlaz Microbiology of solid waste, 1996;97.
46. Oleszkiewicz, J. A., Poggivaldo, H.M., 1997 High solids anaerobic digestion of mixed municipal and industrial waste. J. Environ. Eng. 123, 1087-1092
47. Cho, J.K., S.C. Park and H.N. Chang Biochemical methane potential and solid state anaerobic digestion of Korean food wastes. Bioresource Technology, 1995; 52:245-253
48. Richard, T. 2000. The effect of lignin on biodegradability.
<http://www.cfe.cornell.edu/compost/calc/lignin.html>
49. Nepalese plant, Pokharel and Yadu solid curve, Danish energy agency, 1996
Danish institute of agricultural and fisheries economics, 1999.



APPENDIX A

EXPERIMENTAL RESULTS

Table A-1 Total solid removal efficiency of two-phase mesophilic anaerobic digestion in group 1 (TS 8%, HRT 30, 25, day)

Date	HRT 30 day			HRT 25 day		
	TS inf.	TS eff.	Removal Efficiency	TS inf.	TS eff.	Removal Efficiency
1	82.00	19.52	76.20	76.00	20.29	73.30
3	84.00	19.07	77.30	81.20	20.71	74.50
5	83.10	19.03	77.10	82.00	20.66	74.80
7	80.10	19.22	76.00	82.30	20.25	75.40
9	81.00	19.04	76.50	78.30	18.71	76.10
11	82.60	18.92	77.10	82.30	20.16	75.50
13	81.00	18.63	77.00	81.10	20.60	74.60
15	80.00	18.40	77.00	78.50	20.02	74.50
17	81.20	19.16	76.40	80.00	20.48	74.40
19	82.00	18.29	77.70	82.00	20.17	75.40
21	82.30	18.60	77.40	79.60	19.98	74.90
23	78.30	18.01	77.00	83.10	20.61	75.20
25	82.30	19.18	76.70	83.00	20.67	75.10
27	81.10	18.09	77.70	75.60	18.52	75.50
29	83.00	18.59	77.60	77.00	19.10	75.20
31	80.00	18.00	77.50	-	-	-
33	82.00	18.20	77.80	-	-	-
35	79.60	18.23	77.10	-	-	-
37	83.10	18.78	77.40	-	-	-
Min.	78.30	18.00	76.00	75.60	18.52	73.30
Max.	84.00	19.52	77.80	83.10	20.71	76.10
Mean	81.51	18.68	77.08	80.13	20.06	74.96
SD.	1.45	0.46	0.52	2.52	0.71	0.66

Table A-2 Total solid removal efficiency of two-phase mesophillic anaerobic digestion in group 1 (TS 8%, HRT 20, 15 days)

Date	HRT 20 day			HRT 15 day		
	TS inf.	TS eff.	Removal Efficiency	TS inf.	TS eff.	Removal Efficiency
1	80.00	22.20	72.25	78.30	26.15	66.60
3	82.00	23.04	71.90	82.30	25.51	69.00
5	79.60	22.69	71.50	81.10	26.20	67.70
7	83.10	22.94	72.40	78.50	24.65	68.60
9	83.00	22.41	73.00	80.00	25.12	68.60
11	75.60	20.87	72.40	82.00	25.50	68.90
13	77.00	21.25	72.40	79.60	24.60	69.10
15	83.10	23.43	71.80	83.10	25.35	69.50
17	80.10	22.19	72.30	79.60	24.20	69.60
19	81.00	22.03	72.80	83.10	25.51	69.30
21	82.60	22.80	72.40	-	-	-
23	81.00	22.36	72.40	-	-	-
25	76.00	21.47	71.75	-	-	-
Min.	75.60	20.87	71.50	78.30	24.20	66.60
Max.	83.10	23.43	73.00	83.10	26.20	69.60
Mean	80.32	22.28	72.25	80.76	25.28	68.69
SD.	2.65	0.74	0.42	1.81	0.65	0.91

Table A-3 Total solid removal efficiency of two-phase mesophilic anaerobic digestion in group 2 (TS 12 %, HRT 30, 25 days)

Date	HRT 30 day			HRT 25 day		
	TS inf.	TS eff.	Removal Efficiency	TS inf.	TS eff.	Removal Efficiency
1	121.00	30.01	75.20	120.50	31.21	74.10
3	120.50	29.04	75.90	123.00	31.86	74.10
5	119.00	29.16	75.50	121.00	30.01	75.20
7	120.00	29.28	75.60	119.00	29.75	75.00
9	122.50	30.63	75.00	121.00	31.22	74.20
11	121.20	30.30	75.00	119.00	29.99	74.80
13	118.50	29.98	74.70	120.50	30.13	75.00
15	121.00	29.04	76.00	121.10	30.64	74.70
17	121.50	27.95	77.00	120.00	30.48	74.60
19	120.50	29.04	75.90	122.50	30.26	75.30
21	122.50	29.52	75.90	121.20	30.30	75.00
23	121.00	28.68	76.30	118.50	29.86	74.80
25	120.50	29.52	75.50	121.00	30.61	74.70
27	118.00	27.97	76.30	121.50	30.38	75.00
29	121.00	28.56	76.40	118.00	30.56	74.10
31	119.00	27.37	77.00	-	-	-
33	120.50	29.04	75.90	-	-	-
35	121.10	30.28	75.00	-	-	-
37	118.50	29.15	75.40	-	-	-
Min.	118.0	27.4	74.7	118.00	29.75	74.10
Max.	122.5	30.6	77.0	123.00	31.86	75.30
Mean	120.4	29.2	75.8	120.52	30.48	74.71
SD.	1.28	0.85	0.65	1.41	0.57	0.41

Table A-4 Total solid removal efficiency of two-phase mesophillic anaerobic digestion in group 2 (TS 12 %, HRT 20, 15 days)

Date	HRT 20 day			HRT 15 day		
	TS inf.	TS eff.	Removal Efficiency	TS inf.	TS eff.	Removal Efficiency
1	122.50	35.04	71.40	121.20	43.03	64.50
3	121.00	36.30	70.00	118.50	43.37	63.40
5	120.50	36.27	69.90	121.00	44.04	63.60
7	118.00	34.69	70.60	121.50	44.23	63.60
9	121.00	35.57	70.60	120.50	43.98	63.50
11	119.00	35.70	70.00	122.50	44.35	63.80
13	122.50	35.53	71.00	121.00	44.77	63.00
15	121.20	35.51	70.70	122.50	44.59	63.60
17	118.50	35.79	69.80	121.20	44.84	63.00
19	121.00	37.39	69.10	118.50	45.03	62.00
21	121.50	37.54	69.10	-	-	-
23	120.50	36.75	69.50	-	-	-
25	121.10	37.06	69.40	-	-	-
Min.	118.00	34.69	69.10	118.50	43.03	62.00
Max.	122.50	37.54	71.40	122.50	45.03	64.50
Mean	120.64	36.09	70.08	120.84	44.22	63.40
SD.	1.38	0.89	0.73	1.39	0.64	0.65

Table A-5 Total solid removal efficiency of two-phase mesophilic anaerobic digestion in group 3 (TS 15 %, HRT 30, 25 days)

Date	HRT 30 day			HRT 25 day		
	TS inf.	TS eff.	Removal Efficiency	TS inf.	TS eff.	Removal Efficiency
1	148.00	36.56	75.30	149.00	38.29	74.30
3	151.00	36.84	75.60	148.50	39.06	73.70
5	150.20	36.05	76.00	147.00	39.84	72.90
7	152.50	36.45	76.10	149.00	38.74	74.00
9	148.60	36.41	75.50	148.00	39.96	73.00
11	149.00	36.06	75.80	151.00	42.28	72.00
13	150.10	36.32	75.80	150.20	40.55	73.00
15	151.00	36.24	76.00	152.50	41.02	73.10
17	152.00	36.94	75.70	148.20	40.16	72.90
19	149.60	36.95	75.30	151.00	43.79	71.00
21	150.50	36.57	75.70	152.00	39.52	74.00
23	152.00	36.94	75.70	149.60	41.44	72.30
25	149.00	36.06	75.80	150.50	42.44	71.80
27	151.00	35.94	76.20	152.50	41.18	73.00
29	148.60	36.26	75.60	148.60	38.64	74.00
31	151.20	35.99	76.20	-	-	-
33	149.00	36.36	75.60	-	-	-
35	148.50	35.64	76.00	-	-	-
37	147.00	36.16	75.40	-	-	-
Min.	147.00	35.64	75.30	147.00	38.29	71.00
Max.	152.50	36.95	76.20	152.50	43.79	74.30
Mean	149.94	36.35	75.75	149.84	40.46	73.00
SD.	1.51	0.37	0.28	1.71	1.57	0.93

Table A-6 Total solid removal efficiency of two-phase mesophilic anaerobic digestion in group 3 (TS 15 %, HRT 20, 15 days)

Date	HRT 20 day			HRT 15 day		
	TS inf.	TS eff.	Removal Efficiency	TS inf.	TS eff.	Removal Efficiency
1	151.00	44.85	70.30	149.00	55.58	62.70
3	148.60	44.13	70.30	151.00	57.83	61.70
5	151.20	45.81	69.70	148.60	57.51	61.30
7	149.00	45.89	69.20	151.20	57.76	61.80
9	148.50	45.14	69.60	149.00	58.26	60.90
11	153.00	46.21	69.80	149.00	58.26	60.90
13	149.00	45.15	69.70	148.50	58.51	60.60
15	152.50	46.21	69.70	147.00	59.54	59.50
17	147.00	45.72	68.90	149.00	59.30	60.20
19	149.00	45.30	69.60	148.00	58.90	60.20
21	148.00	45.51	69.25	-	-	-
23	151.00	45.30	70.00	-	-	-
25	150.20	45.66	69.60	-	-	-
Min.	147.00	44.13	68.90	147.00	55.58	59.50
Max.	153.00	46.21	70.30	151.20	59.54	62.70
Mean	149.85	45.45	69.67	149.03	58.14	60.98
SD.	1.79	0.57	0.40	1.26	1.12	0.93

Table A-7 Volatile solid removal efficiency of two-phase mesophilic anaerobic digestion in group 1 (TS 8 %, HRT 30, 25 days)

Date	HRT 30 day			HRT 25 day		
	VS inf.	VS eff.	Removal Efficiency	VS inf.	VS eff.	Removal Efficiency
1	69.70	7.88	88.70	64.60	8.01	87.60
3	71.40	7.71	89.20	69.02	8.21	88.10
5	70.64	7.77	89.00	69.70	8.50	87.80
7	68.09	8.03	88.20	69.96	8.74	87.50
9	68.85	7.85	88.60	66.56	8.25	87.60
11	70.21	7.72	89.00	69.96	8.39	88.00
13	68.85	8.06	88.30	68.94	8.00	88.40
15	68.00	7.82	88.50	66.73	7.87	88.20
17	69.02	8.08	88.30	68.00	8.77	87.10
19	69.70	8.29	88.10	69.70	8.71	87.50
21	69.96	8.39	88.00	67.66	8.05	88.10
23	66.56	7.79	88.30	70.64	8.33	88.20
25	69.96	8.74	87.50	70.55	8.47	88.00
27	68.94	7.72	88.80	64.26	7.97	87.60
29	70.55	7.48	89.40	65.45	8.18	87.50
31	68.00	7.68	88.70	-	-	-
33	69.70	8.02	88.50	-	-	-
35	67.66	8.05	88.10	-	-	-
37	70.64	8.41	88.10	-	-	-
Min.	66.56	7.48	87.50	64.26	7.87	87.10
Max.	71.40	8.74	89.40	70.64	8.77	88.40
Mean	69.28	7.97	88.49	68.11	8.30	87.81
SD.	1.23	0.31	0.47	2.15	0.30	0.36

Table A-8 Volatile solid removal efficiency of two-phase mesophilic anaerobic digestion in group 1 (TS 8 %, HRT 20, and 15 days)

Date	HRT 20 day			HRT 15 day		
	VS inf.	VS eff.	Removal Efficiency	VS inf.	VS eff.	Removal Efficiency
1	68.00	10.81	84.10	66.56	13.58	79.60
3	69.70	10.87	84.40	69.96	15.60	77.70
5	67.66	11.77	82.60	68.94	15.03	78.20
7	70.64	11.09	84.30	66.73	14.01	79.00
9	70.55	11.57	83.60	68.00	14.62	78.50
11	64.26	11.89	81.50	69.70	15.19	78.20
13	65.45	11.85	81.90	67.66	14.55	78.50
15	70.64	13.42	81.00	70.64	15.61	77.90
17	68.09	11.51	83.10	67.66	14.55	78.50
19	68.85	11.64	83.10	70.64	15.33	78.30
21	70.21	12.01	82.90	-	-	-
23	68.85	12.39	82.00	-	-	-
25	64.60	10.92	83.10	-	-	-
Min.	64.26	10.81	81.00	66.56	13.58	77.70
Max.	70.64	13.42	84.40	70.64	15.61	79.60
Mean	68.27	11.67	82.89	68.65	14.81	78.44
SD.	2.25	0.71	1.07	1.54	0.67	0.54

Table A-9 Volatile solid removal efficiency of two-phase mesophilic anaerobic digestion in group 2 (TS 12 %, HRT 30 and 25 days)

Date	HRT 30 day			HRT 25 day		
	VS inf.	VS eff.	Removal Efficiency	VS inf.	VS eff.	Removal Efficiency
1	102.85	13.88	86.50	102.43	12.29	88.00
3	102.43	13.32	87.00	104.55	12.34	88.20
5	101.15	10.62	89.50	102.85	12.86	87.50
7	102.00	10.40	89.80	101.15	11.94	88.20
9	104.13	12.81	87.70	102.85	12.65	87.70
11	103.02	10.82	89.50	101.15	12.64	87.50
13	100.73	12.79	87.30	102.43	12.29	88.00
15	102.85	12.34	88.00	102.94	12.15	88.20
17	103.28	11.15	89.20	102.00	12.04	88.20
19	102.43	12.29	88.00	104.13	13.74	86.80
21	104.13	12.81	87.70	103.02	12.57	87.80
23	102.85	13.37	87.00	100.73	12.89	87.20
25	102.43	11.57	88.70	102.85	12.96	87.40
27	100.30	11.23	88.80	103.28	13.22	87.20
29	102.85	11.21	89.10	100.30	13.04	87.00
31	101.15	11.43	88.70	-	-	-
33	102.43	11.68	88.60	-	-	-
35	102.94	12.35	88.00	-	-	-
37	100.73	10.58	89.50	-	-	-
Min.	100.30	10.40	86.50	100.30	11.94	86.80
Max.	104.13	13.88	89.80	104.55	13.74	88.20
Mean	102.35	11.93	88.35	102.44	12.64	87.66
SD.	1.09	1.05	0.98	1.20	0.49	0.47

Table A-10 Volatile solid removal efficiency of two-phase mesophilic anaerobic digestion in group 2 (TS 12 %, HRT 20 and 15 days)

Date	HRT 20 day			HRT 15 day		
	VS inf.	VS eff.	Removal Efficiency	VS inf.	VS eff.	Removal Efficiency
1	104.13	19.37	81.40	103.02	23.59	77.10
3	102.85	20.57	80.00	100.73	23.17	77.00
5	102.43	20.59	79.90	102.85	23.45	77.20
7	100.30	19.46	80.60	103.28	24.27	76.50
9	102.85	19.95	80.60	102.43	24.48	76.10
11	101.15	20.23	80.00	104.13	23.53	77.40
13	104.13	19.78	81.00	102.85	23.55	77.10
15	103.02	19.88	80.70	104.13	23.84	77.10
17	100.73	20.35	79.80	103.02	24.00	76.70
19	102.85	21.50	79.10	100.73	23.92	76.25
21	103.28	21.58	79.10	-	-	-
23	102.43	21.00	79.50	-	-	-
25	102.94	21.20	79.40	-	-	-
Min.	100.30	19.37	79.10	100.73	23.17	76.10
Max.	104.13	21.58	81.40	104.13	24.48	77.40
Mean	102.54	20.42	80.08	102.71	23.78	76.85
SD.	1.17	0.74	0.73	1.18	0.40	0.43

Table A-11 Volatile solid removal efficiency of two-phase mesophilic anaerobic digestion in group 3 (TS 15 %, HRT 30, 25 days)

Date	HRT 30 day			HRT 25 day		
	VS inf.	VS eff.	Removal Efficiency	VS inf.	VS eff.	Removal Efficiency
1	148.00	36.56	75.30	149.00	38.29	74.30
3	151.00	36.84	75.60	148.50	39.06	73.70
5	150.20	36.05	76.00	147.00	39.84	72.90
7	152.50	36.45	76.10	149.00	38.74	74.00
9	148.60	36.41	75.50	148.00	39.96	73.00
11	149.00	36.06	75.80	151.00	42.28	72.00
13	150.10	36.32	75.80	150.20	40.55	73.00
15	151.00	36.24	76.00	152.50	41.02	73.10
17	152.00	36.94	75.70	148.20	40.16	72.90
19	149.60	36.95	75.30	151.00	43.79	71.00
21	150.50	36.57	75.70	152.00	39.52	74.00
23	152.00	36.94	75.70	149.60	41.44	72.30
25	149.00	36.06	75.80	150.50	42.44	71.80
27	151.00	35.94	76.20	152.50	41.18	73.00
29	148.60	36.26	75.60	148.60	38.64	74.00
31	151.20	35.99	76.20	-	-	-
33	149.00	36.36	75.60	-	-	-
35	148.50	35.64	76.00	-	-	-
37	147.00	36.16	75.40	-	-	-
Min.	147.00	35.64	75.30	147.00	38.29	71.00
Max.	152.50	36.95	76.20	152.50	43.79	74.30
Mean	149.94	36.35	75.75	149.84	40.46	73.00
SD.	1.51	0.37	0.28	1.71	1.57	0.93

Table A-12 Volatile solid removal efficiency of two-phase mesophilic anaerobic digestion in group 3 (TS 15 %, HRT 20, and 15 days)

Date	HRT 20 day			HRT 15 day		
	VS inf.	VS eff.	Removal Efficiency	VS inf.	VS eff.	Removal Efficiency
1	128.35	25.28	80.30	126.65	33.82	73.30
3	126.31	24.88	80.30	128.35	35.94	72.00
5	128.52	26.09	79.70	126.31	33.60	73.40
7	126.65	26.34	79.20	128.52	32.52	74.70
9	126.23	25.75	79.60	126.65	35.46	72.00
11	130.05	26.27	79.80	126.65	33.56	73.50
13	126.65	25.71	79.70	126.23	34.71	72.50
15	129.63	26.31	79.70	124.95	32.74	73.80
17	124.95	26.36	78.90	126.65	33.31	73.70
19	126.65	25.84	79.60	125.80	32.83	73.90
21	125.80	26.10	79.25	-	-	-
23	128.35	25.67	80.00	-	-	-
25	127.67	26.04	79.60	-	-	-
Min.	124.95	24.88	78.90	124.95	32.52	72.00
Max.	130.05	26.36	80.30	128.52	35.94	74.70
Mean	127.37	25.90	79.67	126.68	33.85	73.28
SD.	1.53	0.44	0.40	1.07	1.16	0.87

Table A-13 Methane yield ($\text{L CH}_4\text{STP/g VS}_{\text{add}}$) of two-phase mesophilic anaerobic digestion in group 1 (TS 8 %, HRT 30 days)

Date	HRT 30 day /TS 8%				
	VS influent	OLR ($\text{gVS/L}_{\text{reactor}}\cdot\text{d}$)	L biogas STP/d	L biogas STP/gVSadd	L CH ₄ STP/gVSadd
1	69.70	2.32	20.91	0.75	0.45
3	71.40	2.38	21.99	0.77	0.46
5	70.64	2.35	21.33	0.76	0.45
7	68.09	2.27	21.33	0.78	0.47
9	68.85	2.30	21.11	0.77	0.46
11	70.21	2.34	21.06	0.75	0.45
13	68.85	2.30	21.11	0.77	0.46
15	68.00	2.27	20.94	0.77	0.46
17	69.02	2.30	20.98	0.76	0.46
19	69.70	2.32	21.70	0.78	0.47
21	69.96	2.33	21.08	0.75	0.45
23	66.56	2.22	20.85	0.78	0.47
25	69.96	2.33	21.69	0.78	0.47
27	68.94	2.30	21.69	0.79	0.47
29	70.55	2.35	22.01	0.78	0.47
31	68.00	2.27	20.76	0.76	0.46
33	69.70	2.32	21.47	0.77	0.46
35	67.66	2.26	21.29	0.79	0.47
37	70.64	2.35	22.51	0.80	0.48
Mean	69.28	2.31	21.36	0.77	0.46
Max	71.40	2.38	22.51	0.80	0.48
Min	66.56	2.22	20.76	0.75	0.45
SD.	1.23	0.04	0.47	0.01	0.01

Table A-14 Methane yield ($\text{L CH}_{4\text{STP}}/\text{g VS}_{\text{add}}$) of two-phase mesophilic anaerobic digestion in group 1 (TS 8 %, HRT 25 days)

Date	HRT 25 day /TS 8%				
	VS influent	OLR ($\text{gVS}/\text{L}_{\text{reactor}}\cdot\text{d}$)	L biogas STP/d	L biogas STP/gVSadd	L CH ₄ STP/gVSadd
1	64.60	2.58	18.52	0.72	0.43
3	69.02	2.76	20.11	0.73	0.44
5	69.70	2.79	21.00	0.75	0.45
7	69.96	2.80	20.52	0.73	0.44
9	66.56	2.66	19.17	0.72	0.43
11	69.96	2.80	20.29	0.73	0.44
13	68.94	2.76	20.22	0.73	0.44
15	66.73	2.67	19.39	0.73	0.44
17	68.00	2.72	20.04	0.74	0.44
19	69.70	2.79	20.40	0.73	0.44
21	67.66	2.71	19.76	0.73	0.44
23	70.64	2.83	20.81	0.74	0.44
25	70.55	2.82	20.93	0.74	0.45
27	64.26	2.57	18.85	0.73	0.44
29	65.45	2.62	16.97	0.65	0.39
Mean	68.11	2.72	19.80	0.73	0.44
Max	70.64	2.83	21.00	0.75	0.45
Min	64.26	2.57	16.97	0.65	0.39
SD.	2.15	0.09	1.08	0.02	0.01

Table A-15 Methane yield ($\text{L CH}_4 \text{ STP/g VS}_{\text{add}}$) of two-phase mesophilic anaerobic digestion in group 1 (TS 8 %, HRT 20 days)

Date	HRT 20 day /TS 8%				
	VS influent	OLR ($\text{gVS/L}_{\text{reactor}} \cdot \text{d}$)	L biogas STP/d	L biogas STP/ gVS_{add}	L CH ₄ STP/ gVS_{add}
1	68.00	3.40	15.23	0.56	0.34
3	69.70	3.49	15.33	0.55	0.33
5	67.66	3.38	15.11	0.56	0.34
7	70.64	3.53	16.01	0.57	0.34
9	70.55	3.53	15.62	0.55	0.33
11	64.26	3.21	14.31	0.56	0.33
13	65.45	3.27	14.75	0.56	0.34
15	70.64	3.53	16.06	0.57	0.34
17	68.09	3.40	14.98	0.55	0.33
19	68.85	3.44	15.61	0.57	0.34
21	70.21	3.51	15.82	0.56	0.34
23	68.85	3.44	15.74	0.57	0.34
25	64.60	3.23	14.56	0.56	0.34
Mean	68.27	3.41	15.32	0.56	0.34
Max	70.64	3.53	16.06	0.57	0.34
Min	64.26	3.21	14.31	0.55	0.33
SD.	2.25	0.11	0.56	0.01	0.00

Table A-16 Methane yield (l. CH₄ STP/g VS_{add}) of two-phase mesophilic anaerobic digestion in group 1 (TS 8 %, HRT 15 days)

Date	HRT 15 day /TS 8%				
	VS influent	OLR (gVS/L _{reactor} ·d)	L biogas STP/d	L biogas STP/gVS _{add}	L CH ₄ STP/gVS _{add}
1	66.56	4.44	10.12	0.38	0.23
3	69.96	4.66	10.82	0.39	0.23
5	68.94	4.60	10.94	0.40	0.24
7	66.73	4.45	10.45	0.39	0.24
9	68.00	4.53	10.70	0.39	0.24
11	69.70	4.65	10.92	0.39	0.24
13	67.66	4.51	10.37	0.38	0.23
15	70.64	4.71	11.21	0.40	0.24
17	67.66	4.51	10.69	0.40	0.24
19	70.64	4.71	11.21	0.40	0.24
Mean	68.65	4.58	10.74	0.39	0.23
Max	70.64	4.71	11.21	0.40	0.24
Min	66.56	4.44	10.12	0.38	0.23
SD.	1.54	0.10	0.35	0.01	0.00

Table A-17 Methane yield ($\text{L CH}_4 \text{ STP/g VS}_{\text{add}}$) of two-phase mesophilic anaerobic digestion in group 2 (TS 12 %, HRT 30 days)

Date	HRT 30 day /TS 12%				
	VS influent	OLR ($\text{gVS/L}_{\text{reactor}} \cdot \text{d}$)	L biogas STP/d	L biogas STP/gVS _{add}	L CH ₄ STP/gVS _{add}
1	102.85	3.43	29.14	0.71	0.425
3	102.43	3.41	29.50	0.72	0.432
5	101.15	3.37	28.52	0.71	0.423
7	102.00	3.40	28.02	0.69	0.412
9	104.13	3.47	28.81	0.69	0.415
11	103.02	3.43	28.36	0.69	0.413
13	100.73	3.36	27.46	0.68	0.409
15	102.85	3.43	28.46	0.69	0.415
17	103.28	3.44	28.23	0.68	0.410
19	102.43	3.41	28.20	0.69	0.413
21	104.13	3.47	28.81	0.69	0.415
23	102.85	3.43	27.98	0.68	0.408
25	102.43	3.41	28.13	0.69	0.412
27	100.30	3.34	27.75	0.69	0.415
29	102.85	3.43	28.32	0.69	0.413
31	101.15	3.37	27.58	0.68	0.409
33	102.43	3.41	28.20	0.69	0.413
35	102.94	3.43	28.27	0.69	0.412
37	100.73	3.36	27.53	0.68	0.410
Mean	102.35	3.41	28.28	0.69	0.41
Max	104.13	3.47	29.50	0.72	0.43
Min	100.30	3.34	27.46	0.68	0.41
SD.	1.09	0.04	0.53	0.01	0.01

Table A-18 Methane yield ($\text{L CH}_4_{\text{STP}}/\text{g VS}_{\text{add}}$) of two-phase mesophilic anaerobic digestion in group 2 (TS 12 %, HRT 25 days)

Date	HRT 25 day /TS 12%				
	VS influent	OLR ($\text{gVS}/\text{L}_{\text{reactor}}\cdot\text{d}$)	L biogas STP/d	L biogas STP/gVSadd	L CH ₄ STP/gVSadd
1	102.43	4.10	26.08	0.64	0.38
3	104.55	4.18	27.18	0.65	0.39
5	102.85	4.11	28.11	0.68	0.41
7	101.15	4.05	26.03	0.64	0.39
9	102.85	4.11	26.67	0.65	0.39
11	101.15	4.05	26.30	0.65	0.39
13	102.43	4.10	27.31	0.67	0.40
15	102.94	4.12	28.48	0.69	0.42
17	102.00	4.08	26.45	0.65	0.39
19	104.13	4.17	26.66	0.64	0.38
21	103.02	4.12	26.44	0.64	0.39
23	100.73	4.03	25.99	0.65	0.39
25	102.85	4.11	26.74	0.65	0.39
27	103.28	4.13	26.58	0.64	0.39
29	100.30	4.01	26.14	0.65	0.39
Mean	102.44	4.10	26.74	0.65	0.39
Max	104.55	4.18	28.48	0.69	0.42
Min	100.30	4.01	25.99	0.64	0.38
SD.	1.20	0.05	0.74	0.02	0.01

Table A-19 Methane yield ($\text{l. CH}_4 \text{ STP/g VS}_{\text{add}}$) of two-phase mesophilic anaerobic digestion in group 2 (TS 12 %, HRT 20 days)

Date	HRT 20 day /TS 12 %				
	VS influent	OLR ($\text{gVS/L}_{\text{reactor}} \cdot \text{d}$)	L biogas STP/d	L biogas STP/ gVS_{add}	L CH ₄ STP/ gVS_{add}
1	104.13	5.21	17.70	0.43	0.26
3	102.85	5.14	17.83	0.43	0.26
5	102.43	5.12	18.10	0.44	0.27
7	100.30	5.02	18.05	0.45	0.27
9	102.85	5.14	18.38	0.45	0.27
11	101.15	5.06	17.87	0.44	0.27
13	104.13	5.21	18.81	0.45	0.27
15	103.02	5.15	18.20	0.44	0.27
17	100.73	5.04	18.00	0.45	0.27
19	102.85	5.14	18.44	0.45	0.27
21	103.28	5.16	18.25	0.44	0.27
23	102.43	5.12	18.23	0.45	0.27
25	102.94	5.15	18.25	0.44	0.27
Mean	102.54	5.13	18.16	0.44	0.27
Max	104.13	5.21	18.81	0.45	0.27
Min	100.30	5.02	17.70	0.43	0.26
SD.	1.17	0.06	0.29	0.01	0.00

Table A-20 Methane yield ($\text{L CH}_4 \text{ STP/g VS}_{\text{add}}$) of two-phase mesophilic anaerobic digestion in group 2 (TS 12 %, HRT 15 days)

Date	HRT 15 day /TS 12 %				
	VS influent	OLR ($\text{gVS/L}_{\text{reactor.d}}$)	L biogas STP/d	L biogas STP/gVSadd	L CH ₄ STP/gVSadd
1	103.02	6.87	11.54	0.28	0.17
3	100.73	6.72	11.55	0.29	0.17
5	102.85	6.86	12.07	0.29	0.18
7	103.28	6.89	11.98	0.29	0.17
9	102.43	6.83	12.15	0.30	0.18
11	104.13	6.94	11.66	0.28	0.17
13	102.85	6.86	12.00	0.29	0.18
15	104.13	6.94	12.36	0.30	0.18
17	103.02	6.87	12.36	0.30	0.18
19	100.73	6.72	11.95	0.30	0.18
Mean	102.71	6.85	11.96	0.29	0.17
Max	104.13	6.94	12.36	0.30	0.18
Min	100.73	6.72	11.54	0.28	0.17
SD.	1.18	0.08	0.30	0.01	0.00

Table A-21 Methane yield ($\text{l. CH}_4 \text{ STP/g VS}_{\text{add}}$) of two-phase mesophilic anaerobic digestion in group3 (TS 15 %, HRT 30 days)

Date	HRT 30 day /TS 15%				
	VS influent	OLR ($\text{gVS/L}_{\text{reactor.d}}$)	L biogas STP/d	L biogas STP/gVSadd	L CH ₄ STP/gVSadd
1	125.80	4.19	34.39	0.68	0.41
3	128.35	4.28	33.54	0.65	0.39
5	127.67	4.26	31.32	0.61	0.37
7	129.63	4.32	31.97	0.62	0.37
9	126.31	4.21	32.00	0.63	0.38
11	126.65	4.22	32.51	0.64	0.39
13	127.59	4.25	32.92	0.65	0.39
15	128.35	4.28	33.54	0.65	0.39
17	129.20	4.31	33.08	0.64	0.38
19	127.16	4.24	33.23	0.65	0.39
21	127.93	4.26	32.75	0.64	0.38
23	129.20	4.31	32.64	0.63	0.38
25	126.65	4.22	32.25	0.64	0.38
27	128.35	4.28	32.69	0.64	0.38
29	126.31	4.21	33.01	0.65	0.39
31	128.52	4.28	32.99	0.64	0.39
33	126.65	4.22	32.17	0.64	0.38
35	126.23	4.21	31.64	0.63	0.38
37	124.95	4.17	31.49	0.63	0.38
Mean	127.45	4.25	32.64	0.64	0.38
Max	129.63	4.32	34.39	0.68	0.41
Min	124.95	4.17	31.32	0.61	0.37
SD.	1.29	0.04	0.78	0.02	0.01

Table A-22 Methane yield ($\text{L CH}_4_{\text{STP}}/\text{g VS}_{\text{add}}$) of two-phase mesophilic anaerobic digestion in group3 (TS 15 %, HRT 25 days)

Date	HRT 25 day /TS 15%				
	VS influent	OLR ($\text{gVS}/\text{L}_{\text{reactor}}\cdot\text{d}$)	L biogas STP/d	L biogas STP/ gVS_{add}	L CH ₄ STP/ gVS_{add}
1	126.65	5.07	0.17	0.52	0.31
3	126.23	5.05	0.52	0.54	0.32
5	124.95	5.00	0.90	0.55	0.33
7	126.65	5.07	1.23	0.53	0.32
9	125.80	5.03	1.56	0.53	0.32
11	128.35	5.13	1.91	0.54	0.33
13	127.67	5.11	2.29	0.54	0.32
15	129.63	5.19	2.62	0.54	0.32
17	125.97	5.04	3.01	0.54	0.33
19	128.35	5.13	3.34	0.53	0.32
21	129.20	5.17	3.68	0.54	0.32
23	127.16	5.09	4.07	0.54	0.33
25	127.93	5.12	4.45	0.53	0.32
27	129.63	5.19	4.75	0.54	0.32
29	126.31	5.05	4.51	0.54	0.32
Mean	127.36	5.09	2.60	0.54	0.32
Max	129.63	5.19	4.75	0.55	0.33
Min	124.95	5.00	0.17	0.52	0.31
SD.	1.45	0.06	1.52	0.01	0.00

Table A-23 Methane yield ($\text{L CH}_4 \text{ STP/g VS}_{\text{add}}$) of two-phase mesophilic anaerobic digestion in group3 (TS 15 %, HRT 20 days)

Date	HRT 20 day /TS 15%				
	VS influent	OLR ($\text{gVS/L}_{\text{reactor.d}}$)	L biogas STP/d	L biogas STP /gVSadd	L CH ₄ STP /gVSadd
1	128.35	6.42	18.65	0.36	0.22
3	126.31	6.32	18.95	0.38	0.23
5	128.52	6.43	19.11	0.37	0.22
7	126.65	6.33	18.58	0.37	0.22
9	126.23	6.31	18.34	0.36	0.22
11	130.05	6.50	19.33	0.37	0.22
13	126.65	6.33	18.15	0.36	0.22
15	129.63	6.48	19.01	0.37	0.22
17	124.95	6.25	18.66	0.37	0.22
19	126.65	6.33	18.24	0.36	0.22
21	125.80	6.29	18.28	0.36	0.22
23	128.35	6.42	19.34	0.38	0.23
25	127.67	6.38	19.07	0.37	0.22
Mean	127.37	6.37	18.75	0.37	0.22
Max	130.05	6.50	19.34	0.38	0.23
Min	124.95	6.25	18.15	0.36	0.22
SD.	1.53	0.08	0.42	0.01	0.00

Table A-24 Methane yield ($\text{l. CH}_4 \text{ STP/g VS}_{\text{add}}$) of two-phase mesophilic anaerobic digestion in group3 (TS 15 %, HRT 15days)

Date	HRT 15 day /TS 15 %				
	VS influent	OLR ($\text{gVS/L}_{\text{reactor}} \cdot \text{d}$)	L biogas STP/d	L biogas STP/ gVS_{add}	L CH ₄ STP/ gVS_{add}
1	126.65	8.44	11.99	0.24	0.14
3	128.35	8.56	12.66	0.25	0.15
5	126.31	8.42	12.29	0.24	0.15
7	128.52	8.57	12.59	0.25	0.15
9	126.65	8.44	12.67	0.25	0.15
11	126.65	8.44	12.83	0.25	0.15
13	126.23	8.42	13.13	0.26	0.16
15	124.95	8.33	12.66	0.25	0.15
17	126.65	8.44	13.00	0.26	0.15
19	125.80	8.39	12.75	0.25	0.15
Mean	126.68	8.45	12.66	0.25	0.15
Max	128.52	8.57	13.13	0.26	0.16
Min	124.95	8.33	11.99	0.24	0.14
SD.	1.07	0.07	0.33	0.01	0.00

Table A-25 Alkalinity of two-phase mesophilic anaerobic digestion in group I
(TS 8 %, HRT 30, 25 days)

Date	HRT 30 day			HRT 25 day		
	Alkalinity	VFA	VFA: ALK	Alkalinity	VFA	VFA:ALK
2	1328.13	425.00	0.32	1833.33	550.00	0.30
5	1516.67	455.00	0.30	1540.00	539.00	0.35
8	1364.52	398.00	0.29	1712.12	565.00	0.33
11	1431.03	415.00	0.29	1727.27	570.00	0.33
14	1374.19	426.00	0.31	1544.12	525.00	0.34
17	1450.00	435.00	0.30	1642.86	575.00	0.35
20	1425.00	468.00	0.33	1571.43	550.00	0.35
23	1500.00	450.00	0.30	1527.78	550.00	0.36
26	1467.74	455.00	0.31	1571.43	550.00	0.35
29	1486.67	436.00	0.29	1642.86	575.00	0.35
32	1477.42	458.00	0.31	-	-	-
35	1473.33	432.00	0.29	-	-	-
38	1516.67	435.00	0.29	-	-	-
Min.	1328.13	398.00	0.29	1527.78	525.00	0.30
Max.	1516.67	468.00	0.33	1833.33	575.00	0.36
Mean	1447.03	437.54	0.30	1631.32	554.90	0.34
SD.	59.95	19.41	0.01	100.36	16.26	0.02

Table A-26 Alkalinity of two-phase mesophilic anaerobic digestion in group I
(TS 8 %, HRT 20, 15 days)

Date	HRT 20 day			HRT 15 day		
	Alkalinity	VFA	VFA: ALK	Alkalinity	VFA	VFA: ALK
2	1714.29	600.00	0.35	2210.00	1045.00	0.47
5	2109.38	675.00	0.32	2500.00	1250.00	0.50
8	1769.44	637.00	0.36	3239.58	1555.00	0.48
11	1764.71	600.00	0.34	3173.08	1650.00	0.52
14	1874.29	656.00	0.35	3160.38	1675.00	0.53
17	1985.29	675.00	0.34	3190.00	1700.00	0.53
20	1820.00	637.00	0.35	3372.00	1845.00	0.55
23	1765.71	618.00	0.35	-	-	-
26	1822.22	656.00	0.36	-	-	-
Min.	1714.29	600.00	0.32	2210.00	1045.00	0.47
Max.	2109.38	675.00	0.36	3372.00	1845.00	0.55
Mean	1847.26	639.33	0.35	2977.86	1531.43	0.51
SD.	126.03	28.85	0.01	439.36	282.19	0.03

Table A-27 Alkalinity of two-phase mesophilic anaerobic digestion in group 2
(TS 12 %, HRT 30, and 25 days)

Date	HRT 30 day			HRT 25 day		
	Alkalinity	VFA	VFA: ALK	Alkalinity	VFA	VFA: ALK
2	2068.97	618.00	0.30	1977.78	712.00	0.36
5	2096.77	693.00	0.33	2194.29	768.00	0.35
8	2090.00	637.00	0.30	2436.67	731.00	0.30
11	2106.45	693.00	0.33	2384.85	787.00	0.33
14	2123.33	637.00	0.30	2477.42	768.00	0.31
17	2250.00	675.00	0.30	2384.85	787.00	0.33
20	2119.35	637.00	0.30	2317.65	788.00	0.34
23	2096.77	650.00	0.31	2327.27	768.00	0.33
26	2177.42	675.00	0.31	2693.75	862.00	0.32
29	2186.67	656.00	0.30	2696.97	890.00	0.33
32	2123.33	637.00	0.30	-	-	-
35	2186.67	656.00	0.30	-	-	-
38	2129.03	660.00	0.31	-	-	-
Min.	2068.97	618.00	0.30	1977.78	712.00	0.30
Max.	2250.00	693.00	0.33	2696.97	890.00	0.36
Mean	2134.98	655.69	0.31	2389.15	786.10	0.33
SD.	50.86	23.09	0.01	214.41	53.82	0.02

Table A-28 Alkalinity of two-phase mesophilic anaerobic digestion in group 2
(TS 12 %, HRT 20, and 15 days)

Date	HRT 20 day			HRT 15 day		
	Alkalinity	VFA	VFA: ALK	Alkalinity	VFA	VFA: ALK
2	3009.62	1565.00	0.52	3321.67	1993.00	0.60
5	3264.71	1665.00	0.51	3858.33	2315.00	0.60
8	3412.96	1843.00	0.54	3435.48	2130.00	0.62
11	3260.00	1793.00	0.55	3700.00	2220.00	0.60
14	3357.41	1813.00	0.54	3521.43	2465.00	0.70
17	3363.64	1850.00	0.55	4144.23	2693.75	0.65
20	3298.15	1781.00	0.54	4303.03	2840.00	0.66
23	3227.78	1743.00	0.54	-	-	-
26	3291.07	1843.00	0.56	-	-	-
Min.	3009.62	1565.00	0.51	3321.67	1993.00	0.60
Max.	3412.96	1850.00	0.56	4303.03	2840.00	0.70
Mean	3276.15	1766.22	0.54	3754.88	2379.54	0.63
SD.	115.90	95.66	0.02	367.42	305.33	0.04

Table A-29 Alkalinity of two-phase mesophilic anaerobic digestion in group 3
(TS 15 %, HRT 30, and 25 days)

Date	HRT 30 day			HRT 25 day		
	Alkalinity	VFA	VFA: ALK	Alkalinity	VFA	VFA: ALK
2	2666.67	825.00	0.31	3000.00	1230.00	0.41
5	2725.81	842.00	0.31	3150.00	1323.00	0.42
8	2833.33	850.00	0.30	2956.00	1150.00	0.39
11	2850.00	875.00	0.31	3000.00	1245.00	0.42
14	2790.32	880.00	0.32	3255.81	1400.00	0.43
17	2822.58	875.00	0.31	3522.73	1550.00	0.44
20	2933.33	880.00	0.30	3500.00	1575.00	0.45
23	2906.67	872.00	0.30	3440.00	1548.00	0.45
26	2883.33	865.00	0.30	3409.09	1500.00	0.44
29	2850.00	855.00	0.30	3639.53	1565.00	0.43
32	2822.58	875.00	0.31	-	-	-
35	2886.67	866.00	0.30	-	-	-
38	2933.33	880.00	0.30	-	-	-
Min.	2666.67	825.00	0.30	2956.00	1150.00	0.39
Max.	2933.33	880.00	0.32	3639.53	1575.00	0.45
Mean	2838.82	864.62	0.30	3287.32	1408.60	0.43
SD.	77.63	17.02	0.01	248.90	160.85	0.02

Table A-30 Alkalinity of two-phase mesophilic anaerobic digestion in group 3
(TS 15 %, HRT 20, and 15 days)

Date	HRT 20 day			HRT 15 day		
	Alkalinity	VFA	VFA: ALK	Alkalinity	VFA	VFA: ALK
2	3253.33	1722.00	0.53	4275.00	2565.00	0.60
5	3214.52	1693.00	0.53	4193.55	2600.00	0.62
8	3858.33	1875.00	0.49	4246.03	2675.00	0.63
11	3435.48	2130.00	0.62	4140.63	2650.00	0.64
14	3580.65	2000.00	0.56	4516.13	2800.00	0.62
17	3792.31	2110.00	0.56	4958.33	2975.00	0.60
20	3725.81	2230.00	0.60	4893.00	3215.00	0.66
23	3993.75	2432.00	0.61	-	-	-
26	4103.08	2500.00	0.61	-	-	-
Min.	3214.52	1693.00	0.49	4140.63	2565.00	0.60
Max.	4103.08	2500.00	0.62	4958.33	3215.00	0.66
Mean	3661.92	2076.89	0.57	4460.38	2782.86	0.62
SD.	314.12	285.59	0.05	339.60	235.99	0.02

Table A-31 pH of two-phase mesophilic anaerobic digestion in group 1 (TS 8 %, HRT 30, and 25 days)

Time (days)	HRT 30		HRT 25	
	Acid Tank	Methane tank	Acid Tank	Methane tank
2	3.9	7.4	3.8	7.4
5	3.9	7.4	3.8	7.4
8	3.8	7.4	3.7	7.4
11	3.8	7.3	3.7	7.4
14	3.9	7.4	3.7	7.5
17	3.9	7.4	3.6	7.4
20	3.8	7.4	3.8	7.5
23	3.9	7.4	3.8	7.4
26	3.9	7.4	3.7	7.5
29	3.8	7.3	3.8	7.5
32	3.8	7.4	-	-
35	3.9	7.4	-	-
38	3.9	7.4	-	-
Mean	3.86	7.38	3.74	7.44
Max	3.9	7.4	3.8	7.5
Min	3.8	7.3	3.6	7.4
SD.	0.047	0.038	0.070	0.052

Table A-32 pH of two-phase mesophilic anaerobic digestion in group 1 (TS 8 %, HRT 20, and 15 days)

Time	HRT 20		HRT 15	
	Acid Tank	Methane tank	Acid Tank	Methane tank
2	3.7	7.3	3.7	7.2
5	3.7	7.3	3.6	7.2
8	3.6	7.2	3.5	7.1
11	3.7	7.2	3.5	7.1
14	3.6	7.3	3.5	7.2
17	3.6	7.2	3.6	7.1
20	3.7	7.1	3.5	7.2
23	3.7	7.3	-	-
26	3.7	7.2	-	-
Mean	3.67	7.23	3.56	7.16
Max	3.7	7.3	3.7	7.2
Min	3.6	7.1	3.5	7.1
SD.	0.050	0.071	0.079	0.053

Table A-33 pH of two-phase mesophilic anaerobic digestion in group 2 (TS 12 %, HRT 30, and 25 days)

Time (days)	HRT 30		HRT 25	
	Acid Tank	Methane tank	Acid Tank	Methane tank
2	3.8	7.5	3.7	7.5
5	3.8	7.5	3.7	7.5
8	3.7	7.4	3.7	7.4
11	3.9	7.4	3.6	7.5
14	3.9	7.5	3.6	7.5
17	3.8	7.5	3.7	7.5
20	3.7	7.5	3.7	7.4
23	3.8	7.5	3.7	7.4
26	3.8	7.5	3.7	7.4
29	3.9	7.5	3.7	7.6
32	3.9	7.4	-	-
35	3.8	7.4	-	-
38	3.8	7.4	-	-
Mean	3.82	7.46	3.68	7.47
Max	3.9	7.5	3.7	7.6
Min	3.7	7.4	3.6	7.4
SD.	0.069	0.051	0.042	0.067

Table A-34 pH of two-phase mesophilic anaerobic digestion in group 2 (TS 12 %, HRT 20, and 15 days)

Time (days)	HRT 20		HRT 15	
	Acid Tank	Methane tank	Acid Tank	Methane tank
2	3.6	7.2	3.6	6.9
5	3.5	7.1	3.6	6.9
8	3.6	7.1	3.5	6.9
11	3.7	7	3.5	6.8
14	3.6	7	3.5	6.9
17	3.6	6.9	3.5	6.8
20	3.7	7	3.6	6.9
23	3.6	6.9	-	-
26	3.6	6.9	-	-
Mean	3.61	7.01	3.54	6.87
Max	3.7	7.2	3.6	6.9
Min	3.5	6.9	3.5	6.8
SD.	0.060	0.105	0.053	0.049

Table A-35 pH of two-phase mesophilic anaerobic digestion in group3 (TS 15 %, HRT 30, and 25 days)

Time (days)	HRT 30		HRT 25	
	Acid Tank	Methane tank	Acid Tank	Methane tank
2	3.7	7.4	3.6	7.5
5	3.7	7.5	3.7	7.5
8	3.8	7.5	3.6	7.5
11	3.7	7.5	3.6	7.5
14	3.6	7.4	3.7	7.4
17	3.8	7.5	3.6	7.5
20	3.8	7.5	3.6	7.4
23	3.7	7.4	3.7	7.5
26	3.7	7.5	3.6	7.5
29	3.8	7.4	3.6	7.7
32	3.8	7.4	-	-
35	3.7	7.5	-	-
38	3.7	7.4	-	-
Mean	3.73	7.45	3.63	7.50
Max	3.8	7.5	3.7	7.7
Min	3.6	7.4	3.6	7.4
SD.	0.063	0.052	0.048	0.082

Table A-36 pH of two-phase mesophilic anaerobic digestion in group3 (TS 15 %, HRT 20, and 15 days)

Time (days)	HRT 20		HRT 15	
	Acid Tank	Methane tank	Acid Tank	Methane tank
2	3.6	7	3.5	6.8
5	3.6	7	3.5	6.8
8	3.5	6.9	3.4	6.8
11	3.6	6.9	3.4	6.8
14	3.5	6.8	3.5	6.8
17	3.6	6.9	3.5	6.7
20	3.6	6.9	3.5	6.7
23	3.6	6.9	-	-
26	3.5	6.9	-	-
Mean	3.57	6.91	3.47	6.77
Max	3.6	7.0	3.5	6.8
Min	3.5	6.8	3.4	6.7
SD.	0.050	0.060	0.049	0.049

APPENDIX B

STATISTICAL ANALYSIS

Table B -1 The statistical analysis of TS and VS removal efficiencies and Methane yields at 12 experimental runs

- Tests of Normality

condition		Kolmogorov-Smirnov			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
TS removal	1	.177	19	.121	.943	19	.293
	2	.109	19	.200	.955	19	.487
	3	.129	19	.200	.953	19	.450
	4	.139	15	.200	.936	15	.333
	5	.164	15	.200	.892	15	.072
	6	.191	15	.148	.936	15	.334
	7	.210	13	.120	.932	13	.364
	8	.162	13	.200	.951	13	.616
	9	.204	13	.141	.942	13	.483
	10	.261	10	.052	.849	10	.057
	11	.200	10	.200	.910	10	.281
	12	.134	10	.200	.981	10	.973

* This is a lower bound of the true significance.

a Lilliefors Significance Correction

- Tests of Normality

condition		Kolmogorov-Smirnov			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
VS removal	1	.131	19	.200	.978	19	.914
	2	.128	19	.200	.951	19	.412
	3	.186	19	.082	.930	19	.174
	4	.190	15	.151	.942	15	.410
	5	.164	15	.200	.914	15	.158
	6	.190	15	.149	.942	15	.414
	7	.118	13	.200	.956	13	.687
	8	.162	13	.200	.951	13	.616
	9	.204	13	.141	.942	13	.483
	10	.256	10	.062	.922	10	.371
	11	.239	10	.110	.903	10	.239
	12	.209	10	.200	.924	10	.391

* This is a lower bound of the true significance.

a Lilliefors Significance Correction

- Tests of Normality

condition		Kolmogorov-Smirnov			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
m ³ CH ₄ STP/ kg VS added	1	.102	19	.200	.965	19	.664
	2	.181	19	.101	.956	19	.500
	3	.148	19	.200	.926	19	.148
	4	.178	15	.200	.889	15	.066
	5	.210	15	.074	.904	15	.109
	6	.154	15	.200	.908	15	.124
	7	.176	13	.200	.948	13	.566
	8	.146	13	.200	.967	13	.860
	9	.193	13	.198	.932	13	.364
	10	.234	10	.130	.866	10	.090
	11	.183	10	.200	.898	10	.209
	12	.193	10	.200	.965	10	.844

* This is a lower bound of the true significance.

a Lilliefors Significance Correction

Table B-2 Two –way ANOVA analysis of variance for TS removal efficiency from two phase mesophilic anaerobic digestion of OFMSW.

Descriptive Statistics
Dependent Variable: TS removal

HRTs	TS conc.	Mean	Std. Deviation	N
15.00	8.00	68.6900	.91463	10
	12.00	63.4000	.64807	10
	15.00	60.9800	.93190	10
	Total	64.3567	3.37370	30
20.00	8.00	72.2538	.42005	13
	12.00	70.0846	.72783	13
	15.00	69.6654	.40072	13
	Total	70.6679	1.26270	39
25.00	8.00	74.9600	.65770	15
	12.00	74.7067	.40790	15
	15.00	73.0000	.93121	15
	Total	74.2222	1.11414	45
30.00	8.00	77.0789	.52130	19
	12.00	75.7632	.65253	19
	15.00	75.7526	.27763	19
	Total	76.1982	.80234	57
Total	8.00	73.9491	3.09374	57
	12.00	72.0211	4.60271	57
	15.00	71.0482	5.24312	57
	Total	72.3395	4.54410	171

Tests of Between-Subjects Effects
Dependent Variable: TS removal

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	3446.306	11	313.301	778.421	.000
Intercept	825182.619	1	825182.619	2050234.613	.000
HRTS	3028.972	3	1009.657	2508.578	.000
TSCONC	322.752	2	161.376	400.952	.000
HRTS * TS conc.	168.835	6	28.139	69.914	.000
Error	63.995	159	.402		
Total	898353.207	171			
Corrected Total	3510.301	170			

a R Squared = .982 (Adjusted R Squared = .981)

Multiple Comparisons

Dependent Variable: TS removal

LSD

(I) HRTs	(J) HRTs	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
15.00	20.00	-6.3113	.15407	.000	-6.6156	-6.0070
	25.00	-9.8656	.14953	.000	-10.1609	-9.5702
	30.00	-11.8416	.14310	.000	-12.1242	-11.5590
20.00	15.00	6.3113	.15407	.000	6.0070	6.6156
	25.00	-3.5543	.13880	.000	-3.8284	-3.2802
	30.00	-5.5303	.13184	.000	-5.7907	-5.2699
25.00	15.00	9.8656	.14953	.000	9.5702	10.1609
	20.00	3.5543	.13880	.000	3.2802	3.8284
	30.00	-1.9760	.12651	.000	-2.2259	-1.7262
30.00	15.00	11.8416	.14310	.000	11.5590	12.1242
	20.00	5.5303	.13184	.000	5.2699	5.7907
	25.00	1.9760	.12651	.000	1.7262	2.2259

Based on observed means.

* The mean difference is significant at the .05 level.

Multiple Comparisons

Dependent Variable: TS removal

LSD

(I) TS conc	(J) TS conc	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
8.00	12.00	1.9281	.11884	.000	1.6934	2.1628
	15.00	2.9009	.11884	.000	2.6662	3.1356
12.00	8.00	-1.9281	.11884	.000	-2.1628	-1.6934
	15.00	.9728	.11884	.000	.7381	1.2075
15.00	8.00	-2.9009	.11884	.000	-3.1356	-2.6662
	12.00	-.9728	.11884	.000	-1.2075	-.7381

Based on observed means.

* The mean difference is significant at the .05 level.

Table B-3 Two –way ANOVA analysis of variance for VS removal efficiency from two phase mesophilic anaerobic digestion of OFMSW.**Descriptive Statistics**

Dependent Variable: VS removal

HRTs	TS conc.	Mean	Std. Deviation	N
15.00	8.00	78.4400	.54201	10
	12.00	76.8450	.43490	10
	15.00	73.2800	.86897	10
	Total	76.1883	2.27989	30
20.00	8.00	82.8923	1.06963	13
	12.00	80.0846	.72783	13
	15.00	79.6654	.40072	13
	Total	80.8808	1.63882	39
25.00	8.00	87.8133	.36029	15
	12.00	87.6600	.47329	15
	15.00	86.0200	.73892	15
	Total	87.1644	.97983	45
30.00	8.00	88.4895	.46654	19
	12.00	88.3474	.97887	19
	15.00	87.7684	.85248	19
	Total	88.2018	.84293	57
Total	8.00	85.2719	3.90982	57
	12.00	84.2640	4.81020	57
	15.00	82.9184	5.48900	57
	Total	84.1515	4.84948	171

Tests of Between-Subjects Effects

Dependent Variable: VS removal

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	3917.963	11	356.178	707.914	.000
Intercept	1119229.656	1	1119229.656	2224497.413	.000
HRTS	3663.133	3	1221.044	2426.856	.000
TSCONC	201.865	2	100.933	200.606	.000
HRTS * TSCONC	95.885	6	15.981	31.762	.000
Error	79.999	159	.503		
Total	1214929.085	171			
Corrected Total	3997.962	170			

a R Squared = .980 (Adjusted R Squared = .979)

Multiple Comparisons

Dependent Variable: VS removal

LSD

(I) HRTs	(J) HRTs	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
15.00	20.00	-4.6924	.17226	.000	-5.0326	-4.3522
	25.00	-10.9761	.16719	.000	-11.3063	-10.6459
	30.00	-12.0134	.15999	.000	-12.3294	-11.6974
20.00	15.00	4.6924	.17226	.000	4.3522	5.0326
	25.00	-6.2837	.15518	.000	-6.5902	-5.9772
	30.00	-7.3210	.14740	.000	-7.6121	-7.0299
25.00	15.00	10.9761	.16719	.000	10.6459	11.3063
	20.00	6.2837	.15518	.000	5.9772	6.5902
	30.00	-1.0373	.14145	.000	-1.3167	-.7579
30.00	15.00	12.0134	.15999	.000	11.6974	12.3294
	20.00	7.3210	.14740	.000	7.0299	7.6121
	25.00	1.0373	.14145	.000	.7579	1.3167

Based on observed means.

* The mean difference is significant at the .05 level.

Multiple Comparisons

Dependent Variable: VS removal

LSD

(I) TS conc	(J) TS conc	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
8.00	12.00	1.0079	.13287	.000	.7455	1.2703
	15.00	2.3535	.13287	.000	2.0911	2.6159
12.00	8.00	-1.0079	.13287	.000	-1.2703	-.7455
	15.00	1.3456	.13287	.000	1.0832	1.6080
15.00	8.00	-2.3535	.13287	.000	-2.6159	-2.0911
	12.00	-1.3456	.13287	.000	-1.6080	-1.0832

Based on observed means.

* The mean difference is significant at the .05 level.

Table B-4 Two –way ANOVA analysis of variance for VS removal efficiency from two phase mesophilic anaerobic digestion of OFMSW.**Descriptive Statistics**

Dependent Variable: m3 CH4 STP/kg VS add

HRTs	TS conc	Mean	Std. Deviation	N
15.00	8.00	.23470	.003561	10
	12.00	.17470	.004218	10
	15.00	.14990	.004175	10
	Total	.18643	.036413	30
20.00	8.00	.33654	.004156	13
	12.00	.26600	.006377	13
	15.00	.22077	.003609	13
	Total	.27444	.048492	39
25.00	8.00	.43360	.012141	15
	12.00	.39307	.010977	15
	15.00	.32133	.004320	15
	Total	.38267	.047905	45
30.00	8.00	.46247	.008092	19
	12.00	.41921	.007707	19
	15.00	.38416	.009287	19
	Total	.42195	.033349	57
Total	8.00	.38619	.085501	57
	12.00	.33449	.095202	57
	15.00	.28926	.089028	57
	Total	.33665	.097889	171

Tests of Between-Subjects Effects

Dependent Variable: m3 CH4 STP/kg VS add

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1.620	11	.147	2574.459	.000
Intercept	16.219	1	16.219	283540.889	.000
HRTS	1.338	3	.446	7796.542	.000
TSCONC	.259	2	.130	2264.341	.000
HRTS * TSCONC	1.380E-02	6	2.300E-03	40.210	.000
Error	9.095E-03	159	5.720E-05		
Total	21.009	171			
Corrected Total	1.629	170			

a R Squared = .994 (Adjusted R Squared = .994)

Multiple Comparisons

Dependent Variable: m3 CH4 STP/kg VS add
LSD

(I) HRTs	(J) HRTs	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
15.00	20.00	-.08800	.001837	.000	-.09163	-.08438
	25.00	-.19623	.001783	.000	-.19975	-.19271
	30.00	-.23551	.001706	.000	-.23888	-.23214
20.00	15.00	.08800	.001837	.000	.08438	.09163
	25.00	-.10823	.001655	.000	-.11150	-.10496
	30.00	-.14751	.001572	.000	-.15062	-.14441
25.00	15.00	.19623	.001783	.000	.19271	.19975
	20.00	.10823	.001655	.000	.10496	.11150
	30.00	-.03928	.001508	.000	-.04226	-.03630
30.00	15.00	.23551	.001706	.000	.23214	.23888
	20.00	.14751	.001572	.000	.14441	.15062
	25.00	.03928	.001508	.000	.03630	.04226

Based on observed means.

* The mean difference is significant at the .05 level.

Multiple Comparisons

Dependent Variable: m3 CH4 STP/kg VS add
LSD

(I) TS conc.	(J) TS conc.	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
8.00	12.00	.05170	.001417	.000	.04890	.05450
	15.00	.09693	.001417	.000	.09413	.09973
12.00	8.00	-.05170	.001417	.000	-.05450	-.04890
	15.00	.04523	.001417	.000	.04243	.04803
15.00	8.00	-.09693	.001417	.000	-.09973	-.09413
	12.00	-.04523	.001417	.000	-.04803	-.04243

Based on observed means.

* The mean difference is significant at the .05 level.

Table B-5 One-way ANOVA analysis of variance for TS removal efficiency from two phase mesophilic anaerobic digestion of OFMSW.

ANOVA

TS removal

HRTs		Sum of Squares	df	Mean Square	F	Sig.
15.00	Between Groups	310.949	2	155.474	219.493	.000
	Within Groups	19.125	27	.708		
	Total	330.074	29			
20.00	Between Groups	50.186	2	25.093	86.851	.000
	Within Groups	10.401	36	.289		
	Total	60.587	38			
25.00	Between Groups	34.092	2	17.046	34.881	.000
	Within Groups	20.525	42	.489		
	Total	54.618	44			
30.00	Between Groups	22.107	2	11.053	42.808	.000
	Within Groups	13.943	54	.258		
	Total	36.050	56			

Multiple Comparisons

Dependent Variable: TS removal
LSD

HRTs	(I) TS conc	(J) TS conc	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
15.00	8.00	12.00	5.2900	.37639	.000	4.5177	6.0623
		15.00	7.7100	.37639	.000	6.9377	8.4823
	12.00	8.00	-5.2900	.37639	.000	-6.0623	-4.5177
		15.00	2.4200	.37639	.000	1.6477	3.1923
	15.00	8.00	-7.7100	.37639	.000	-8.4823	-6.9377
		12.00	-2.4200	.37639	.000	-3.1923	-1.6477
20.00	8.00	12.00	2.1692	.21083	.000	1.7416	2.5968
		15.00	2.5885	.21083	.000	2.1609	3.0160
	12.00	8.00	-2.1692	.21083	.000	-2.5968	-1.7416
		15.00	.4192	.21083	.054	-.0084	.8468
	15.00	8.00	-2.5885	.21083	.000	-3.0160	-2.1609
		12.00	-.4192	.21083	.054	-.8468	.0084
25.00	8.00	12.00	.2533	.25526	.327	-.2618	.7685
		15.00	1.9600	.25526	.000	1.4449	2.4751
	12.00	8.00	-.2533	.25526	.327	-.7685	.2618
		15.00	1.7067	.25526	.000	1.1915	2.2218
	15.00	8.00	-1.9600	.25526	.000	-2.4751	-1.4449
		12.00	-1.7067	.25526	.000	-2.2218	-1.1915
30.00	8.00	12.00	1.3158	.16486	.000	.9853	1.6463
		15.00	1.3263	.16486	.000	.9958	1.6568
	12.00	8.00	-1.3158	.16486	.000	-1.6463	-.9853
		15.00	.0105	.16486	.949	-.3200	.3411
	15.00	8.00	-1.3263	.16486	.000	-1.6568	-.9958
		12.00	-.0105	.16486	.949	-.3411	.3200

* The mean difference is significant at the .05 level.

Table B-6 One-way ANOVA analysis of variance for VS removal efficiency from two phase mesophilic anaerobic digestion of OFMSW.**ANOVA**

VS removal

HRTs		Sum of Squares	df	Mean Square	F	Sig.
15.00	Between Groups	139.596	2	69.798	169.135	.000
	Within Groups	11.142	27	.413		
	Total	150.738	29			
20.00	Between Groups	80.045	2	40.022	65.452	.000
	Within Groups	22.013	36	.611		
	Total	102.058	38			
25.00	Between Groups	29.646	2	14.823	49.420	.000
	Within Groups	12.597	42	.300		
	Total	42.243	44			
30.00	Between Groups	5.544	2	2.772	4.371	.017
	Within Groups	34.246	54	.634		
	Total	39.790	56			

Multiple Comparisons

Dependent Variable: VS removal

LSD

HRTs	(I) TS conc	(J) TS conc	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
15.00	8.00	12.00	1.5950	.28729	.000	1.0055	2.1845
		15.00	5.1600	.28729	.000	4.5705	5.7495
	12.00	8.00	-1.5950	.28729	.000	-2.1845	-1.0055
		15.00	3.5650	.28729	.000	2.9755	4.1545
	15.00	8.00	-5.1600	.28729	.000	-5.7495	-4.5705
		12.00	-3.5650	.28729	.000	-4.1545	-2.9755
20.00	8.00	12.00	2.8077	.30671	.000	2.1856	3.4297
		15.00	3.2269	.30671	.000	2.6049	3.8490
	12.00	8.00	-2.8077	.30671	.000	-3.4297	-2.1856
		15.00	.4192	.30671	.180	-.2028	1.0413
	15.00	8.00	-3.2269	.30671	.000	-3.8490	-2.6049
		12.00	-.4192	.30671	.180	-1.0413	.2028
25.00	8.00	12.00	.1533	.19998	.448	-.2502	.5569
		15.00	1.7933	.19998	.000	1.3898	2.1969
	12.00	8.00	-.1533	.19998	.448	-.5569	.2502
		15.00	1.6400	.19998	.000	1.2364	2.0436
	15.00	8.00	-1.7933	.19998	.000	-2.1969	-1.3898
		12.00	-1.6400	.19998	.000	-2.0436	-1.2364
30.00	8.00	12.00	.1421	.25837	.585	-.3759	.6601
		15.00	.7211	.25837	.007	.2030	1.2391
	12.00	8.00	-.1421	.25837	.585	-.6601	.3759
		15.00	.5789	.25837	.029	.0609	1.0970
	15.00	8.00	-.7211	.25837	.007	-1.2391	-.2030
		12.00	-.5789	.25837	.029	-1.0970	-.0609

* The mean difference is significant at the .05 level.

Table B-7 One-way ANOVA analysis of variance for Methane yield from two phase mesophilic anaerobic digestion of OFMSW.

ANOVA

m³ CH₄ STP/kg VS add

HRTs		Sum of Squares	df	Mean Square	F	Sig.
15.00	Between Groups	.038	2	.019	1190.614	.000
	Within Groups	.000	27	.000		
	Total	.038	29			
20.00	Between Groups	.089	2	.044	1870.817	.000
	Within Groups	.001	36	.000		
	Total	.089	38			
25.00	Between Groups	.097	2	.048	507.545	.000
	Within Groups	.004	42	.000		
	Total	.101	44			
30.00	Between Groups	.058	2	.029	415.473	.000
	Within Groups	.004	54	.000		
	Total	.062	56			

Multiple Comparisons

Dependent Variable: m3 CH4 STP/kg VS add
LSD

HRTs	(I) TS conc	(J) TS conc	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
15.00	8.00	12.00	.06000	.001787	.000	.05633	.06367
		15.00	.08480	.001787	.000	.08113	.08847
	12.00	8.00	-.06000	.001787	.000	-.06367	-.05633
		15.00	.02480	.001787	.000	.02113	.02847
	15.00	8.00	-.08480	.001787	.000	-.08847	-.08113
		12.00	-.02480	.001787	.000	-.02847	-.02113
20.00	8.00	12.00	.07054	.001908	.000	.06667	.07441
		15.00	.11577	.001908	.000	.11190	.11964
	12.00	8.00	-.07054	.001908	.000	-.07441	-.06667
		15.00	.04523	.001908	.000	.04136	.04910
	15.00	8.00	-.11577	.001908	.000	-.11964	-.11190
		12.00	-.04523	.001908	.000	-.04910	-.04136
25.00	8.00	12.00	.04053	.003569	.000	.03333	.04774
		15.00	.11227	.003569	.000	.10506	.11947
	12.00	8.00	-.04053	.003569	.000	-.04774	-.03333
		15.00	.07173	.003569	.000	.06453	.07894
	15.00	8.00	-.11227	.003569	.000	-.11947	-.10506
		12.00	-.07173	.003569	.000	-.07894	-.06453
30.00	8.00	12.00	.04326	.002722	.000	.03781	.04872
		15.00	.07832	.002722	.000	.07286	.08377
	12.00	8.00	-.04326	.002722	.000	-.04872	-.03781
		15.00	.03505	.002722	.000	.02960	.04051
	15.00	8.00	-.07832	.002722	.000	-.08377	-.07286
		12.00	-.03505	.002722	.000	-.04051	-.02960

* The mean difference is significant at the .05 level.

Table B-8 Stepwise regression for total solids removal from two phase mesophilic anaerobic digestion of OFMSW.**Model Summary**

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	.899	.809	.808	1.99359	
2	.937	.879	.877	1.59227	.261

a Predictors: (Constant), HRTs

b Predictors: (Constant), HRTs, TS conc

c Dependent Variable: TS removal

ANOVA

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	2838.628	1	2838.628	714.228	.000
	Residual	671.673	169	3.974		
	Total	3510.301	170			
2	Regression	3084.366	2	1542.183	608.278	.000
	Residual	425.935	168	2.535		
	Total	3510.301	170			

a Predictors: (Constant), HRTs

b Predictors: (Constant), HRTs, TS conc

c Dependent Variable: TS removal

Coefficients

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	54.677	.678		80.615	.000
	HRTs	.743	.028	.899	26.725	.000
2	(Constant)	59.555	.734		81.127	.000
	HRTs	.743	.022	.899	33.461	.000
	TS conc	-.418	.042	-.265	-9.845	.000

a Dependent Variable: TS removal

Excluded Variables

Model		Beta In	t	Sig.	Partial Correlation	Collinearity Statistics Tolerance
1	TS conc	-.265	-9.845	.000	-.605	1.000

a Predictors in the Model: (Constant), HRTs

b Dependent Variable: TS removal

Table B-8 Stepwise regression for volatile solids removal from two phase mesophilic anaerobic digestion of OFMSW**Model Summary**

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	.922	.850	.849	1.88161	
2	.943	.889	.888	1.62509	.318

- a Predictors: (Constant), HRTs
 b Predictors: (Constant), HRTs, TS conc
 c Dependent Variable: VS removal

ANOVA

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	3399.627	1	3399.627	960.225	.000
	Residual	598.336	169	3.540		
	Total	3997.962	170			
2	Regression	3554.286	2	1777.143	672.923	.000
	Residual	443.676	168	2.641		
	Total	3997.962	170			

- a Predictors: (Constant), HRTs
 b Predictors: (Constant), HRTs, TS conc
 c Dependent Variable: VS removal

Coefficients

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	64.822	.640		101.262	.000
	HRTs	.813	.026	.922	30.988	.000
2	(Constant)	68.692	.749		91.684	.000
	HRTs	.813	.023	.922	35.879	.000
	TS conc.	-.332	.043	-.197	-7.653	.000

- a Dependent Variable: VS removal

Excluded Variables

Model	Beta In	t	Sig.	Partial Correlation	Collinearity Statistics
1 TS conc	-.197	-7.653	.000	-.508	Tolerance
					1.000

- a Predictors in the Model: (Constant), HRTs
 b Dependent Variable: VS removal

Table B-9 Stepwise regression for methane yield from two phase mesophilic anaerobic digestion of OFMSW**Model Summary**

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	.891	.793	.792	.044657	
2	.978	.957	.957	.020321	.316

a Predictors: (Constant), HRTs

b Predictors: (Constant), HRTs, TS conc

c Dependent Variable: m3 CH₄ STP/kg VS add**ANOVA**

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	1.292	1	1.292	647.829	.000
	Residual	.337	169	.002		
	Total	1.629	170			
2	Regression	1.560	2	.780	1888.356	.000
	Residual	.069	168	.000		
	Total	1.629	170			

a Predictors: (Constant), HRTs

b Predictors: (Constant), HRTs, TS conc

c Dependent Variable: m3 CH₄ STP/kg VS add**Coefficients**

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-4.015E-02	.015		-2.643	.009
	HRTs	1.585E-02	.001	.891	25.452	.000
2	(Constant)	.121	.009		12.895	.000
	HRTs	1.585E-02	.000	.891	55.934	.000
	TS conc	-1.380E-02	.001	-.405	-25.459	.000

a Dependent Variable: m3 CH₄ STP/kg VS add**Excluded Variables**

Model		Beta In	t	Sig.	Partial Correlation	Collinearity Statistics
						Tolerance
1	TS conc	-.405	-25.459	.000	-.891	1.000

a Predictors in the Model: (Constant), HRTs

b Dependent Variable: m3 CH₄ STP/kg VS add

APPENDIX C

CALCULATION PROCEDURES

C - 1 Hydraulic retention time (HRT)

The HRT is the ratio of the reactor volume to the flow rate of the influent substrate:

$$\text{HRT} = V / Q$$

where:

HRT = hydraulic retention time, (days)

V = reactor volume, (l)

Q = flow rate, (l/day)

Therefore, it is the time that a fluid element spends in the reactor. This is strictly true ideal reactor.

C - 2 Organic loading rate (OLR)

The organic loading rate is the substrate quantity introduced into the reactor volume in a given time:

$$\text{OLR} = (Q \cdot S) / V$$

where:

OLR = organic loading rate, (kg substrate / m³ reactor day)

Q = substrate flow rate, (m³/day)

S = substrate concentration in the inflow, (kgVS / m³)

Here, the substrate can be defined by means of different measured parameters, as: TS, TVS, COD or BOD.

C – 3 Gas production rate (GPR)

It is the produced biogas/reactor volume ratio, in a given time:

$$\text{GPR} = Q_{\text{biogas}} / V$$

where:

GPR = gas production rate (m^3 biogas / m^3 reactor day)

Q_{biogas} = biogas flow rate, (m^3/day)

V = reactor volume, (m^3).

C - 4 Specific gas production (SGP)

This parameter indicates the biogas produced by a unit of mass of substrate, in terms of the total volatile solids in the feed, as m^3 biogas/kg substrate feed. This index is strictly linked both to the biodegradability of the feed substrate and to the process attitude. The SGP value is often used to compare the performances of different anaerobic processes.

$$\text{SGP} = Q_{\text{biogas}} / Q \cdot S$$

where:

SGP = specific gas production, (m^3 biogas / kg substrate feed)

Q_{biogas} = biogas flow rate, (m^3/day)

Q = inlet flow rate, (m^3/day)

S = substrate concentration in the influent; (kg substrate / m^3).

C - 5 Methane yield

This parameter indicates the biogas produced by a unit of mass of substrate, in terms of the total volatile solids in the feed, as m^3 CH₄/kg substrate feed. (same as SGP)

C - 6 Substrate removed effectiveness

The removal efficiency or substrate conversion, although it represents an unquestionable parameter, can be expressed in several ways.

In fact, different methods to mature substrates or different equations can be found. This is because in anaerobic digestion processes mass balances are difficult to

close and researchers developed different equations to fit the data. Generally, the simplest and most used equation is the following:

$$\eta\% = \frac{Q * S - Q * Se}{Q * S} \times 100$$

Where:

$\eta\%$ = total volatile solids removed, as percentage (%)

Q = inlet and out let flow rate, (m³/day)

S = total volatile solids concentration in the in let flow rate, (kg/m³)

Se = concentration of total volatile solids in the effluent flow rate, (kg/m³)

It is important to observe that some researchers prefer the measurement of the substrate in terms of total solids or volatile solids, whereas others prefer the use of the COD.

According to Ross et al. (1992) the efficiency removal in terms of volatile percentage of the total solids can be expressed as;

$$\%VS_{removal} = \frac{VS.in - VS.out}{VS.in - (VS.in * VS.out)} \times 100$$

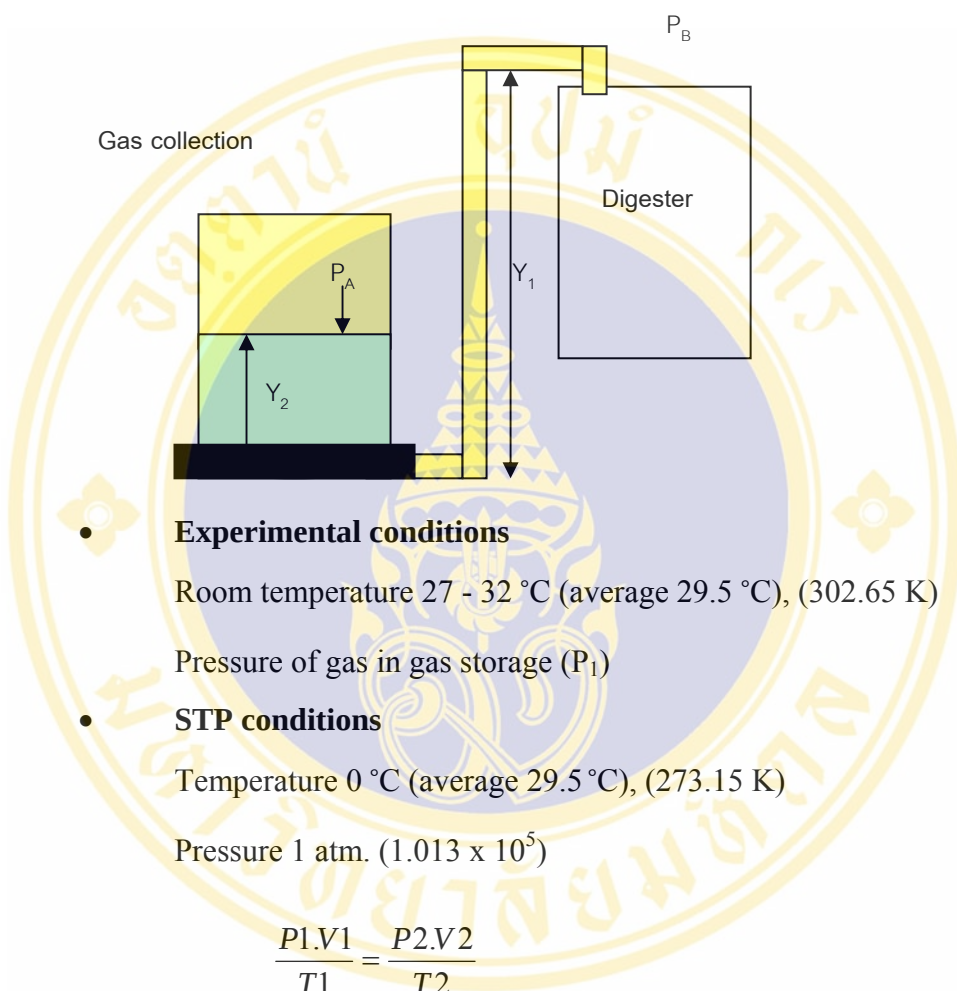
Where:

VS_{in} = percentage of volatile matter in the inflow, (%)

VS_{out} = percentage of volatile matter in the outflow, (%)

With this approach only the biodegradable fraction of the fed volatile solids is considered at the denominator of the equation.

C - 7 Calculation of biogas from experimental condition to standard temperature and pressure, STP



Where;

P_1, P_2 = Pressure of gas at experimental and STP conditions respectively

T_1, T_2 = Temperature at experimental and STP conditions respectively

V_1, V_2 = Volume of gas at experimental and STP conditions respectively

- **Find P_1**

Pressure A = Pressure B

$P_1 + pgy_2 = P_2 + pgy_1$

$P_1 = P_2 + pg(y_1 - y_2)$

$P_1 = P_2 + pgh$

Where;

$$\begin{aligned}
 P_2 &= 1.013 \times 10^5 \text{ N/m}^2 (1 \text{ atm}) \\
 P &= 1,000 \text{ kg/m}^3 \\
 g &= 9.8 \text{ m/s}^2 \\
 h &= \text{height of gas column in gas collection (m)}
 \end{aligned}$$

Example

- Volume of gas in experimental condition 13 l/d

- Height of gas column in gas collection 26.5×10^{-2} m

$$\begin{aligned}
 P_1 &= (1.013 \times 10^5) + (1,000 \times 9.8 \times 26.5 \times 10^{-2}) \\
 &= 103,897 \text{ N/m}^2 \\
 &= 1.03 \text{ atm}
 \end{aligned}$$

From eq.1

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \quad \longrightarrow \quad V_2 = \frac{P_1 V_1 T_2}{T_1 P_2}$$

P_1 = Pressure of gas at experimental (103,897 N/m²)

P_2 = Pressure of gas at STP (101,300 N/m²)

T_1 = Temperature at experimental (302.65 K)

T_2 = Temperature at STP (273.15 K)

V_1 = Volume of gas at experimental (13 l.)

So V_2 = 12.03 l/d @STP #

APPENDIX D

PHOTOGRAPHS OF THE EXPERIMENTS



Figure D-1. Thermo-controller sets



Figure D-2. Acidogenic reactors



Figure D-3. Methanogenic reactors

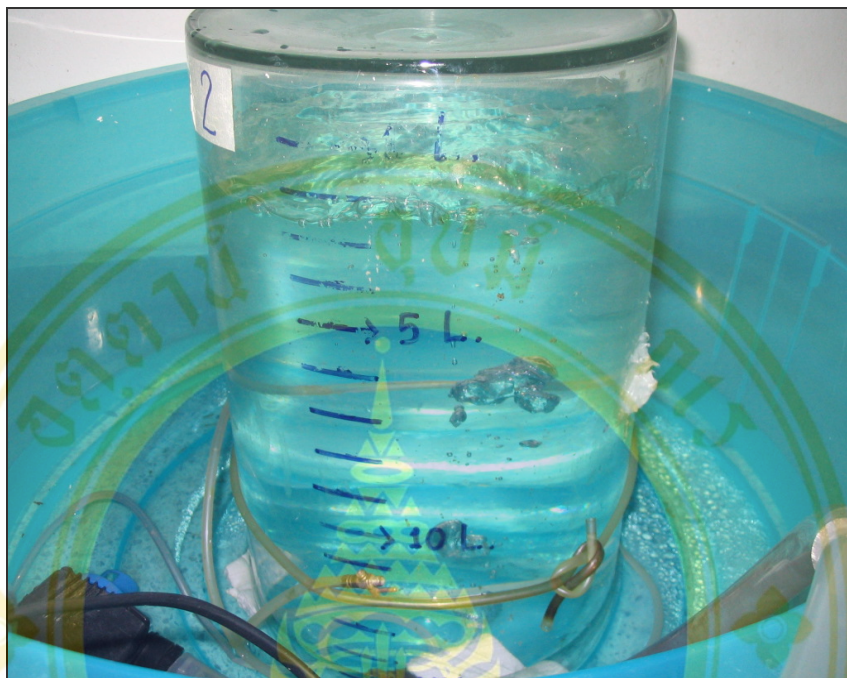


Figure D-4. Gas measurement device (water displacement method)

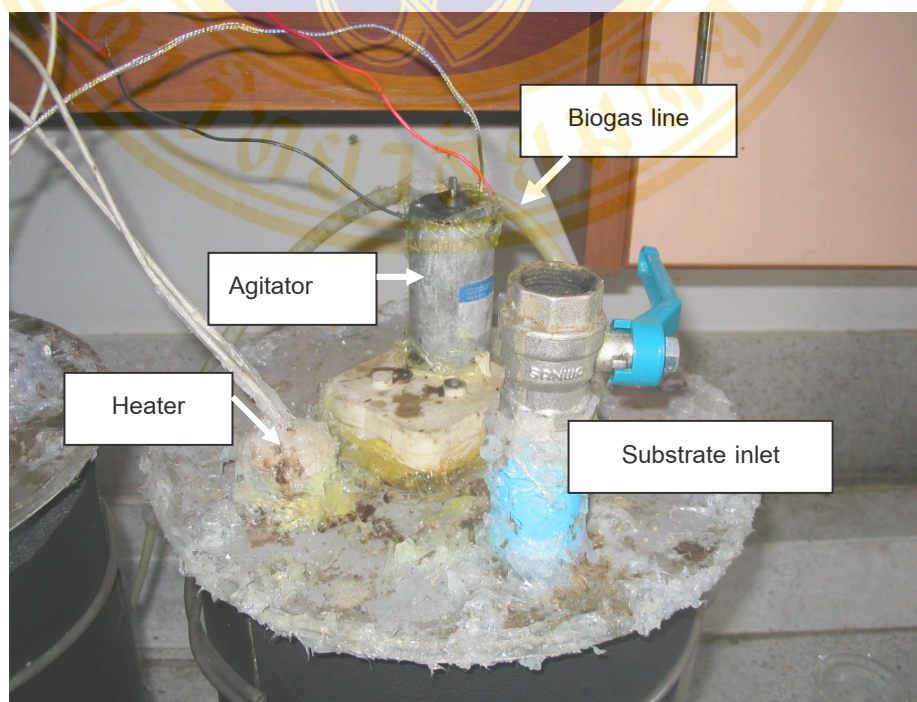


Figure D-5. Top view of methanogenic reactors



Figure D-6. Digested slurry is black after digestion.



Figure D-7 Liquid after separate between solid and liquid (from digested)



Figure D-8 Solid after separate between solid and liquid (from digested)



Figure D-9 Comparison between digested, liquid and solid from anaerobic digestion



Figure D-10 Municipal solid waste from Chonburi province

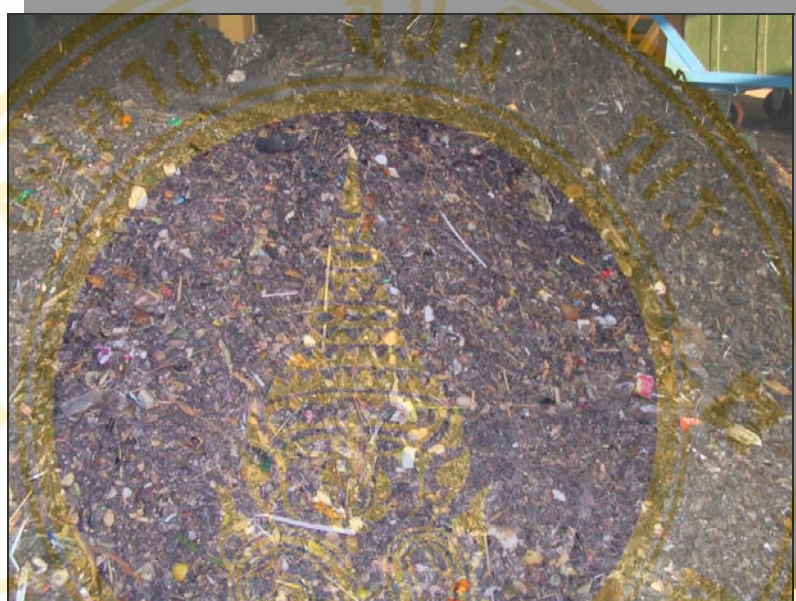
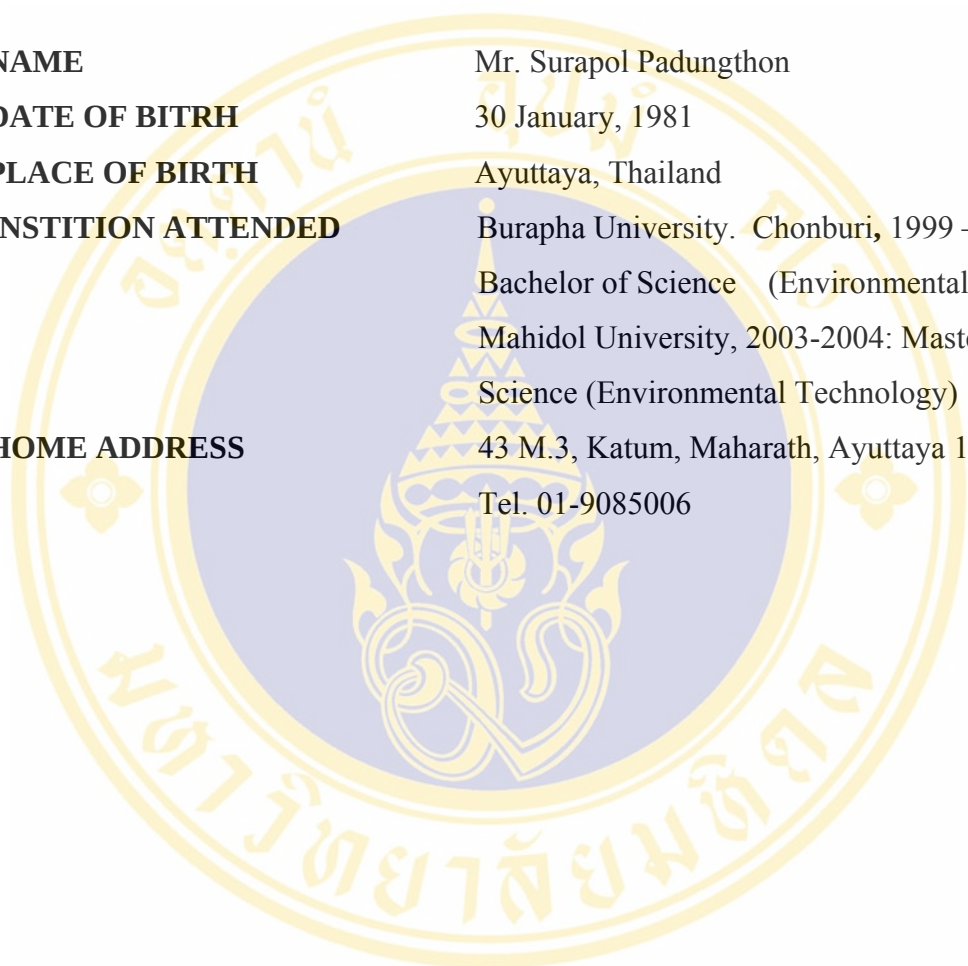


Figure D-11 Oraganic Fraction Municipal Solid Waste from Chonburi province

BIOGRAPHY

The background of the table features a large, faint, circular seal of Mahidol University. The seal is gold-colored with a blue center. It contains a central emblem with a crown and a heart, surrounded by Thai script. The text "มหาวิทยาลัยมหิดล" (Mahidol University) is written around the perimeter of the seal.

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